Revision Notes

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Memorandum

To: Prof. Lixin Wang, Editor of *Hydrology and Earth System Science*

Subject: **Revision of hess-2016-420**

Dear Prof. Wang,

We have substantially revised our manuscript entitled as "Comparisons of stemflow yield and efficiency between two xerophytic shrubs: the effects of leaves and implications in drought tolerance" after considering all the comments made by Prof. David Dunkerley and another anonymous reviewer. These comments were of great help to improve the overall quality of this manuscript.

The following are the general reply and point-to-point response to all the comments, including (1) Response to Reviewer #1 (Prof. David Dunkerley), (2) Response to Reviewer #2, (3) Revised manuscript with changes marked, and (4) the revised manuscript with no changes marked, respectively.

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Response to Reviewer #1, Prof. David Dunkerley:

General reply:

R1C1: This paper reports field data on stemflow volumes from a dryland field site in China, collected over two successive annual wet seasons. The paper is systematically presented, though rather too long in light of the scope and volume of the primary data that are presented. The field data are of interest because they include stemflow measurements at the scale of individual branches.

Reply:

Thank you for your constructive advices and the "minor revision" recommendation for this manuscript, which has been revised from the following aspects.

1) Some speculative discussion has been deleted in the revised version, and the focus of this work has been shifted to interpret and discuss the measured stemflow data (see Reply to R1C10, please).

2) To explain leaf's effects affecting stemflow yield, a direct evidence has been provided with a controlled experiment of comparing stemflow yield between the foliated and manually defoliated shrubs during the 2015 rainy season (in P.11, Line 235–251, in P.18, Line 433–447, in P.31, Line 758–778, in P.33, Line 812–820 and P.50, Line 1107–1110).

3) To demonstrate the effectiveness in analyzing the abiotic influential factors on stemflow yield and efficiency, more critical meteorological characteristics have been added, including the air temperature, air relative humidity, wind speed and solar radiation in P.9, Line 196–201, in P.14, Line 324–334, and from P.21, Line 529–535.

Reply for comments on Introduction:

R1C2: I felt that the authors needed some evidence to support their repeated claims (e.g. line 58-59) that stemflow exerts a high influence on the survival of dryland shrubs, especially under drought conditions (e.g. line 107 refers to '….a novel characterization of plant drought tolerance….' as one of the outcomes proposed for the present study).

Reply:

Thank you for this comment. New references have been cited as required to support the claim that "stemflow exerts a high influence on the survival of dryland shrubs, especially under drought conditions" in P.4, Line 72–78.

Besides, we have deleted the claim for "a novel characterization of plant drought tolerance", and re-addressed the research objectives and outcomes in P.7, Line 139–142: "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".

Reply for comments on experiment design:

R1C3: The authors collected only data on rainfall and on stemflow volumes. They did not record soil moisture near the plant stems, or observe the fate of stemflow near the soil surface – where, for instance, it might be involved in lateral flow through organic litter materials, or indeed trickle away as overland flow. Instead, they were content to assume tacitly that all of the stemflow was plant-available. Soils are only briefly described, but the authors do note in passing that the surface textures differed between the two shrub species examined (refer to lines 136-137), one being loess and the other, sand.

Reply:

Thank you for commenting on the experimental design of this study. We did not take soil moisture and the relevant fluxes above or under the ground into account at this manuscript, and the reasons were as follow:

1) The objectives of this study.

We aimed to quantify and compare stemflow yield and efficiency of *C. korshinskii* and *S. psammophila* at branch and shrub scales, to explore the biotic influential mechanism particularly at a finer leaf scale, and to identify the most influential meteorological characteristics. Therefore, only the aboveground eco-hydrological process was involved (from P.6, Line 128 to P.7, Line 139), which was illustrated by the following Fig. R1-1.

2) Different surface soil textures.

As pointed in this comment, the surface soil texture differed between the two experimental stands: sand for *S. psammophila* and loess for *C. korshinskii*, respectively. So, it was difficult to compare the contributions of stemflow to the soil moisture dynamics between those two shrub species.

Therefore, in terms of the specific research objectives and the actual stand conditions, we focused on the inter- and intra-specific difference of stemflow yield and efficiency and its bio-/abiotic influential factors between *C. korshinskii* and *S. psammophila* at this manuscript. But, given that stemflow was well documented as an important source of available moisture at dryland ecosystems (Dunkerley, 2000; Yang, 2010; Navar, 2011; Li, et al., 2013) (in P.24, Line 594–598), it was necessary and of great significance to explore the relation between stemflow and soil moisture dynamics. This has been listed in our following research plans.

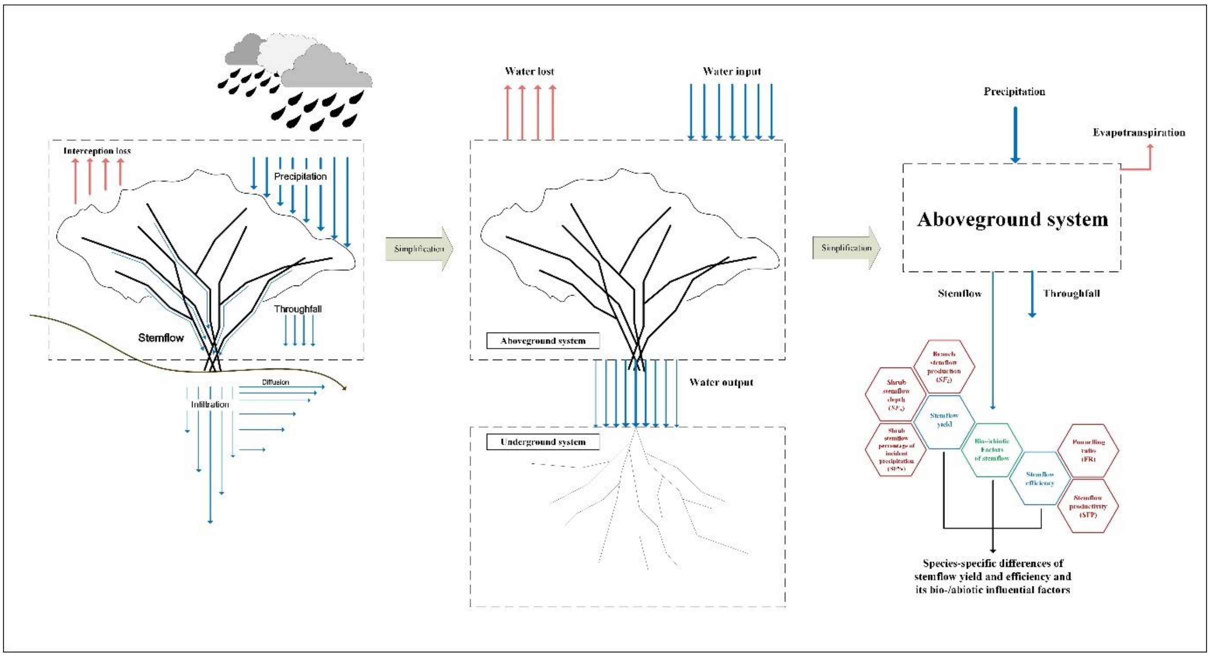

Fig. R1-1. The conceptual framework describing the research objectives and scope: stemflow yield and efficiency and its bio-/abiotic influential factors of *C. korshinskii* and *S. psammophila*.

R1C4: Field experiments were conducted only during the rainy season (line 143) but about a quarter of the annual rainfall comes in the drier season, and I think that conditions (in drier season) then needed to be considered also, as the longer, 8 month dry season is possibly the time when plant available moisture is more critical.

Reply:

Thank you for this advice on continuing experiments in drier season. It is indeed important for the survival of dryland shrubs to receive enough water supply during dry period.

But different from the Mediterranean climate area, the dry season is the cold and dormant season at the experimental sites. During this period, most of dryland shrubs, including *S. psammophila* and *C. korshinskii*, defoliate. Despite of less precipitation supply, there is less water demand as well. On the contrary, the rainy season was the warm and growing season at this area. During this period, the dryland shrubs foliate, bloom, reproduce and compete with each other for lights and water. The greater water demand makes them more sensitive to the precipitation variation. It is common for these dryland shrubs to experience several wetting-drying cycles (Cui and Caldwell, 1997), especially at northern Loess Plateau of China, where rains are sporadic (in P.24, Line 583–594). Therefore, how to employ the precipitation pulse and small rains to improve water availability is of great importance for dryland shrubs at the rainy season. As an important water resource for soil available moisture, to produce stemflow with a great amount in an efficient manner might be an effective strategy to acquire water (Murakami, 2009) and withstand drought (Martinez-Meza and Whitford, 1996) (in P.24, Line 594–598).

Nevertheless, it indeed makes this study more systematical and convincing to involve stemflow measurements in drier season. We would consider it seriously in the future, if condition permits.

R1C5: Only four individuals of each species were instrumented to collect stemflow data. This is not a large sample, though I appreciate the tedium of instrumenting multi-stemmed plants. Furthermore, of the four plants, only about one third of the branches were instrumented for *C. korshinskii*, and less than half for *S. psammophila*. This reduces the effective sample size still further.

Reply:

Thank you for commenting on the effective sample size of this study.

Prior to explaining the effective sample size, it is necessary to introduce that both of *C. korshinskii* and *S. psammophila* are the modular organisms, whose zygote develops into a discrete unit (module), and then produces more units like itself, rather than developing into a complete organism (Allaby, 2010). Each module seeks its own survival goals and the resulting organism level behavior is not centrally controlled (Firn, 2004) (in P.9, Line 202–205). It is required to involve both of the genets (shrubs) and ramets (branches) while counting the sample size of modular organisms (He, 2004).

The branches of *S. psammophila* and *C. korshinskii* compete with each other for lights and water, which are the ideal experiment objects to study stemflow at the branch scale (in P.9, Line 204–207). Thus, in this study, we experimented on individual branches and ignored the canopy variance by selecting sample shrubs with similar intra-specific canopy area and height, e.g., 2.1 ± 0.2 m and 5.1 ± 0.3 m^2 for *C. korshinskii*, and 3.5 ± 0.2 m and 21.4 ± 5.2 m^2 for *S. psammophila*. 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 (in P.10, Line 217–220). Although it is not a great sample size in shrubs amount, it might be enough to discuss stemflow yield and efficiency and the influential mechanism at branch scale.

R1C6: Given that it has often been reported that stemflow may fall from branches when rain becomes intense (and overtaxes the ability of stems to conduct all of the incident water), I wondered about the possible effects of trapping and diverting stemflow from so many branches into collecting vessels. This presumably reduced branch drip and so, perhaps, the branch flow carried by branches lying beneath higher ones from which the stemflow had been diverted. I think that the authors need to consider and discuss this possibility, in relation to the possible path of rainfall and throughfall (both free and released) through the canopy of these shrubs.

Reply:

Thank you for commenting on the possible effects of experimental setting on stemflow measurements.

In this study, we installed one aluminum foil collar to trap stemflow at one branch, which were fitted around the entire branch circumference and close to the branch base. The installed position and the weight of aluminum foil collars ensured limited effects on the original branch inclination. Besides, nearly all sample branches were selected on the skirts of the crown, where was more convenient for installation and ensured the sample branches with 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) (in P.10, Line 223–228). Additionally, other selection criteria were also applied: 1) no intercrossing stems, and 2) no turning point in height from branch tip to the base, so as to avoid stemflow converging and bypassing under the influence of neighboring branches and the irrelevant drip-offs (the released throughfall) (Dong, et al., 1987). After completing measurements, the stemflow was returned 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 at this manuscript (from P. 10, Line 230 to P.11, Line 234).

R1C7: Relevant field data that I would have liked to see included in the paper are on air temperature, humidity, and windspeed. Solar radiation data would also be informative, together with data on whether the rainfall was recorded primarily during daylight hours or at night, since this is relevant to evaporative losses and to the efficiency with which stemflow can be conveyed across the plant surfaces. The authors can hopefully shed light on at least some of these issues.

Reply:

Thank you for commenting on the abiotic influential mechanism of stemflow yield and efficiency. Actually, as shown at the following Fig. R1-2, the meteorological station has been installed to automatically record the wind speed and direction (Model 03002, R. M. Young Company, Traverse City, Michigan, USA), the air temperature and humidity (HMP 155, Vaisala, Helsinki, Finland), and the solar radiation (CNR 4 net radiometer, Kipp & Zonen B.V., Delft, the Netherland). These description has been supplemented in P.9, Line 196–201, and the picture of meteorological station had been updated in Fig.1 in P.55, Line 1142–1144. The detailed meteorological characteristics of rainfall events for stemflow measurements had been supplemented at the "Result" section in P.14, Line 324–334 and indicated by the Fig. 3 in P.58, Line 1149–1151.The relation of meteorological characteristics with stemflow yield and efficiency has been re-analyzed (e.g., indicated at the following Table R1-1 and Table R1-2), and the new findings had been updated from P.20, Line 501 to P.21, Line 506.

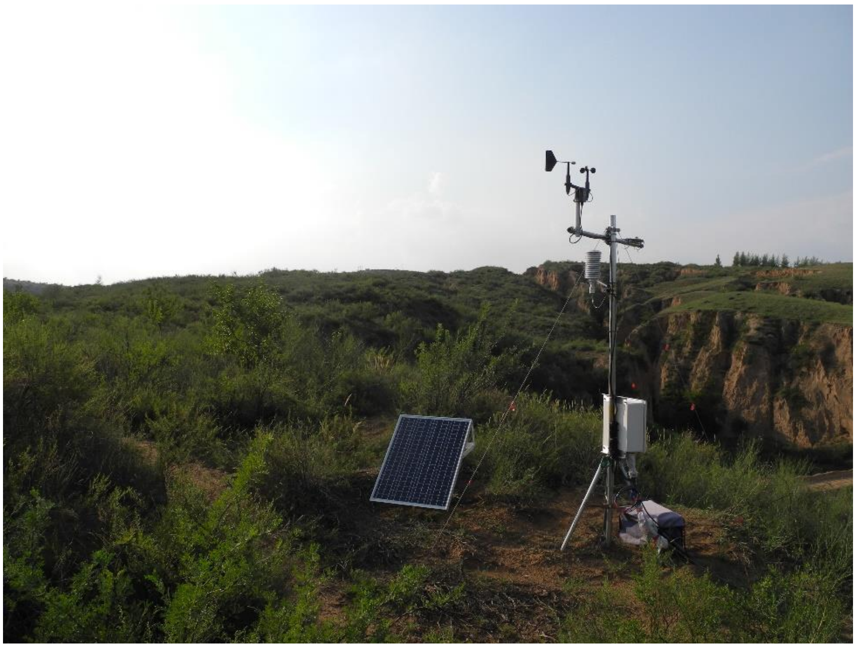

Fig. R1-2. The meteorological station was installed to record the wind speed and direction, the air temperature and humidity, and the solar radiation at Liudaogou catchment.

Table R1-1. The significant meteorological characteristics related with the branch stemflow volume (SF_b) tested by the Pearson and partial correlation analysises.

Shrub species	Significant correlation ($p < 0.05$)	Non-significant correlation ($p > 0.05$)
C. korshinskii	P, I_{10}, RD, H	I, I_5, I_{30}, RI, WS, T, SR
S. psammophila	P, I_5, I_{10}, I_{30}	I, RD, RI, WS, T, H, SR

Note: P means the incident precipitation amount; I, I_5, I_{10}, I_{30} are the average rainfall intensity, and the maximum rainfall intensity in 5, 10, and 30 minutes, respectively; RD is rainfall duration; RI is rainfall intervals; WS is the wind speed; T and H are the air temperature and humidity, respectively; SR is the solar radiation.

Table R1-2. The relation of branch stemflow volume (SF_b) with meteorological characteristics.

Shrubs	BD categories (mm)	Regression models	R^2	VIF	AIC	Contributions to SF_b (%)	
						P	I_{10}
C. korshinskii	5–10	$SF_b = -7.60+10.98*P$	0.94	1	235.6	100	0
		$SF_b = -0.29+11.86*P-1.14*I_{10}$	0.96	1.2	217.4	85.7	14.3
	10–15	$SF_b = -17.40+24.28*P$	0.93	1	296.4	100	0
		$SF_b = 2.64+26.94*P-3.36*I_{10}$	0.97	1.2	264.5	82.0	18.0
	15–18	$SF_b = -66.40+49.15*P$	0.94	1	338.9	100	0
		$SF_b = -32.91+53.75*P-5.77*I_{10}$	0.97	1.2	313.5	84.1	15.9
	>18	$SF_b = -51.74+63.49*P$	0.95	1	348.3	100	0

		$SF_b = -19.50+67.89*P-5.53*I_{10}$	0.97	1.2	333.5	87.5	12.5
	Avg.(BD)	$SF_b = -27.20+29.01*P$	0.95	1	298.7	100	0
		$SF_b = -7.46+31.64*P-3.33*I_{10}$	0.98	1.2	271.3	84.4	15.6
S. psammophila	5–10	$SF_b = -4.66+21.19*P$	0.96	1	N/A	100	0
	10–15	$SF_b = -20.21+12.74*P$	0.94	1	N/A	100	0
	15–18	$SF_b = -47.78+24.03*P$	0.95	1	N/A	100	0
	>18	$SF_b = -120.99+49.35*P$	0.96	1	N/A	100	0
	Avg.(BD)	$SF_b = -43.99+21.19*P$	0.96	1	N/A	100	0

Note: P is the incident precipitation amount; I_{10} is the maximum rainfall intensity in 10 minutes; BD is the branch basal diameter; VIF is the variance inflation factor; AIC is the Akaike information criterion; R^2 is the code of determination; N/A refers to not applicable.

Reply for comments on Results and Discussion:

R1C8: The authors are imprecise when reporting their results. For instance, line 287 reports average branch stemflow volumes in mL, but the authors do not state whether this is across all rainfall, or averaged per rainfall event, or processed in some other way. For reported stemflow volumes, the associated time period must be stated. Likewise, in line 297, 298, etc., are the volumes reported the sum of stemflow for all branches or the mean per branch or something else? The reporting needs to be much clearer. It is the same when the authors discuss funneling ratios in line 342 and following. Are the figures in this section ratios for individual rainfall events, or averaged over all events? As mentioned earlier, the authors also need to consider how the complete trapping of stemflow from upper branches might have affected the stemflow on lower branches, that might have received less drip from above.

Reply:

Thank you for commenting on some imprecise or vague expressions at this manuscript.

We have checked this manuscript carefully and revised these imprecise expressions as required, e.g., adding the corresponding time period in P.17, Line 397, Line 407, Line 414 and Line 419, in P.19. Line 455 and Line 472, in P.23, Line 556 and Line 426, adding the description regarding the sum or the average value for different rainfall events in P.17, Line 397, Line 407 and Line 419, in P.19, Line 454, Line 472 and Line 473–475, in P.21, Line 526, and in P.23, Line 556 and Line 567, and the description regarding the sum or average value for different plant traits in P.17, Line 399 and Line 407, in P.20, Line 476–477, and in P.23, Line 555 and Line 557–558.

The experimental setting for stemflow collection has been explained at Reply for R1C6, in which we described the practices on how to minimize the influences on the authentic branch stemflow measurements.

R1C9: I felt that the authors were vague in their discussion of other results. For instance, lines

366-367 state that precipitation amount was the most important rainfall characteristic that affected stemflow in the studied shrub species. Here I presume they mean that precipitation amount had affected aggregate stemflow volume (and presumably measured at rainfall event scale). Other aspects of stemflow, for instance the peak flux or rate of delivery of stemflow to the base of the plant, are much more likely to have been affected by rainfall intensity. I am not sure why the authors only consider overall stemflow volume, and they should make a case for neglecting other ways to characterize stemflow, including the timing of its delivery from the plant. Stemflow volume alone does not provide a complete exploration of the origin and fate of stemflow.

Reply:

Thank you for this comment.

As stated in this comment, the peak flux, the intensity and the rate of delivery of stemflow were indeed good indicators to characterize stemflow and explain the origin and fate of stemflow from the temporal aspects. This manuscript focused on the stemflow yield and efficiency, and their relationships with plant traits and meteorological characteristics (from P.6, Line 130 to P.7, Line 138). The indicators of SF_b, SF_d, SF%, SFP and FR were commonly used in the previous studies (Honda et al., 2015; Levia et al., 2015; Zimmermann et al., 2015; Su et al., 2016), which could provide feasible explanations to explore the bio-/abiotic influential mechanism of stemflow yield and efficiency. Actually, we have already recorded stemflow temporal dynamics, which will be interpreted in our next research.

R1C10: The fundamental argument of the paper is again in need of supporting evidence from the beginning of the Discussion at line 393. The authors discuss ‘effective utilization’ of precipitation but as pointed out above, have no data relating to this. Their data only estimate stemflow volumes on above-ground parts of the plants. How this translates to soil moisture in the root zone (allowing for evaporation and interception on litter) is not clear.

The authors should not make claims that are not supported (or supportable) using their available data. They argue in lines 404-405 about the ‘effective utilization of precipitation’ by the two shrub species in rainfalls of < 2 mm. However, any stemflow delivered to the base of the shrubs in what are likely to be short showers, might be largely lost to evaporation once the short event ended. This should illustrate how spurious it might be to infer utilization from stemflow data not supported by soil moisture data, or indeed by measures of transpiration by the plants. The authors proceed (e.g. line 420) to argue about energy conservation, again speculating about the utilization of stemflow from rainfall events of < 2 mm. All of this is completely unsupported by the data, and should be eliminated from the paper, or at least highlighted as completely speculative. Again, in line 430-431 the authors speculate about drought tolerance; not only do they have no supporting data, but the data that they do have were derived during the rainy season, and not in drought conditions at all. How the shrub foliage etc. might change during drought years remains unknown and the authors should eliminate all of their speculation about drought tolerance. Their data relate to stemflow alone, and they should restrict themselves primarily to discussing and interpreting those data.

Lines such as 476-478 inclusive are completely speculative, though the authors write as though they are presenting a result from their work. They refer to stemflow production under ‘water stress conditions’ though they did not observe this; they refer to their estimated stemflow being ‘of significant importance for the survival of the xerophytic shrubs, particularly during long intervals with no rainfall’ though they present absolutely no evidence to support this claim, having no data from long periods with no rainfall. All of this speculation should be eliminated from the paper, or at the very least identified as speculation not supported by any data.

Overall, the focus of the paper needs to shift from speculation to the discussion of what can validly be determined from the field evidence available, namely, the estimated stemflow volumes.

Reply:

Thank you for your comments and advices on some speculative discussions for the original version of this manuscript. The focus of the revised manuscript has been shifted from the addressing of some speculations to the interpreting of the measured stemflow data, and we discussed the benefits brought by higher stemflow yield and efficiency for dryland shrubs more cautiously.

To avoid confusions in this study, “precipitation utilization” has been deleted (in P.22, Line 546 and in P.24, Line 582) or changed to “employ precipitation to produce stemflow” (in P.22, Line 550 and in P.23, Line 564). Besides, we revised this manuscript carefully and tried best to guarantee the fact-based conclusions and precise expressions. The expressions of “water stress conditions” (in P.26, Line 647), “particularly during long intervals with no rainfall” (in P.26, Line 649) as described in this comment have been deleted, and “the utilization of stemflow from rainfall events of <2 mm” have been revised in P.26, Line 649.

For the better evidence-based arguments, new supporting materials have been added at the revised manuscript, including (1) new experimental data in a controlled experiment of the foliated and manually defoliated shrubs of *C. korshinskii* and *S. psammophila* during the 2015 rainy season, (2) new meteorological characteristics including wind speed, air temperature and humidity and solar radiation during the 2014 and 2015 rainy seasons, (3) new references addressing the importance of stemflow as potential resource for soil moisture replenishment at the root zone and the deep layer, and the normal functioning of dryland shrubs. Please see Reply for R1C1 for a detailed description.

Other comments:

Line 41: what are ‘stemflow channels’? Does this imply fixed pathways?

Reply:

Thanks for the correcting. We have revised the “stemflow channels divert precipitation” to “stemflow delivers precipitation” in P.4, Line 57. Additionally, the verb “channel” has also been replaced by “deliver” or “transport” in P.5, Line 87 and in P.23, Line 554.

Line 41: ‘pointedly’ should be ‘directly’ or similar.
Reply: Done (in P.4, Line 57).

Line 44: what is meant by ‘biogeochemical reactivity at the terrestrial-aquatic interface’?
Reply:

The “biogeochemical reactivity at the terrestrial-aquatic interface” refers to the nutrients cycling assisted by the microorganism activity while the nutrients-enriched stemflow infiltrated to the soil matrix, which was cited from the reporting of McClain et al. (2013), including total nitrogen (TN), total phosphors (TP), NH_4^+-N, NO_3^--N, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, etc. (Zhang et al., 2013).

For an easier understanding, this sentence had been changed to “The double-funnelling effects of stemflow and preferential flow create “hot spot” and “hot moment” by enhancing nutrients cycling rates at the surface soil matrix” in P.4, Line 60–61.

Line 58: please cite references to support the claim about ‘disproportionately high influence [of stemflow] on survival and competitiveness of xerophytic shrub species’.
Reply: Done (in P.4, Line 72–76 and in P.24, Line 594–598).

Line 81: insert missing space before ‘Murakami’.
Reply: Done (in P.6, Line 114–115).

Line 155: how do branches exist ‘as independent individuals’?
Reply:

Thank you for your question. It related to the biological attributes of modular organisms. Please see Reply for R1C5 for a detailed explanation. For a better understanding, the expression of “existed as independent individuals” had been deleted at the revised manuscript (in P.9, Line 203–204).

Line 214: ‘at the’ should be ‘in a’.
Reply: Done (in P.13, Line 301).

Line 238: should ‘4080-mm’ be ’40-80 mm’?
Line 475: should ‘events of 12-mm’ read ‘events of 1-2 mm’?
Line 268 and many other instances: do not write ’18-mm’; the hyphen is not allowed in the SI metric system. There must be a space between the numerical quantity and the symbol for the unit of measurement (e.g. ’18 mm’ is correct).
Reply:

Thank you for the correcting and explaining. We had corrected these errors at the revised manuscript (in P.8, Line 173, in P26, Line 650, and in P.16, Line 386).

Line 280: do the authors data justify 4 decimal places of precision? This requires fixing in many places, such as line 475.

Reply:

Thank you for this comment. At the revised manuscript, we kept the fixed one decimal place of precision for all the indicator except for the SFP with the two decimal places, because SFP of one decimal place was too rough to tell a clear difference between different precipitation and BD categories.

Line 492: ‘had not determined yet’ should read ‘have not yet been determined’.

Reply: This sentence had been deleted at the revised manuscript. A similar mistake had been corrected in P.6, Line 107.

Reference:

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Response to Reviewer #2:

General reply:

R2C1: This study explored stemflow yield in relations to rainfall characteristics and the plant traits of branches and leaves for two dominant shrubs (*C. korshinskii* and *S. psammophila*) during rainy seasons in the northern Loess Plateau of China. This manuscript reports important data on stemflow measurements at the scale of individual branches and highlights the effect of canopy structure (e.g. biomass, the leaf area of the branches, the leaf numbers of the branches, stemflow productivity, and the funnelling ratio) on stemflow production. The finding of this study is interesting and fall into the scope of the HESS. However, my main concern is the title, results and discussions are not really robust and can't be fully supported by data, and the interpretation is weak.

Reply:

Thank you for your comments and interests in this study. We have substantially revised the Title and the sections of Introduction, Materials and Methods, Results, and Discussions at the revised manuscript. Please see the detailed replies to the following comments.

R2C2: (1) Title: The "the effects of leaves and implications in drought tolerance" in the title is not well reflected in the results of this study. Although measurements of leaf area index (LAI), the foliage orientation, the leaf area of the branches and the leaf numbers of the branches were made in the study, results of species-specific variation of plant traits (line 236-283) just mainly qualitatively described leaf traits, branch morphology and biomass, which were not directly linked with stemflow characteristics. Moreover, results of this study indicated that precipitation amount was the most influential rainfall characteristic and stem biomass and leaf biomass were the most influential plant traits that affected stemflow in *C. korshinskii* and *S. psammophila*, so the effects of leaves on stemflow were not well investigated in this study. In the case of implications in drought tolerance, authors mainly discussed with personal speculations, there were not solid soil water data to verify it. So I suggest author could delete "the effects of leaves and implications in drought tolerance" from the title.

Reply:

Thank you for your comments and advices regarding the title of this manuscript.

We had revised the title as "Comparisons of stemflow and its bio-/abiotic influential factors between two xerophytic shrub species" (please see P.1, Title).

The effects of leaves on stemflow has been further interpreted with a controlled experiment of comparing stemflow yield between the foliated and manually defoliated shrubs during the

2015 rainy season (in P.11, Line 235–251, in P.18, Line 433–447, in P.31, Line 758–778, in P.33, Line 812–820, and in P.50, Line 1107–1110).

Some speculation, such as "drought tolerance" has been deleted from the title and other places in P.2, Line 39, in P.7, Line 140, in P.8, Line 166, in P.24, Line 601–603, and in P.32, Line 804. Please see the detailed description at Reply to R1C10 at Response to Reviewer #1.

R2C3: (2) Introduction: The objectives of this study were not clear, what's the new findings made by this study? What's the knowledge gaps in stemflow researches for shrubs? In fact, stemflow of *C. korshinskii* and *S. psammophila* were already studied in China, what's the difference between studies? I wonder if authors can highlight the stemflow yield from branches and stemflow productivity between shrubs.

Reply:

Thank you for your comments and constructive advices regarding the new findings of this manuscript, which were listed as follow.

1) We introduced the indicator of stemflow productivity (Yuan et al., 2016) and assessed stemflow efficiency for the first time with the combined results of funnelling ratio and stemflow productivity in this study (in P.2, Line 26). Along with other indicators of SF_b, SF_d and SF%, the inter- and intra-specific differences of stemflow yield and efficiency were studied comprehensively at this manuscript (as indicated at the following Table R2-1).

2) We studied the effects of meteorological characteristics and plant traits particularly at the finer leaf scale affecting stemflow yield and efficiency.

A direct evidence regarding leaf's effects on stemflow yield was provided at this manuscript with a controlled experiment of comparing the branch stemflow yield (SF_b) between the foliated and manually defoliated *C. korshinskii* and *S. psammophila* during the 2015 rainy season. In relative to the previous studies, it was believed the first controlled experiment at field, which guarantee the identical stand conditions and meteorological characteristics (as indicated at the following Table R2-2). We found that the newly exposed branch surface at the defoliated period and the resulting rainfall intercepting effect might be of significance for stemflow production, which was generally ignored by previous studies.

Table R2-1. Comparison of the advantage and drawback between stemflow indicators.

NO.	Stemflow indicators	Expressions	Advantages	Drawbacks
1	Stemflow volume (SF_v, mL)	N/A	Simple and clear to present stemflow yield.	Hard to compare the SF_b-specific differences because of the huge variation of plant traits between
2	Stemflow equivalent water depth (SF_d, mm)	$SF_d = SF_v/CA$		
3	Stemflow percentage of	$SF\% = SF_d/P$		

	incident precipitation (SF%, %)			different plant functional types.
4	Funneling ratio (FR)	FR = SF_v/(P*S)	1) Available to compare inter-specific stemflow efficiency; 2) Commonly used to evaluate stemflow efficiency.	Relative a weak connection with plant growth, e.g., biomass accumulation and allocating patterns.
5	Stemflow productivity (SFP, mL·g^{-1})	SFP = SF_v/BMB	Characterizing stemflow efficiency and relating closely with biomass accumulating and allocating.	No response to variation of meteorological characteristics.

Note: CA is the canopy area; P is the precipitation amount; and BMB is the branch biomass.

Table R2-2. Previous studies regarding leaf's effects on stemflow by comparing stemflow yield at the foliated and defoliated period.

The effects of leaves on stemflow yield	**Relevant studies**	**Reference**
Negative effects	Oak forest in Holland	Dolman, 1987
	Oak forest in Spain	Muzylo et al., 2009
	Laurel forest in Japan	Masukata et al., 1990
	Beech plantation in England	Neal et al., 1993
Positive effects	Stewartia forest in Japan	Liang et al., 2009
Neglectable effects	Desert shrubs in USA	Martinez-Meza and Whitford, 1996
	Broad-leaves forest in Japan	Deguchi et al., 2006

R2C4: (3) Materials and Methods: As shrubs grow during the rainy period, at what period (time) or measurement frequency do authors measure plant traits, particularly for biomass (line 175), how can you confirm them represent real plant trait dynamics, which were not clearly described in the text. Line 155: what's the "modular organisms and multi-stemmed shrub"?

Reply:

Thank you for your comments on experimental design of this manuscript.

It is a good question regarding the time dependency of plant traits measurements, particularly for biomass. We measured biomass and leaf traits simultaneously at middle August when the shrubs showed maximum vegetative growth during the rainy season (in P.12, Line 262). If conducting the dynamic measurements, the shrubs would be constantly disturbed even destroyed, and the results of stemflow yield and efficiency would be biased in this study. The variation of those plant traits was small during the experimental period, and they were generally ignored (Siles et al., 2010a, b; Levia, et al., 2015; Zhang et al., 2015).

The modular organism are those organisms, whose zygote develops into a discrete unit (module), and then produces more units like itself, rather than developing into a complete organism (Allaby, 2010). Each module seeks its own survival goals and the resulting organism level behavior is not centrally controlled (Firn, 2004) (in P.9, Line 202–205). The multi-stemmed shrubs have no trunk but have multiple branches that radiate from their base (in P.8, Line 167–169), e.g., *C. korshinskii* and *S. psammophila* in this study. These two shrub species are the ideal experimental objects to study stemflow at the branch scale.

R2C5: (4) Results: For the most part of the "3.1 Species-specific variation of plant traits", it is not really the results of the study, I would suggest authors move some of the description of *C. korshinskii* and *S. psammophila* to the section of "Materials and Methods". Line 387-390: it is not clear, why big difference existed between rains 10 mm and the heavy rain.

Reply:

Thank you for your comments. The description of plant traits of *C. korshinskii* and *S. psammophila* has been moved to the "Materials and Methods" section as required in P.8, Line 169–175.

We have discussed the reasons for different plant trait of leaves and branches affecting SFP between smaller rains ≤10 mm and heavier rains >15 mm, respectively. It might relate to the specific stemflow producing processes during different-sized rains. Please see the detailed description in P.22, Line 529–535.

R2C6: (5) Discussions: I would suggest authors focus on the interpretation of the results of this study, but not speculations on utilization of more rains via a low precipitation, there was not direct evidence or robust data to support the proposed conclusion.

Reply:

Thank you for your comments on interpreting the results of this manuscript.

The focus of the revised manuscript has been shifted from the discussing of some speculations to the interpreting of the measured stemflow data. We have deleted the vague expressions of "water stress conditions" (in P.26, Line 647), "particularly during long intervals with no rainfall" (in P.26, Line 649). The phrase of "implication in drought tolerance" has also been deleted in the title (in P1, the Title). To avoid confusions at this manuscript, "precipitation utilization" has been deleted (in P.22, Line 546, and in P.24, Line 582) or changed to "employ precipitation to produce stemflow" (in P.22, Line 550, and in P.23, Line 564). More detailed description please see Reply to R1C1and Reply to R1C10 at the Response to reviewer #1.

R2C7: (6) English languages needs refine by a native English speakers.

Reply:

Thank you for this comment. We have already sent this manuscript for a professional language editing. Please see the certificate as follow. Furthermore, the language of revised manuscript has been double checked.

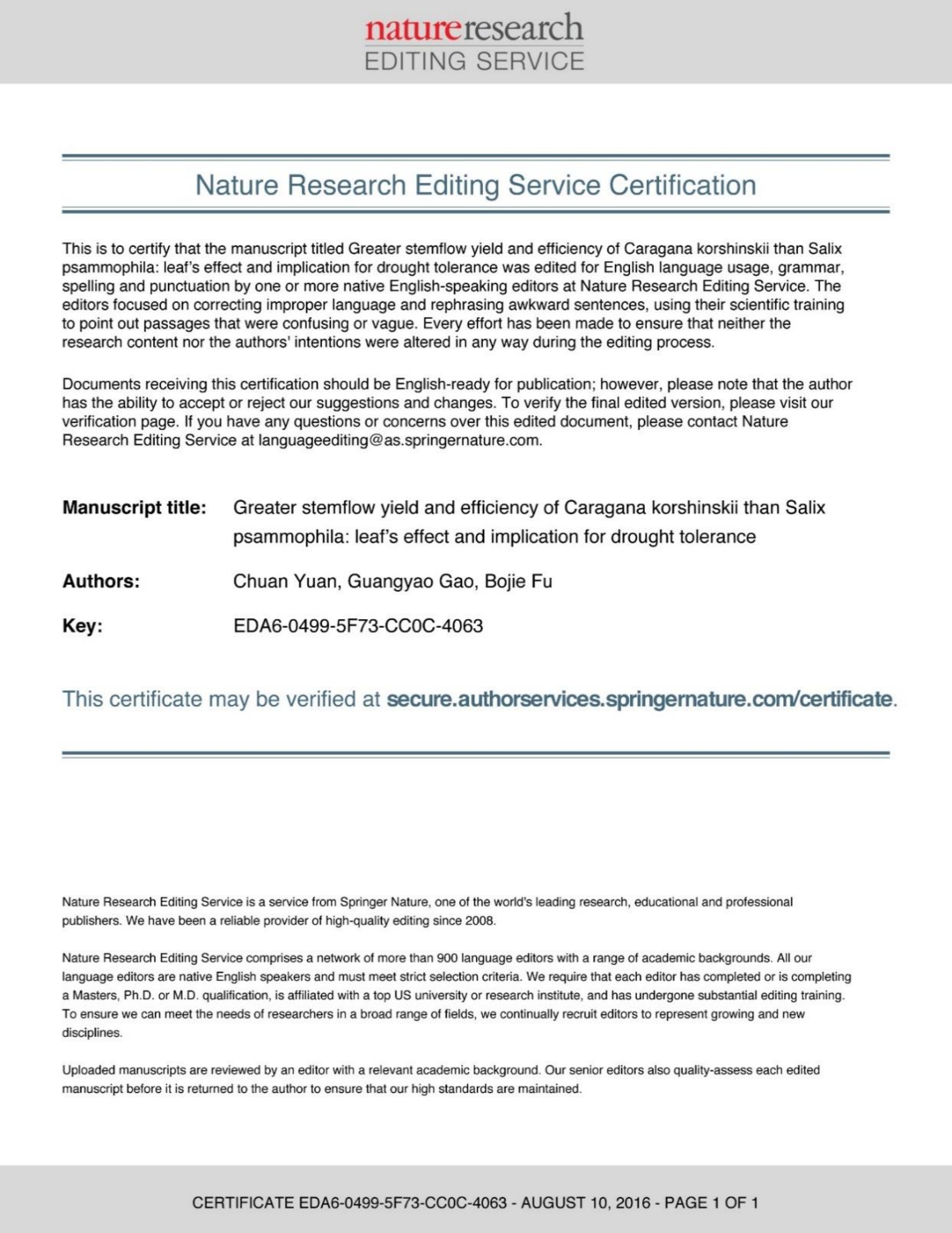

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Fig. R2-1. The certificate for language editing.

If you have any further questions about this revision, please contact us.

Sincerely Yours,

Dr. Guangyao Gao (gygao@rcees.ac.cn)

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Comparisons of stemflow ~~yield~~ and ~~efficiency~~its bio-/abiotic influential factors between two xerophytic ~~shrubs: the effects of leaves and implications in drought tolerance~~shrub species

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Abstract.

Stemflow transports enriched precipitation to the rhizosphere and ~~is highly important for the survival of xerophytic shrubs~~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. ~~In this study,~~ 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), ~~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~~meteorological 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.~~ , respectively. 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~~of stemflow ~~production~~yield and ~~production~~ efficiency between the two species, 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~~*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 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.~~ 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 in *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.

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

1 Introduction

Stemflow ~~channels divert~~delivers 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~~nutrients cycling rates at the ~~terrestrial-aquatic interface~~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 ~~efficient production of~~ stemflow~~ is~~, a vital eco-hydrological flux, is involved in replenishing soil water ~~replenishment~~at shallow and deep layers (Pressland 1973~~) as well as~~), 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 ~~the survival and competitiveness of~~ xerophytic shrub species~~.~~ (Andersson, 1991; Levia, et al., 2003; Li, 2011). Therefore, it is important to quantify the ~~quantification of~~ inter- and intra-specific stemflow ~~production is important~~yield, to assess the stemflow production efficiency and to elucidate the underlying bio-/abiotic mechanisms.

Stemflow ~~production~~yield includes the stemflow volume and depth, and it describes the total flux ~~channelled~~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 ~~is~~was expressed as the quotient of the volume of stemflow ~~produced~~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 ~~production~~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 ~~production~~yield per unit of branch biomass. The SFP describes the efficiency in an energy-conservation manner by comparing the stemflow ~~volume~~yield of a unit biomass increment of different-sized branches.

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 ~~and Xiao,~~et al., 2016), biomass (Yuan et al., 2016~~; Li et al., 2016~~), etc. Although comparisons of stemflow ~~production~~yield during summer (the growing or foliated season) and winter (the dormant ~~seasons usually~~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~~), 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~~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 ~~(*C. korshinskii* and *S. psammophila*) endemic to a semiarid area of northern China~~ 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 ~~of this study~~ were to

(1) quantify the inter- and intra-specific stemflow ~~production~~yield (SF_b, SF_d and SF%) and ~~the production~~ efficiency (SFP and FR~~);~~) at different precipitation levels; (2) ~~investigate the effects of~~ identify the ~~rainfall~~most influential meteorological characteristics ~~and~~ affecting stemflow yield, and (3) investigate the biotic influential mechanism of plant traits ~~on the stemflow in these two shrub species; and (3) specifically identify~~ especially at the finer leaf ~~characteristics that affect~~scale by comparing the stemflow ~~with respect to morphology, structural characteristics and the biomass partitioning pattern.~~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 ~~provide a novel characterization of plant drought tolerance and species competitiveness in terms of stemflow and further the~~ advance our understanding of the ~~effects~~ecological importance of stemflow for dryland shrubs and the significance 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~~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 year^{-1} (Zhao ~~and Shao, 2009~~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~~ 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 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 ~~rainfall~~meteorological characteristics, plant traits and stemflow. To avoid the effects of gully micro-geomorphology on meteorological 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,~~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 ~~exist as independent individuals. Therefore, we focused on the inter- and intra-specific branch stemflow~~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 ~~canopy~~ areas, e.g., 2.1 ± 0.2 m and 5.~~14~~1 ± 0.~~26~~3 m^2 for C1~~-~~–C4, and 3.5 ± 0.2 m and 21.~~35~~4 ± 5.~~21~~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).~~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 ~~volume~~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 ~~C5-C7~~C6–C8 (2.0~~-~~–2.1 m and 5.~~84-~~8–6.~~77~~8 m^2) and ~~S5-S7~~S6–S8 (3.0~~-~~–3.4 m and 15.~~43-~~4–19.~~20~~2 m^2), thus allowing the development of allometric models for the estimation of the corresponding biomass and leaf traits of C1~~-C4~~–C5 and S1~~-S4~~–S5 (Levia and Herwitz, 2005; Siles et al., 2010a, ~~2010b~~b; Stephenson et al., 2014). A total of 66 branches for ~~C5-C7~~C6–C8 and 61 branches for ~~S5-S7~~S6–S8 were measured ~~when the~~

~~shrubs showed maximum vegetative growth~~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 ~~C5–C7~~C6–C8 and 14 branches of ~~S5–S7~~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):

~~$PT_e = a * BD^b$~~ $PT_e = a * BD^b$ (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), ~~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)).~~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 ~~production~~yield 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%, %):

~~$SF_d = 10 * \sum_{i=1}^{n} SF_{b_i}/CA$~~

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

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

where SF_{bi} is the volume of stemflow ~~production~~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 ~~production~~ efficiency of different-sized branches in ~~terms of energy conservation~~association with biomass allocation pattern:

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

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~~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 ~~at the~~ in a clearing:

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

2.4 Data analysis

A Pearson correlation analysis was performed to test the relationship between SF_b and each of the ~~rainfall~~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~~). The same analysis method was~~), 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. ~~3.1 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 2–4-mm in width and 40–80 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~~3. Meteorological characteristics of rainfall events for stemflow measurements during the 2014 and 2015 rainy seasons.

3.2 Species-specific variation of plant traits

~~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) (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~~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. ~~3~~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.~~48~~5 ± 4.~~16~~2 mm vs. 13.~~73~~7 ± 4.~~36~~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.~~93~~9 ± 10.~~81~~8 g) and a larger

BMS (an average 141.~~07~~1 ± 110.~~78~~8 g) than did *S. psammophila* (an average of 27.~~85~~9 ± 20.~~71~~7 g and 130.~~65~~7 ± 101.~~35~~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 ~~that of~~did *S. psammophila* in all the BD categories. The PBMS-specific difference increased with an increasing branch size, ranging from 1.~~24~~2% for the 5–10~~-~~ mm branches to 7.~~22~~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 ~~an increase in~~increasing branch size, *C. korshinskii* had a larger LAB (an average of 2509.~~05~~1 ±1355.~~30~~3 cm^2~~) and~~), LNB (an average of 12479 ±8409) and SSAL (18.2 ±0.5 cm^2 g^{-1}), but a smaller ILAB (an average of 21.~~94 ±2.99~~9 ±3.0 mm^2) and SSAS (2.5 cm^2 g^{-1}) than did *S. psammophila* for each BD level (~~Table 1).~~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.~~21~~2-fold and 2.~~41~~4-fold larger for *C. korshinskii*, and ILAB was 5.~~32~~3-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~~3 Stemflow ~~production~~yield of the foliated and defoliated *C. korshinskii* and *S. psammophila*

In this study, stemflow ~~production~~yield was expressed as SF_b on the branch scale and SF_d

and SF% on the shrub scale. ~~The~~For the foliated shrubs, SF_b was ~~an average of~~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 >~~20-~~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 ~~of stemflow~~ was ~~measured~~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 ~~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~~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.~~000~~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.~~64~~6 mm and 8.9% during rains >20 mm for *C. korshinskii* and from less than 0.01 mm and 0.7% to 2.~~23~~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 ~~maximum~~ differences in SF_d and SF% ~~were~~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 ~~production~~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*~~3.3 Stemflow production efficiency of *C. korshinskii* and *S. psammophila*~~

~~**Combined**~~

With the combined results ~~for~~of SFP and FR, ~~the~~ stemflow~~ production~~ 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 ~~3~~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 ~~that of~~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 ~~3~~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 ~~4~~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 º~~-~~ branches 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 º~~-~~ branches.

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

3.~~4~~5 Bio~~/~~-/abiotic influential factors of stemflow ~~production~~yield 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~~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 analysis methods indicated that the precipitation amount was the most important rainfall characteristic that affected stemflow in these two shrub species~~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. ~~4~~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.~~69~~7 mm, 0.~~72~~7 mm, 1.~~35~~4 mm and 0.~~81~~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. ~~4~~5, fast growth was evident during rains ≤10 mm, but SF% slightly increased afterwards for both shrub species.

Fig. ~~4~~5. Relationships of branch stemflow ~~production~~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~~, and~~ 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 ~~heavy~~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 ~~Effective utilization~~Differences of ~~precipitation via~~ stemflow ~~production~~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 ~~production~~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, ~~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.~~respectively. Additionally, *C. korshinskii* had a 2.8-fold larger SF_b than ~~that of~~did *S. psammophila* for the 5–10~~-~~ mm branches. Therefore, compared with *S. psammophila*, more effectively might *C. korshinskii* ~~utilize~~employ precipitation via greater stemflow ~~production~~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 ~~channel~~deliver raindrops (Siegert and Levia, 2014~~), thus leading to greater stemflow production.~~). 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 ~~in~~of China (Yang et al., 2008). The average FR ~~for~~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* ~~in the~~at western Loess Plateau of China. Furthermore, these two shrub species had a larger FR than those of many other endemic xerophytic shrubs ~~from~~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). ~~Therefore, both~~Both of *C. korshinskii* and *S. psammophila* ~~utilized~~employed precipitation in ~~a relatively~~an efficient manner ~~by producing~~to produce stemflow, and *C. korshinskii* produced stemflow even more efficiently~~. The FR-specific difference achieved a maximum of 3.5-fold larger~~ for ~~*C. korshinskii*~~all precipitation categories particularly during rains ≤2 mm~~ and~~, the inter-specific difference of which decreased with increasing precipitation ~~to 2.0-fold larger during rains >20 mm.~~(Table 5).

~~SFP characterized~~The higher stemflow ~~production in terms~~efficiency 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.*~~ also supported by SFP (Table 4), which characterized stemflow efficiency of different-sized~~*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,~~ 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~~, was maximized to 5.6 mL g^{-1} and 4.6 mL g^{-1} for *C.*~~ (Table

4).

In conclusion~~*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~~employed different-sized rains to produce stemflow in a greater ~~stemflow,~~amount and more efficient manner. That meant a lot for xerophytic shrubs particularly ~~for 5–10-mm young shoots~~during the rainy season. Because, during ~~rains ≤2 mm~~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.

~~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~~

4.2 Effects of precipitation threshold to ~~start~~produce stemflow

Precipitation below the threshold wet the canopy and ~~then~~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 ~~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~~sandland (Li et al., 2009) and the 1.9 mm threshold for *R. soongorica* at ~~the west of~~western 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~~2013). Generally, for many xerophytic shrub species, the precipitation threshold ~~usually~~generally ranges ~~between~~in 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~~at western Loess Plateau of China (with a MAP of 420 mm) (Jian et al., 2014). While at Haizetan ~~in the south of~~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.~~54~~5 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~~*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.

~~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 ±0.2 m~~

~~and a canopy area of 5.14 ± 0.26 m^2, than *S. psammophila*, which had a canopy height of 3.5 ± 0.2 m and a canopy area of 21.35 ± 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~~

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 (~~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 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,~~The factors, such as a relatively large number of leaves (Levia et al., 2015; Li ~~and Xiao,~~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 ~~production~~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 ~~better~~beneficial leaf morphology for stemflow ~~production~~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. ~~2~~6). Additionally, experimental measurements indicated that *C. korshinskii* had a larger MTA, LAB, LNB and ~~SLW~~LAI (an average of 54.4 °, 2509.~~05~~1 cm^2, 12479 and ~~126.04 g cm^{-}~~2.4, respectively) and a smaller ILAB (an average of 21.~~94~~9 mm^2) than did *S. psammophila* (an average of 48.5 °, 1797.~~93~~9 cm^2, 2404, ~~73.87 g cm^{-2}~~1.7 and 87.~~52~~5 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~~features for stemflow ~~production~~yield.

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

~~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*.~~

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; Muzylo 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 ~~increase~~larger in *C. korshinskii* was observed for the branch stemflow ~~production~~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 ~~largest~~ inter-specific ~~difference~~differences in stemflow ~~production~~yield (SF_b, SF_d and SF%) and the production efficiency (SFP and FR) ~~was~~ were maximized for the 5–10 mm branches and during rains ≤2 mm~~, which were the most frequent rainfall events. Although the total amount of rainfall was limited, it was of great importance~~. The smaller threshold precipitation (0.9 mm for *C. korshinskii* ~~to survive and thrive, particularly during~~vs. 2.1 mm for *S. psammophila*), and the beneficial leaf traits might be partly responsible for 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~~superior stemflow yield and efficiency in *C. korshinskii*.

~~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.~~

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*.

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

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

Table 4. Comparison of stemflow productivity (SFP) between the ~~funneling~~foliated *C. korshinskii* and *S. psammophila.*

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

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 (~~SSAL (cm^2 g~~ cm^2~~$^{-1}$)	~~126.4~~22.8	~~126.0~~17.3	~~125.7~~14.3	~~125~~12.6	~~126.~~18.2 ±0~~±0.3~~.5	~~95.6~~18.4	~~74.5~~13.6	~~63.0~~10.8	~~58.1~~8.6	~~73.9 ±14.5~~12.7 ±0.4
	~~HV~~SSAS (cm^2 g^{-1})	~~0.0438~~3.4	~~0.0513~~2.3	~~0.0572~~1.9	~~0.0615~~1.6	2.5 ±0.~~0507 ±0.0064~~1	~~0.0010~~10.4	~~0.0009~~5.4	~~0.0009~~3.3	~~0.0009~~1.9	5.1 ±0.~~0009 ±0.0001~~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. ~~SLW is~~SSAL and SSAS are the specific ~~leaf weight, and HV was the Huber value.~~ 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 ~~leaf~~stem biomass to that of branch. The average values mentioned above are expressed as the means ±SE.

Table 2. Comparison of stemflow ~~production~~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	
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~~1	0.~~24~~2	0.~~63~~6	0.~~91~~9	1.~~85~~9	2.~~64~~6	1.~~00~~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.~~01~~1	0.~~11~~1	0.~~48~~5	0.~~89~~9	1.~~27~~3	2.~~23~~2	0.~~78~~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 ~~production~~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.	Incident precipitation amount (mm)					Avg.	Precipitation amount (mm)					Avg.
		1.7	6.7	6.8	7.6	22.6	(P)	1.7	6.7	6.8	7.6	22.6	(P)	1.7	6.7	6.8	7.6	22.6	(P)
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 ~~4~~5. Comparison of the ~~funneling~~funnelling ratio (FR) for the foliated *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~~2	127.~~68~~7	168.~~14~~1	125.~~30~~3	193.~~06~~1	170.~~31~~3	149.~~90~~9
	30~~-~~–60	125.~~89~~9	133.~~77~~8	178.5	157.~~84~~8	205.~~19~~2	182.~~07~~1	164.~~65~~7
	60~~-~~–80	135.~~51~~5	148.~~94~~9	192.~~45~~5	165.~~83~~8	217.~~03~~0	188.~~64~~6	176.~~06~~1
	>80	133.~~17~~2	167.~~44~~4	205.~~53~~5	182.~~61~~6	276.~~02~~0	226.~~08~~1	198.~~16~~2
	Avg.(BA)	129.~~17~~2	144.~~84~~8	187.~~74~~7	162.~~34~~3	219.~~61~~6	190.~~34~~3	173.~~34~~3
Intra-specific differences in *S. psammophila* (*SP*)	≤30	32.~~60~~6	37.~~33~~3	52.~~02~~0	59.~~00~~0	65.~~75~~8	85.~~19~~2	~~54.97~~55.0
	30~~-~~–60	34.~~50~~5	43.~~44~~4	65.~~67~~7	70.~~63~~6	77.~~74~~7	92.~~28~~3	64.~~78~~8
	60~~-~~–80	37.~~83~~8	47.~~92~~9	~~77.99~~78.0	78.~~41~~4	82.~~31~~3	97.~~72~~7	72.~~39~~4
	>80	44.~~88~~9	~~54.99~~55.0	93.~~45~~5	94.~~74~~7	94.~~09~~1	115.~~72~~7	85.~~57~~6
	Avg.(BA)	36.~~65~~7	46.~~01~~0	72.~~57~~6	75.~~34~~3	80.~~45~~5	96.~~09~~1	69.~~25~~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~~Comparison of leaf morphologies of *C. korshinskii* and *S. psammophila*~~.

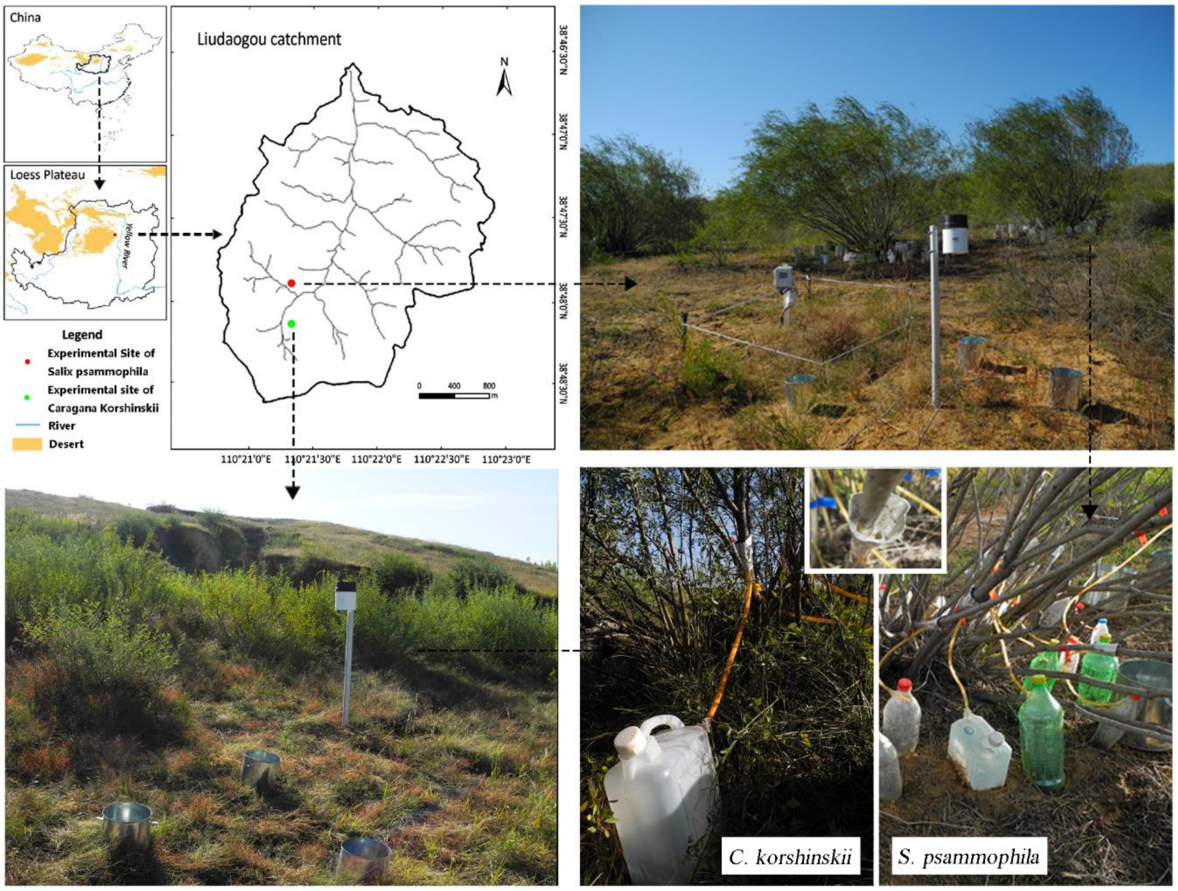
~~**Fig. 3**~~

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. ~~4~~5. Relationships of branch stemflow ~~production~~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*


China
Loess Plateau
Yellow River
Liudaogou catchment
N
Legend
Experimental Site of Salix psammophila
Experimental site of Caragana Korshinskii
River
Desert
0 400 800 m
38°46'30"N
38°47'0"N
38°47'30"N
38°48'0"N
38°48'30"N
110°21'0"E
110°21'30"E
110°22'0"E
110°22'30"E
110°23'0"E
C. korshinskii
S. psammophila

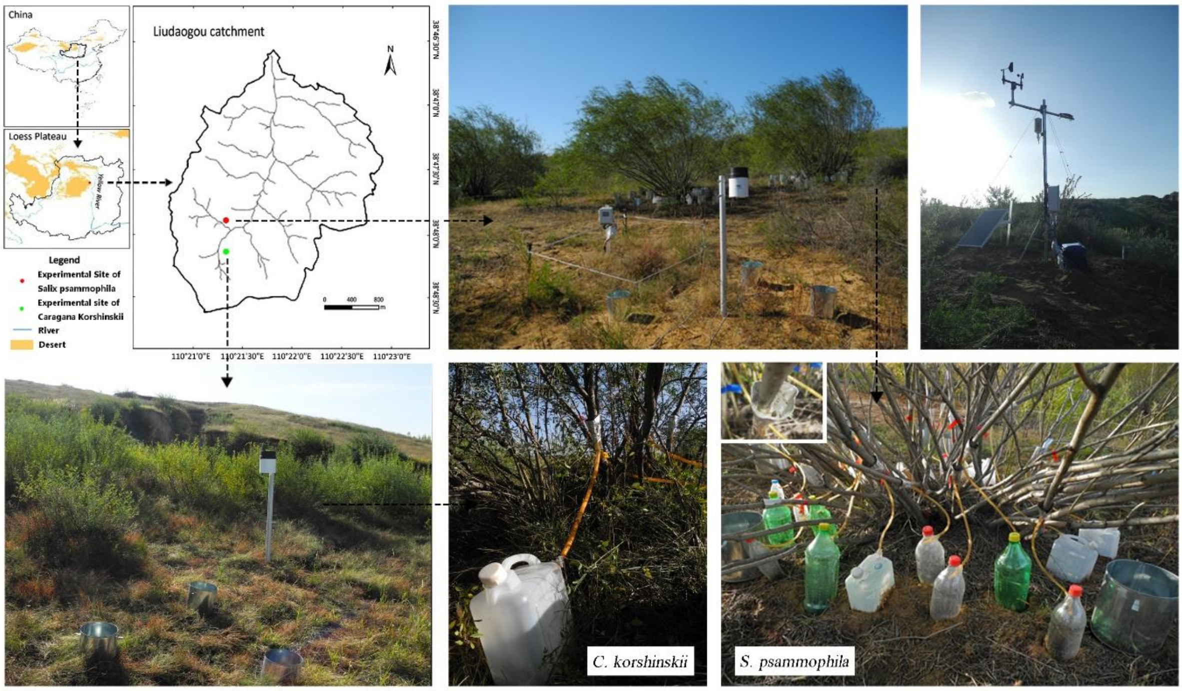
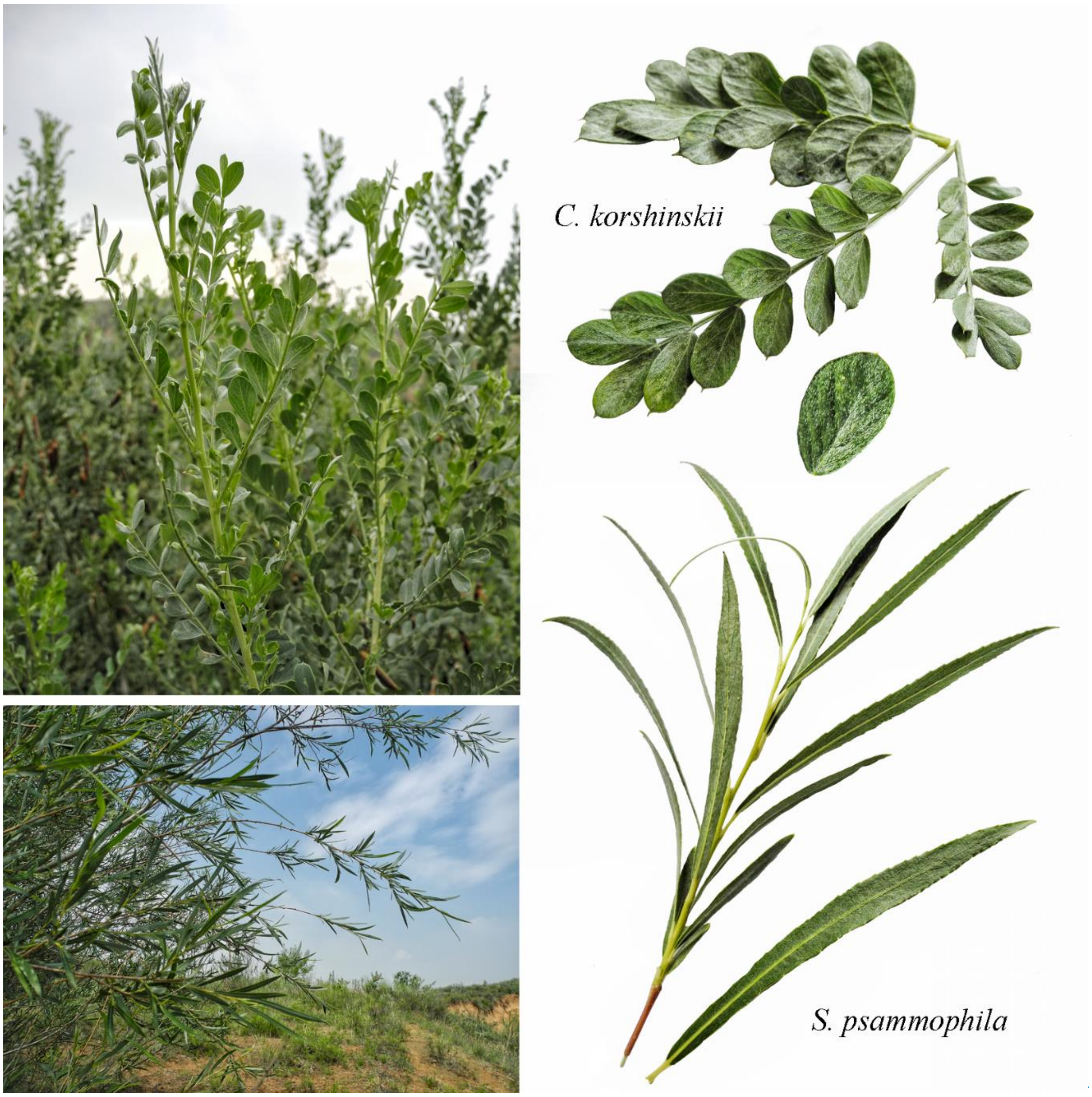


Fig. 1. Location of the experimental stands and facilities for stemflow measurements of *C. korshinskii* and *S. psammophila* at the Liudaogou catchment in the Loess Plateau of China.


C. korshinskii
S. psammophila

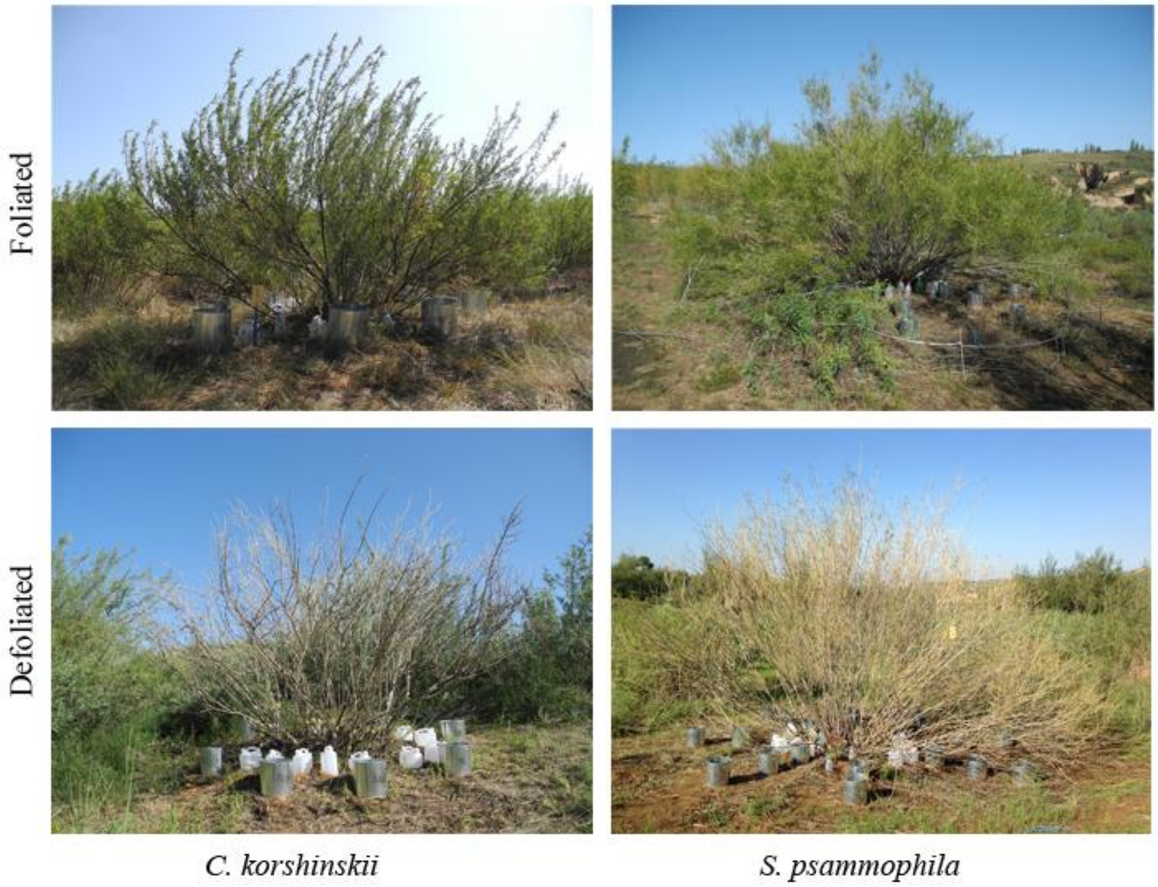


Fig. 2. The controlled experiment for stemflow yield between the foliated and manually defoliated shrubs.

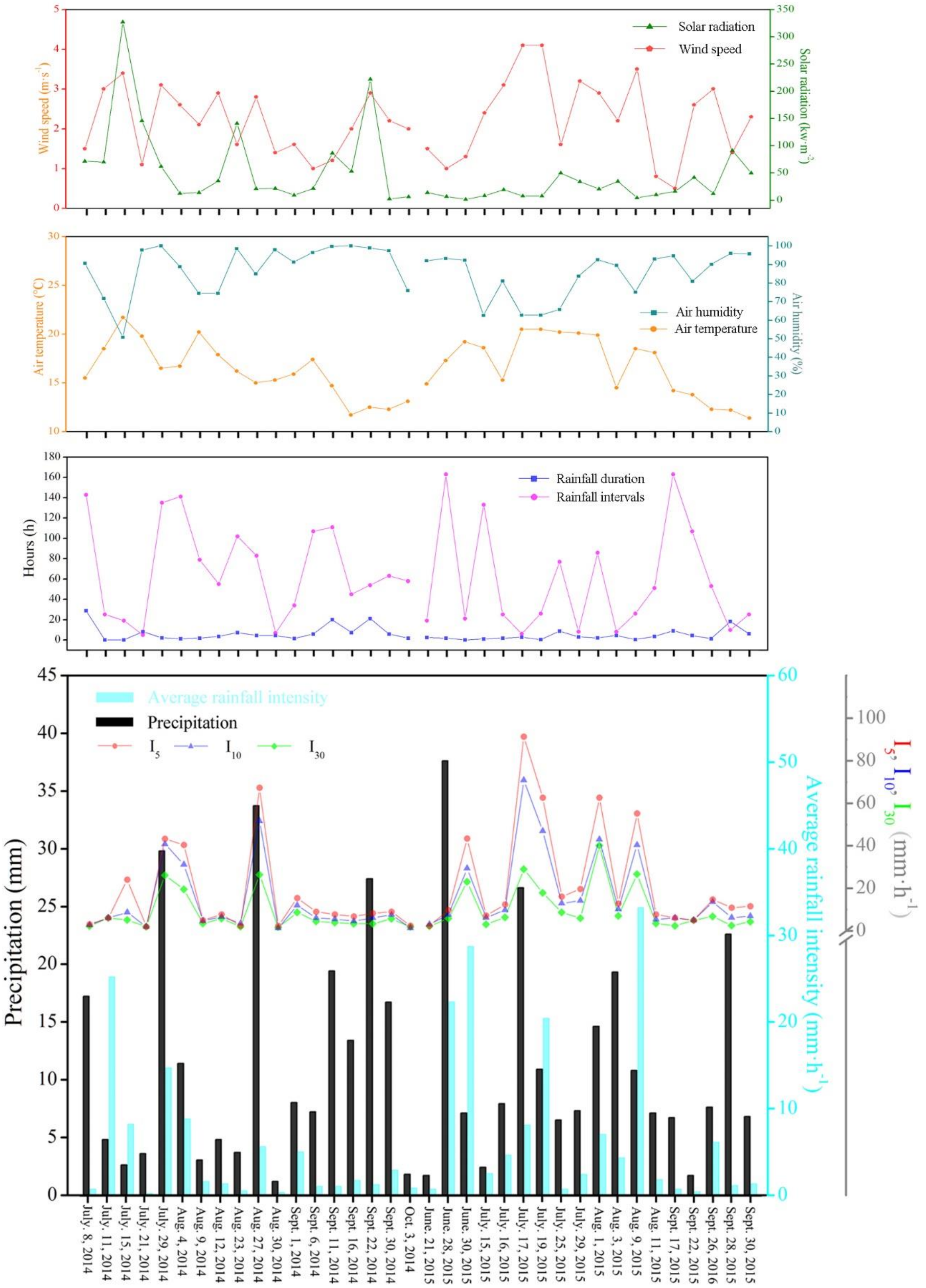
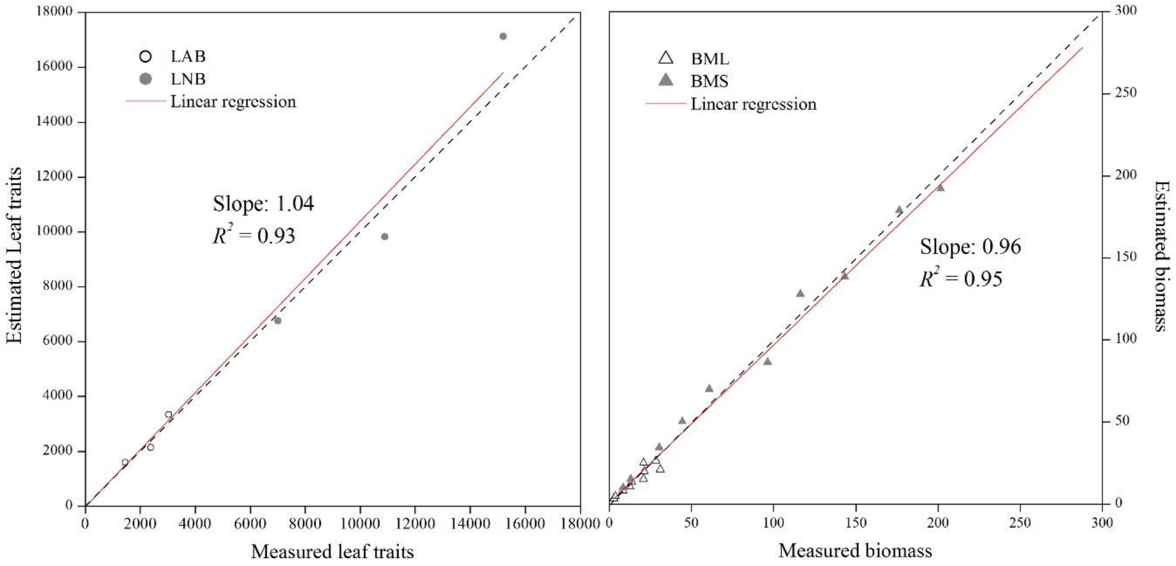


Fig. 3. Meteorological characteristics of rainfall events for stemflow measurements during the 2014 and 2015 rainy seasons.

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



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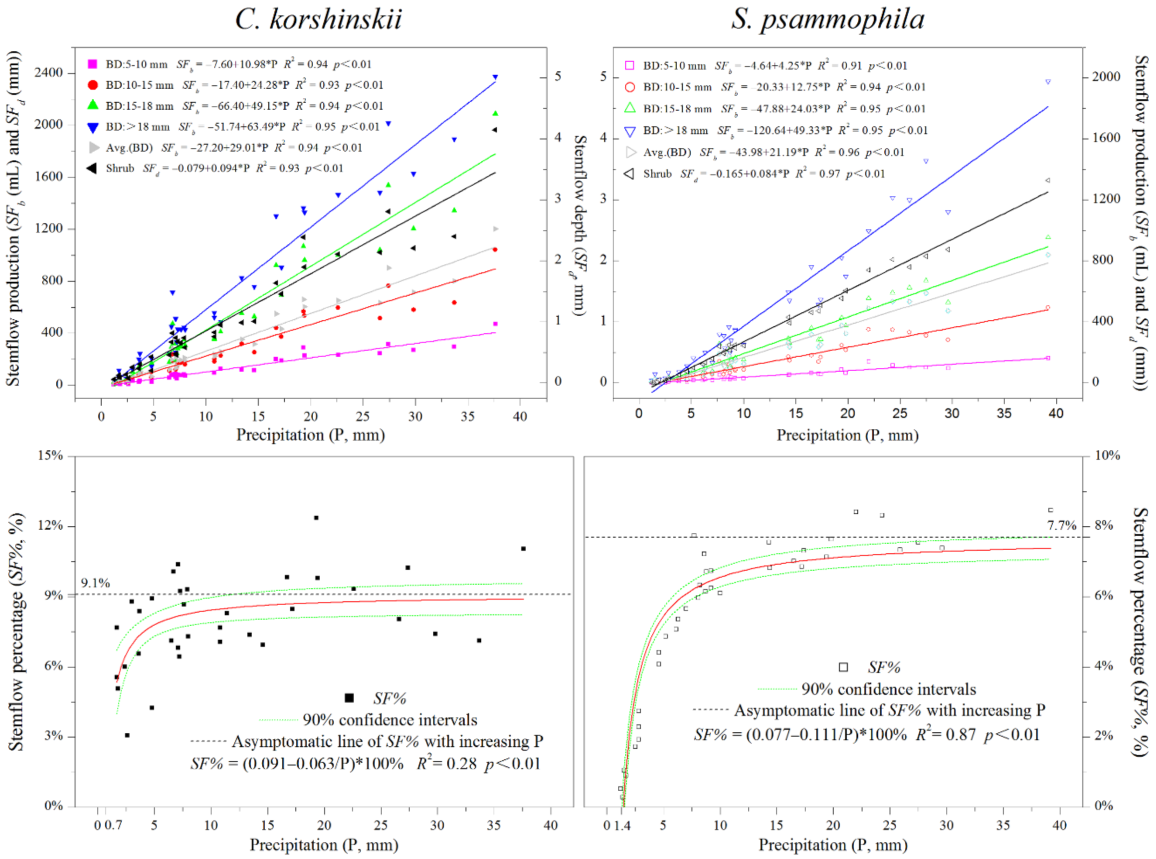

Fig. ~~4~~5. Relationships of branch stemflow ~~production~~volume (SF_b), shrub stemflow depth (SF_d) and stemflow percentage ($SF\%$) with precipitation amount (P) for *C. korshinskii* and *S. psammophila*.

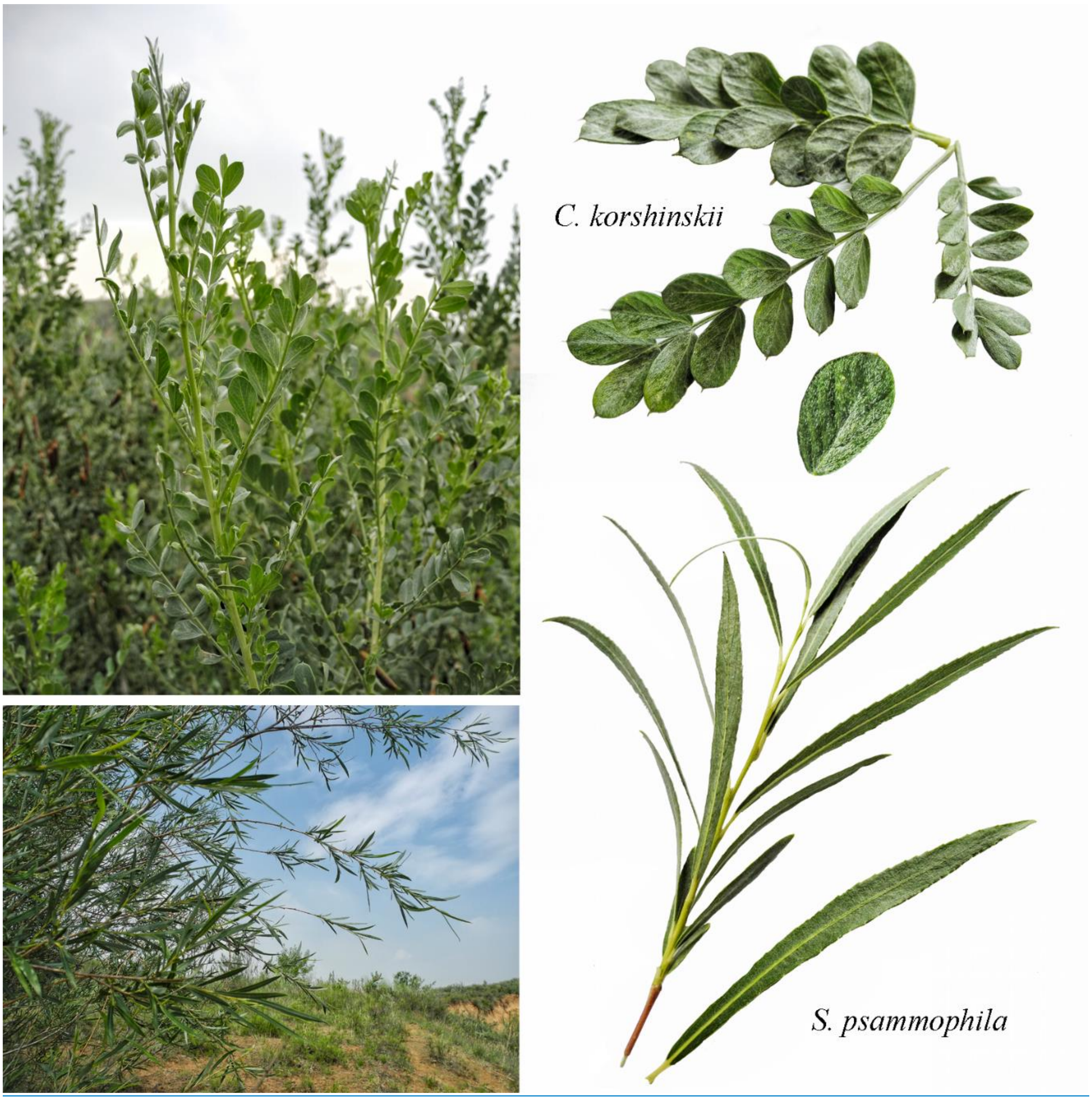

Fig. 6. Comparison of leaf morphologies of *C. korshinskii* and *S. psammophila*–

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*, respectively. 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 in *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 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 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, et al., 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.

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·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):

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

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%, %):

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

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

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:

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

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:

$$\mathrm{FR} = 10*SF_b\,/(\mathrm{P}*\mathrm{BBA}) \tag{5}$$

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 ≤30° branches to 2.3-fold larger for the >80 °branches.

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., 2014). 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; Muzylo 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*.

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

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

Table 4. Comparison of stemflow productivity (SFP) between the foliated *C. korshinskii* and *S. psammophila*.

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

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	
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	0.1	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)						Avg.(P)
		≤2	2–5	5–10	10–15	15–20	>20	
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
Intra-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.

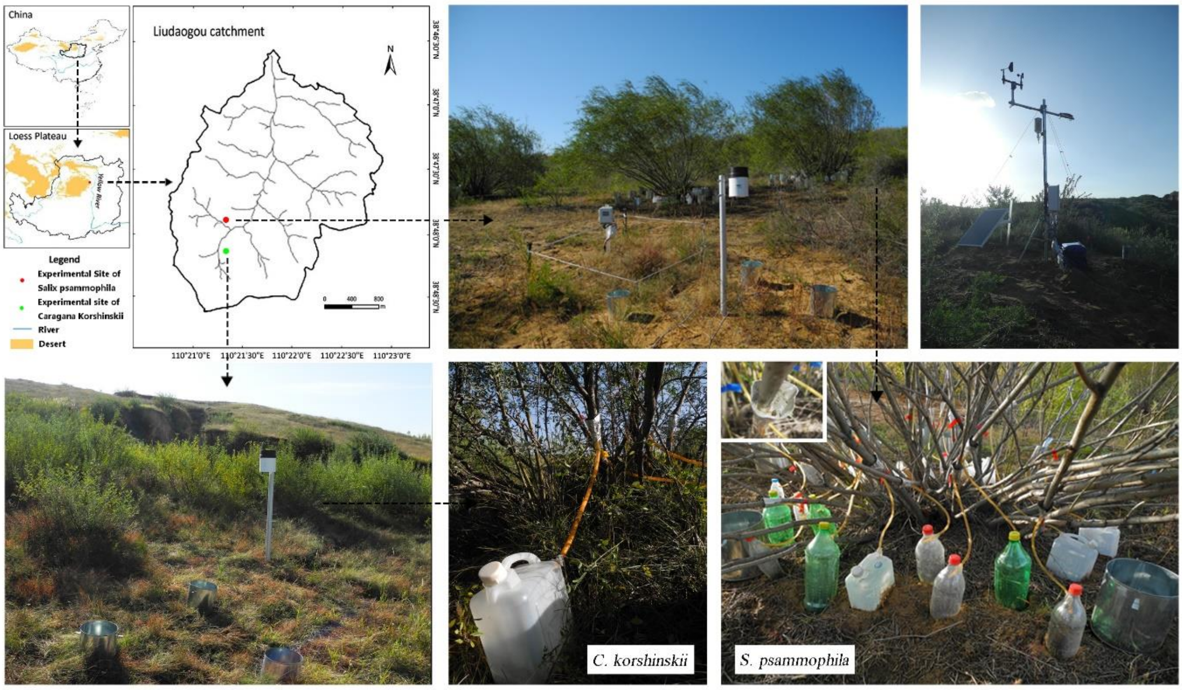
Fig. 2. The controlled experiment for stemflow yield between the foliated and manually defoliated shrubs.

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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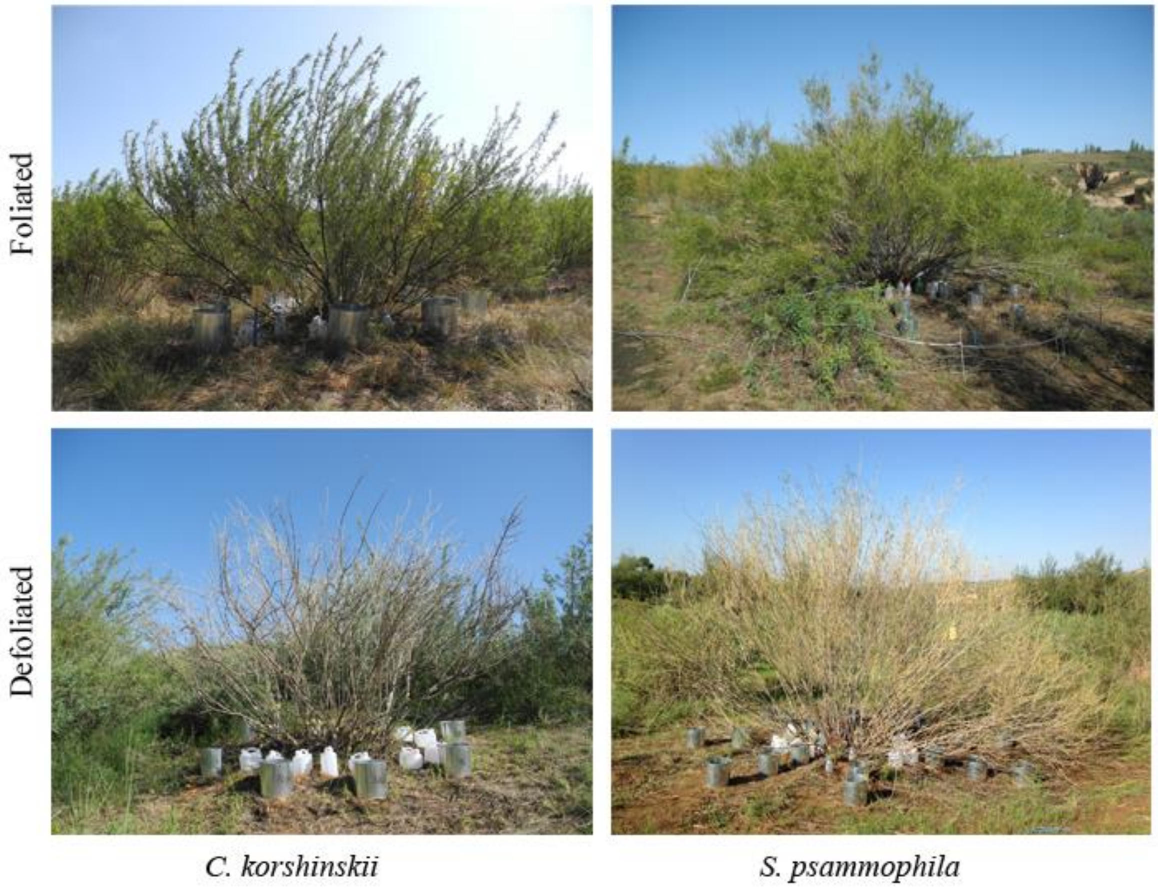

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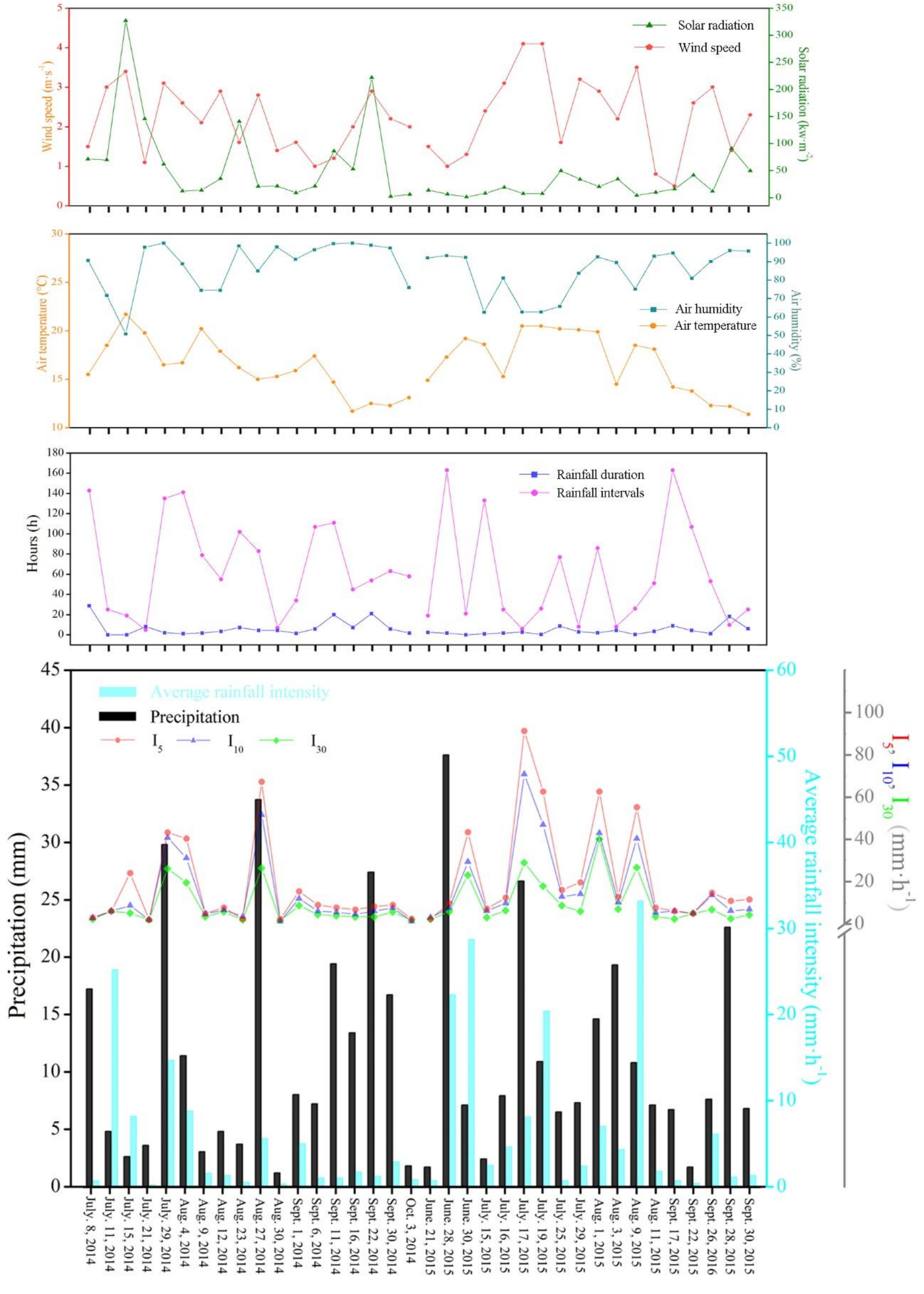

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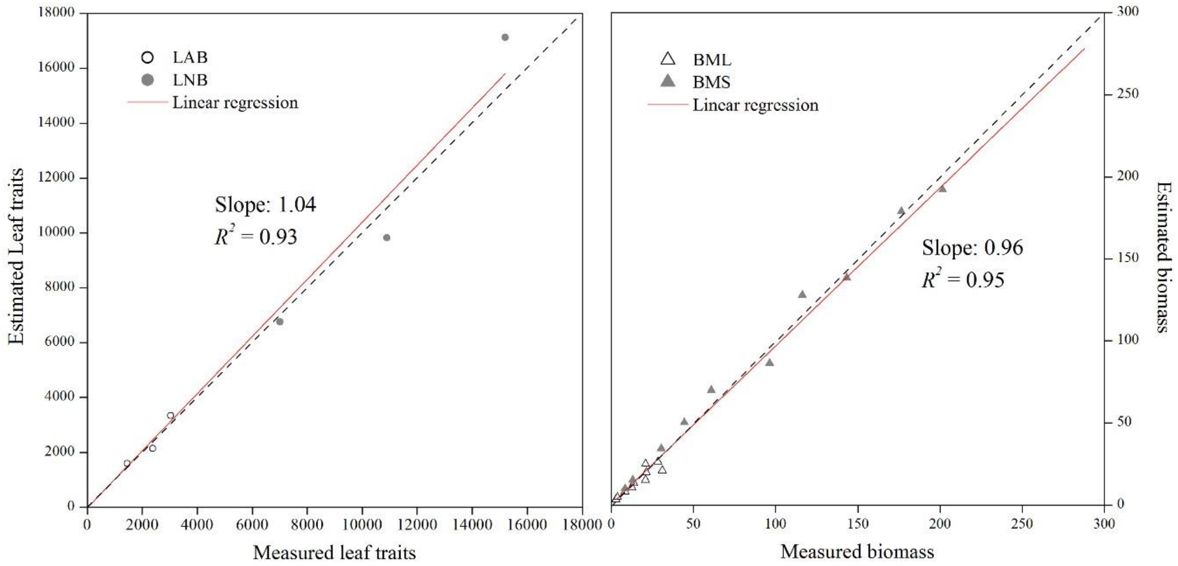

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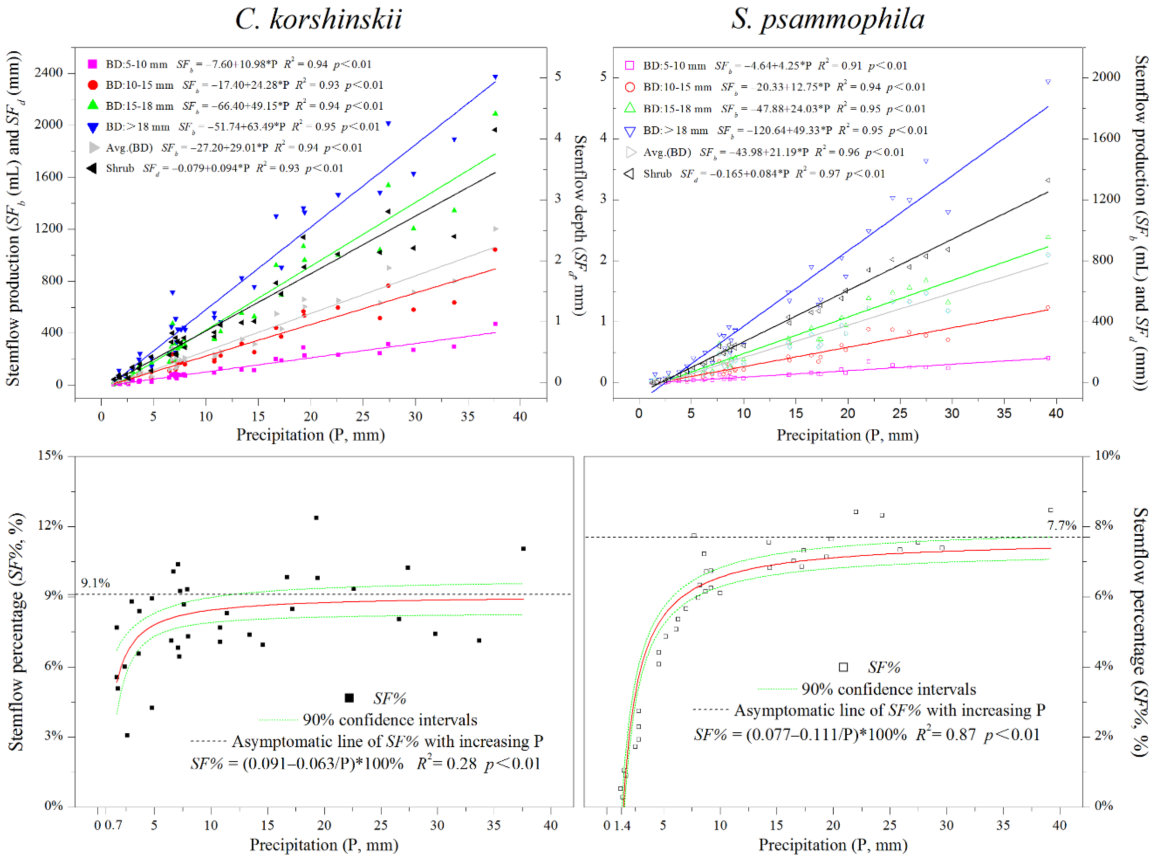

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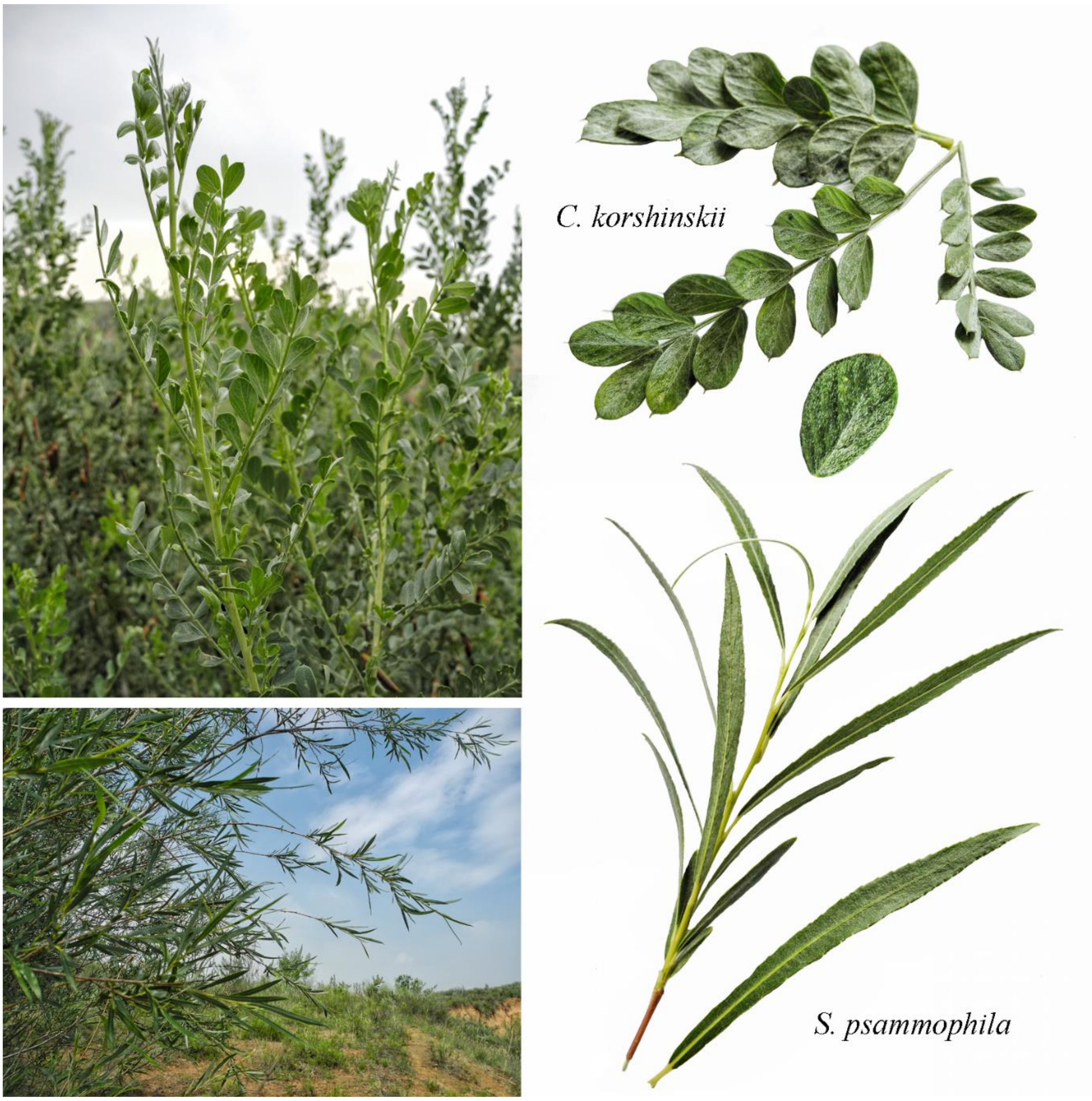

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