

## Rainfall partitioning characteristics of three typical sand-fixing shrubs in Horqin Sand Land, north-eastern China

Wenkai Shou, Ala Musa, Zhimin Liu, Jianqiang Qian, Cunyang Niu and Yuhang Guo

### ABSTRACT

Rainfall partitioning by vegetation affects water balance and utilization by plants. *Caragana microphylla*, *Hedysarum fruticosum*, and *Salix gordejvii* are three typical, morphologically different sand-fixing shrubs in Horqin Sand Land. However, few studies have compared rainfall partitioning by these shrubs. We examined rainfall partitioning differences among these shrubs in Horqin Sand Land, north-eastern China. On average, throughfall, stemflow (SF), and interception for *C. microphylla* accounted for 64.2, 11.0, and 24.8% of the individual incident rainfall, respectively; for *H. fruticosum*, they accounted for 71.2, 6.3, and 22.5%; and for *S. gordejvii*, they accounted for 75.3, 5.3, and 19.4%. The average funneling ratio for *H. fruticosum* ( $162.7 \pm 33.2$ ) was larger than that for *C. microphylla* ( $100.1 \pm 16.9$ ) and *S. gordejvii* ( $106.2 \pm 23.1$ ). Rainfall partitioning was significantly correlated with canopy area, branch number, and stem basal area for *C. microphylla* and *S. gordejvii*. SF volumes of 3,167, 676, and 2,210 L were estimated to have channeled into the plots for *C. microphylla*, *H. fruticosum* and *S. gordejvii*, respectively, indicating that *C. microphylla* is more effective in channeling SF to the root zone. These results suggest that *C. microphylla* may be more advantageous for sand-fixing and vegetation restoration in sand lands.

**Key words** | *Caragana microphylla*, *Hedysarum fruticosum*, interception, *Salix gordejvii*, stemflow, throughfall

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### INTRODUCTION

The response of terrestrial ecosystems to global change is of current scientific interest (Vitousek 1994; Weltzin *et al.* 2003). Global climate changes are likely to alter patterns of global air circulation and hydrologic cycling, resulting in changes in precipitation regimes (Volder *et al.* 2013).

Vegetation modifies precipitation intensity and distribution via three pathways: throughfall (TF) (precipitation passing directly through or dripping from the canopy to the soil surface), stemflow (SF) (rainfall that reaches the base area of a plant by flowing down the branches and stems), and interception (precipitation that is captured by the canopy and subsequently returned to the atmosphere through evaporation) (Marin *et al.* 2000; Swaffer *et al.* 2014; Schumacher & Christiansen 2015). An understanding

of rainfall partitioning by the vegetation is helpful for explaining the pattern of soil moisture (Liang *et al.* 2011; Wang *et al.* 2011), soil solution chemistry (Zhang *et al.* 2013; Shiklomanov & Levia 2014), groundwater recharge (Buttle *et al.* 2014), runoff generation and soil erosion (Cattan *et al.* 2009; Perez-Suarez *et al.* 2014), and spatial distribution of understory vegetation (Barbier *et al.* 2009).

Rainfall partitioning is influenced by plant characteristics such as canopy area and volume, plant height, branch number and angle, and stem basal area (Llorens & Domingo 2007; Frost & Levia 2014; Zimmermann & Zimmermann 2014) as well as by rainfall characteristics such as the amount, intensity, and duration of rainfall (Huber & Iroume 2001; Carlyle-Moses 2004; Muzyllo *et al.* 2012). The

regulation of TF and SF by vegetation is closely associated with the strategies of drought resistance employed by plants (Martinez-Meza & Whitford 1996; Levia & Frost 2003; Siegert & Levia 2014). Studies of rainfall partitioning have been conducted for plants growing in arid zones (Crockford & Richardson 2000; Perez-Suarez *et al.* 2014; Sadeghi *et al.* 2015) to elucidate adaptations to water-limited environments and to guide restoration.

Regarding rainfall partitioning by sand-binding shrubs, the following questions remain to be answered: (1) how much water is available after a rainfall event, and how does this differ between species and regions; (2) how do different shrub species use available rain water, i.e. how much rainfall water is utilized as SF and TF by different species; and (3) what are the rainfall use efficiency and water use strategies of different shrub species with reference to rainfall availability, SF, and TF. Since rainfall partitioning is mainly influenced by a plant's morphological characteristics (Mauchamp & Janeau 1993; Germer *et al.* 2010), it is essential to select shrub species with distinct canopy architecture to investigate it. Presumably, canopy size and shape, branch angle, branch number, stem roughness, and stem thickness are some of the canopy characteristics that control rainfall partitioning.

Horqin Sand Land is a typical semiarid sand region located in southeastern Inner Mongolia in north-eastern China. Due to environmental changes and human activities, this region has suffered severe land degradation. In recent decades, some sand-binding shrubs have been introduced to stabilize the shifting sand (Zhao *et al.* 2007). Among these species, *Caragana microphylla*, *Hedysarum fruticosum* and *Salix gordejewii* are the most important ones. In recent years, the vegetation used for stabilizing the dunes has deteriorated, which may have been caused by water deficit (Wang *et al.* 2005). Until now, few studies on rainfall redistribution characteristics of the shrubs in this region, each with distinct morphology, have been conducted.

In this study, we selected three shrub species with distinct morphological characteristics, i.e. *C. microphylla* (umbrella-shaped canopy, multiple smooth stems, and numerous ovate leaves), *H. fruticosum* (rough stems and thin leaves) and *S. gordejewii* (loosely branched, slender stems, and leptophyllous leaves) to investigate rainfall partitioning and SF funneling. Our objectives were (1) to

determine how much rainwater is available to the different species, (2) to determine how much available rainwater is utilized as SF and TF by the different species, and (3) to elucidate the rainfall use efficiency and water use strategies of the different shrub species.

## MATERIALS AND METHODS

### Study site

The study site was located in the Songshushan Nature Reserve (43°3'36" N, 119°14'6" W) of Horqin Sand Land, Inner Mongolia Autonomous Region, north-eastern China. It has a temperate semi-arid climate, i.e. dry and windy in winter and spring, warm and rainy in summer, and cool in autumn. Mean annual temperature is 6.2 °C with the coldest and the hottest mean monthly temperatures of -14.0 °C in January and 40.5 °C in July, respectively. Mean annual precipitation is 351 mm, of which 69% is concentrated in June and July. The annual potential evaporation is 2,352 mm. The dominant winds blow in a north-westerly direction from March to May and in a south-westerly direction from June to September. Average wind speed is 2.9 m/s; mean annual vapor pressure is 6.6 kpa; and mean annual relative humidity is 47%.

The study area is a semiarid region surrounded by fixed, semi-fixed, and active sand dunes, with the vegetation consisting of shrubs such as *C. microphylla*, *S. gordejewii*, and *H. fruticosum* and herbs such as *Pennisetum centrasiaticum*, *Corispermum macrocarpum*, and *Setaria viridis* (Zhao *et al.* 2007).

### Experimental design

#### Target species

Three typical sand-fixing shrubs with distinct morphological characteristics were used in this study: *C. microphylla*, a multiple-stemmed, smooth-stemmed shrub (1–2 m tall) with numerous ovate leaves that forms an umbrella-shaped canopy; *S. gordejewii*, a loosely branched shrub (1.5–2 m tall) with slender stems and leptophyllous leaves; and *H. fruticosum*, a leguminous shrub (0.5–1.5 m tall) with rough stems and thin leaves. Considering these different

characteristics, each shrub species represents different canopy types: *C. microphylla* represents a dense-branch-type shrub; *S. gordejvii* represents a loose-stem-type shrub; and *H. fruticosum* represents a thin-leaf-type shrub.

*Caragana microphylla* is highly effective in stabilizing the shifting sand in north-eastern China (Zhang et al. 2006). *S. gordejvii*, widely distributed in the semiarid area of northern China, can survive in the shifting sand dunes as a pioneer species (Yuan et al. 2005). *H. fruticosum* is widely distributed as a sand-fixing species in arid and semi-arid sandy regions of Inner Mongolia. There have been many studies concentrated on rainfall use efficiency and water use strategies of these shrub species by investigating plant transpiration, photosynthesis, and water transportation (Liu et al. 2003; Ma et al. 2004), however, comparisons of rainfall partitioning by these shrub species with regard to the morphological characteristics are not well understood.

Nine 10 × 10 m plots were selected to monitor TF and SF. Three shrubs of each species were selected in each plot for a total of 27 shrubs selected for monitoring. All gross rainfall, TF, and SF measurements were taken during the growing season from May to September of 2014.

## Rainfall

Gross rainfall data were collected from 25 rainfall events. Gross rainfall data were obtained at the Songshushan Experiment Station, approximately 0.5 km east of the study plots. Gross rainfall was measured in an open area without obstructions using a standard rain gauge (diameter = 20 cm) and was

observed immediately after a rainfall event or before sunrise if the rainfall occurred overnight (Carlyle-Moses 2004).

## Throughfall

TF was collected during 16 rainfall events with cylindrical polyethylene gauges similar to the standard rain gauges (diameter = 20 cm). The gauges were arranged under the canopy of each shrub in four directions (0, 90, 180 and 270 °). Corresponding to the differences in canopy area among species (Table 1), a varying number of gauges were installed from shrub base to crown periphery at each direction for each species. Four gauges were used in each of the four directions for *C. microphylla* and *S. gordejvii*, and three gauges for each direction were used for *H. fruticosum*. Thus, 16 TF collectors were used for each *C. microphylla* and *S. gordejvii* shrub and 12 for each *H. fruticosum* shrub. TF was measured immediately after the rainfall ended or in the morning the next day in case the rainfall event occurred overnight. TF was calculated as the following:  $TF = \sum_{i=1}^n TV_i / n * GA$ , where TF is throughfall amount (mm), TV is throughfall volume (L) for each gauge,  $n$  is the number of throughfall gauges under each shrub canopy, and GA is the gauge projection area (m<sup>2</sup>).

## Stemflow

SF was measured during 16 rainfall events by self-made collectors (Figure 1). Different stem diameter classes were chosen to collect the SF. Aluminum foil tape (approximately

**Table 1** | Characteristics of the canopy morphology for *C. microphylla*, *H. fruticosum* and *S. gordejvii* in the study area

Variables	Average value		
	<i>C. microphylla</i>	<i>H. fruticosum</i>	<i>S. gordejvii</i>
Canopy area (m <sup>2</sup> )	4.01 (± 1.67)	2.66 (± 1.27)	4.15 (± 1.97)
Number of branches	31 (± 7) <sup>ab</sup>	19 (± 8) <sup>b</sup>	36 (± 20) <sup>a</sup>
Stem basal diameter (cm)	1.39 (± 0.28) <sup>a</sup>	0.89 (± 0.13) <sup>b</sup>	0.93 (± 0.09) <sup>b</sup>
Branch angle (°)	52.8 (± 9.8)	58.2 (± 11.5)	56.3 (± 13.6)
Stem basal area (cm <sup>2</sup> )	41.94 (± 15.61) <sup>a</sup>	10.35 (± 6.11) <sup>b</sup>	21.34 (± 12.35) <sup>b</sup>
Shrub height (m)	1.56 (± 0.37) <sup>ab</sup>	1.39 (± 0.15) <sup>b</sup>	1.62 (± 0.24) <sup>a</sup>
Canopy volume (m <sup>3</sup> )	2.39 (± 1.47)	1.42 (± 0.84)	2.04 (± 1.06)

Mean ± standard deviation are reported.

Different letters in rows indicate significant differences among three shrub species at  $P \leq 0.05$ .



**Figure 1** | Photograph of the method to collect the SF.

6 cm wide) was wrapped around a branch to form a funnel-form groove at the upper portion, using adhesive to glue the branch and the aluminum foil tape at the antapical half. A flexible plastic tube was used to connect the groove and a plastic bottle. Silicon was used to seal the gap of the conjoining line and the bottom of the aluminum foil tape to prevent water leakage. Rainfall running down the stem and flowing into the groove was ultimately collected in the plastic bottle through the flexible plastic tube. The SF volume was measured with a measuring cylinder immediately after each rainfall event or at sunrise if the rainfall event occurred overnight. SF was calculated by using the following formula:

$SF = \sum_{i=1}^n SV_i * Mi / SA$ , where  $n$  is the total number of stems on the shrub,  $SV_i$  is the stemflow volume (L) of stem diameter class  $i$ ,  $Mi$  is the number of stems in diameter class  $i$ , and  $SA$  is the projected area of shrub canopy ( $m^2$ ). The stemflow funneling ratio ( $F$ ) was calculated with the following formula:  $F = SFv / BA \times P$ , where  $SFv$  is the stemflow volume (L),  $BA$  is the stem basal area ( $m^2$ ), and  $P$  is the amount of rainfall (mm). Plot SF was estimated using the volume of SF collected by each of the measured stems and then relating the basal area of these stems to the total plot basal area, following the upscaling method described by Swaffer et al. (2014).

## Interception

Although canopy interception cannot be measured directly, the value of this partitioning part was calculated by subtracting the sum of TF and SF from gross rainfall.

## Canopy characteristics

Canopy variables measured on each shrub included: shrub height, canopy area and volume, branch number and angle, stem basal area, and stem basal diameter (Table 1). Canopy area was calculated by taking the east-west and north-south diameters through the center of the fullest part of the canopy. Canopy volume was calculated by using the volume formula of an inverted cone. All branches on each shrub base were counted to determine the branch number. Canopy angle was measured using an angle protractor. Stem basal diameter was measured using a Vernier caliper and used to calculate stem basal area.

## Statistical analysis

Statistical analyses and model development were completed using Systat SigmaPlot v12.0 Systat Software Inc. and SPSS

**Table 2** | Characteristics of rainfall partitioning of three shrub species during the experimental period in the study area

Rainfall amount (mm)	Frequency percentage (%)	Rainfall percentage (%)	Rainfall intensity (mm h <sup>-1</sup> )	<i>C. microphylla</i>			<i>H. fruticosum</i>			<i>S. gordejvii</i>		
				TF (%)	SF (%)	I (%)	TF (%)	SF (%)	I (%)	TF (%)	SF (%)	I (%)
<2	32	1.9	0.5	30.0	13.5	56.5	45.6	9.7	44.7	47.1	8.1	44.8
2–5	12	4.5	1.3	48.9	13.1	38.0	59.6	8.9	31.5	69.9	7.0	23.1
5–10	28	20.2	2.3	62.0	11.3	26.7	67.5	6.4	26.1	72.8	5.4	22.3
10–15	4	4.5	1.2	67.3	10.4	22.3	80.6	4.3	15.1	74.1	4.7	21.2
15–20	4	6.9	11.3	55.8	10.6	33.6	60.2	5.6	34.2	64.1	3.9	32.0
>20	20	62.1	3.9	71.9	10.3	17.8	80.0	6.0	14.0	83.0	5.9	11.2

TF: Throughfall; SF: Stemflow; I: Interception.

Statistics v17.0 SPSS Inc. All model parameters were chosen based on goodness of fit and residual analyses. Levels of significance, including the standard errors associated with model parameters, were given at the 95% confidence interval ( $p < 0.05$ ) unless otherwise stated.

## RESULTS

### Rainfall characteristics

During the measurement period, 25 rainfall events, divided into six classes (Table 2), were observed, and 246.2 mm of rainfall were recorded (Figure 2). The precipitation of individual events averaged 9.8 mm, and ranged from 0.1 to 34.8 mm. The precipitations events below 2 mm accounted for 32% of all events, and those below 10 mm accounted for 72% of events. Small precipitation events were frequent but produced a small percentage of the total precipitation amount, whereas large precipitation events were rare but were the main water supply source.

### TF, SF, and interception

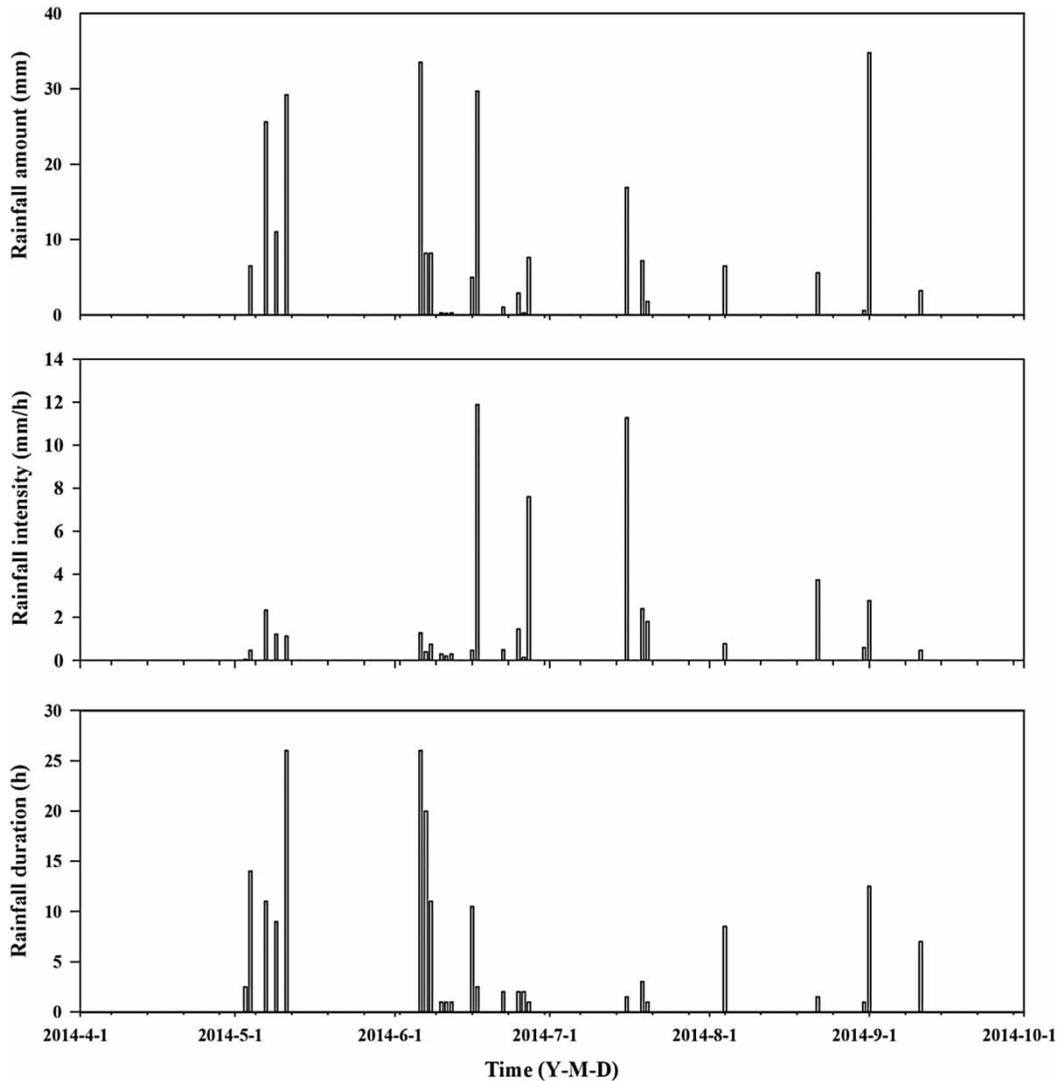
Of the 25 rainfall events, it was possible to collect TF and SF during 16 of them. Individual TF (mm), SF (mm) and interception (mm) for each shrub were strongly positively correlated with individual rainfall (mm). The rainfall threshold values for initiation of TF for *C. microphylla*, *H. fruticosum* and *S. gordejvii* were 1.6, 1.0, and 1.1 mm, respectively. Similarly, the rainfall threshold values for SF initiation were 0.73, 0.27, and 1.54 mm (Figure 3(a), 3(c) and 3(e)).

TF of *C. microphylla* ranged from 1.4 to 24.6 mm and accounted for 43.5–79.5% (mean = 64.2%) of individual rainfall events, that of *H. fruticosum* ranged from 1.7 to 28.0 mm and accounted for 49.2–85.0% (mean = 71.2%), and that of *S. gordejvii* ranged from 2.0 to 30.2 mm and accounted for 55.7–93.7% (mean = 75.3%). Similarly, SF of *C. microphylla* ranged from 0.3 to 4.0 mm and accounted for 9.0–16.0% (mean = 11.0%) of individual rainfall events, that of *H. fruticosum* ranged from 0.2 to 2.2 mm and accounted for 4.2–8.9% (mean = 6.3%), and that of *S. gordejvii* ranged from 0.2 to 2.4 mm and accounted for 3.1–7.0% (mean = 5.3%). Interception by *C. microphylla* ranged from 1.2 to 8.5 mm and accounted for 9.5–46.8% (mean = 24.8%) of individual rainfall events, that of *H. fruticosum* ranged from 0.8 to 10.2 mm and accounted for 8.6–46.6% (mean = 22.5%), and that of *S. gordejvii* ranged from 0.5 to 7.1 mm and accounted for 1.7–41.2% (mean = 19.4%) (Figure 4(a)–4(c)).

TF percentage increased, but interception percentage decreased with individual event rainfall amount for the three shrub species. However, an inflection point occurred at 16.9 mm (the corresponding rainfall intensity was 11.3 mm h<sup>-1</sup>), where TF percentage decreased but interception percentage increased for *C. microphylla*, *H. fruticosum*, and *S. gordejvii* (Table 2).

### Correlations between rainfall partitioning and canopy characteristics

For *C. microphylla*, SF and interception were positively correlated with canopy area. For *S. gordejvii*, SF increased



**Figure 2** | Rainfall amount (mm), rainfall intensity (mm/h) and rainfall duration (h) during the experimental period in the study area.

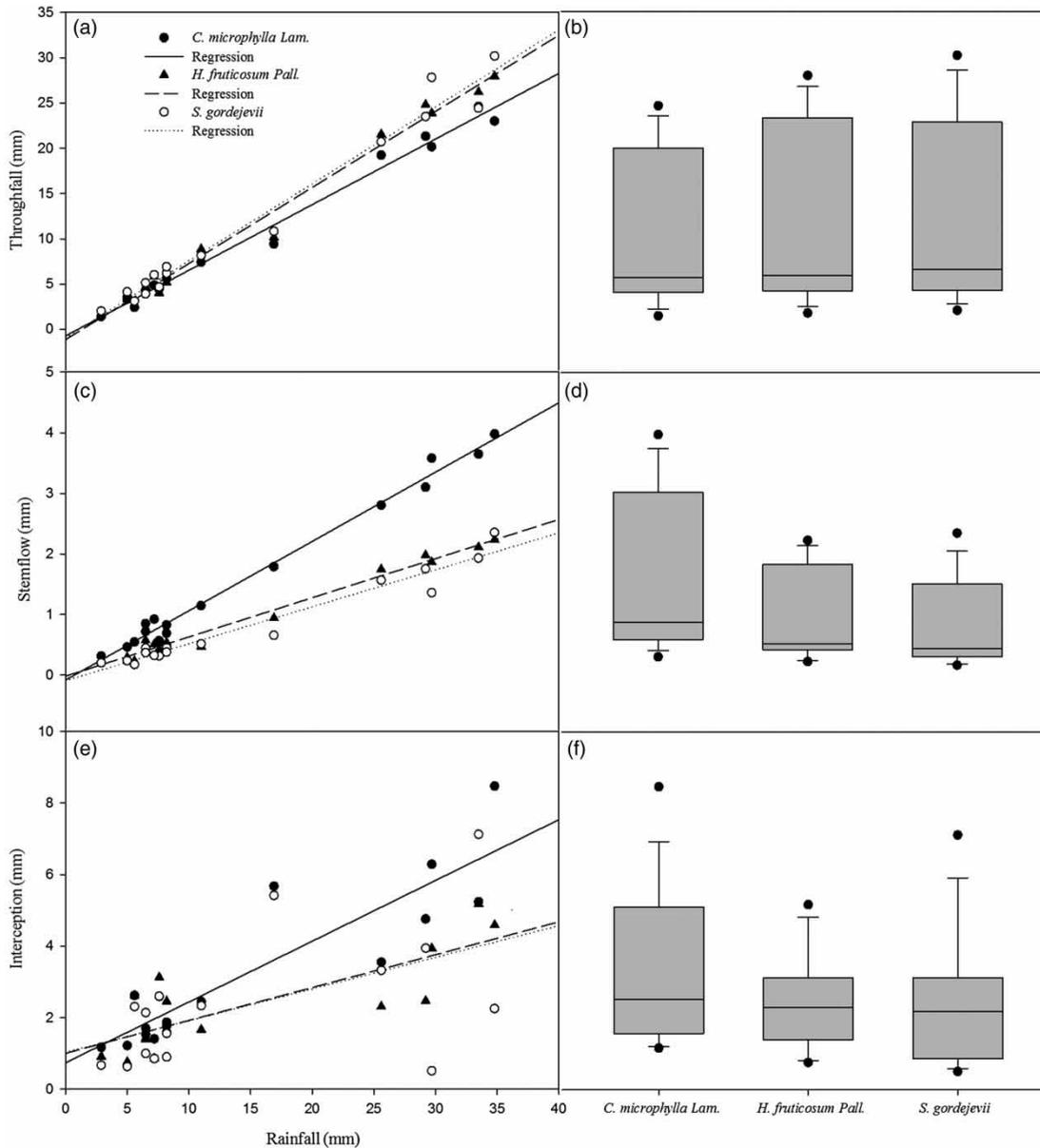
with branch number and decreased with stem basal area; however, its interception was significantly positively correlated with stem basal area. There was no significant correlation between rainfall partitioning and any canopy characteristics for *H. fruticosum* (Table 3).

### SF funneling ratio

Funneling ratios of *C. microphylla* first increased and then decreased, with a threshold at approximately 7.2 mm. *H. fruticosum* and *S. gordejewii* showed a similar trend with the threshold at approximately 6.5 mm (Figure 5(a)).

*H. fruticosum* exhibited a high variability in its funneling ratio value. In contrast, *C. microphylla* and *S. gordejewii* exhibited low variability. The average funneling ratio was  $100.1 \pm 16.9$ ,  $162.7 \pm 33.2$  and  $106.2 \pm 23.1$  for *C. microphylla*, *H. fruticosum* and *S. gordejewii*, respectively (Figure 5(b)).

The stem basal area of the shrubs significantly influenced the SF funneling ratio. The funneling ratio value decreased with stem basal area ( $y = 248.064 x^{-0.246}$ ;  $R^2 = 0.445$ ;  $p < 0.0001$ ) (Figure 6). The volumes of SF channeled into the plots were estimated to be 3,167, 676, and 2,210 L for *C. microphylla*, *H. fruticosum*, and *S. gordejewii*, respectively (Table 4).



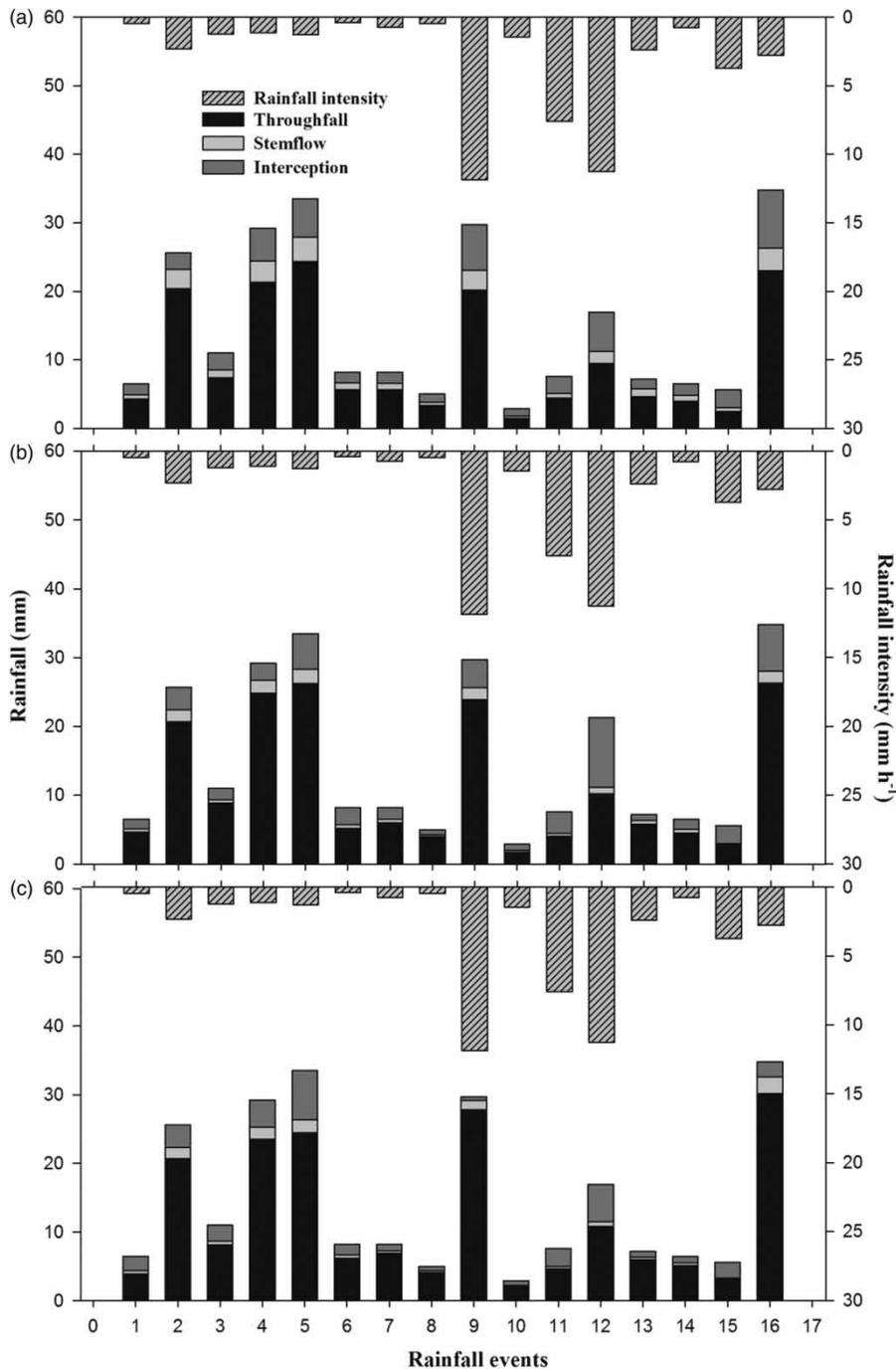
**Figure 3** | The relationship between individual rainfall (mm) and (a) individual TF (mm) and (c) individual SF (mm) and (e) individual interception (mm) for three shrub species over the study period. Box plots depict comparisons among *C. microphylla*, *H. fruticosum* and *S. gordejvii* for (b) TF, (d) SF and (f) interception data at the median and 25th and 75th percentile. Whiskers show the 5th and 95th percentile.

## DISCUSSION

### Rainfall partitioning

Over the study period, TF, SF, and interception were found to be positively correlated with rainfall amount for all three species, which is in accordance with the conclusions drawn

from other regions (Návar 2011; Zhang *et al.* 2013; Swaffer *et al.* 2014; Fan *et al.* 2015). This means that rainfall processes rather than plant species and study regions are the determinant factors in rainfall partitioning. However, the correlation between interception and rainfall amount was less prominent, indicating that interception was less influenced by rainfall characteristics than SF and TF.



**Figure 4** | Rainfall partitioning into TF, SF and interception and its associated rainfall intensity during observation periods for (a) *C. microphylla*, (b) *H. fruticosum* and (c) *S. gordejewii*.

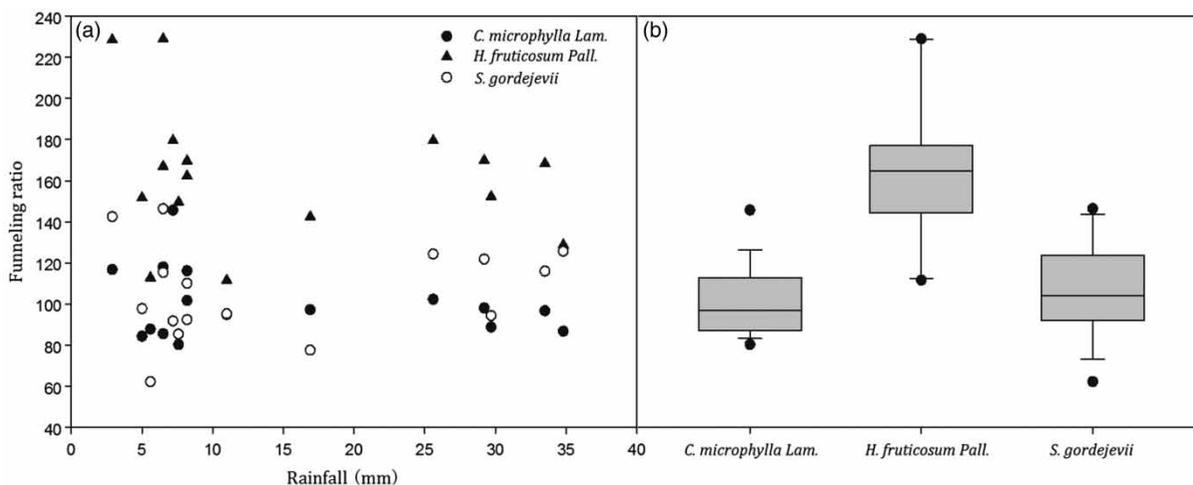
Different shrub species partition rainfall into TF, SF, and interception differently, resulting in different amounts of available rainwater. The TF percentage of *S. gordejewii* (75.3%) was the highest, followed by *H. fruticosum* (71.2%) and *C. microphylla* (64.2%); while the SF

percentage of *C. microphylla* (11.0%) was higher than that of *H. fruticosum* (6.3%) and *S. gordejewii* (5.3%); and the interception percentage of *C. microphylla* (24.8%) was higher than that of *H. fruticosum* (22.5%) and *S. gordejewii* (19.4%). These results indicate that *C. microphylla* exhibits

**Table 3** | Correlation coefficients between rainfall partitioning and canopy characteristics of three shrub species

Variables	Correlation coefficient								
	<i>C. microphylla</i>			<i>H. fruticosum</i>			<i>S. gordejvii</i>		
	TF	SF	Interception	TF	SF	Interception	TF	SF	Interception
Canopy area (m <sup>2</sup> )	-0.331	0.707*	0.696*	-0.271	0.451	0.079	-0.168	0.591	0.523
Number of branches	-0.639	0.283	0.065	-0.196	0.035	0.187	-0.067	0.857**	0.635
Stem basal diameter (cm)	-0.203	-0.457	0.446	0.31	-0.073	-0.25	0.574	-0.121	-0.481
Branch angle (°)	0.071	-0.472	-0.398	-0.199	0.399	0.034	-0.097	-0.019	0.055
Stem basal area (cm <sup>2</sup> )	-0.417	-0.46	0.543	0.201	-0.026	-0.169	0.179	-0.844**	0.704*
Shrub height (m)	-0.256	-0.381	0.41	-0.141	-0.045	0.141	0.209	-0.177	-0.023
Canopy volume (m <sup>3</sup> )	-0.235	0.546	0.529	0.166	-0.392	-0.007	0.201	0.479	-0.468

Note: \* $P < 0.05$ ; \*\* $P < 0.01$ .

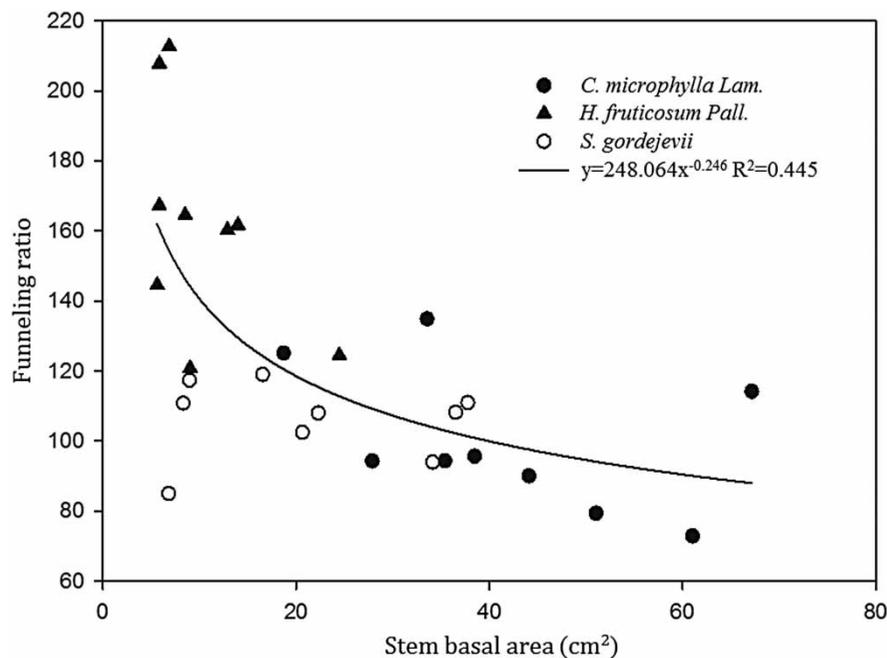
**Figure 5** | The relationship between individual rainfall and SF funneling ratio for *C. microphylla*, *H. fruticosum* and *S. gordejvii*. Box plots portray comparisons among *C. microphylla*, *H. fruticosum* and *S. gordejvii* for stem funneling ratio data at the median and 25th and 75th percentile. Whiskers show the 5th and 95th percentile.

a higher interception and a higher SF than *H. fruticosum* or *S. gordejvii*. Large variations in rainfall partitioning patterns can be found between species in different areas, with SF percentages ranging from 2.2 to 43.3% (Table 5). The difference in rainfall partitioning of shrub species may be attributed to the differences in morphological characteristics of the plant species. For example, the multiple-stems, umbrella-shaped canopy, smooth stems, and numerous ovate leaves of *C. microphylla* enable it to better intercept rainwater and thus generate greater SF production. *H. fruticosum*, on the other hand, is a shrub with rough stems and thin leaves, thus its canopy reduces interception and its branches are capable of absorbing

SF. The slender and loose stems and leptophyllous leaves of *S. gordejvii* are unfavorable for rainfall interception but enhance net precipitation.

For all three species, TF percentage increased but interception percentage decreased with rainfall amount. However, high-intensity individual rainfall events resulted in lower TF production and higher interception. High intensity rainfall with larger raindrop volume, terminal velocity, and kinetic energy enhances the proportion of rain intercepted by the canopy, thereby reducing the water available for TF production (Carlyle-Moses 2004).

The thresholds for TF initiation of *C. microphylla*, *H. fruticosum*, and *S. gordejvii* were 1.6, 1.0, and 1.1 mm,



**Figure 6** | The relationship between stem basal area and average SF funnelling ratio for *C. microphylla*, *H. fruticosum* and *S. gordejvii* using total rainfall, SF volume and stem basal area measurements over the study period.

**Table 4** | Estimated SF funnelling ratio and volume of SF generated in the study area, using the regression from Figure 5 and the volume of rainfall observed

Species	Pg (mm)	Number of branches	Stem basal area (cm <sup>2</sup> )		Funnelling ratio		SF (L)
			min	max	min	max	
<i>C. microphylla</i>	246.2	31	0.80	67.17	88	262	3,167
<i>H. fruticosum</i>	246.2	19	0.31	24.48	113	331	676
<i>S. gordejvii</i>	246.2	36	0.51	37.77	102	293	2,210

respectively, indicating that they are species-specific. The threshold for SF initiation for *S. gordejvii* (1.54 mm) was larger than that for *C. microphylla* (0.73 mm) and *H. fruticosum* (0.27 mm). The higher value of *S. gordejvii* is likely to be due to the long, thick, and coarse branches with high bark storage capacities that are unfavorable for channeling SF (Levia & Herwitz 2005). The multiple smooth stems and ovate, small, waxy leaves of *C. microphylla* led to its rapid generation and large production of SF.

#### Rainfall partitioning in relation to canopy characteristics

There was a weak correlation between rainfall partitioning and canopy characteristics such as stem basal diameter, branch angle, shrub height, and canopy volume, but some

studies have found that SF is correlated with canopy area, shrub height, branch number, and canopy volume for *Cara-gana korshinskii* and *Hippophae rhamnoides* (Jian et al. 2014). The differences between our results and those of previous studies may be explained by two possible reasons. First, canopy structure and characteristics are species-specific, and bark surface structure, stem number, and density affect rainfall partitioning pattern (Zhang et al. 2015). Second, seasons and precipitation conditions may play a role in how plants partition rainfall. For example, in the dry season, the interception percentage by a canopy may be greater during low intensity, low volume precipitation events than a similar event in the wet season (Deguchi et al. 2006). To arrive at more general conclusions, future research should include more parameters relevant to rainfall partitioning.

**Table 5** | Gross rainfall (Pg) partitioning into TF, SF and interception (I) in different shrub species

No.	Location	Shrub species	Pg (mm)	TF (%)	SF (%)	I (%)	References
1	USA	<i>Prosopis glandulosa</i>	230	62.8	5.4	31.8	Martinez-Meza & Whitford (1996)
		<i>Flourensia cernua</i>	230	55.8	10.6	34.6	
2	USA	<i>Larrea tridentata</i>	235	64.7	16.8	18.5	Whitford et al. (1997)
3	Spain	<i>Rosmarinus officinalis</i>	290	31.5	43.3	25.2	Serrato & Diaz (1998)
		<i>Thymus vulgaris</i>	290	37.2	29.8	33	
		<i>Juniperus oxycedrus</i>	232	44.5	18.7	36.5	
4	Spain	<i>Anthyllis cytisoides</i>	300	40	20	40	Domingo et al. (1998)
		<i>Retama sphaerocarpa</i>	300	72	7	21	
5	China	<i>Tamarix ramosissima</i>	263	–	2.2	–	Li et al. (2008)
		<i>Caragana korshinskii</i>	263	–	3.7	–	
		<i>Reaumuria soongorica</i>	263	–	7.2	–	
6	China	<i>Salix psammophila</i>	395	–	7.6	–	Yang et al. (2008)
		<i>Artemisia sphaerocephala</i>	395	–	2.7	–	
7	China	<i>Caragana korshinskii</i>	427	–	12.3	–	Jian et al. (2014)
		<i>Hippophae rhamnoides</i>	427	–	8.4	–	
8	China	<i>Caragana korshinskii</i>	413	74.3	9	16.7	Zhang et al. (2015)
		<i>Artemisia ordosica</i>	413	74.8	2.9	22.3	
9	China	<i>Caragana microphylla</i>	238	64.2	11	24.8	In this study
		<i>Hedysarum fruticosum</i>	238	71.2	6.3	22.5	
		<i>Salix gordejvii</i>	238	75.3	5.3	19.4	

–: not available.

### SF funneling ratio

The average funneling ratios for the three species were considerably outweighed by 1, indicating that the rainwater caught by the funnels was greater than that caught by the rain gauges placed in the open areas (Li et al. 2008; Wang et al. 2013; Jian et al. 2014). That *H. fruticosum* contributed to more SF than *C. microphylla* and *S. gordejvii* could be due to its branches being smoother and slimmer than *C. microphylla* and *S. gordejvii*.

Because SF funneling ratios decrease exponentially with stem basal area (Figure 6), it is reasonable to scale SF at the individual level up to the stand level by using stem basal area (Macinnis-Ng et al. 2014). Although the average funneling ratio of *H. fruticosum* was larger than that of *C. microphylla* or *S. gordejvii* at the individual scale, SF of *C. microphylla* was the largest at the plot scale, indicating that there are discrepancies in calculating SF fractions across scales.

### Implications

Available water, which is dependent on rainfall partitioning in arid regions (Levia & Frost 2003; Frost & Levia

2014), is the most important factor for shrubs used for sand stabilization, especially when potential evapotranspiration is much larger than precipitation. Since *C. microphylla*, *H. fruticosum* and *S. gordejvii* are good sand-fixing shrubs in northern China (Zhang et al. 2006; Zhao et al. 2007), it is necessary to know their rainwater use strategies under different rainfall partitioning patterns. Our study indicates that *C. microphylla*, a dense-branch-type shrub, which can intercept more rainwater and generate larger SF fractions than the other two shrubs, represents a ‘capturing type’ strategy of rainwater use. *H. fruticosum*, a thin-leaf-type shrub, which can result in more SF production, represents a ‘funneling type’ strategy of rainwater use. *S. gordejvii*, a loose-stem-type shrub, which has larger TF production but generates less SF production, represents a ‘through type’ strategy of rainwater use. Therefore, *C. microphylla* has an advantage in enhancing net precipitation through greater interception over *H. fruticosum* and *S. gordejvii*, facilitating the formation of ‘moist islands’ around its root zone (Zhao et al. 2007). Thereby, it is the best sand binder of the three tested here with regard to rainwater use efficiency in semiarid sand lands.

## CONCLUSIONS

The different morphological characteristics of shrub species affect how rainfall is partitioned into TF, SF, and interception, resulting in different rainwater use strategies. Dense-type shrubs (umbrella-shaped canopy, multiple smooth stems and numerous ovate leaves) such as *C. microphylla* represent a ‘capturing type’ strategy of rainwater use. Thin-leaf-type shrubs (rough stems and thin leaves) such as *H. fruticosum* represent a ‘funneling type’ strategy of rainwater use. Loose-stem-type shrubs (loosely branched slender stems, and leptophyllous leaves) such as *S. gordejewii* represent a ‘through type’ strategy of rainwater use. From the perspective of rainfall partitioning, *C. microphylla* may be the best shrub for re-vegetation in arid sandy regions.

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