Evapotranspiration of xerophytic shrub *Salsola passerina* and *Reaumuria soongorica* in an arid desert ecosystem of NW China

Yanxia Jin, Xinping Wang, Yafeng Zhang, Yanxia Pan, Haojie Xu, Rui Hu and Wei Shi

ABSTRACT

Understanding the actual evapotranspiration (ET) variation of the sparsely distributed xerophytic shrubs is crucial to accurately upscale community ET to ecosystem scale. Here we quantified the actual ET of two dominant xerophytic shrubs of the Tengger Desert in northwestern China, i.e. *Salsola passerina* and *Reaumuria soongorica*, by using four large weighing lysimeters. The results showed that with the increase in precipitation from 140 to 171 mm in the year 2015/2016, the daily mean evaporation (E) of the bare area, and ET of the single shrub communities of *S. passerina*, *R. soongorica*, and the associated shrub community (*S. passerina* + *R. soongorica*) increased 50, 60, 44, and 47%, respectively; correspondingly, the total E and ET increased 49, 61, 44, and 47%, respectively. The variation of soil moisture within 0–40 cm depth plays a vital role in regulating the E and ET. The new shoot length, as one of important parameters of the xerophytic shrub, was significantly exponentially related to the cumulative ET. From the long- and short-term perspective, event-based precipitation and wind speed are the dominant driving factors behind changes in E and ET, respectively. Relative humidity is the main influencing factor for E and ET after a large rainfall event within 8 days.

Key words | arid desert ecosystem, evapotranspiration, *Reaumuria soongarica*, *Salsola passerina*, weighing lysimeter

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INTRODUCTION

Evapotranspiration (ET), including soil evaporation (E) and plant transpiration (T), is a fundamental process of ecological, hydrological and atmospheric systems and a major component of water balance especially in the desert area, where ET accounts for more than 95% of precipitation. The controlling factors of ET vary in different ecosystems, and are dynamic across intra-annual to decade time scales (Wilcox *et al.* 2003; Huxman *et al.* 2005; Ryu *et al.* 2008). ET is one of the most problematic components of the hydrological cycle, and is one of the most difficult variables to accurately quantify since it exhibits high spatial and temporal variability (Gebler *et al.* 2015).

Numerous methods have been applied to measure or estimate ET. At regional or global scales, the remote sensing approach has been increasingly used to map the spatial distribution of ET (Kramber *et al.* 2010; Mariotto *et al.* 2011; Anderson *et al.* 2012a, 2012b; Wang *et al.* 2013; Xiong *et al.* 2015). Nevertheless, using the remote sensing method to accurately estimate ET in arid regions with large barren or sparsely vegetated areas is still a challenge for the areas characterized by high spatial heterogeneity of aerodynamic and land surface properties (Vinukollu *et al.* 2011; Tian *et al.* 2013). At scales smaller than 1 km^2, soil water balance, Bowen ratio energy balance (BREB), eddy covariance and

doi: 10.2166/nh.2018.170

the large weighing lysimeter technique had been widely used for measuring ET directly or indirectly (Allen *et al.* 2011a, 2011b). The advantages of the soil water balance method are that it is not limited by time and space scales and complies with the principle of water balance. Disadvantages and challenges are that deep percolation losses or gains are difficult to measure, and that differential spatial wetting of soil due to local spatial variation in irrigation (or precipitation) additions is difficult to be obtained (Cholpankulov *et al.* 2008). The BREB method is a practical and relatively reliable micrometeorological method with the advantage of low cost, and simple and straight forward measurements. The numerical instability of the BREB equation, however, is evident during periods of Bowen ratio values in the vicinity of -1, and heavy reliance of the ET estimate on the accuracy and representativeness of the net radiation and soil heat flux density measurements (Allen *et al.* 2011a). The eddy covariance method is increasingly used in ET measurement because of high frequency, non-destructive, continuous direct recording (30 min), automated systems, and the ability to measure radiation, latent, sensible heat flux and CO_2 flux simultaneously. Eddy covariance has disadvantages including complex instrumentation, energy balance closure error (approximately 10–30%), and underestimation of ET (Foken 2008; Ding *et al.* 2010).

A number of previous studies suggested that a large weighing lysimeter is the most accurate and reliable field method and the data are regarded as standard for actual ET measurements in desert areas which are used to provide baseline information for development, calibration, and validation of other measurement techniques (Payero & Irmak 2007; Goss & Ehlers 2009; Marin *et al.* 2010; Evett *et al.* 2012; Yang *et al.* 2014; Marek *et al.* 2016). Despite the rather high costs of installation and maintenance, boundary effects, limited areal extent (areas generally ranging from 0.05 to 40 m^2), considerable effort for data processing, and extreme sensitivity to environmental factors, numerous lysimeter facilities exist worldwide (Wang *et al.* 2004b; Lanthaler 2005; Ruiz-Peñalver *et al.* 2015). Furthermore, a weighable lysimeter can not only register ET on a natural surface at ground level, but can also allow a precision determination of the mass change and outflow in high temporal resolution, and calculation of precipitation by rain, dew, fog, rime and snow in a hitherto unprecedented accuracy (Meissner *et al.* 2007; Vera-Repullo *et al.* 2015; Hoffmann *et al.* 2016). It should be noted that although lysimeter measurements are prone to random and systematic errors due to size and external factors like wind, heavy precipitation and animals etc. (Nolz *et al.* 2013; Schrader *et al.* 2013), random errors can be greatly reduced by using relatively large size lysimeters (e.g. ≥ 1 m^2) (von Unold & Fank 2008), and systematic errors can be handled by filtering noisy lysimeter data (Vaughan & Ayars 2009; Peters *et al.* 2014, 2016; Hannes *et al.* 2015). Actually, lysimeters have been successfully used to obtain accurate ET rates for both short and long periods because of their high accuracy and time resolution (Allen *et al.* 1998), and to estimate water and solute fluxes directly at arid sites (Gee & Hillel 1988). Gee *et al.* (2009) have suggested that lysimeter and direct water balance measurement techniques are more reliable at arid sites than other estimation methods.

The desert ecosystems are sensitive to environmental changes, and have the potential for catastrophic changes (Newman *et al.* 2006). Desert ecosystems in China are characterized by vegetation patchiness, of which the vegetation patterns, composition and ecosystem processes are determined by hydrological processes (Li *et al.* 2013). Highly variable precipitation with discrete pulses characteristics is often the sole source of water in these desert ecosystems (Noy-Meir 1973; Loik *et al.* 2004; Magliano *et al.* 2015). Therefore, a quantitative understanding of the hydrologic balance induced by desert vegetation is vitally important for assessing the spatial patterns of vegetation and improving water use efficiency in the desert (Rietkerk Max *et al.* 2004; Wu *et al.* 2014). Furthermore, ET is of prime interest in the hydrologic balance for water allocation and vegetation water use (Kool *et al.* 2014). Quantifying ET of the dominant xerophytic shrub community in a desert ecosystem where the shrub mainly utilizes precipitation provides insights into hydrologic processes in desert regions. At present, however, the long-term observation of the ET of typical xerophytic shrubs like *Reaumuria soongorica* (C_3 plant) and *Salsola passerina* (C_4 plant) community, which are widely distributed across desert regions of China, has not been reported. *R. soongorica* and *S. passerina* may exist either in single shrub communities or in associated shrub communities and are considered as climax communities. One recent study indicated that the associated shrubs community of the two shrubs decrease the transpiration rate of the entire community (Su *et al.* 2012). This raises a question: of the single shrub community or the associated shrubs community, which plays a more important role in contributing to regional ET? We hypothesized that ET differs between the single shrub and associated shrubs community. If this is the case, how do morphological traits, rainfall, soil moisture characteristics and other meteorological variables affect ET variability? Therefore, we initiated the following specific objectives: (1) characterizing actual E and ET variations at daily and annual time scale by large automatic weighing lysimeters; (2) quantifying the influences of morphological traits, rainfall, soil moisture characteristics and other meteorological variables on E and ET. The *R. soongorica* and *S. passerina* xerophytic shrubs are regarded as climax communities of the study area; the present study on ET of those communities is expected to be used to assess the ecological water requirement and evaluate ET estimation models in arid desert ecosystems.

MATERIALS AND METHODS

Study site and plant description

The experiments were conducted at the Shapotou Desert Experimental Research Station (SDERS) of the Chinese Academy of Sciences, which is located at the southeastern border of the Tengger Desert, NW China (37°32′N, 105°02′E) at an elevation of 1,339 m. The area was classified as ecotone between desertified steppe and sandy desert with an annual mean precipitation of 186 mm, approximately 80% of the rainfall events occurring between May and October in the growing season with a large inter-annual variability as high as 45.7%. Annual mean potential evaporation reached 3,000 mm (observed by an evaporation pan of type E-601). The groundwater table below the land surface is more than 60 m. Therefore, the effective water source for plants is primarily precipitation (Berndtsson & Chen 1994). The climate at the experimental site is characterized by an abundance of sunshine and low relative humidity. The minimum average monthly relative humidity is 32.7% during April, and the maximum is 54.9% during August. The sunshine hours range from 6.7 to 6.9 h per day from October to January, and from 7.0 to 8.2 h per day in the remaining months. The annual average temperature is 10.0°, with historical extreme maximum and minimum temperatures of 38.1° in July and −25.1° in January, respectively, during the last 50 years (Gao *et al.* 2016). The average annual wind velocity is 3.5 m s^{-1} (2 m height) and 122 d involve dust events (Liu *et al.* 2006).

Reaumuria soongorica (Pall.) Maxim and *Salsola passerina* Bunge are perennial extremely xerophytic shrubs and are considered as climax communities in the southeast edge of the Tengger Desert. The shrubs are constructive and dominant species of steppe and typical deserts and play a vital role in sustaining the ecological stability of the deserts due to their drought-resistant nature. *R. soongorica* is many-branched and ranges in height between 10 and 70 cm; characterized by short and cylindrical leaves with a length of 1–5 mm and width of 0.5–1 mm, and normally 4–6 clustered on shortened branches. In addition, there is a unique adaptive strategy for *R. soongorica* leaves to enter a state of dormancy during dehydration but revive when rewetted; roots are at depths between 10 and 100 cm and 93% of the feeder root area is typically maintained in the 0–60 cm depth (Xu & Li 2009; He *et al.* 2015). *S. passerina* is also many-branched with a height between 15 and 50 cm, with a 2–3 mm length and 2 mm width of cone or triangle shaped leaves and root depths between 0 and 50 cm (Yang *et al.* 2013).

Lysimeters

A set of large automatic weighing lysimeters with accuracy of ±0.1000 kg (equivalent to 0.025 mm water of the 4 m^2 lysimeter) is established in the SDERS of the Chinese Academy of Sciences. The outer cylinder of the lysimeter was 250 cm in depth and 256 cm in diameter. The inner cylinder was 250 cm in depth and 226 cm in diameter (Figure 1).

The gap between the outer and inner cylinders was covered with polyurethane foam to prevent water, soil, and rodents from getting inside the outer box, as well as to help minimize heat transfer between the atmosphere

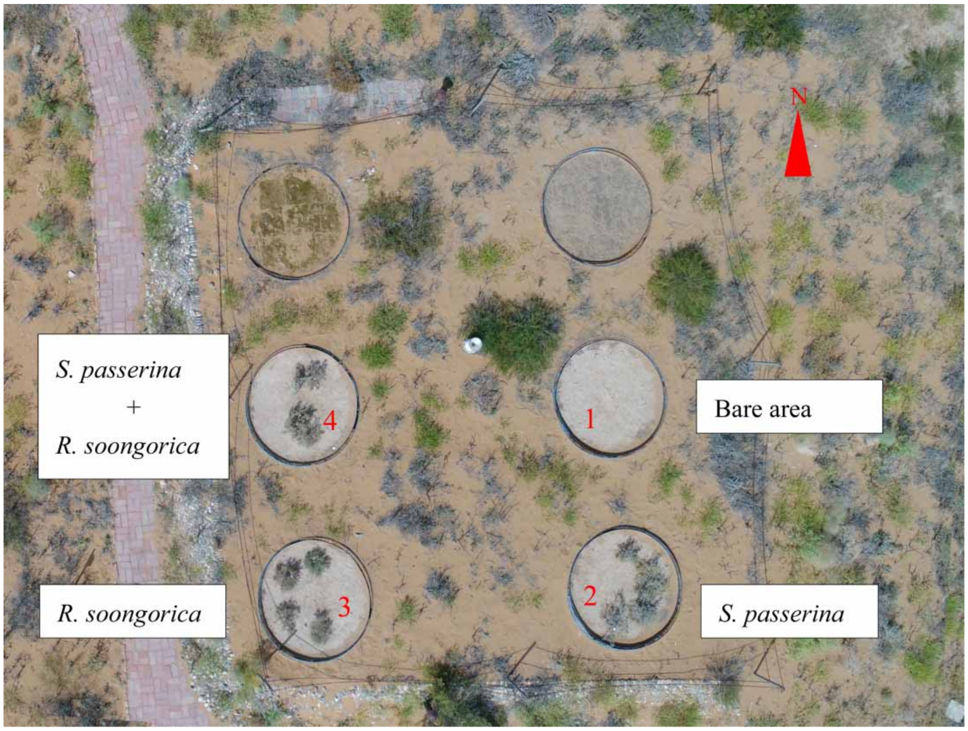

Figure 1 | Layout of electronic auto weighing lysimeters used in the experiments.

and the airspace between the two cylinders. The lysimeter bottom was first covered with a 20 cm drainage layer graded from 1 to 2 cm gravel, serving as a capillary break. Then the local fine dune sands were repacked with a depth of 220 cm, which had an initial average volumetric soil water content of 2.5%, and the volumetric field capacity of the dune sand was about 6.7% (Wang *et al.* 2004a). Each lysimeter had two heat flux plates 80 mm in diameter (HFP01SC, Hukseflux Thermal Sensors, Delft, The Netherlands) at 5 and 7 cm below soil surface, respectively. The Stevens pF Sensors (for measuring soil matric potential and soil temperature) and TDR probes (for measuring water content) were installed at soil depths of 10, 20, 40, 60, 80, 100, 160, 180, 200, and 220 cm within each lysimeter. In addition, two samplers (flexible polymer tube) were installed at soil depths of 100 and 150 cm for percolation collection which was extracted by a vacuum pump.

Four electronic auto weighing lysimeters were used to determine actual evaporation from a bare ground surface and actual ET of xerophytic shrub from a vegetated area under natural precipitation. Each vegetated lysimeter transplanted four xerophytic shrubs (Figure 1).

Shrubs measurements

The root depth was determined during the transplantation process, and it was found that both the experimental shrubs are shallow-rooted with a root depth varying between 0 and 60 cm, which concentrates within the soil profile at around 40 cm depth. The morphological traits of vegetated shrubs in lysimeters are shown in Table 1. The shrub height and new shoot length were measured with a ruler, and the Canopy projection area (approximated as an ellipse) was determined by measuring the longer and shorter sides of the plant canopy, and then calculated by the formula of the ellipse area. The relative cover of vegetation was estimated by canopy projection area and lysimeter area. The leaf area index (LAI) was measured directly by a LAI-2000 plant canopy analyzer (LI-COR, Inc., Lincoln, NE, USA). The measurements were carried out at the end of each month during the growing season in 2015 and 2016.

Table 1 | The values (means ± SE) of the relative cover, canopy height, canopy projection area, new shoot length, and LAI of the xerophyte shrub *S. passerina* and *R. soongorica* in the lysimeter

Year	Lysimeter number	Relative cover (%)	Canopy height (cm)	Canopy projection area (×100 cm^2)	New shoot length (cm)	LAI
2015	2	12	26.0 ± 1.6	11.5 ± 1.3	7.9 ± 1.5	1.7 ± 0.1
	3	11	22.4 ± 1.0	11.1 ± 0.7	6.6 ± 0.8	1.3 ± 0.1
	4	10	25.9 ± 1.0	10.4 ± 0.4	7.0 ± 1.1	1.8 ± 0.1
2016	2	26	37.5 ± 2.0	26.0 ± 2.0	12.0 ± 1.3	2.2 ± 0.2
	3	16	31.4 ± 1.6	15.8 ± 1.0	10.0 ± 0.5	1.8 ± 0.1
	4	12	30.7 ± 0.8	11.7 ± 0.7	9.3 ± 0.9	2.1 ± 0.2

Actual E and ET calculations

Changes in lysimeter weight are used to quantify loss (E and ET) of water from the lysimeter soil monolith, measured by a set of three electronic sensors (load cell) for each lysimeter. The lysimeter mass change in kg for every 30 minutes is converted to a mass equivalent relative lysimeter storage value (mm of water) by dividing it by the cross-section area of the lysimeter (4 m^2) and the density of water (taken as 1,000 kg m^{-3}) (Marek *et al.* 2016).

Daily E and ET were the sum of the differences between two measurements within one day. For every day period (24 h), E and ET were calculated using the following formulation (Meißner *et al.* 2010):

$$E(T) = P - S \pm \Delta S \quad (1)$$

where E is evaporation from nonvegetated lysimeter (mm), ET is evapotranspiration from vegetated lysimeters (mm), P is the precipitation (mm), S is drainage loss (mm), ΔS is the change of stored soil water in the lysimeter (mm). It should be noted that in our study, no drainage loss was observed. E and ET calculation can be simplified as:

$$E(T) = P \pm \Delta S \quad (2)$$

Precipitation, water addition and meteorological variables

Details of measuring event-based precipitation and meteorological variables were demonstrated by Wang *et al.* (2016) and Zhang *et al.* (2015). In order to understand the change of actual E and ET in accordance with rain depth and distribution of precipitation based on the daily time scale in the given years of 2015 and 2016, we assigned an individual day of recorded precipitation to a rain event.

The year 2016 can be considered a relatively wet year compared to the mean annual precipitation of 186 mm, since 42 mm precipitation was artificially added to the four lysimeters, with 15, 6 and 21 mm added to the four lysimeters on 20 May, 27 May and 29 June in 2016, respectively. The added precipitation was only excluded in Table 2 to analyze natural precipitation distribution.

RESULTS

Distribution and variability of the natural precipitation

The annual precipitation was 140 and 171 mm in 2015 and 2016, with 85 and 89%, respectively, i.e. 119 and 151 mm falling during the growing season from May to October of

Table 2 | The distribution and accumulative amount of natural precipitation during experimental years 2015 and 2016

	0–5 mm		5–10 mm		> 10 mm	
	Frequency (%)	Accumulative precipitation (mm)	Frequency (%)	Accumulative precipitation (mm)	Frequency (%)	Accumulative precipitation (mm)
2015	89	68	8	36	4	37
2016	80	68	13	44	7	58

the experimental years 2015 and 2016, respectively. Apparently, the monthly precipitation distribution was fairly heterogeneous during the growing season of 2015 and 2016. A total of 53 and 45 events occurred in 2015 and 2016, respectively. The precipitation events with 0–5 mm accounted for 89 and 80% of annual total events in 2015 and 2016, followed by 5–10 and >10 mm rainfall events, which accounted for 8 and 4% in 2015, respectively, and 13 and 7% in 2016, respectively (Table 2).

Variations of E and ET

Figure 2 shows the seasonal patterns of E and ET in the growing season of 2015 and 2016. Arrival times of precipitation events were consistent with periods of relatively high E and ET of the bare area and xerophytic shrub community, especially under large precipitation events. The daily E of bare lysimeter increased from 0.1 to 2.3 mm/d, the daily ET of *S. passerine* (ET_S) increased from 0.3 to 2.3 mm/d, the daily ET of *R. soongorica* (ET_R) increased from 0.3 to 2.5 mm/d, the daily ET of mixed community of *S. passerine* and *R. soongorica* (ET_{S+R}) increased from 0.3 to 2.5 mm/d at the end of the large precipitation event with a total amount of 24.8 mm on 20 May, 2015. In the growing season of 2015, ET_S and ET_R had the maximum values of 138 and 138 mm, respectively, followed by ET_{S+R} (128 mm) and E (114 mm). In contrast, in the growing season of 2016, ET_S had the maximum value (221 mm), followed by ET_R (198 mm), ET_{S+R} (189 mm), and E (170 mm). Total E, ET_S, ET_R, and ET_{S+R} of the growing season increased by 49, 61, 44 and 47%, respectively, from 2015 to 2016. It can be seen that E was lower than the corresponding precipitation, with a low soil evaporation to precipitation ratio (E/P) of 0.95 and 0.88 in 2015 and 2016, respectively. ET of xerophytic shrubs exceeded the corresponding precipitation, except the mixed community of *S. passerine* and *R. soongorica* during the growing season of 2016, where the ET to precipitation ratio (ET_{S+R}/P) was 0.98. During the growing season of 2015, the ET_S/P, ET_R/P and ET_{S+R} /P ratio were 1.15, 1.15, and 1.07 in 2015, respectively. The ET_S/P and ET_R/P were 1.14 and 1.02 in 2016, respectively. The daily average E and ET_S, ET_R, ET_{S+R} were 0.62, 0.75, 0.75 and 0.70 mm d^{-1}, respectively, in 2015; they were 0.93, 1.20, 1.08 and 1.03 mm d^{-1}, respectively, in 2016. It is clear that daily

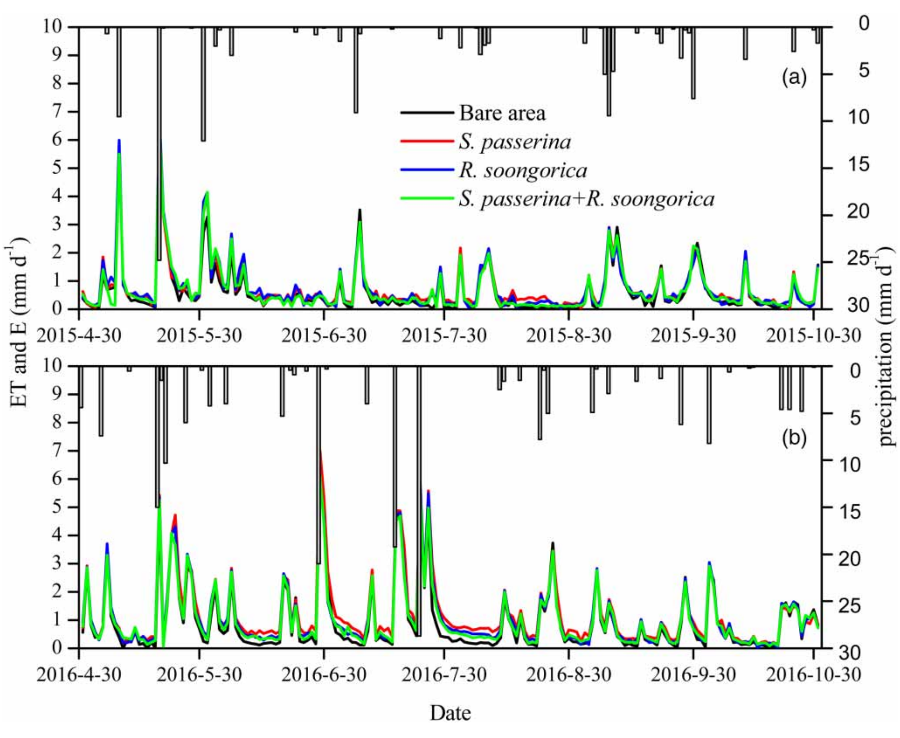

Figure 2 | Variation of the daily P (bar chart), E and ET (solid line) for four lysimeters in 2015 (a) and 2016 (b).

average E, ET_S, ET_R, and ET_{S+R} increased by 50, 60, 44 and 47%, respectively, from 2015 to 2016.

The daily E, ET_S, ET_R, and ET_{S+R} after a large rainfall event (20 May 2015) were selected to characterize their response to precipitation during certain time intervals (8 days). The daily E, ET_S, ET_R, and ET_{S+R} increased in accordance with rainfall (20 May) and showed a sharp decline on the second day (21 May) and then slowly declined (Figure 3). They had the minimum values on the sixth day (25 May), and after that there was a slight increase.

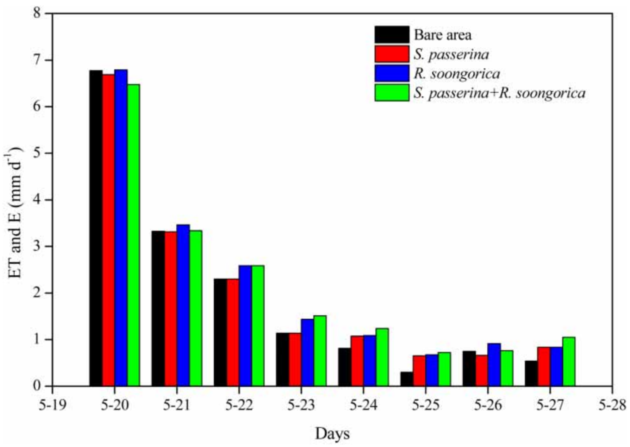

Figure 3 | E and ET course of bare soil and shrub communities after a certain rainfall event within 8 days.

Relationship of E, ET and precipitation

There was a significant linear relationship between the accumulative E or ET and the accumulative P in the growing season of 2015 (Figure 4(a)) and 2016 (Figure 4(b)), respectively. The percentages of precipitation explanation for E and ET were more than 98%. Hence, E and ET were dominated by rainfall patterns in the period from May to October. The slope of the linear regression of ET on P is larger than that of E on P.

Relationship of E, ET to environmental variables

As seen from Figure 5, E and ET had a significant positive correlation with wind speed, solar radiation and air temperature, but a significant negative correlation with relative humidity on the daily time scale during the growing season. Wind speed is the main factor affecting E and ET on a short time scale during the growing season, interpreting around 72% of E and 71% of ET variation, which was higher than other meteorological factors. Although the daily E, ET_S, ET_R, and ET_{S+R} after a large rainfall event within 8 days were significantly correlated to all meteorological factors, it was more affected by the relative humidity compared with the other climatic variables (Table 3).

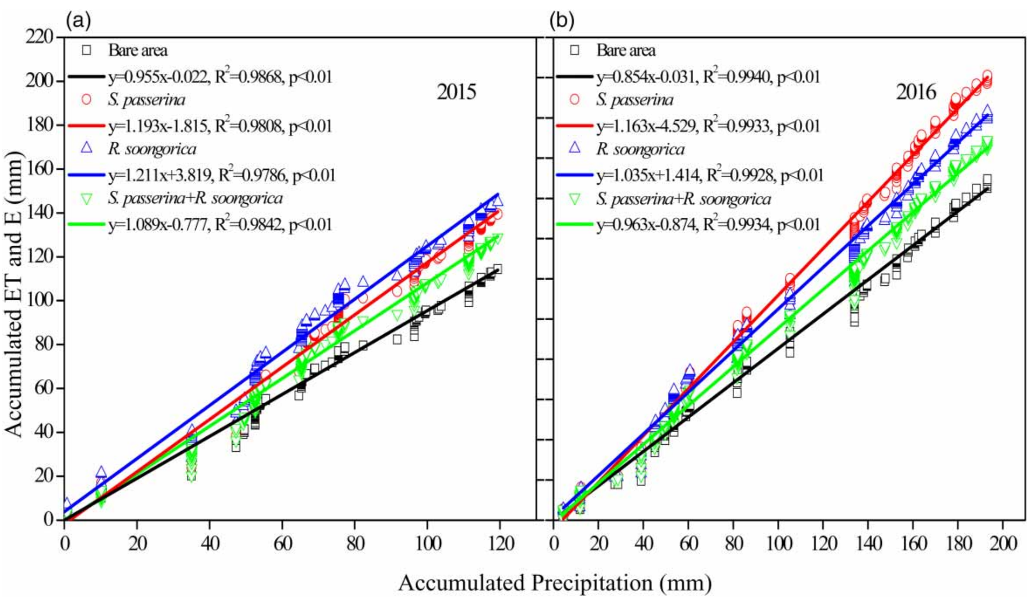

Figure 4 | Relationship between accumulated E, ET and precipitation in the growing season of 2015 (a) and 2016 (b).

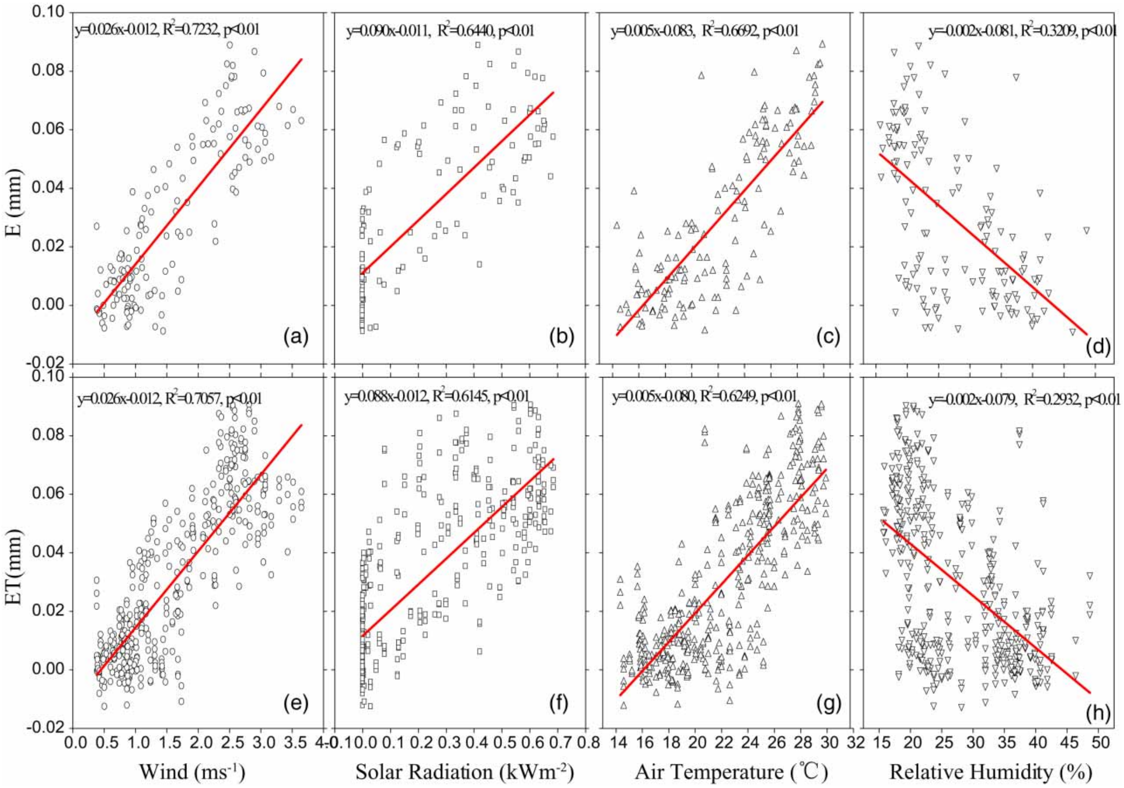

Figure 5 | Relationship between E, ET and wind (a and e), solar radiation (b and f), air temperature (c and g), relative humidity (d and h) at daily time scale during the growing season.

Relationship of E, ET with soil water content

Differences in soil water content from the consecutive soil layers within four experimental lysimeters were used to determine the wetting front. One relatively large rainfall event with a cumulative rainfall of 24.8 mm started from 8:15 am (0 h) and ended at 22:00 pm (14 h) on 20th May in 2015 and was selected for the analysis (Figure 6). The wetting front reached a maximum depth of 40 cm, with no noticeable changes found in soil moisture at 60 and 80 cm depth within 8 days (Figure 6(a)–6(h)). The soil moisture at the upper soil profiles of 10 and 20 cm in all lysimeters increased to a maximum on the following day (Figure 6(b)) after the rainfall event and then declined slowly. In contrast, the change in soil moisture at a depth of 40 cm lagged more than 24 h behind that of the upper soil layers (Figure 6(c)). Figure 6 also shows that the wetting front advances are similar in all lysimeters after rainfall, but differences are shown at profiles of 20 cm. For example, soil moisture content was higher at the 20 cm depth of vegetated lysimeters than that of non-vegetation lysimeters (Figure 6(b)–6(h)). Soil moisture content was also higher at 40 cm depth of lysimeters of single *S. passerina* (Figure 6(c) and 6(d)) and the associated shrubs community (Figure 6(c)–6(d)).

Table 3 | Pearson correlation coefficient between meteorological factors and E of bare area, ET of *S. passerina* community (ET_S), *R. soongorica* community (ET_R), and mixed community of *S. passerine* and *R. soongorica* (ET_{S+R})

E and ET (mm)	Wind ($m\ s^{-1}$)	Solar radiation ($Kw\ m^{-2}$)	Air temperature (°C)	Relative humidity (%)
E	0.4145**	0.3839**	0.6010***	−0.6307***
ET_S	0.4656***	0.3120*	0.5692***	−0.5839***
ET_R	0.3432*	0.5054***	0.6071***	−0.6367***
ET_{S+R}	0.4707***	0.5032***	0.6677***	−0.6887***

***Indicates significant correlation at $P < 0.001$; **indicates significant correlation at $P < 0.01$; *denotes significant correlation $P < 0.05$.

As seen from Table 4, E was significantly correlated with soil moisture content at depths of 10 and 20 cm

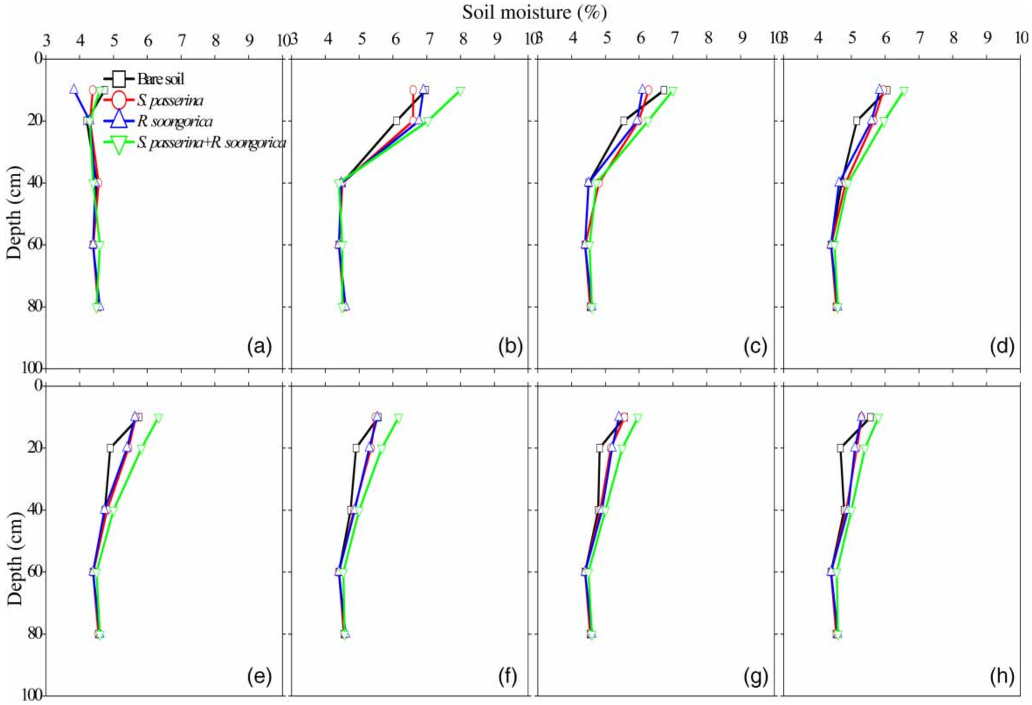

Figure 6 | The wetting front advances under and after rainfall with intensity of 2.1 mm h^{-1} ($P = 24.8$ mm) from May 20th to 27th ((a)–(h)) in 2015.

($P < 0.01$), and 40 cm ($P < 0.05$). ET_S was significantly correlated with soil moisture content at depths of 10 cm ($P < 0.05$) and 20 cm ($P < 0.01$). ET_R was significantly correlated with soil moisture content at depths of 10 and 20 cm ($P < 0.01$), and 40 cm ($P < 0.05$). Soil moisture content at depths of 10 and 20 cm was significantly correlated with ET_{S+R} ($P < 0.01$). The correlation between E, ET and soil water content at depths from 60 to 220 cm was not significant ($P > 0.05$).

Relationship of ET and shrubs' morphological traits

The canopy height, canopy projection area, new shoot/branch length and LAI of *S. passerina* in the lysimeter #2 increased by 44, 126, 51 and 30%, respectively, from 2015 to 2016. The corresponding values for *R. soongorica* in lysimeter #3 were 40, 43, 50 and 37%, respectively. For the mixed community in the lysimeter #4, they were 18, 12, 34 and 15%, respectively (Table 1). The cumulative ET increased

Table 4 | Pearson correlation coefficient between series of soil water content at 10–220 cm depth and E of bare area, ET of *S. passerina* community (ET_S), *R. soongorica* community (ET_R), and mixed community of *S. passerine* and *R. soongorica* (ET_{S+R})

	Soil water content (%)									
E and ET (mm)	**10 cm**	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**	**160 cm**	**180 cm**	**200 cm**	**220 cm**
E	0.5161**	0.3448**	0.2486*	0.2099	0.1818	0.2133	0.1388	0.1619	0.1971	0.1063
ET_S	0.3348*	0.6750**	0.3186	0.4400	0.2895	0.3135	0.1883	0.1547	0.1391	0.1079
ET_R	0.4100**	0.4238**	0.2002*	0.1956	0.1917	0.1750	0.0973	0.1121	0.1234	0.1116
ET_{S+R}	0.5606**	0.5789**	0.1941	0.1924	0.1853	0.1730	0.0679	0.0946	0.0580	0.0793

**Indicates significant correlation at $P < 0.01$; *denotes significant correlation $P < 0.05$.

exponentially with increasing canopy height, canopy projection area, new shoot length and LAI (Figure 7).

DISCUSSION

Generally, ET exceeds precipitation inputs on both daily and annual time scales in desert ecosystems, where substantial bare soil evaporation with low plant cover drives the ecohydrology process (Noy-Meir 1973; Testi *et al.* 2004). In the present study, the ET/P ratio varied from 1.07 to 1.15 in 2015, and varied from 0.98 to 1.14 in 2016, suggesting no deep drainage. The E/P ratio was 0.95 in 2015 and 0.88 in 2016, suggesting only a tiny fraction of the rainfall contributed to the increase in soil water storage for the bare area. Actually, no percolation was observed for bare lysimeter and vegetated lysimeters. Wang *et al.* (2004c) suggested that the ET/P in natural vegetation of the Tennger Desert was 1.18, and the soil evaporation to precipitation ratio (E/P) in the shifting sand dune area was 0.71. Eddy covariance measurements showed that the ET/P was 1.03, 1.07, 0.82, and 1.11 from 2009 to 2012, respectively (Gao *et al.* 2016). Our findings also agree well with research on ET in other regions. In the Gurbantonggut desert in western China, the annual ET/P of the halophyte community was 1.20 in a dry year (ET was 155 mm, P was 129 mm) and 1.22 in a wet year (ET was 259 mm, P was 213 mm) (Liu *et al.* 2012). In the Chihuahua desert grassland, long-term measurements showed that ET/P was 1.09, with an average annual ET of 299 mm and a precipitation of 272 mm

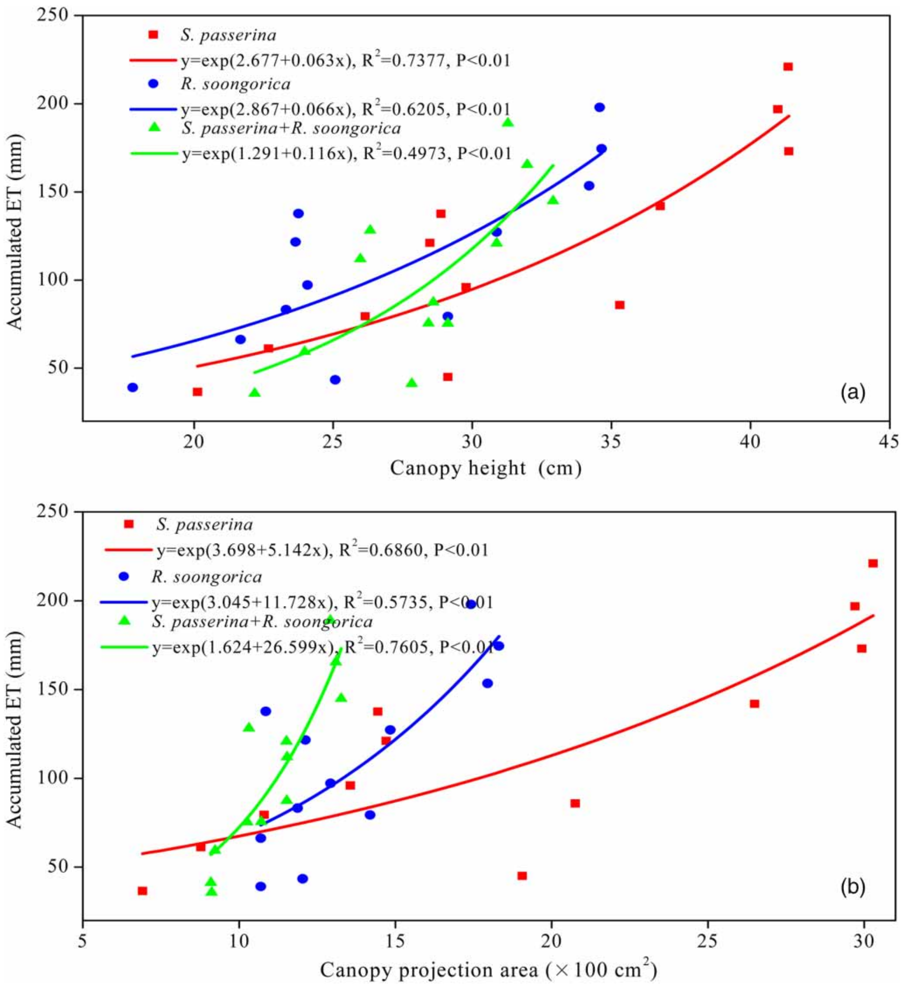

Figure 7 | Relationship between accumulated ET and canopy height (a), canopy projection area (b), new shoot length (c), LAI (d). *(Continued.)*

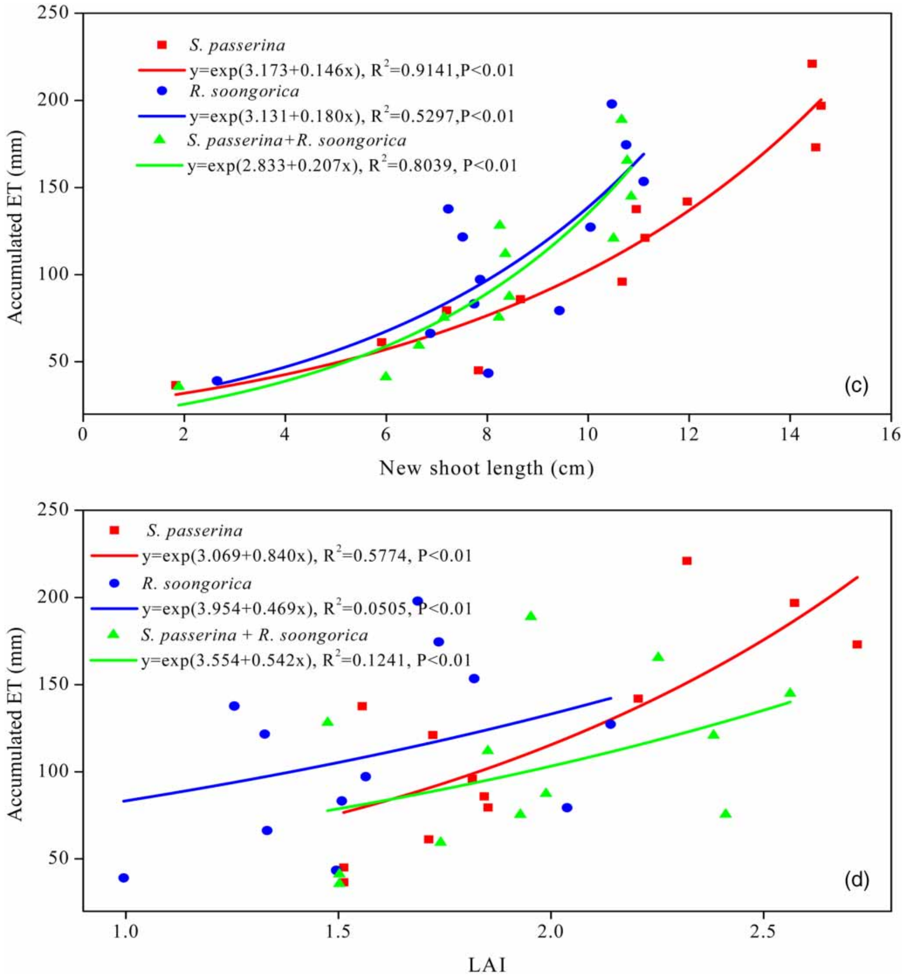

Figure 7 | Continued.

(Mielnick *et al.* 2005). As expected, the results of the actual ET shown in our study confirm the high reliability and accuracy of the large automatic weighing lysimeter as compared to previous studies in the arid desert region. It also highlights the importance of E, which is mainly dependent on precipitation and contributes to most of the actual ET in arid areas (Zhang *et al.* 2017).

Effects of precipitation and environmental variables on ET

A significant correlation between accumulative E, ET and P ($R^2 > 0.9786$, $P < 0.01$) indicates that both E and ET vary with P, which was consistent with the previous findings of Wang *et al.* (2004b). Precipitation in the study area is largely composed of small events with relatively short dry intervals, 64% precipitation events are less than 5 mm with 80% of dry intervals less than 10 days in length (Wang *et al.* 2005). Episodic large rainfall events (>10 mm) accounted for only 4 and 7% of the total precipitation event in 2015 and 2016, and the amount of large precipitation events accounted for 31 and 38% of the total precipitation in the growing season. Large precipitation events sharply increased E and ET on the daily time scale, especially E, then led to larger annual E and ET as our results indicate (Figures 2 and 3). Due to low canopy coverage, more incident radiation transmitted to the bare soil resulted in greater soil evaporation after large rainfall events (Zhang *et al.* 2010). On the other hand, they can elevate the soil moisture at 0–20 cm in a greater number of growing season days (Heisler-White *et al.* 2008). The occurrence of large precipitation events, moreover, are related to the distinguishing of wet and dry years, and likely led to increased soil moisture at greater depths (Sala *et al.* 1992). Our results indicated that E and ET were mainly affected by wind speed, followed by air temperature, solar radiation and relative humidity on a daily time scale during the growing season (Figure 5). Similar results have been reported in previous studies. For example, during 1955–2008 in northwest China, Huo *et al.* (2013) found that the contribution of wind speed to the decrease in reference evapotranspiration (ET_0) was greater than that of other meteorological variables. For ET_0, wind speed was the most sensitive meteorological variable, followed by relative humidity, temperature and radiation. Liu *et al.* (2010) reported that the meteorological variables for ET_0 varied with location. In addition, our results showed that the meteorological factors regulating E and ET are significantly rainfall event-dependent (Table 3). The results of the present study (Figures 4 and 5, and Table 3), coupled with those from literature, allow us to assume that wind speed is the dominant environmental factor affecting actual E and ET on a daily time scale, whereas precipitation controls patterns of actual E and ET on an annual time scale. It is notable that relative humidity is one of the driving meteorological factors for E and ET within 8 days after a large rainfall event. Therefore, the importance of the spatiotemporal scale and occurrence of rainfall events should be taken into account when analyzing the changes and influencing factors of E and ET.

Effects of soil water content on ET

Soil moisture is a crucial link between hydrologic and biogeochemical processes because of its direct influence in transpiration and indirect influence; for example, its dominant effect on nitrogen mineralization, as well as the key abiotic limiting factor in desert regions (Rodriguez-Iturbe 2000; Wang *et al.* 2017). Low soil water contents provide little buffer against climate extremes, which is one of the reasons why desert environments are particularly vulnerable to climate variability (Scanlon *et al.* 2005). ET dominates the fate of soil water content, since the percolation is usually a very small component of the water budget (less than 5%) (Wilcox *et al.* 2003). Our study suggested that the soil moisture content at 10 and 20 cm depths within four lysimeters are significantly correlated with E and ET ($P < 0.01$, $P < 0.05$), which throws light on the importance of these depths of soil water content on ET (Table 4). ET is primarily water limited in arid ecosystems, where soil moisture is especially important and controls the available water for ET (Chen *et al.* 2008). Limited soil water supply results in a decline in the global land ET (Jung *et al.* 2010). Soil moisture replenishment by infiltration and hydraulic redistribution and loss through soil evaporation, plant transpiration and deep drainage results in ET being the most interactive component of the water budget (Loik *et al.* 2004). We found that for a relatively smaller rainfall event of 24.8 mm the wetting front was limited to 40 cm depth (Figure 6), whereas for a consecutive series of large rainfall events with a cumulative rainfall of 42.5 mm, the wetting front could reach a depth of 90 cm, which was comparable to the previous study in the same region (Wang *et al.* 2011). In other words, a heavy rainfall (>24.8 mm) can replenish the soil water in the rooting zone of *S. passerina*, *R. soongorica* and their mixed community since their roots are mainly distributed at a depth of 0–40 cm. In the mobile dunes of the Horqin Sandy Land, a rainfall amount of 13.4 mm with rainfall intensity of 40.1 mm h^{-1} could replenish soil water at 60 cm depth (Liu *et al.* 2015). The rainfall events with higher intensity will make a greater contribution to the soil moisture replenishment (Wang *et al.* 2008). In contrast, neither 27 mm nor 19 mm precipitation events resulted in recharge at 30 cm at a shrub-dominated station in the Chihuahuan Desert, likely due to runoff generation (Reynolds *et al.* 2000). Only large rain events (1 day with >25 mm or consecutive days each with >15 mm rainfall) generated a considerable wetting front at 15 cm and little change was observed at 30 cm of the soil profile (Scott *et al.* 2006). The presence of the vegetation allows precipitation to infiltrate into deeper soil layers (Figure 6), most probably because vegetation cover affects soil infiltration by providing more opportunities for infiltration (reducing runoff generation) and by modifying the structure of the soil pore spaces as a result of the formation of the root system (Huang *et al.* 2013). In addition, the presence of biological soil crusts with vegetation induced large soil moisture content beneath 10 cm (Wang *et al.* 2007), resulting in a relatively higher ET value.

Effects of vegetation on ET

Vegetation plays a dominant role in controlling the ET process by modifying transpiration (T) through stomata of plant leaves and E of intercepted precipitation in these regions, particularly in arid ecosystems (Méndez-Barroso *et al.* 2014). Shrubs were found to significantly reduce the soil evaporation under canopy in the Negev Desert (Kidron 2009). Conversely, the covering of vegetation hindered the rapid formation of a dry sand layer which is a constraining factor for soil water evaporation (Liu *et al.* 2015). The presence of biological soil crusts would not greatly change soil evaporation in arid and semiarid environments (Xiao *et al.* 2010). A contradictory result was obtained by Kidron & Tal (2012), who that found crusted plots have an average evaporation rate of 1.38 times higher than the bare sand and decreased evaporation under biocrusts. We found that single shrub communities have higher annual ET compared to associated shrub communities (Figure 2), because the transpiration rate of the associated shrub community was lower than that of the single shrub community (Su *et al.* 2012). In addition, our results indicated that lysimeter #2 exhibits a larger increase in canopy height, canopy projection area, new shoot length and LAI compared to two other vegetated lysimeters. This is mainly due to C_4 plant (*S. passerina*) which has more rapid growth than C_3 plant (*R. soongorica*) (Pearcy *et al.* 1981), while lysimeter #4 exhibits a small increase in morphological traits, most probably because the association retarded the growth of both *S. passerina* and *R. soongorica* (Su *et al.* 2012). LAI is the main vegetation characteristic that affects ET (Barbour *et al.* 2005), and as LAI increased, ET increased logarithmically (Zhao *et al.* 2016). However, our study indicated that new shoot length with a high coefficient of determination should be a more important contributing factor to a higher cumulative ET, as shown in Figure 7(c). Accordingly, we argue that the growth parameters such as canopy height, canopy projection area, new shoot/branch length and LAI explain the variation of xerophytic shrub ET at long term scales, for the reason that those growth parameters indirectly indicate an increase in vegetation biomass productivity associated with high transpiration (Scanlon *et al.* 2005; Suzuki *et al.* 2007).

CONCLUSIONS

We identified that annual scale variations in actual E and ET of typical xerophytic shrubs are mainly driven by precipitation and their diurnal dynamics are mainly caused by wind speed. However, diurnal variations of E and ET mainly depend on relative humidity after a large rainfall event within 8 days. Soil moisture within 40 cm of soil depth is significantly correlated with E and ET of typical xerophytic shrubs. The cumulative ET increased exponentially with increment of canopy height, canopy projection area and LAI, especially new shoot length. The cumulative ET of single *S. passerina* and *R. soongorica* community was greater than that of the associated shrub community in two growing seasons, indicating that single distributed *S. passerina* and *R. soongorica* communities will increase ET. Moreover, higher E/P suggested the relatively important contribution of soil evaporation to ET in the water-limited arid desert ecosystems. Our findings highlighted that research into ET trends for *S. passerina* and *R. soongorica* communities is particularly important in the desert region of northwest China. Furthermore, an *in situ*, long-term continuous study of ET by large weighing lysimeters can also lead to sufficient data for validation of ET model simulation.

ACKNOWLEDGEMENTS

This work was funded by the National Key Research and Development Program of China (2016YFE0203400), and the National Natural Science Foundation of China (Grant nos. 41771101 and 41530750).

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First received 18 October 2017; accepted in revised form 3 June 2018. Available online 22 June 2018