Comparisons of stemflow and its bio-/abiotic influential factors between two xerophytic shrub species

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Abstract.

Stemflow transports enriched precipitation to the rhizosphere and functioned as an efficient terrestrial flux 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. This study was conducted during the 2014 and 2015 rainy seasons at northern Loess Plateau of China. We measured the branch stemflow volume (SF_b), shrub stemflow equivalent water depth (SF_d), stemflow percentage of incident precipitation (SF%), stemflow productivity (SFP), funnelling ratio (FR), the meteorological characteristics and plant traits of branches and leaves of *C. korshinskii* and *S. psammophila* This study evaluated stemflow efficiency for the first time with the combined results of SFP and FR, and sought to determine the inter- and intra-specific differences of stemflow yield and efficiency between the two species, as well as the specific bio-/abiotic mechanisms that affected stemflow. The results indicated that *C. korshinskii* had a greater stemflow yield and efficiency at all precipitation levels, and the largest inter-specific difference was generally in the 5–10 mm branches during rains of ≤2 mm. Precipitation amount was the most influential meteorological characteristic that affected stemflow yield and efficiency in these two endemic shrub species, and branch angle was the most influential plant trait on FR. For SF_b, stem biomass and leaf biomass were the most influential plant traits for *C. korshinskii* and *S. psammophila*, respectively. For SFP of these two shrubs, leaf traits (the individual leaf area) and branch traits (branch size and biomass allocation pattern) had great influence during smaller rains of ≤10 mm and heavier rains of >15 mm, respectively. The lower precipitation threshold of *C. korshinskii* to start stemflow (0.9 mm vs. 2.1 mm for *S. psammophila*) entitled *C. korshinskii* to employ more rains to harvest water via stemflow. The beneficial leaf traits (e.g., leaf shape, arrangement, area, amount, etc.) might partly explain the great stemflow production of *C. korshinskii*. Comparison of SF_b between the foliated and manually defoliated shrubs during the 2015 rainy season indicated that the newly exposed branch surface at the defoliated period and the resulting rainfall intercepting effects might be an important mechanism affecting stemflow.

1 Introduction

Stemflow delivers precipitation directly 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 nutrients cycling rates at the surface soil matrix (McClain et al., 2003; Johnson and Lehmann, 2006; Sponseller, 2007), 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 stemflow, a vital eco-hydrological flux, is involved in replenishing soil water at shallow and deep layers (Pressland 1973), particularly the root zone (Whitford et al., 1997; Dunkerley 2000; Yang 2010), even during light rains (Li et al., 2009). It might allow the endemic shrubs to remain physically active during drought spells (Navar and Bryan, 1990; Navar, 2011). The stemflow is an important potential source for available water at rain-fed dryland ecosystem (Li et al., 2013). Therefore, producing stemflow with a greater amount in a more efficient manner might be an effective strategy to utilize precipitation by reducing the evaporation loss (Devitt and Smith, 2002; Li et al., 2009), 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; Zhang et al., 2016) and have underestimated its disproportionately high influence on xerophytic shrub species (Andersson, 1991; Levia and Frost, 2003; Li, 2011). Therefore, it is important to quantify the inter- and intra-specific stemflow yield, to assess the stemflow production efficiency and to elucidate the underlying bio-/abiotic mechanisms.

Stemflow yield includes the stemflow volume and depth, and it describes the total flux delivered 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 canopy structure, the shrub species and the eco-zone. Herwitz (1986) introduced the funnelling ratio (FR), which was expressed as the quotient of the volume of stemflow yield 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 yield under different precipitation conditions. However, the FR does not provide a good 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 of stemflow productivity (SFP), expressed as the volume of stemflow yield per unit of branch biomass. The SFP describes the efficiency in an energy-conservation manner by comparing the stemflow yield of a unit biomass increment of different-sized branches. Hence, it is necessary to combine the results of stemflow volume, depth, percentage of incident precipitation, FR and SFP to comprehensively describe the inter- and intra-specific stemflow yield and efficiency at branch and shrub scales.

The precipitation amount is an abiotic mechanism that has generally 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; 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 et al., 2016), biomass (Yuan et al., 2016), etc. Although comparisons of stemflow yield during summer (the growing or foliated season) and winter (the dormant or defoliated season) generally indicate negative effects of leaves because the more stemflow occurred at the leafless period (Dolman, 1987; Masukata at al., 1990; Neal et al., 1993; Mużyło et al., 2012), both negligible and positive effects have also been confirmed by Martinez-Meza and Whitford (1996), Deguchi et al. (2006) and Liang et al. (2009). 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., 2014a, b), air temperature and consequent precipitation type (snow-to-rain vs. snow) (Levia, 2004). Besides, they ignore the effects of the exposed stems at leafless period, which comprise of a new canopy-atmosphere interface and substitute the leaves to intercept raindrops. Therefore, a controlled experiment with the 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 xerophytic shrub species during the 2014 and 2015 rainy seasons. Furthermore, a controlled experiment with defoliated and manually defoliated shrubs was conducted for the two shrub species during the 2015 rainy season. The detailed objectives were to (1) quantify the inter- and intra-specific stemflow yield (SF_b, SF_d and SF%) and efficiency (SFP and FR) at different precipitation levels; (2) identify the most influential meteorological characteristics affecting stemflow yield, and (3) investigate the biotic influential mechanism of plant traits especially at the finer leaf scale by comparing the stemflow yield in the defoliated and manually defoliated shrubs. Given that only the aboveground eco-hydrological process was involved, we focused on stemflow in this study. The achievement of these research objectives would advance our understanding of the ecological importance of stemflow for dryland shrubs and the significance of leaves 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 6.9 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 $\cdot$year^{-1} (Zhao et al., 2010), 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. Two representative experimental stands were established in the southwest of the Liudaogou catchment (Fig. 1). Both *C. korshinskii* and *S. psammophila* were multi-stemmed shrubs that had an inverted-cone canopy and no trunk, with the branches running obliquely from the base. *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 of *C. korshinskii* was concave and lanceolate-shaped, with an acute leaf apex and an obtuse base. Both sides of the leaves were densely sericeous with appressed hairs (Liu et al., 2010). In comparison, *S. psammophila* usually grew to 3–4 m and had an odd number of strip-shaped leaves of 2–4 mm in width and 40–80 mm in length. The young leaves were pubescent and gradually became subglabrous (Chao and Gong, 1999). These two shrub species 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 meteorological characteristics, plant traits and stemflow. To avoid the effects of gully micro-geomorphology on meteorological recording, 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, the rainfall characteristics, e.g., 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). Besides, a meteorological stations was also installed at each experimental stand to record other meteorological characteristics (Fig. 1), e.g., wind speed (WS, m s^{-1}) and direction (WD, °) (Model 03002, R. M. Young Company, Traverse City, Michigan, USA), the air temperature (T, ℃) and humidity (H, %) (Model HMP 155, Vaisala, Helsinki, Finland), and the solar radiation (SR, kW m^{-2}) (Model CNR 4, Kipp & Zonen B.V., Delft, the Netherland).

C. korshinskii and *S. psammophila*, as modular organisms and multi-stemmed shrub species, have branches of that seek their own survival goals and compete with each other for lights and water (Firn, 2004; Allaby, 2010). They are ideal experiment objects to conduct stemflow study at the branch scale. Therefore, we focused on branch stemflow and ignored the canopy variance 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 canopy heights and areas, e.g., 2.1 ± 0.2 m and 5.1 ± 0.3 m^2 for C1–C4, and 3.5 ± 0.2 m and 21.4 ± 5.2 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* (17, 21, 7, 8 for the basal diameter categories of 5–10 mm, 10–15 mm, 15–18 mm and >18 mm, respectively) and 98 branches of *S. psammophila* (20, 30, 20 and 28 branches at the BD categories 5–10 mm, 10–15 mm, 15–18 mm and >18 mm, respectively) were selected for stemflow measurements following the criteria: 1) no intercrossing stems; 2) no turning point in height from branch tip to the base (Dong, et al., 1987); 3) representativeness in amount and branch size. Stemflow was collected using aluminum foil collars, which was fitted around the entire branch circumference and close to the branch base and sealed by neutral silicone caulking (Fig. 1). Nearly all sample branches were selected on the skirts of the crown, where was more convenient for installation and made the sample branches limited shading by other branches lying above as well. Associated with the limited external diameter of foil collars, that minimized the accessing of throughfall (both free and released). A 0.5-cm-diameter PVC hose led the stemflow to lidded containers. The stemflow yield 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. After completing measurements, we return stemflow back to the branch base to mitigate the unnecessary drought stress for the sample branches. By doing so, we tried the best to measure the authentic stemflow yield at branch scale with least unnecessary disturbance, including the effects of free and released throughfall on stemflow measurements in this manuscript.

Besides, the controlled experiment with foliated and manually defoliated shrubs was conducted during the rainy season of 2015 for *C. korshinskii* (five rain events from September 18 to September 30) and for *S. psammophila* (ten rain events from August 2 to September 30) (Fig. 2). Considering the workload to remove all the leaves of 85 branches and 94 branches at *C. korshinskii* (designated as C5) and *S. psammophila* (designated as S5) nearly twice a month, only one shrub individual was selected with similar intra-specific canopy height and area (2.1 m and 5.8 m^2 for C5, 3.3 m and 19.9 m^2 for S5) as other sampled shrubs. A total of 10 branches of C5 (3, 3 and 4 branches at the BD categories 5–10 mm, 10–15 mm and >15 mm), and 17 branches of S5 (4, 5 and 7 branches at the BD categories 5–10 mm, 10–15 mm and >15 mm) were selected for stemflow measurements. Given a limited amount of sample branches and rainfall events, stemflow measurements in this experiment were just used for a comparison with that of the foliated shrubs, but not for a quantitative analysis with meteorological characteristics and plant traits. If no specific stating, it was important to notice that the stemflow yield and efficiency in this study referred to those of the foliated shrubs.

Fig. 2. The controlled experiment for stemflow yield between the foliated and manually defoliated shrubs.

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 C6–C8 (2.0–2.1 m and 5.8–6.8 m^2) and S6–S8 (3.0–3.4 m and 15.4–19.2 m^2), thus allowing the development of allometric models for the estimation of the corresponding biomass and leaf traits of C1–C5 and S1–S5 (Levia and Herwitz, 2005; Siles et al., 2010a, b; Stephenson et al., 2014). A total of 66 branches for C6–C8 and 61 branches for S6–S8 were measured once 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), when the shrubs showed maximum vegetative growth. 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 C6–C8 and 14 branches of S6–S8.

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):

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

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), and the percentage of stem biomass to that of branch (PBMS = BMS/(BML+BMS)*100%, %). Besides, the total stem surface area of individual branch (SA) was computed representing by that of the main stem, which was idealized as the cone (SA = π*BD*BL/20, cm^2). So that, specific surface area representing with LAB (SSAL = LAB/(BML+BMS), cm^2 g^{-1}) and in SA (SSAS = SA/(BML+BMS), cm^2 g^{-1}) could be calculated. It was important to notice that this method underestimated the real stem surface area by ignoring the collateral stems and assuming main stem as the standard corn, so the SA and SSAS would not feed into the quantitative analysis, but apply to reflect a general correlation with SF_b in this study.

In this study, stemflow yield was defined as the branch 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 yield 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 efficiency of different-sized branches in association with biomass allocation pattern:

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

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 yield (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 in a clearing:

$$\text{FR} = 10 * SF_b / (\text{P} * \text{BBA}) \qquad (5)$$

2.4 Data analysis

A Pearson correlation analysis was performed to test the relationship between SF_b and each of the meteorological 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), and kept the regression model having the least AIC values and largest R^2. The separate contribution of individual variables to stemflow yield and efficiency was computed by the method of variance partitioning. The same analysis methods were 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 Meteorological characteristics

Stemflow was measured at 36 rainfall events in this study, 18 events (209.8 mm) in 2014 and 18 events (205.3 mm) in 2015, which accounted for 32.7% and 46.2% of total rainfall events, and 73.1% and 74.9% of total precipitation amount during the experimental period of 2014 and 2015, respectively (Fig. 3). There were 4, 7, 10, 5, 4 and 6 rainfall events at precipitation categories of ≤2 mm, 2–5 mm, 5–10 mm, 10–15 mm, 15–20 mm, and >20 mm, respectively. The average rainfall intensity of incident rainfall events was 6.3 ± 1.5 mm h^{-1}, and the average value of I_5, I_{10} and I_{30} were 20.3 ± 3.9 mm h^{-1}, 15.0 ± 2.9 mm h^{-1} and 9.2 ±1.6 mm h^{-1}, respectively. RD and RI were averaged 5.5 ± 1.1 h and 63.1 ± 8.2 h. The average T, H, SR, WS and WD were 16.5 ± 0.5 ℃, 85.9% ± 2.2%, 48.5 ± 11.2 kw m^{-2}, 2.2 ± 0.2 m s^{-1} and 167.1 ± 13.9, respectively.

Fig. 3. Meteorological characteristics of rainfall events for stemflow measurements during the 2014 and 2015 rainy seasons.

3.2 Species-specific variation of plant traits

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. 4, 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. 4. 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., 12.5 ± 4.2 mm vs. 13.7 ± 4.4 mm, 60 ± 18 °vs. 60 ± 20 °, and 161.5 ± 35.0 cm vs. 267.3 ± 49.7 cm, respectively. Regarding branch biomass accumulation, *C. korshinskii* had a smaller BML (an average of 19.9 ± 10.8 g) and a larger BMS (an average 141.1 ± 110.8 g) than did *S. psammophila* (an average of 27.9 ± 20.7 g and 130.7 ± 101.4 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 did *S. psammophila* in all the BD categories. The PBMS-specific difference increased with an increasing branch size, ranging from 1.2% for the 5–10 mm branches to 7.2% for the >18 mm branches.

Although an increase in LAB and LNB and a decrease in ILAB, SSAL and SSAS were observed for both shrub species with increasing branch size, *C. korshinskii* had a larger LAB (an average of 2509.1 ± 1355.3 cm^2), LNB (an average of 12479 ± 8409) and SSAL (18.2 ± 0.5 cm^2 g^{-1}), but a smaller ILAB (an average of 21.9 ± 3.0 mm^2) and SSAS (2.5 cm^2 g^{-1}) than did *S. psammophila* for each BD level (averaged 1797.9 ± 1118.0 g, 2404 ± 1922, 12.7 ± 0.4 cm^2 g^{-1}, 93.1 ± 27.8 mm^2 and 5.1 ± 0.3 cm^2 g^{-1}) (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 12.2-fold and 2.4-fold larger for *C. korshinskii*, and ILAB was 5.3-fold larger for *S. psammophila*.

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

3.3 Stemflow yield of the foliated and defoliated *C. korshinskii* and *S. psammophila*

In this study, stemflow yield was expressed as SF_b on the branch scale and SF_d and SF% on the shrub scale. For the foliated shrubs, SF_b was averaged 290.6 mL and 150.3 mL for individual branches of *C. korshinskii* and *S. psammophila*, respectively, per incident rainfall events during the 2014 and 2015 rainy seasons. 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 the average of 119.0 mL for the 5–10 mm branches to 679.9 mL for the >18 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 the average of 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 2375.9 mL was averaged for the >18 mm branches of *C. korshinskii* during rains >20 mm at the 2014 and 2015 rainy seasons, but only the average SF_b of 6.8 mL 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 averaged 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 at the 2014 and 2015 rainy seasons. 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 1.0 mm and 8.0% per incident rainfall events during the 2014 and 2015 rainy seasons, 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 2.6 mm and 8.9% during rains >20 mm for *C. korshinskii* and from less than 0.01 mm and 0.7% to 2.2 mm and 7.9% for the corresponding precipitation categories of *S. psammophila*, respectively. Additionally, the individual *C. korshinskii* shrubs had a larger stemflow yield than did *S. psammophila* for all precipitation categories. The differences in SF_d and SF% maximized as a 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 yield (SF_b, SF_d and SF%) between the foliated *C. korshinskii* and *S. psammophila*.

While comparing the intra-specific difference of SF_b between different leaf states, SF_b of the defoliated *S. psammophila* was 1.3-fold larger than did the foliated *S. psammophila* on average, ranging from the 1.1-, 1.0- and 1.4-fold larger for the 5–10 mm, 10–15 mm and >15 mm branches, respectively. A larger difference was noted during smaller rains (Table 3). On the contrary, SF_b of the defoliated *C. korshinskii* was averaged 2.5-fold smaller than did the foliated *C. korshinskii* at all rainfall events. Except for a 1.2-fold larger at the 5–10 mm branches, the 3.3-fold smaller of SF_b was measured at the 10–15 mm and >15 mm branches of the defoliated *C. korshinskii* than did the foliated *C. korshinskii* (Table 3). While comparing the SF_b-specific difference at the same leaf states, a smaller SF_b of the foliated *S. psammophila* was noted than did the foliated *C. korshinskii*. However, SF_b of the defoliated *S. psammophila* was 2.0-fold larger than did the defoliated *C. korshinskii* on average at nearly all BD categories except for the 5–10 mm branches (Table 3).

Table 3. Comparison of stemflow yield (SF_b) of the foliated and manually defoliated *C. korshinskii* and *S. psammophila*.

3.4 Stemflow efficiency of *C. korshinskii* and *S. psammophila*

With the combined results of SFP and FR, stemflow efficiency were assessed for *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 per incident rainfall events during the 2014 and 2015 rainy seasons (Table 4). 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 did *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 4. Comparison of stemflow productivity (SFP) between the foliated *C. korshinskii* and *S. psammophila*.

FR averaged 172.3 and 69.3 for the individual branches of *C. korshinskii* and *S. psammophila* per rainfall events during the 2014 and 2015 rainy seasons, respectively (Table 5). As the precipitation increased, an increasing trend was observed, ranging from the average FR of 129.2 during rains ≤2 mm to 190.3 during rains >20 mm for *C. korshinskii* and from the average FR of 36.7 to 96.1 during the corresponding precipitation categories for *S. psammophila*. FR increased with increasing BA from the average of 149.9 for the ≤30º branches to 198.2 for the >80 ºbranches of *C. korshinskii* and from the average of 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 ºbranches.

Table 5. Comparison of the funnelling ratio (FR) between the foliated *C. korshinskii* and *S. psammophila*.

3.5 Bio-/abiotic influential factors of stemflow yield and 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 rest of 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 methods were applied to analyse the influence of meteorological characteristics on SF_b of these two shrub species. Tested by the Pearson correlation and partial correlation analysises, SF_b related significantly with the precipitation amount, I_{10}, RD and H for *C. korshinskii*, and with P, I_5, I_{10}, I_{30} for *S. psammophila*. The step-wise regression finally identified the precipitation amount as the most influential meteorological characteristics for the two shrub species. Although I_{10} was another influential factor for *C. korshinskii*, it only made a 15.6% contribution to the SF_b on average

SF_b and SF_d had a good linear relationship with the precipitation amount ($R^2 \geq 0.93$) for both shrub species (Fig. 5). 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 0.7 mm, 0.7 mm, 1.4 mm and 0.8 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. 5, fast growth was evident during rains ≤10 mm, but SF% slightly increased afterwards for both shrub species.

Fig. 5. Relationships of branch stemflow volume (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 of these two shrub species at all precipitation levels. ILAB was the most important plant trait affecting SFP during rains ≤10 mm of these species. However, during heavier rain >15 mm, BD and PBMS were the most significant biotic factors for *C. korshinskii* and *S. psammophila*, respectively. For these two shrubs species, it was leaf trait (ILAB) and branch traits (biomass allocation pattern and branch size) that played bigger roles on SFP during smaller rains ≤10 mm and heavier rains >15 mm, respectively. So, it seemed that the rainfall interception process of leaves controlled SFP during the smaller rains, which functioned as the water resource for stemflow production. But while water supply was adequate during heavier rains, the stemflow delivering process of branches might be the bottleneck.

4 Discussion

4.1 Differences of stemflow yield and efficiency between two shrub species

Stemflow yield 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 (Table 2). Although the greatest stemflow yield 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, respectively. Additionally, *C. korshinskii* had a 2.8-fold larger SF_b than did *S. psammophila* for the 5–10 mm branches. Therefore, compared with *S. psammophila*, more effectively might *C. korshinskii* employ precipitation via greater stemflow yield, particularly the 5–10 mm young shoots during rains ≤2 mm.

The FR values indicated the stemflow efficiency with which individual branches could intercept and deliver raindrops (Siegert and Levia, 2014). The average FR of individual branches of *S. psammophila* was 69.3 per individual rainfall during the 2014 and 2015 rainy seasons, which agreed well with the 69.4 of *S. psammophila* in the Mu Us sandland of China (Yang et al., 2008). The average FR of individual branches of *C. korshinskii* was 173.3 in this study, in contrast to the values of 156.1 (Jian et al., 2014) and 153.5 (Li et al., 2008) for *C. korshinskii* at western Loess Plateau of China. Furthermore, these two shrub species had a larger FR than those of many other endemic xerophytic shrubs at 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). Both of *C. korshinskii* and *S. psammophila* employed precipitation in an efficient manner to produce stemflow, and *C. korshinskii* produced stemflow even more efficiently for all precipitation categories particularly during rains ≤2 mm, the inter-specific difference of which decreased with increasing precipitation (Table 5).

The higher stemflow efficiency of *C. korshinskii* for all the precipitation and BD categories was also supported by SFP (Table 4), which characterized stemflow efficiency of different-sized branches in association with biomass allocating patterns. Besides, for both of *C. korshinskii* and *S. psammophila*, the highest SFP was noted at the 5–10 mm branches, 2.19 mL g^{-1} vs. 1.64 mL g^{-1} on average, and the maximum of 5.60 mL g^{-1} vs. 4.59 mL g^{-1} during rains >20 mm (Table 4).

In conclusion, compared with *S. psammophila*, *C. korshinskii* employed different-sized rains to produce stemflow in a greater amount and more efficient manner. That meant a lot for xerophytic shrubs particularly during the rainy season. Because, during this period, they foliate, bloom, reproduce and compete with each other for lights and water. The great water demand made them sensitive to the precipitation variation. It was common for dryland shrubs to experience several wetting-drying cycles (Cui and Caldwell, 1997) when rains are sporadic. The hierarchy of rainfall events has a corresponding hierarchy of ecological responses at the arid environment (Schwinning and Sala, 2004), including the rapid root nutrient uptaking (Jackson and Caldwell, 1991), root elongating (Brady et al., 1995), Mycorrhizal hyphae infection (Jasper et al., 1993), etc. That benefited the formation and maintenance of “fertile islands” (Whitford et al., 1997), “resource islands” (Reynolds et al., 1999) or “hydrologic islands” (Rango et al., 2006). Given that the stemflow was well documented as an important source of rhizosphere soil moisture at dryland ecosystems (Dunkerley, 2000; Yang, 2010; Navar, 2011; Li, et al., 2013), *C. korshinskii* produced stemflow with a greater amount in an more efficient manner might be of great importance in employing precipitation to acquire water (Murakami, 2009) at dryland ecosystems.

4.2 Effects of precipitation threshold to produce stemflow

Precipitation below the threshold wet the canopy and finally evaporated, so it theoretically 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 of xerophytic shrub species was as small as 0.3 mm for *T. vulgaris* at 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., 2013). This result was consistent with the 0.8 mm for *R. offcinalis* at 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 sandland (Li et al., 2009) and the 1.9 mm threshold for *R. soongorica* at western Loess Plateau (Li et al., 2008) and the 1.8 mm threshold for *A. ordosica* at Tengger desert of China (Wang et al., 2013). Generally, for many xerophytic shrub species, the precipitation threshold generally ranges in 0.4–2.2 mm.

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 at western Loess Plateau of China (with a MAP of 420 mm) (Jian et al., 2014). While at Haizetan at southern 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 ≤2.5 mm accounted for 60% of the total rainfall events and 5.4% of the total precipitation amount at 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 1–2 mm, which encompassed 21.3% of all rainfall events during the rainy season, did not produce stemflow, but stemflow yield during rains 1–2 mm was an extra benefit for *C. korshinskii*. Although the total amount was limited, the soil moisture replenishment and the resulting ecological responses were not negligible for dryland shrubs and the peripheral arid environment (Li et al., 2009). A 2 mm summer rain might stimulate the activity of soil microbes, resulting in an increase of soil nitrate in the semi-arid Great Basin at western USA (Cui and Caldwell, 1997), and a brief decomposition pulse (Austin et al., 2004). The summer rains ≥3 mm are usually necessary to elevate rates of carbon fixation in some higher plants at Southern Utah of USA (Schwinning et al., 2003), or for biological crusts to have a net carbon gain at Eastern Utah of USA (Belnap et al., 2004). That benefited the formation and maintenance of the "resource island" at the arid and semi-arid regions (Reynolds et al., 1999). Therefore, a greater stemflow yield and higher stemflow efficiency at rain pulse and light rains, and a smaller precipitation threshold might entitle *C. korshinskii* with more available water at the root zone, because stemflow functioned as an important source of available moisture at dryland ecosystems (Dunkerley, 2000; Yang, 2010; Navar, 2011; Li, et al., 2013). That agreed with the findings of Dong and Zhang (2001) that *S. psammophila* belonged to the water-spending paradigm from the aspect of leaf water relations and anatomic features, and the finding of Ai et al. (2015) that *C. korshinskii* belonged to the water-saving paradigm and had larger drought tolerance ability than *S. psammophila* from the aspect of root anatomical structure and hydraulic traits.

4.3 Effects of leaf traits on stemflow yield

Recent studies at the leaf scale indicated that leaf traits had a significant influence on stemflow (Carlyle-Mose, 2004; Garcia-Estringana et al., 2010). The factors, such as a relatively large number of leaves (Levia et al., 2015; Li et al., 2016), a large leaf area (Li et al., 2015), a high LAI (Liang et al., 2009), a big leaf biomass (Yuan et al., 2016), 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 (Xu et al., 2005), 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 yield, and providing a beneficial morphology that enables the leaves to function as a highly efficient natural water collecting and channelling system.

According to the documenting at *Flora of China* and the field observations in this study (Chao and Gong, et al., 1999; Liu et al., 2010), *C. korshinskii* had beneficial leaf morphology for stemflow yield than did *S. psammophila*, owing to a lanceolate and concaved leaf shape, a pinnate compound leaf arrangement and a densely sericeous pressed pubescence (Fig. 6). Additionally, experimental measurements indicated that *C. korshinskii* had a larger MTA, LAB, LNB and LAI (an average of 54.4°, 2509.1 cm^2, 12479 and 2.4, respectively) and a smaller ILAB (an average of 21.9 mm^2) than did *S. psammophila* (an average of 48.5°, 1797.9 cm^2, 2404, 1.7 and 87.5 mm^2, respectively). 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 features for stemflow yield.

Fig. 6. Comparison of leaf morphologies of *C. korshinskii* and *S. psammophila*.

A controlled experiment was conducted for the foliated and manually defoliated *C. korshinskii* and *S. psammophila* simultaneously at the 2015 rainy season. Compared with the previous studies comparing stemflow yield between the leafed period (summer and growing season) and the leafless period (winter and dormant season) (Dolman, 1987; Masukata et al., 1990; Neal et al., 1993; Martinez-Meza and Whitford, 1996; Deguchi et al., 2006; Liang et al., 2009; Mużyło et al., 2012), we improved this method and guaranteed the identical meteorological conditions and stand conditions, which was believed to provide more convincing evidence for leaf's effect on stemflow yield.

However, contradictory results was reached in this study. SF_b of the foliated *C. korshinskii* was 2.5-fold larger than did the defoliated *C. korshinskii* on average (Table 3), which seemed to demonstrate an overall positive effects of leaves affecting stemflow yield. But, it contradicted with the average 1.3-fold larger SF_b of the defoliated *S. psammophila* than did the foliated *S. psammophila*. Despite of the identical stand and meteorological conditions, the changing interception area for raindrops was not taken into account as did the previous studies, which was mainly represented by leaf area and stem surface area at the foliated and defoliated state, respectively. For comparing the inter-specific SF_b, the normalized area indexes of SSAL and SSAS was analysed in this study. At the foliated state, a 1.4-fold larger SSAL of the *C. korshinskii* was corresponded to a 1.6-fold larger SF_b than that of *S. psammophila*, respectively. But at the defoliated state, a 2.0-fold larger SSAS of *S. psammophila* corresponded to a 1.8-fold larger SF_b than that of *C. korshinskii*, respectively (Table 1 and Table 3). Indeed, it greatly underestimated the real stem surface area of individual branches by ignoring the collateral stems and computing SA with the surface area of the main stem, which was assumed as a standard cone. However, the positive relations of SF_b with SSAL and SSAS at different leaf states might shed light on the long-standing discussion about leaf's effects on stemflow. Although an identical meteorological and stand conditions and similar plant traits were guaranteed, the experiment by comparing stemflow yield between the foliated and defoliated periods might provide no feasible evidence for leaf's effects (positive, negative or neglectable) affecting stemflow yield, if the newly exposed branch surface at the defoliated period and the resulting rainfall intercepting effect were not considered.

5 Conclusions

Compared with *S. psammophila*, *C. korshinskii* produced a larger amount of stemflow more efficiently during different-sized rains; an average 1.9, 1.3, 1.4, 1.6 and 2.5-fold larger in *C. korshinskii* was observed for the branch stemflow volume (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 inter-specific differences in stemflow yield (SF_b, SF_d and SF%) and the production efficiency (SFP and FR) were maximized for the 5–10 mm branches and during rains ≤2 mm. The smaller threshold precipitation (0.9 mm for *C. korshinskii* vs. 2.1 mm for *S. psammophila*), and the beneficial leaf traits might be partly responsible for the superior stemflow yield and efficiency in *C. korshinskii*.

Precipitation amount had the largest influence on both stemflow yield and efficiency for the two shrub species. BA was the most influential plant trait on FR. For SF_b, stem biomass and leaf biomass were the most influential plant traits in *C. korshinskii* and *S. psammophila*, respectively. But for SFP, leaf traits (the individual leaf area) and branch traits (branch size and biomass allocation pattern) had a larger influence in these two shrub species during smaller rains ≤10 mm and heavier rains >15 mm, respectively.

By comparing SF_b between the foliated and manually defoliated shrubs simultaneously at the 2015 rainy season, a contradiction was noted: the larger stemflow yield of *C. korshinskii* at the foliated state, but the larger stemflow yield of *S. psammophila* at the defoliated state. That corresponded to the inter-specific difference of the specific surface area representing by leaves (SSAL) and stems (SSAS) at different leaf states, respectively. It shed lights on the feasibility of experiments by comparing stemflow yield between the foliated and defoliated periods, which might provide no convincing evidence for leaf's effects (positive, negative or neglectable) affecting stemflow yield, if the newly exposed branch surface at the defoliated period and the resulting rainfall intercepting effects were not considered.

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Table captions

Table 1. Comparison of leaf traits, branch morphology and biomass indicators of *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
	SSAL (cm^2 g^{-1})	22.8	17.3	14.3	12.6	18.2 ±0.5	18.4	13.6	10.8	8.6	12.7 ±0.4
	SSAS (cm^2 g^{-1})	3.4	2.3	1.9	1.6	2.5 ±0.1	10.4	5.4	3.3	1.9	5.1 ±0.3
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
	SA (cm^2)	176.8	314.1	508.6	630.7	326.1 ±20.6	268.0	514.1	827.7	1312.3	711.0 ±38.9
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. SSAL and SSAS are the specific surface area representing with LAB and SA, respectively. BD, BL and BA are average branch basal diameter, length and angle, respectively. SA is the surface area of stems. BML and BMS are biomass of leaves and stems, respectively. PBMS is the percentage of stem biomass to that of branch. The average values mentioned above are expressed as the means ± SE.

Table 2. Comparison of stemflow yield (SF_b, SF_d and $SF\%$) between the foliated *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	
e	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	0.1	0.2	0.6	0.9	1.9	2.6	1.0
	$SF\%$ (%)	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	<0.1	0.1	0.5	0.9	1.3	2.2	0.8
	$SF\%$ (%)	N/A	0.7	3.0	6.1	6.8	7.2	7.9	5.5
Inter-specific differences (the ratio of the stemflow yield 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.

Table 3. Comparison of stemflow yield (SF_b) of the foliated and manually defoliated *C. korshinskii* and *S. psammophila*.

Leaf states	BD categories (mm)	*C. korshinskii*						*S. psammophila*						**SF_b(CK)/SF_b(SP)**					
		Incident precipitation amount (mm)					Avg. (P)	Incident precipitation amount (mm)					Avg. (P)	Precipitation amount (mm)					Avg. (P)
		1.7	6.7	6.8	7.6	22.6		1.7	6.7	6.8	7.6	22.6		1.7	6.7	6.8	7.6	22.6	
Foliated	5–10	12.9	85.1	93.0	77.7	254.8	104.7	3.6	32.1	55.1	40.6	140.7	46.9	3.6	2.7	1.7	1.9	1.8	2.2
	10–15	28.6	197.0	274.6	190.1	694.3	276.9	10.1	67.7	141.5	119.6	351.4	130.8	2.8	2.9	1.9	1.6	2.0	2.1
	>15	51.0	382.3	616.0	370.7	1225.7	529.1	16.6	112.5	279.9	272.9	721.3	279.6	3.1	3.4	2.2	1.4	1.7	1.9
	Avg.(BD)	30.2	221.5	317.5	211.4	708.8	297.9	11.9	82.4	191.6	178.6	489.6	186.6	2.5	2.7	1.7	1.2	1.4	1.6
Defoliated	5–10	17.3	87.3	116.7	85.7	264.7	114.3	4.8	22.3	46.7	43.5	152.7	52.4	3.6	3.9	2.5	2.0	1.7	2.2
	10–15	11.0	50.0	65.3	50.0	151.0	65.5	12.0	72.4	159.2	118.2	396.8	129.0	0.9	0.7	0.4	0.4	0.4	0.5
	>15	14.7	105.5	183.3	102.7	504.0	182.0	28.2	177.8	460.1	326.0	947.3	358.7	0.5	0.6	0.4	0.3	0.5	0.5
	Avg.(BD)	13.2	83.4	121.8	79.4	306.6	120.9	17.9	110.2	288.6	198.4	626.3	223.3	0.7	0.8	0.4	0.4	0.5	0.5
SF_b(Def) /SFb(Fol)	5–10	1.3	1.0	1.3	1.1	1.0	1.2	1.3	0.7	0.8	1.1	1.1	1.1	N/A	N/A	N/A	N/A	N/A	N/A
	10–15	0.4	0.3	0.2	0.3	0.2	0.3	1.2	1.1	1.1	1.0	1.1	1.0	N/A	N/A	N/A	N/A	N/A	N/A
	>15	0.3	0.3	0.3	0.3	0.4	0.3	1.7	1.6	1.6	1.2	1.3	1.4	N/A	N/A	N/A	N/A	N/A	N/A
	Avg.(BD)	0.4	0.4	0.4	0.4	0.4	0.4	1.5	1.3	1.5	1.1	1.3	1.3	N/A	N/A	N/A	N/A	N/A	N/A

Note: BD is the branch basal diameter; P is the precipitation amount; SF_b (Def)/SF_b (Fol) refers to the ratio between branch stemflow volume of the foliated and manually defoliated shrubs; and SF_b (SP)/SF_b (CK) refers to the ratio between branch stemflow volume of *S. psammophila* and *C. korshinskii*; N/A refers to not applicable.

Table 4. Comparison of stemflow productivity (SFP) between the foliated *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 5. Comparison of the funnelling ratio (FR) for the foliated *C. korshinskii* and *S. psammophila*.

Intra- and inter-specific differences	BA categories (°)	Precipitation categories (mm) ≤2	2–5	5–10	10–15	15–20	>20	Avg.(P)
Intra-specific differences in *C. korshinskii* (*CK*)	≤30	100.2	127.7	168.1	125.3	193.1	170.3	149.9
	30–60	125.9	133.8	178.5	157.8	205.2	182.1	164.7
	60–80	135.5	148.9	192.5	165.8	217.0	188.6	176.1
	>80	133.2	167.4	205.5	182.6	276.0	226.1	198.2
	Avg.(BA)	129.2	144.8	187.7	162.3	219.6	190.3	173.3
eIntra-specific differences in *S. psammophila* (*SP*)	≤30	32.6	37.3	52.0	59.0	65.8	85.2	55.0
	30–60	34.5	43.4	65.7	70.6	77.7	92.3	64.8
	60–80	37.8	47.9	78.0	78.4	82.3	97.7	72.4
	>80	44.9	55.0	93.5	94.7	94.1	115.7	85.6
	Avg.(BA)	36.7	46.0	72.6	75.3	80.5	96.1	69.3
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.

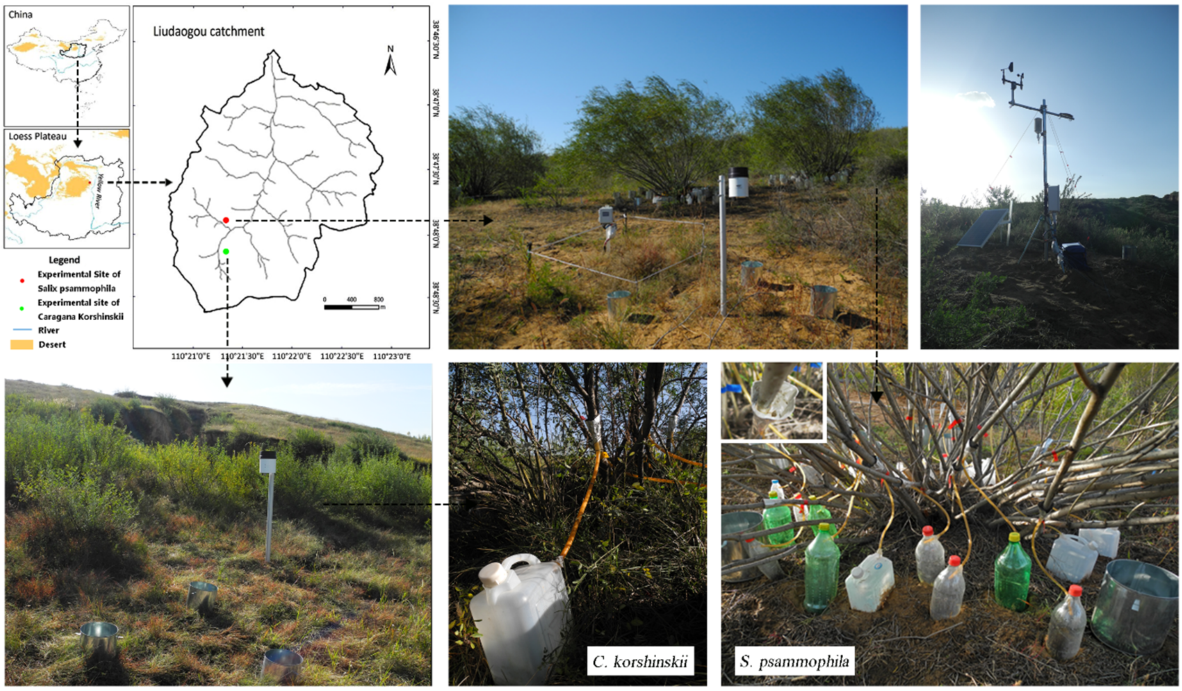
Fig. 2. The controlled experiment for stemflow yield between the foliated and manually defoliated shrubs.

Fig. 3. Meteorological characteristics of rainfall events for stemflow measurements during the 2014 and 2015 rainy seasons.

Fig. 4. 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. 5. Relationships of branch stemflow volume (SF_b), shrub stemflow depth (SF_d) and stemflow percentage ($SF\%$) with precipitation amount (P) for *C. korshinskii* and *S. psammophila*.

Fig. 6. Comparison of leaf morphologies of *C. korshinskii* and *S. psammophila*.



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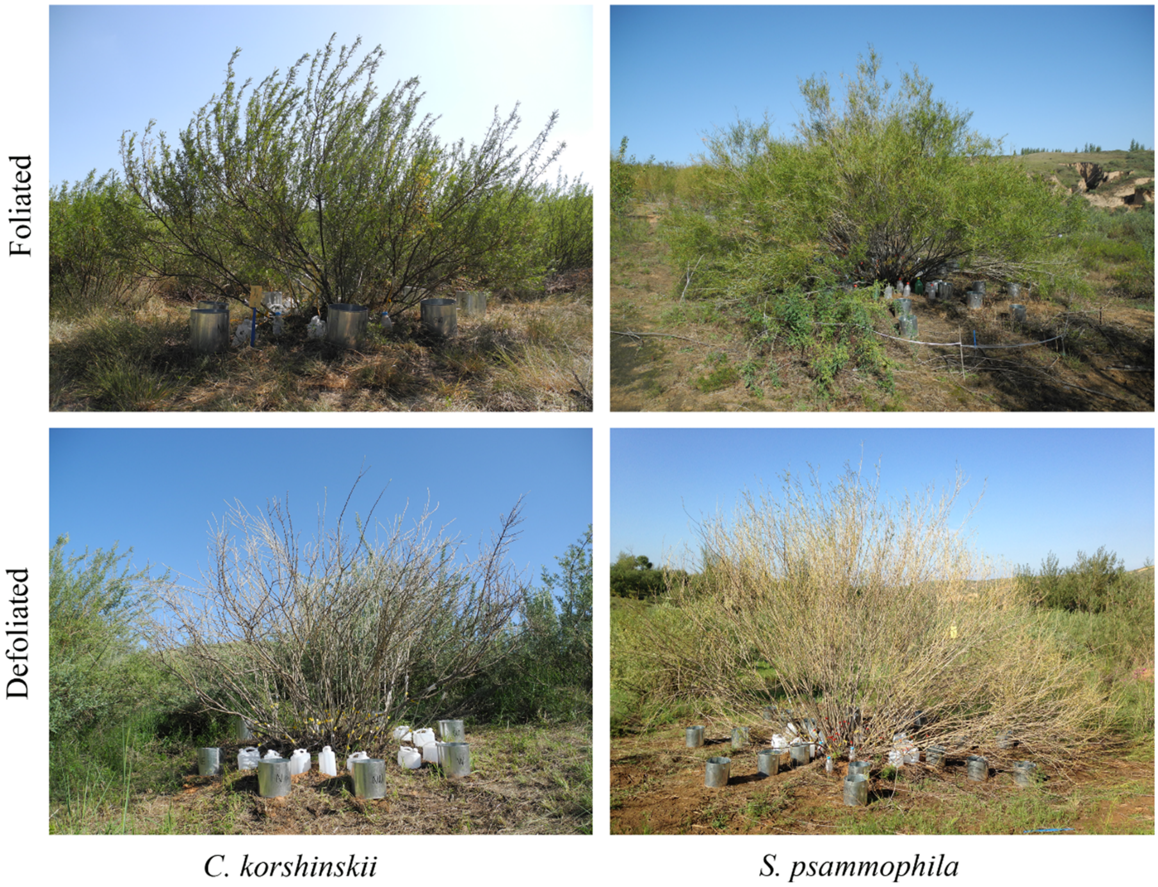

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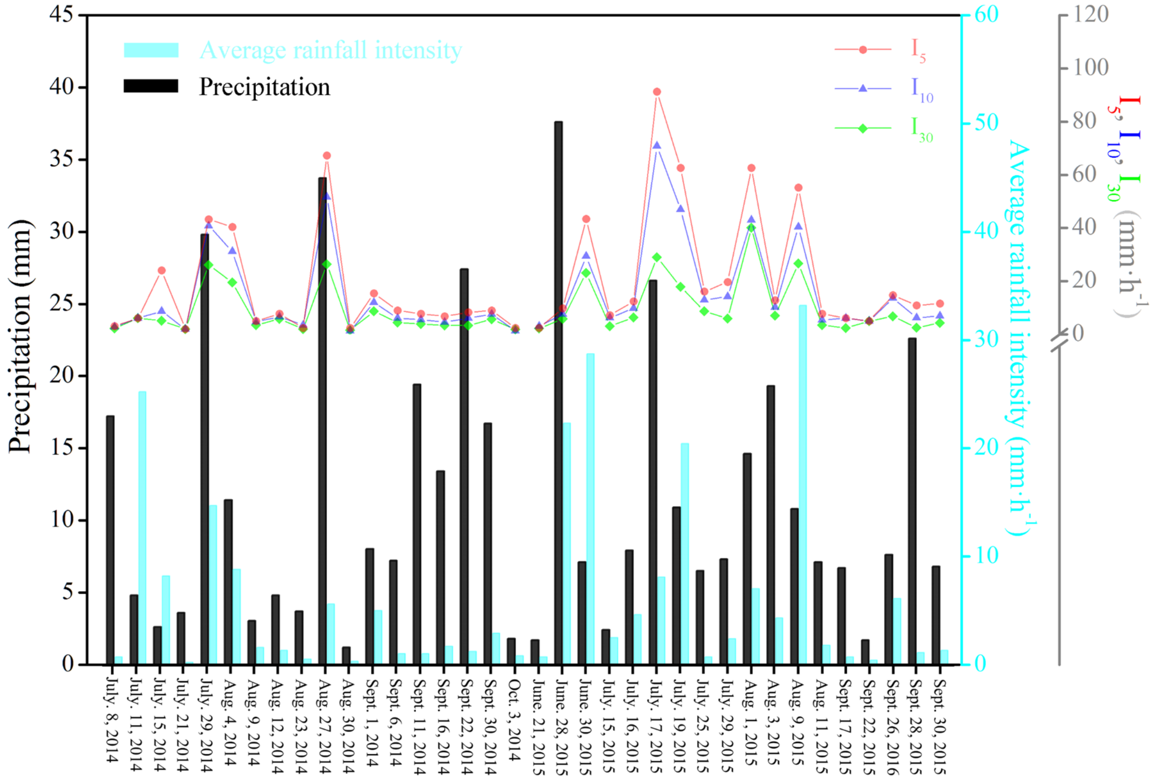

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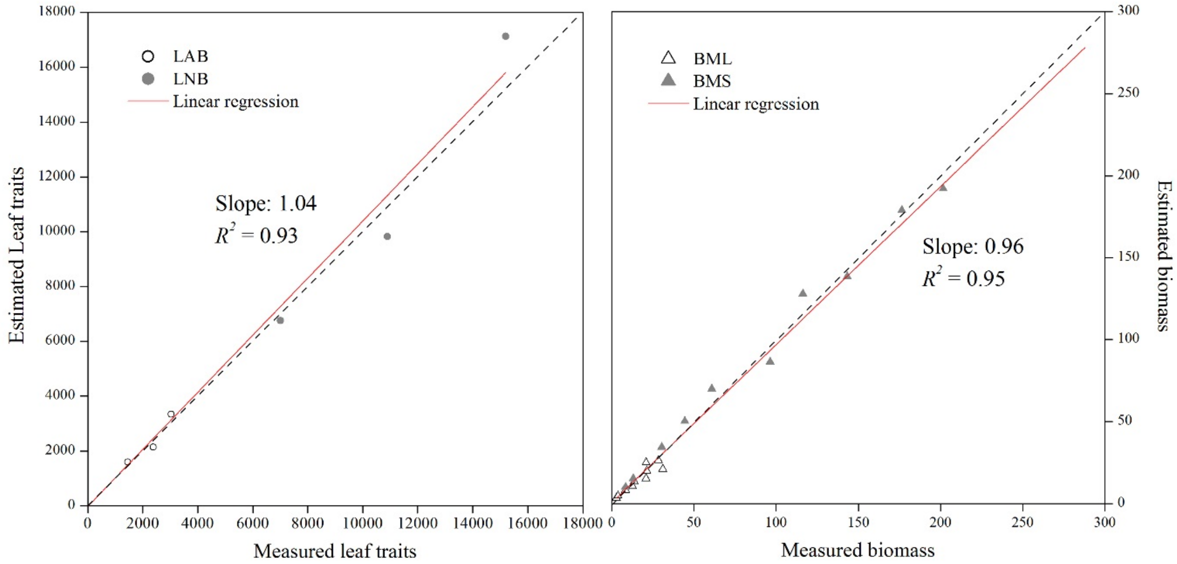

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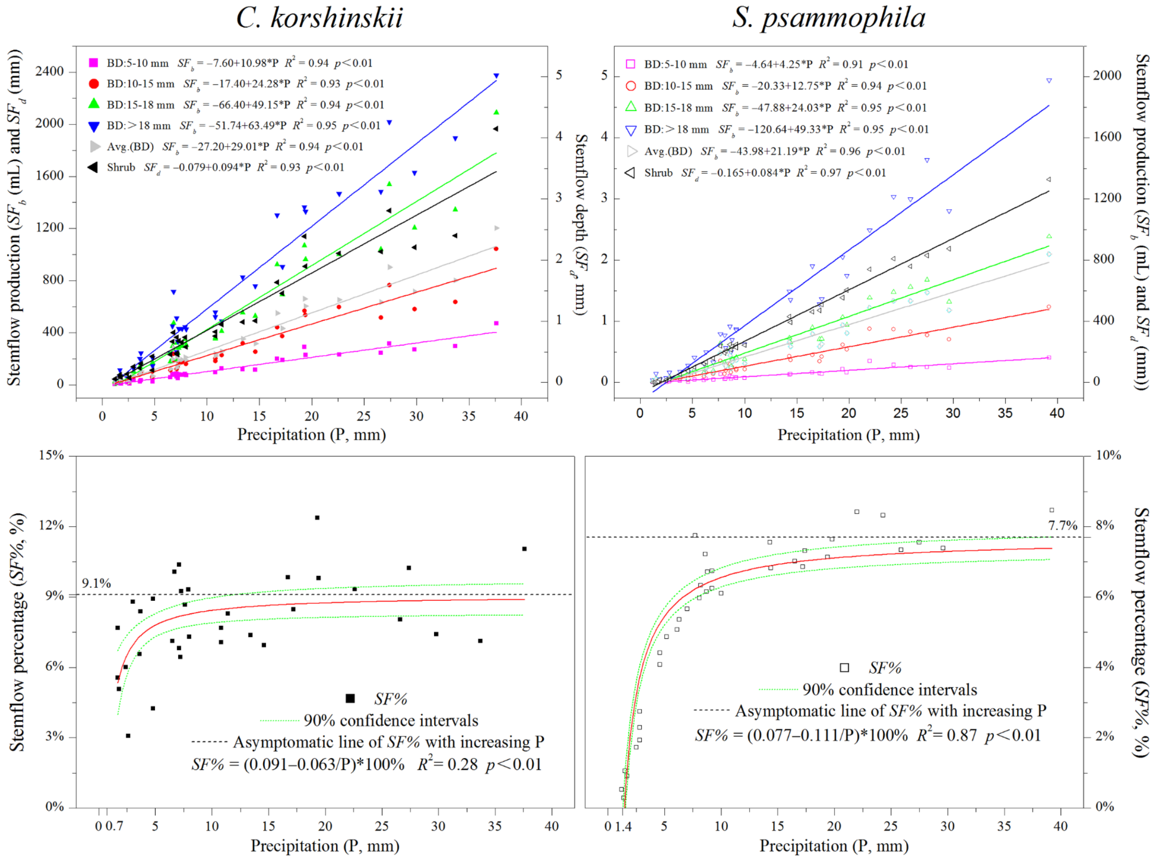

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