Differential intra-specific stemflow funnelling efficiencies of *Caragana korshinskii* within arid desert ecosystems

Ya-feng Zhang, Xin-ping Wang, Rui Hu and Yan-xia Pan

ABSTRACT

Stemflow is known as a highly localized point input of rainwater and solutes around tree/shrub bases where roots are concentrated, thus having considerable effects on hydrology and biogeochemistry of vegetated ecosystems. Stemflow shows a pronounced inter-specific variation due to morphological differences among species, while the intra-specific variation of stemflow has been poorly explored. We systematically examined the effects of shrub morphological metrics on intra-specific funnelling efficiencies by quantifying the stemflow of nine shrubs of *Caragana korshinskii* within a water-limited arid desert ecosystem of northern China. Stemflow volume was used to compare the absolute amount of stemflow generated by shrubs of varying size, and funnelling ratio was used to assess their funnelling efficiencies. Both rainfall depth and shrub morphological metrics significantly affected stemflow volume, while funnelling ratio was more associated with shrub morphology. Under the same rainfall condition, smaller shrubs produced lower volumes of stemflow, while gaining access to rainfall via higher funnelling ratio than larger shrubs. Our findings highlight a large variation in funnelling efficiency among individual shrubs within the same species, and in particular, smaller shrubs might profit more from sporadic small rainfall events than larger shrubs.

Key words | *Caragana korshinskii*, desert ecosystem, funnelling ratio, morphological metrics, stemflow

Ya-feng Zhang
Xin-ping Wang (corresponding author)
Rui Hu
Yan-xia Pan
Shapotou Desert Research and Experiment Station,
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences,
Lanzhou 730000,
China
E-mail: *zyf7759961@163.com*

INTRODUCTION

Drylands cover about 41% of Earth's terrestrial surface (Reynolds *et al.* 2007; Huang *et al.* 2015), characterized by a two-phase mosaic composed of vegetated patches interspersed with bare patches (Aguiar & Sala 1999; Tongway *et al.* 2001; Rietkerk & Van de Koppel 2008), where precipitation is scarce and typically unpredictable and hence a key limiting factor of ecosystem functioning (e.g., Noy-Meir 1973). Shrubs are the dominant vegetation over the vast drylands, and play a crucial role in the hydrological and biogeochemical cycles in terms of redistributing incident precipitation (Schlesinger & Pilmanis 1998; Llorens & Domingo 2007; Zhang *et al.* 2016a). Precipitation falling on the shrub canopy either is intercepted and subsequently evaporated (interception loss) or reaches the ground diffusely by throughfall or concentrated by funnelling down the stems in the form of stemflow.

Stemflow is volumetrically small (normally 5–10% of incident precipitation) in comparison to the other components of the canopy water balance; it is, however, of high eco-hydrological and chemical importance due to its very local input to nature (Johnson & Lehmann 2006; Levia & Germer 2015). Nutrient-enriched stemflow funnels down the shrub stems and infiltrates into deep soil layers through preferential pathways such as roots, creating islands of soil moisture and nutrients (e.g., Mauchamp & Janeau 1993; Navar 2011; Schwärzel *et al.* 2012; Zhang *et al.* 2013, 2016b). Stemflow is thus considered to be an important biological transfer mechanism in contributing to the

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development of 'fertile islands' under shrub canopies in the arid and semi-arid environments where water and nutrients are typically limited (Garner & Steinberger 1989; Whitford *et al.* 1997).

Stemflow has been reported to be influenced by a suite of biotic and abiotic factors, including canopy structure and architecture (e.g., Crockford & Richardson 2000; Park & Cameron 2008; Wang *et al.* 2013), rainfall depth, intensity and duration (e.g., Dunkerley 2014; Zhang *et al.* 2015), antecedent dry period (Tobon *et al.* 2004), wind direction and speed (e.g., Xiao *et al.* 2000; Van Stan *et al.* 2011) and vapour pressure deficit (e.g., Staelens *et al.* 2008; Pugh & Small 2013). The complex interactions among these factors also make it difficult to determine how a single factor affects stemflow production (Levia & Germer 2015).

Stemflow shows a highly inter-specific variation (the variation among species) due to morphological differences among tree/shrub species in a wide range of ecosystems (Van Dijk & Bruijnzeel 2001; Levia & Frost 2003; Llorens & Domingo 2007; Swaffer *et al.* 2014; Janeau *et al.* 2015; Zhang *et al.* 2015). For example, Llorens & Domingo (2007) reported that in the European Mediterranean area, stemflow percentage averaged 3%, with a variation coefficient of 111%, ranging from about 1% for *Picea abies*, *Pinus sylvestris* and *Quercus pyrenaica* and 12% for *Pinus nigra*. Yet the intra-specific variation (the variation within the same species) of stemflow has been poorly explored. A handful of recent studies from forested ecosystems showing high stemflow generating efficiencies for small trees (Germer *et al.* 2010; Siegert & Levia 2014; Su *et al.* 2016) are stimulating further research in various ecosystems. In the present study, event-based measurements on stemflow of nine shrubs of *C. korshinskii* varying from small to large were made during three rainy seasons of 2011–2013 within a water-limited arid desert ecosystem. The objectives of our study were: (1) to quantify the amount of rainwater flowing down the shrub stem and (2) to evaluate the differential funnelling efficiencies among individual shrubs within the same species. Achievement of these research objectives is important to gain a better understanding of vertical and horizontal water distribution under shrub canopies, and of different water acquisition strategies of individual shrubs within the same species in water-limited arid desert ecosystems.

MATERIALS AND METHODS

Site information

Field measurements were carried out during three growing seasons of 2011–2013 at the Water Balance Experimental Field (WBEF) (Figure 1(a)) of Shapotou Desert Research and Experiment Station of Chinese Academy of Sciences (37°32′ N, 105°02′ E, with an elevation of 1,300 m a.s.l.), on the southeastern fringe of the Tengger Desert in northwestern China. Mean annual precipitation is 191 mm with 80% of rain falling between July and September. Most storms are of a low amount and intensity, with around 80% of the rainfall intensities $\leq$5 mm h^{-1} (Zhang *et al.* 2015). The groundwater is at a depth of 50–80 m, and therefore inaccessible to plant roots. Potential evapotranspiration is approximately 2,500 mm during the growing season (April–October), resulting in a large annual moisture deficit. Mean maximum and minimum air temperature is 24.7 °C in July and −6.1 °C in January, respectively. Annual mean wind velocity is approximately 2.8 m s^{-1}.

C. korshinskii is a multiple-stemmed deciduous perennial leguminous shrub with an inverted cone shape, and is one of the successful shrubs used in revegetation for protecting the Baotou-Lanzhou railway against encroaching sand dunes in the Shapotou area (Li *et al.* 2006; Li 2012). The stems are smooth, the leaves are pinnately compound and opposite or subopposite in arrangement and 6–10 cm long, and each pinna has five to eight pairs of ovate leaflets (7–8 mm in length and 2–5 mm in width). The average height and the average canopy diameter of *C. korshinskii* at WBEF was 145 and 130 cm, respectively.

Shrub selection and measurements

Nine robust and healthy shrubs of *C. korshinskii* were selected for field observation (Figure 1(b)) according to the gradient of stem numbers of *C. korshinskii* in WBEF, and their morphological characteristics are quantified in Table 1. A shrub with more stems is also more likely to have a greater canopy area, thus we assume the nine shrubs represent the range of sizes of *C. korshinskii* at larger community scales. Stem diameter was measured with a vernier caliper at each stem base, and stem angle

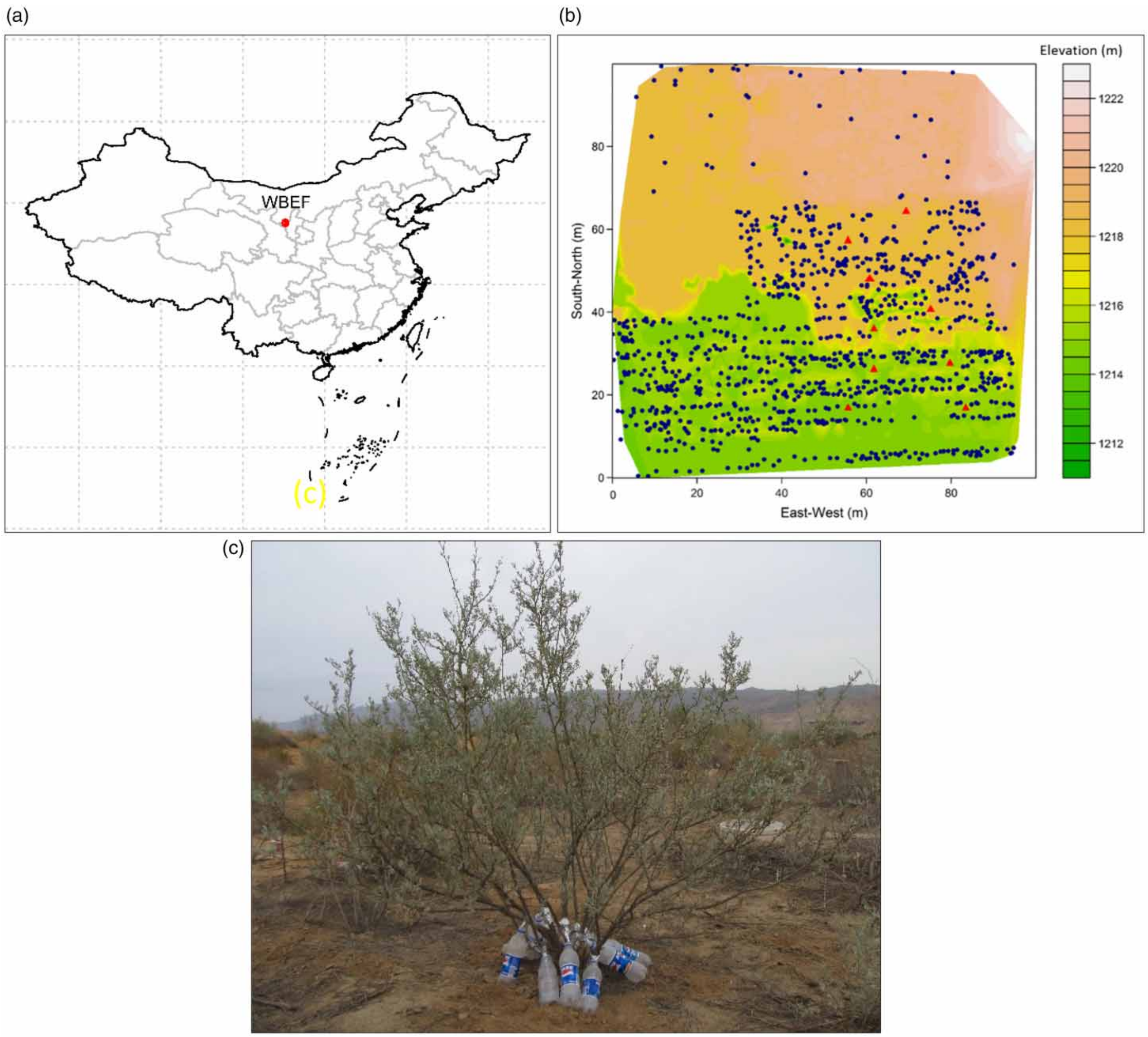

Figure 1 | Map showing the location of the Water Balance Experimental Field (WBEF) (a); topography of the WBEF and the spatial distribution of *C. korshinskii* (the nine shrubs selected for the experiments are depicted by a solid triangle and the others by a solid circle) in the WBEF (b); and the method of collecting stemflow for *C. korshinskii* (c).

was determined by a protractor. The plant area index (PAI, $m^2\,m^{-2}$), one-sided plant area (stems, twigs, leaves) per ground area, was estimated using a LAI-2000 plant canopy analyser (Li-Cor, Inc., USA). Shrub height was measured at the centre of the canopy using a tape. The projected canopy area (approximated as an ellipse) was calculated by taking the east–west and north–south diameters through the centre of the fullest part of the canopy (Martinez-Meza & Whitford 1996). Shrub volume was estimated by considering canopy shape as an inverted elliptic cone. Basal area was defined as the sum of the cross-sectional area of individual stems of a given shrub.

Stemflow and rainfall measurements

Stemflow was collected using an aluminium foil collar that was fitted around the entire circumference of individual shrub stems (Figure 1(c)). Stemflow volume was measured by a graduated cylinder for each individual stem after the cessation of each rainfall event.

Table 1 | Descriptive statistics (mean ± SE) of morphological metrics of *C. korshinskii* selected in the experiments

	Stem				Shrub			
No.	Number	Diameter (cm)	Length (cm)	Angle (°)	Height (cm)	Canopy area (m²)	Volume (m³)	PAI
CK_1	1	1.8 ± NA	98 ± NA	50 ± NA	114	0.39	0.15	0.69
CK_2	2	2.2 ± 0.0	94 ± 5.5	77 ± 5	115	0.59	0.23	0.77
CK_3	3	1.5 ± 0.2	77 ± 1.7	60 ± 19	126	0.60	0.25	0.54
CK_4	5	1.4 ± 0.2	50 ± 5.9	59 ± 3	92	0.66	0.20	0.95
CK_5	6	2.5 ± 0.2	159 ± 18.3	73 ± 3	245	3.69	3.02	0.71
CK_6	7	1.9 ± 0.5	119 ± 14.3	72 ± 5	216	2.23	1.61	0.78
CK_7	9	2.5 ± 0.4	151 ± 12.3	60 ± 8	203	5.19	3.51	1.02
CK_8	11	1.7 ± 0.2	83 ± 2.6	56 ± 3	158	2.69	1.42	0.68
CK_9	12	1.8 ± 0.1	103 ± 9.1	60 ± 4	182	2.07	1.26	1.01
Mean	6	1.9	107	62	152	1.82	1.26	0.76
SE	1	0.1	5.7	2.1	18	0.53	0.40	0.06

PAI: plant area index.
NA: not available.

Funnelling ratio was used to compare differential stemflow funnelling efficiencies among individual shrubs of *C. korshinskii*. According to Herwitz (1986), it is defined as:

$$FR = \frac{V_{SF}}{B \times R/10} \quad (1)$$

where V_{SF} is the stemflow volume (mL), B is the stem basal area (cm^2) of stemflow generating shrub, and R is depth equivalent of the incident gross rainfall (mm). Funnelling ratio represents the ratio of stemflow volume collected at the shrub base to the volume that would have been expected in a rain gauge occupying the same area as the stem basal area in the absence of the shrub. Funnelling ratio exceeding 1 indicates that the canopy component other than the stems are contributing to the stemflow input.

A standard tipping bucket rain gauge (Adolf Thies GMVH & Co. KG, Germany) with a resolution of 0.1 mm was installed in an open area approximately 50 m from the study plot. Individual events were separated by at least 4 h without rainfall.

Statistical analyses

Descriptive statistics were compiled for shrub morphological metrics, rainfall depth, stemflow volume and funnelling ratio. The correlations among shrub morphological metrics were analysed using Pearson correlation. The linear function was used to determine the relationships of stemflow volume with rainfall and shrub morphological metrics. The linear and the exponential decay functions were used to determine the relationships between funnelling ratio and shrub morphological metrics. All the descriptive statistics, correlations and fitted functions were performed using SPSS 16.0 statistical software (SPSS Inc., Chicago, IL, USA).

RESULTS

Rainfall, stemflow volume and funnelling ratio

In total, 37 rainfall events (totalling 410.3 mm) that can produce stemflow were recorded during the study period, ranging in depth from 2.4 to 28.8 mm with a mean of 11.1 mm and a variation of coefficient (CV) of 61% (Table 2).

A great variability in stemflow volume can be found among rainfall events for individual shrubs. Stemflow volume increased significantly ($P < 0.01$) with rainfall depth for all studied shrubs (Figure 2). Total event stemflow volumes differed considerably among individual shrubs of *C. korshinskii* (Table 2). For example, the sum of stemflow volume produced by CK_7 (190,049 mL) was 43.3 times

Table 2 | Total shrub stemflow volume on a rainfall event basis

		Total event stemflow volumes (mL)								
Event	Rainfall (mm)	CK_1	CK_2	CK_3	CK_4	CK_5	CK_6	CK_7	CK_8	CK_9
2011-06-26	5.6	6	45	102	67	345	70	241	230	146
2011-07-02	11.9	180	1,340	1,870	1,545	2,975	2,680	3,730	4,330	4,415
2011-07-28	13.9	135	735	910	810	3,625	1,605	4,125	2,280	2,490
2011-08-15	21.3	192	1,031	1,384	1,344	5,802	2,519	6,662	3,064	3,954
2011-08-18	20.2	180	2,090	1,600	1550	8,090	4,020	12,730	2,875	3,760
2011-08-23	10.6	120	900	460	760	4,095	2,030	7,180	2,560	2,600
2011-09-02	4	50	410	365	300	1,165	878	1,805	930	704
2011-09-04	8.4	20	320	230	242	910	650	2,015	895	549
2011-09-05	3.1	10	92	132	100	502	439	743	372	284
2011-09-09	11	125	1,348	798	858	4,174	3,275	9,247	3,824	2,802
2011-09-15	6.1	55	575	375	395	2,225	1,415	4,675	1,395	1,170
2011-09-16	12	125	1,300	990	845	4,280	2,785	9,260	2,425	2,520
2011-09-18	4.3	14	285	255	262	1,280	950	2,450	713	698
2011-10-09	6.4	50	515	315	360	1,715	1,031	4,295	1,077	698
2011-10-12	7.3	65	590	450	465	2,660	1,430	5,335	1,695	1,560
2011-11-07	8.6	60	610	455	496	2,160	1,332	4,540	1,262	1,052
2012-04-11	4.4	15	130	215	235	965	625	1,360	594	510
2012-04-30	6.1	30	370	410	285	2,055	1,185	2,270	1,110	1,560
2012-05-23	18.1	220	1,920	1,730	1,365	5,470	3,665	10,700	5,070	5,415
2012-05-28	3.7	25	250	235	175	850	314	1,315	735	690
2012-06-27	23.2	340	2,250	2,030	2,220	5,620	4,765	11,460	5,240	7,500
2012-06-28	14.8	155	1,970	1,380	1,265	3,780	3,815	15,520	3,880	5,494
2012-07-08	2.4	25	205	170	150	420	310	1,540	500	865
2012-07-17	20.4	270	1,610	1,750	1,465	4,020	3,240	13,535	3,800	5,870
2012-07-21	17.5	200	1,650	1,500	1,340	3,410	3,320	10,530	4,000	5,560
2012-07-30	3.5	5	10	45	30	250	59	475	160	138
2012-09-01	28.8	350	2,330	2,310	2,330	4,620	1,810	6,425	4,350	6,070
2012-09-11	3.5	20	195	133	94	362	322	1,656	286	676
2012-09-25	9.1	100	860	815	640	1,460	1,040	6,020	1,075	3,380
2013-05-15	8.4	80	850	685	545	1,360	2,770	1,335	1,225	1,760
2013-06-09	6.2	30	145	185	170	635	625	625	600	660
2013-06-21	19.4	245	415	1,570	1,660	5,815	2,660	5,000	4,760	4,690
2013-07-03	18.1	300	1,220	1,180	1,050	3,580	2,390	7,460	4,160	4,850
2013-07-09	14.6	180	1,250	990	1,105	1,290	1,795	5,460	3,070	3,520
2013-07-26	17.7	200	1,720	1,530	1,175	3,500	2,920	6,535	3,995	4,140
2013-08-06	8.6	105	380	790	485	985	1,005	1,425	1,825	2,137
2013-10-31	7.1	105	210	360	207	661	683	370	618	734

(*continued*)

Table 2 | continued

Event	Rainfall (mm)	Total event stemflow volumes (mL) CK_1	CK_2	CK_3	CK_4	CK_5	CK_6	CK_7	CK_8	CK_9
Mean	11.1	119	868	830	767	2,624	1,795	5,137	2,189	2,584
Sum	410.3	4,387	32,126	30,704	28,390	97,111	66,427	190,049	80,980	95,621
Min.	2.4	5	10	45	30	250	59	241	160	138
Max.	28.8	105	610	685	545	2,160	1,430	4,540	1,695	2,137
C.V. (%)	61	83	80	78	81	75	70	81	74	80

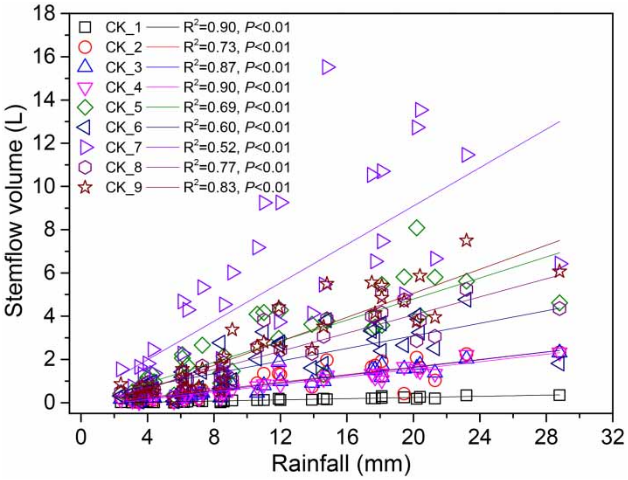

Figure 2 | Stemflow volume in relation to rainfall depth for individual shrubs.

greater than CK_1 (4,387 mL). These findings highlight the important interactions between rain event magnitude and intra-specific stemflow yield.

Mean event funnelling ratio also differed considerably among individual sample shrubs of *C. korshinskii*, suggesting the differential funnelling efficiencies among shrubs (Table 3). For example, the funnelling ratio was 37 for CK_1 and 123 for CK_3. Generally, the event funnelling ratio for individual shrubs had an increased tendency with rainfall depth (Figure 3(b)) until a threshold value around 12 mm and then began to decline (Figure 3(a)).

Stemflow volume and funnelling ratio in relation to shrub morphology

The relationship between the total stemflow yield from all the individual stemflow events and shrub morphological metrics was analysed separately (Figure 4). Stemflow volume had a significant positive linear relationship with projected canopy area ($R^2 = 0.92$, $P < 0.001$), shrub volume ($R^2 = 0.83$, $P < 0.001$), basal area ($R^2 = 0.94$, $P < 0.001$), shrub height ($R^2 = 0.49$, $P = 0.036$), number of stems ($R^2 = 0.45$, $P = 0.047$), stem diameter ($R^2 = 0.53$, $P < 0.001$) and stem length ($R^2 = 0.19$, $P < 0.001$), respectively. It had an increased tendency with PAI (Figure 4(d)), although the relation was not statistically significant ($P = 0.13$). No clear relation was found between stemflow volume and stem angle (Figure 4(g)). Moreover, for morphological metrics (Table 1), significant positive relations ($r > 0.7$, $P < 0.05$) were found among canopy area, canopy volume, basal area and stem diameter.

Morphological metrics clearly affected stemflow funnelling efficiencies for shrubs within the same species (Figure 5). Funnelling ratio decreased at first and then became constant after a threshold value with increasing projected canopy area (Figure 5(a)), shrub volume (Figure 5(b)), basal area (Figure 5(c)) and stem diameter (Figure 5(h)), respectively, being fitted by an exponential decay function. Funnelling ratio was negatively correlated with PAI (Figure 5(d)), shrub height (Figure 5(e)) and number of stems (Figure 5(f)), respectively, although the relations were not statistically significant for the former two parameters; it increased with stem angle (Figure 5(g)), although the relation was rather weak ($R^2 = 0.08$). No clear relationship was found between funnelling ratio and stem length (Figure 5(i)).

DISCUSSION

Stemflow volume represents the quantity of stemflow flux. In our study, stemflow volume increased with some shrub

Table 3 | Stemflow funnelling ratio on a rainfall event basis

		Event funnelling ratio								
Event	**Rainfall (mm)**	**CK_1**	**CK_2**	**CK_3**	**CK_4**	**CK_5**	**CK_6**	**CK_7**	**CK_8**	**CK_9**
2011-06-26	5.6	4.3	11.1	32.5	15.1	19.8	4.5	8.2	14.3	7.6
2011-07-02	11.9	60.8	155.1	280.5	163.5	80.5	80.9	59.5	126.5	108.8
2011-07-28	13.9	39.0	72.8	116.9	73.4	84.0	41.5	56.3	57.0	52.5
2011-08-15	21.3	36.2	66.7	116.0	79.5	87.7	42.5	59.4	50.0	54.5
2011-08-18	20.2	35.8	142.5	141.4	96.7	129.0	89.2	119.6	49.5	54.6
2011-08-23	10.6	45.5	116.9	77.5	90.3	124.4	68.8	128.6	84.0	72.0
2011-09-02	4	50.2	141.2	162.9	94.5	93.8	78.8	85.6	80.8	51.6
2011-09-04	8.4	9.6	52.5	48.9	36.3	34.9	27.8	45.5	37.0	19.2
2011-09-05	3.1	13.0	40.9	76.0	40.6	52.2	50.8	45.5	41.7	26.9
2011-09-09	11	45.7	168.8	129.5	98.2	122.2	106.9	159.5	120.9	74.7
2011-09-15	6.1	36.2	129.8	109.7	81.6	117.5	83.3	145.4	79.5	56.3
2011-09-16	12	41.9	149.2	147.3	88.7	114.9	83.3	146.5	70.3	61.6
2011-09-18	4.3	13.1	91.3	105.9	76.7	95.9	79.3	108.1	57.7	47.6
2011-10-09	6.4	31.4	110.8	87.9	70.9	86.3	57.8	127.4	58.5	32.0
2011-10-12	7.3	35.8	111.3	110.0	80.2	117.4	70.3	138.7	80.7	62.7
2011-11-07	8.6	28.0	97.7	94.4	72.6	80.9	55.6	100.2	51.0	35.9
2012-04-11	4.4	13.7	40.7	87.2	67.3	70.6	51.0	58.7	46.9	34.0
2012-04-30	6.1	19.8	83.5	120.0	58.9	108.5	69.8	70.6	63.3	75.0
2012-05-23	18.1	48.8	146.1	170.6	95.0	97.3	72.7	112.2	97.4	87.8
2012-05-28	3.7	27.2	93.1	113.4	59.6	74.0	30.5	67.5	69.1	54.7
2012-06-27	23.2	58.9	133.6	156.2	120.5	78.0	73.8	93.8	78.5	94.8
2012-06-28	14.8	42.1	183.3	166.5	107.7	82.3	92.6	199.0	91.2	108.9
2012-07-08	2.4	41.9	117.6	126.5	78.7	56.4	46.4	121.8	72.4	105.7
2012-07-17	20.4	53.2	108.7	153.1	90.5	63.5	57.0	125.9	64.8	84.4
2012-07-21	17.5	45.9	129.8	153.0	96.5	62.8	68.1	114.2	79.5	93.2
2012-07-30	3.5	5.7	3.9	23.0	10.8	23.0	6.1	25.8	15.9	11.6
2012-09-01	28.8	48.8	111.4	143.2	101.9	51.7	22.6	42.3	52.5	61.8
2012-09-11	3.5	23.0	76.7	67.8	33.8	33.3	33.0	89.8	28.4	56.7
2012-09-25	9.1	44.2	130.1	159.9	88.6	51.7	41.0	125.6	41.1	109.0
2013-05-15	8.4	38.3	139.3	145.6	81.7	52.1	118.4	30.2	50.7	61.5
2013-06-09	6.2	19.4	32.2	53.3	34.5	33.0	36.2	19.1	33.6	31.2
2013-06-21	19.4	50.6	29.4	144.2	107.6	96.3	49.1	48.8	85.1	70.8
2013-07-03	18.1	66.6	92.8	116.4	73.1	63.7	47.4	78.2	79.9	78.6
2013-07-09	14.6	49.5	117.9	121.0	95.3	28.5	44.1	71.0	73.1	70.7
2013-07-26	17.7	45.4	133.8	154.3	83.6	63.7	59.2	70.1	78.5	68.6
2013-08-06	8.6	49.1	60.8	164.0	71.0	36.9	42.0	31.4	73.8	72.9
2013-10-31	7.1	50.1	61.8	165.0	72.0	37.9	43.0	32.4	74.8	73.9

(*continued*)

Table 3 | continued

		Event funnelling ratio								
Event	**Rainfall (mm)**	**CK_1**	**CK_2**	**CK_3**	**CK_4**	**CK_5**	**CK_6**	**CK_7**	**CK_8**	**CK_9**
Mean	11.1	37	100	123	78	73	57	85	65	63
Min.	2.4	4	4	23	11	20	4	8	14	8
Max.	28.8	67	183	281	164	129	118	199	127	109
C.V. (%)	61	43	45	39	37	43	44	53	38	42

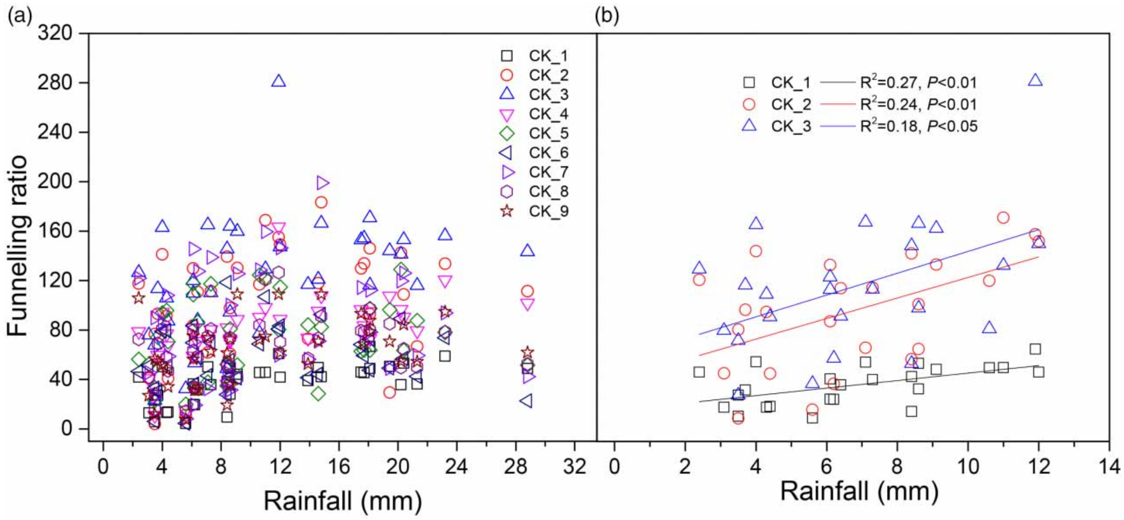

Figure 3 | Funnelling ratio in relation to rainfall depth for individual shrubs (a) and an example from three shrubs (CK_1, CK_2 and CK_3) showing the relationship between funnelling ratio and rainfall depth for rainfall ≤12 mm (b).

size metrics such as canopy area, canopy volume, basal area and stem diameter (Figure 4), and significant positive Pearson correlations ($r > 0.7$, $P < 0.05$) were found among these metrics. This indicates that smaller shrubs generate lower quantities of stemflow than larger shrubs, which is supported by studies from forested ecosystems that larger trees within the same species are inclined to generate higher volumes of stemflow due to large canopies, i.e., rainwater collecting area (e.g., Levia *et al.* 2010; Honda *et al.* 2015). However, this does not mean that larger trees/shrubs profit more from stemflow than smaller ones, because basal area, not canopy area, is the true area over which stemflow is delivered to the soil (Herwitz 1986; Germer *et al.* 2010; Levia *et al.* 2011). Although stemflow volume is an important metric for calculating watershed inputs and overall budgets, it is unreasonable to use this metric to assess the hydrologic implications of stemflow by leaving out the stemflow-affected area (Germer *et al.* 2010). Also, this unstandardized metric is unsuitable for use in hydrologic models (Levia & Germer 2015). This metric thereby inevitably fails to compare the funnelling efficiencies among individual plants. Alternatively, the stemflow funnelling ratio is an effective quantitative tool to assess how efficient a tree/shrub is at funnelling water to its base, because it identifies the true delivering area (shrub basal area) of stemflow and allows researchers to readily compare results with other studies and achieve meaningful cross-site comparisons (Llorens & Domingo 2007; Levia & Germer 2015).

In our study, funnelling ratio differed considerably among individual shrubs within the same species (Table 3), with a mean funnelling ratio range of 37–123 (CV = 33%), suggesting that the shrub basal area of *C. korshinskii* can receive 37–123 times the amount of rainwater

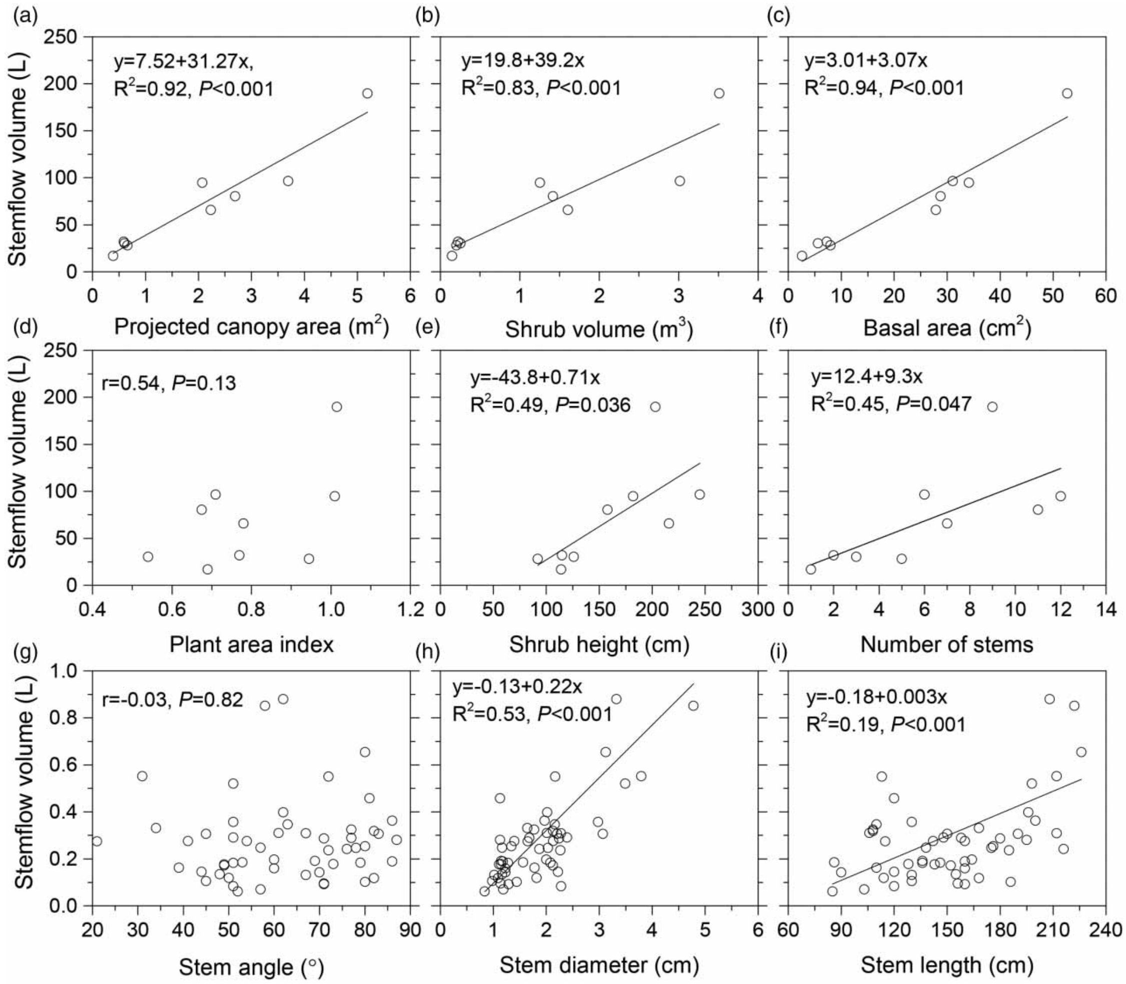

Figure 4 | Stemflow volume during study period in relation to shrub morphological metrics: (a)–(f) refer to the total amount of stemflow collected by individual shrubs; (g)–(i) refer to the total amount of stemflow collected by individual stems.

by stemflow as compared to an open area. This fell in the range of studies from arid and semi-arid environments (Navar 1993; Llorens & Domingo 2007; Li *et al.* 2008; Yang *et al.* 2008; Wang *et al.* 2011). For example, Li *et al.* (2009) reported an average funnelling ratio of 77.8 and 48.7 for shrubs *H. scoparium* and *S. psammophila*, respectively; Garcia-Estringana *et al.* (2010) observed that the average funnelling ratio for nine Mediterranean shrubs was 104 with a range of 30–250. Stemflow is thus considered as an essential water resource available for growth and survival of shrubs, which may further contribute to the stability of shrub communities in water-limited arid desert environments. Moreover, we found an exponential decay relationship between funnelling ratio and some shrub size metrics (Figure 5). This suggests that smaller shrubs gain access to rainfall via higher funnelling ratio than larger shrubs. Our findings thus highlight the importance of morphological metrics on stemflow yield, and in particular, small shrubs might profit from sporadic rainfall events. Small shrubs generally lack deep developed roots to draw water from deep soil layers, whereas small shrubs are more efficient at funnelling rainwater than their large counterparts. This is of eco-hydrological importance for the survival and growth of juvenile shrubs in drought conditions of arid desert ecosystems. Moreover, according to Kidron (2015), each millimetre of rain infiltrates to ~10–11 mm in sand; it is therefore expected that long-term mean precipitation (191 mm) in our study area should

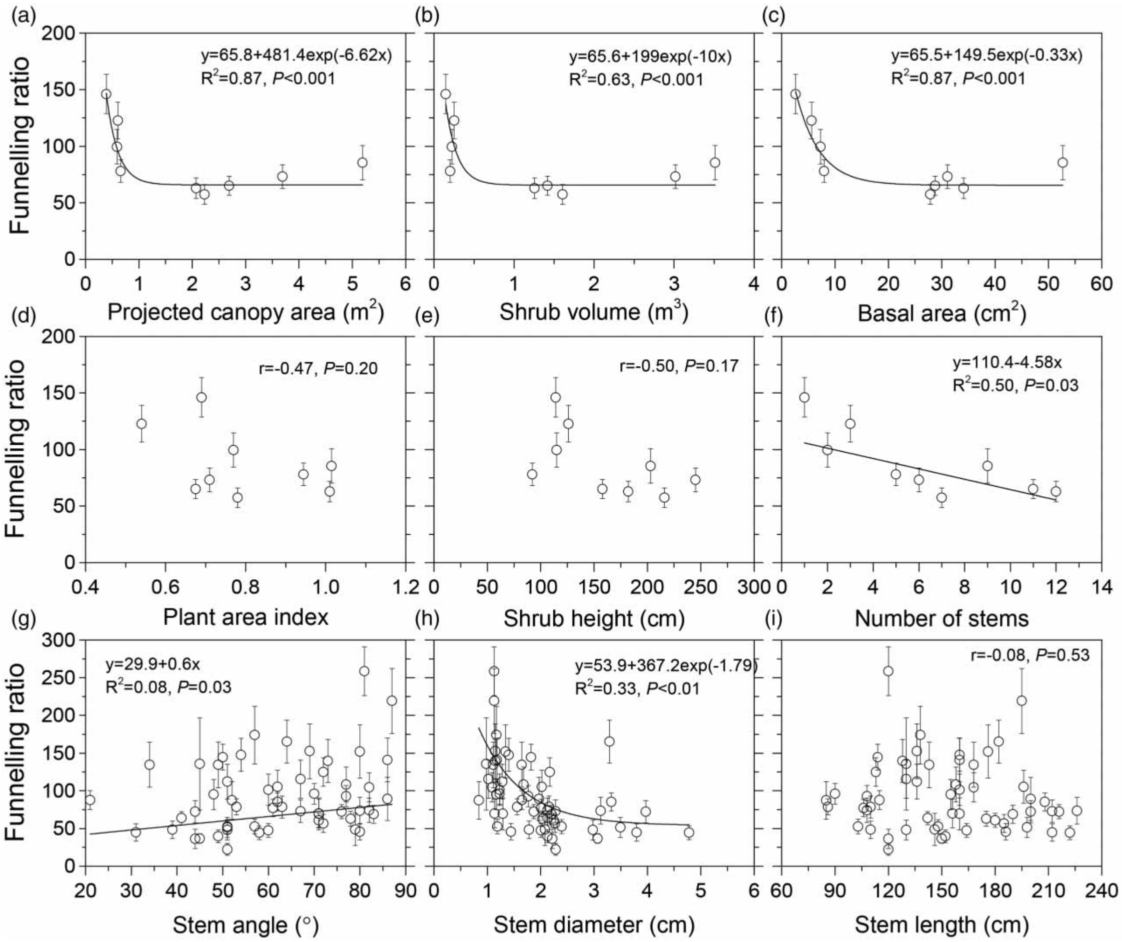

Figure 5 | Mean event funnelling ratio in relation to shrub morphological metrics: (a)–(f) refer to the funnelling ratio of individual shrubs; (g)–(i) refer to the funnelling ratio of individual stems. Error bar indicates confidence interval (a = 0.05) of the associated mean value.

result in an infiltration of ~191–210 cm. Funnelling ratio is an important parameter for a better understanding of shrub-related infiltration (Levia & Germer 2015). In our study, shrubs had a high funnelling ratio with small shrubs possessing higher funnelling efficiencies than larger ones, it is therefore reasonable to estimate that the infiltration under shrub canopies should be greater than in bare sand soil; it is, however, difficult to precisely estimate infiltration depth due to complex root structure and the great difference between stemflow infiltration process and vertical rainfall infiltration process (Liang *et al.* 2009).

Not surprisingly, stemflow volume increased significantly ($P < 0.01$) with rainfall depth for all studied shrubs (Figure 2). For funnelling ratio, it first showed an increased tendency with rainfall depth until a threshold value around 12 mm and then began to decline (Figure 3). With increasing rainfall depth, a general increase in funnelling ratios (e.g., Figure 3(b)) can be found in the literature, whereas deviations exist as to this relationship after exceeding a certain point of rainfall depth. For co-occurring evergreen broadleaved trees (*Cyclobalanopsis multinervis* and *Cyclobalanopsis oxyodon*) and deciduous broadleaved trees (*Fagus engleriana* and *Quercus serrata* var. brevipetiolata) in a subtropical forest, Su *et al.* (2016) found that funnelling ratio displayed a tendency to increase with incident rainfall up to a rainfall depth of 50 mm, above which funnelling ratio remained relatively constant despite increasing rainfall. In a northern hardwood stand in southern Ontario under growing season conditions, Carlyle-Moses & Price (2006) found that stemflow funnelling ratios increased with increasing rainfall depth in a linear fashion until a peak (17.4 mm) was reached with funnelling ratios declining with greater rainfalls. Similar results as Carlyle-Moses & Price (2006) have been found for desert shrubs in China with a threshold value of 11 mm for *C. korshinskii* and 17 mm for *Reaumuria soongorica* and *Tamarix ramosissima* (Li *et al.* 2008), and for a juniper (*Juniperus virginiana*, redcedar) woodland and a tallgrass prairie with a threshold value of 35 mm in the south-central Great Plains of the US (Zou *et al.* 2015). According to Carlyle-Moses & Price (2006), a greater proportion of a tree becomes saturated with increasing rainfall input and thus the area contributing to stemflow increases until a threshold rainfall input that saturates all areas capable of producing stemflow is reached; once this threshold rainfall depth has been exceeded, funnelling ratios would be expected to decrease since the numerator in Equation (1) will be limited by the maximum contributing area of the tree, while the denominator will increase in proportion with the rainfall input.

CONCLUSIONS

Both stemflow volume and funnelling ratio differed considerably among individual shrubs within the same species. Greater incident rainfalls resulted in larger event stemflow volumes, while funnelling ratio seems to be less affected by rainfall depth. Smaller shrubs generate a lower quantity of stemflow, while gaining access to rainfall via higher funnelling ratio than larger shrubs, suggesting that small shrubs may have a favourable soil water condition around the shrub base for survival and growth when competing with larger ones in water-limited arid desert environments. Investigation into soil moisture variations related to the stemflow induced by shrubs of varying sizes is called for in the future to obtain direct and more convincing evidence of differential intra-specific stemflow funnelling efficiencies on the growth of shrubs.

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