Dew formation characteristics in the gravel desert ecosystem and its ecological roles on *Reaumuria soongorica*

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ABSTRACT

As an additional source of water to plants besides rainfall, dew may have a positive impact on vegetation in the arid ecosystems. Knowledge regarding dew formation characteristics and its ecological effects on vegetation water status and photosynthetic performance in the gravel desert ecosystem is still lacking. In this study, the dew variability and formation frequency on a gravel desert were measured by microlysimeters. We quantified dew formation characteristics, investigated vegetation water response to dew events in the gravel desert ecosystem at the edge of a desert oasis, Northwestern China. The results showed water adsorption was a primary pathway of dew formation in such system, and the average daily amount of dew is 0.06 mm. Dew occurred on 36 % of growing season days, the number of days with dew amounts > 0.03 mm accounted for 82 % of the total dew events, and the cumulative amount of dew for those days was 3.41 mm. Relative humidity, air temperature, wind speed, the difference between air temperature and soil surface temperature had significant effects on dew formation. A threshold of RH ≥ 30 % is taken to mark possible condensation in the gravel desert ecosystem. A significant positive correlation between dew amounts and the relative moisture in the near-surface air was found when RH ≥ 30 %. The moderate wind velocity (1-1.8 m/s) was favorable to dew formation, and when wind speed > 5.47 m/s， there was no dew formation. Because of the water-absorbing scales on the leaves of *Reaumuria soongorica*, dew events significantly improved their relative water content, water potential, and photosynthetic performance in the early morning and ameliorating the adverse effects of plants exposed to prolonged drought.

The study highlights dew is an important supplementary source of water in the gravel desert ecosystem. Although the absolute dew amounts were found not high, it can be a frequent and stable water resource. Furthermore, this study provides a comprehensive understanding of the effects of dew on plant water status in the gravel desert ecosystem.

KEYWORDS

Dew; ecohydrology; plant water status; super-xerophytic shrub; gravel desert ecosystem

1. Introduction

In arid ecosystems, the survival of organisms and the stability of ecological systems are tightly coupled to water availability. Precipitation usually falls only sporadically in such areas, and large precipitation events are rare during the dry period (Loik et al., 2004). Nonrainfall water, particularly fog and dew, could be the only water source for biota during rainless periods and may have positive impact on ecological environment in water-limited systems (Kidron, 2000; Wang et al., 2019). As a result, the ecophysiology of desert organisms may be geared towards obtaining and utilizing nonrainfall water. Dew, as one of the nonrainfall water components, is defined as the condensation of water vapor on a sufficiently cooled substrate surface (Beysens, 1995). The ecological roles of dew as a supplementary water resource in arid ecosystem cannot be neglected. However, only limited studies have reported the important roles of dew for small animals (Steinberger et al., 1989), plants (Stone, 1957; Stewart, 1977; Barradas and Glez-Medellín, 1999; MunnÉ-Bosch et al., 1999; Ben－Asher et al., 2010; Zhuang and Ratcliffe, 2012), and biological soil crusts (Lange et al., 1977; Pintado et al., 2005; del Prado and Sancho, 2007) in the desert environment. Currently, dew is still not well characterized in most ecosystems. Such information is lacking from drylands where dew potentially plays a critical role in vegetation establishment and survival.

Dew formation is a natural physical process, described in some arid areas, semi-arid, humid tropical islands and in cold alpine areas (Beysens, 1995; Jacobs et al., 1999; Jacobs et al., 2000; Kidron, 2000; Richards, 2005; Zhang et al., 2014; Richards, 2016). Considering the surface soil moisture content and sparse plants in desert regions, atmospheric water vapor is the primary source for dew formation. The most important factors affecting dew formation are related to the near-surface meteorological parameters. It was shown that low air and soil surface temperature, high relative air humidity, and moderate wind speed are the most favorable weather conditions for the dew formation (Monteith, 1957; Duvdevani, 1964; Zangvil, 1996; Beysens, 2016; Kaseke et al., 2017; Fang, 2020; Feng et al., 2021). In addition, the amounts and duration of dew are determined by the physical properties of the underlying surface, such as different soil surfaces (bare soil, sandy soils, soil with plant cover, and stone-covered surface) (Duvdevani, 1947; Li, 2002). However, information regarding dew formation rules and its affecting factors in the gravel desert environments is still scarce.

There is evidence suggesting that dew not only is hydrologically significant (Zangvil, 1996) but also supplies up to 63% of plant water requirements in certain environments (Hill et al., 2015; Wang et al., 2019). The importance of dew on the water status and physiology of plants is receiving increasing attention. It was shown that diverse plant functional types benefited from dew including coniferous species, rainforest trees, presaharian plants and Mediterranean plants (Stone, 1957; Grammatikopoulos and Manetas, 1994; Barradas and Glez-Medellín, 1999; Breshears et al., 2008; Zhuang and Ratcliffe, 2012). Different species may show different responses, likely related to the differences in their anatomical and physiological characteristics (leaf with trichomes vs. leaf without trichomes, and C_3 vs. C_4). Currently, many of these studies are from relatively humid areas, and there are limited number of reports from desert ecosystems where dew potentially play a critical role in vegetation survival. We also lack an understanding on how the perennial super-xerophytic shrub, lived in the gravel ecosystem, responds to dew formation. More importantly, the mechanisms of dew alleviating vegetation water stress are still uncertain. Enhancing understanding of dew effects on plant water relations and plant physiology will improve our knowledge of the potential importance of dew on ecohydrological processes in drylands.

The gravel desert as one of the main landscape types in arid desert regions in China, are widely distributed with an area close to 3.87×10^7 hm^2. The Hexi Corridor in China represents a typical gravel desert ecosystem. Furthermore, it has unique features: the vegetation structure, composition, and function all differ from those in the dune desert ecosystem. In the gravel desert, there are limited shrubs with shallow roots, large gravel content and coarse soil, and highly intensified wind erosion. Considering the scarcity of rainfall and the lack of surface runoff in the gravel desert ecosystem, dew may have positive impact on gravel environments. Understanding how dew formation is regulated and how plants are able to harvest and utilize dew during the dry period in the gravel desert ecosystem will help in developing appropriate strategies to manage such ecosystems.

In this study, a typical gravel desert at the edge of a desert oasis was chosen as the study site. The objectives of this study were: (1) to address dew amount and formation frequency during the growing season in the gravel ecosystem based on the microlysimeter method, (2) to illuminate the relationship between dew formation and meteorological factors, (3) to analyze the effects of dew on the water relations and photosynthesis for the dominant super-xerophytic shrub *Reaumuria soongorica* in the gravel desert.

2. Materials and methods

2.1 Study site

The study was performed in a typical gravel desert ecosystem, near the Linze Inland River Basin Research Station. The station is part of the Chinese Ecosystem Research network (39°24′N, 100°07′E) and it is in the middle reaches of the Heihe River Basin in the Hexi Corridor of Gansu Province (Fig. 1a). The study site has an elevation of 1405 m above sea level. The southern piedmont is an inclined plain, and the northern end is the margin of the Badain Jaran Desert (Luo et al., 2019). Soil at the study site is classified as gray-brown desert soil (Table 1), derived from diluvial-alluvial materials of the denuded monadnock. Due to highly intense wind, the surface layer is strongly eroded and covered by coarse gravels. Gravel comprises a significant proportion (12.7 %) of the soil profile. The aboveground vegetation is discontinuous and the ground surface is dotted with scarce shrub patches (Fig. 1b). The dominant shrubs are *Reaumuria soongorica*, and *Nitraria sphaerocarpa*, with a few herbaceous species such as *Allium mongolicum Rgl*, *Bassia dasyphylla* (Fisch. And Mey.), *Artemisia scoparia Waldst. et Kit.*, *Halogeton glomeratus* (M.B.) C.A.Mey. The climate in the study area is arid desert climate characterized by cold winters and hot dry summers. The mean annual temperature is 7.6 °C. The average annual precipitation is 117 mm with 65% occurring from July to October. The duration of sunlight totals 3045 h, and the average annual potential evaporation is 2390 mm, which is twenty times greater than the annual precipitation. Windy days and wind storms are frequent in this area. Wind speed is greatest (21 m/s) in spring, and wind direction is predominantly from the northwest.

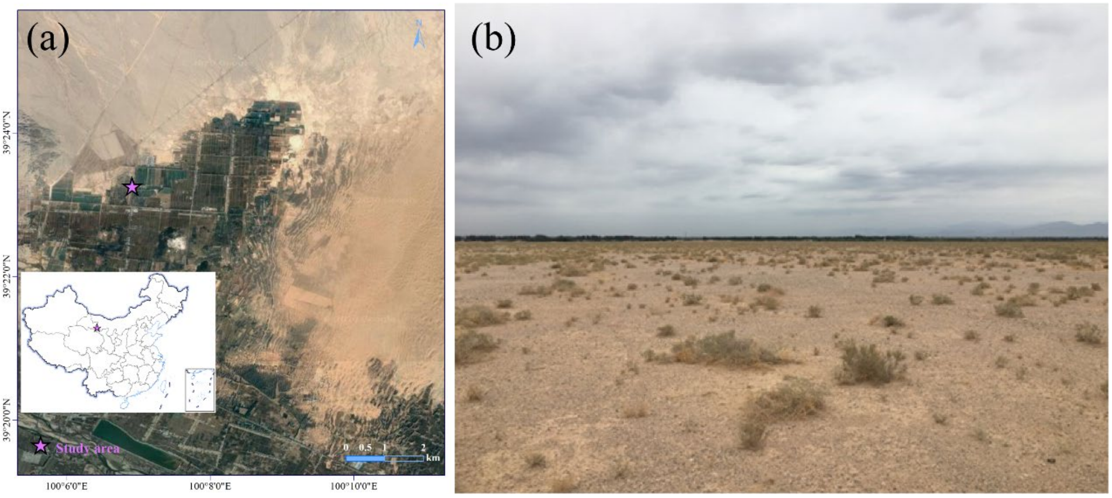

Fig. 1 Location of the study area (a); The landscape of the gravel desert ecosystem in the study area (b).

Table 1 Soli physical properties of the study area.

Soil depth （cm）	**Soil particle size distribution (%)**			**Bulk density (g cm^{-3})**	**Soil moisture content (%)**
	Sand (0.05-2.00 mm)	Silt (0.002-0.05 mm)	Clay (< 0.002 mm)		
0-20	90.56±2.05	6.96±1.22	2.04±0.17	1.57±0.02	1.02±0.05
20-40	93.14±1.24	5.21±0.94	1.62±0.21	1.56±0.02	1.11±0.09
40-60	92.46±1.45	4.02±1.03	3.08±0.12	1.59±0.02	1.57±0.03

2.2 Experimental design and data collection

During June and October of 2016, the dew amounts were measured using microlysimeters at three locations. The bottom-closed PVC cylinders (7.5 cm in diameter and 3 cm in height) were pushed into the soil to collect undisturbed soil columns used as dew collectors in the study. The cylindrical PVC containers located at the ground level, and 15 containers were placed at three locations. The distance between each location was 50 m. PVC cylinders were weighed with soil using an electronic balance (precision: ± 0.01g) at sunset and before sunrise each day from June to October, and the difference in weights (morning versus that of the previous sunset) was the dew amount on that day. To exclude the effect of rain, measurements were performed only when the surface soil moisture content was 1.5 % and therefore the values represent dew only. A meteorological station was equipped to measure meteorological variables, such as relative air humidity (RH), air temperature (T_{air}), wind speed (WS) and dew-point temperature (DP).

To investigate whether dew affects vegetation water response and photosynthetic response, measurements were taken after the occurrence of dew overnight followed by a clear day when we could collect the dew from the dew plate (Fig. 2), so we initially defined the days as dew-present days. The days without dew formation from the dew plate were considered dew-absent days. To eliminate the influence of meteorological elements on plant response to dew, we checked the data of key meteorological factors (wind, relative air humidity, air temperature, and photo synthetic radiation). If there are not significant differences in meteorological factors of the clear day, we defined the days as measurement days. During each field investigation, all the dew-present days were pooled together, and the dew-absent days were pooled together for statistical analyses.

Diurnal shoot water potential of *Reaumuria soongorica* was estimated before sunrise (i.e., 05:30-06:00 a.m. local time) with a Pressure Chamber Instrument. Relative water content (RWC, %) at early morning, and calculated by equation (Limm et al., 2009):

$$RWC = (FW\text{-}DW)/(TW\text{-}DW)\times 100 \quad , \qquad (1)$$

where FW is leaf fresh weight, TW is turgid weight 24 h after putting leaf into water, and DW is dry weight after drying at 85 °C until it reaches a constant weight.

Net photosynthetic rate (Pn) and stomatal conductance (Gs) of *Reaumuria soongorica* were measured from 8:00 to 18:00 with a Li-6400 Portable Photosynthetic system (Li-COR, USA).

Fig. 2 The illustration of dew collectors.

2.3 Statistical analysis

All data was expressed as mean ± standard error (SE). Meteorological data determining the occurrence of dew was determined by comparing nights with and without dew. Significant differences in meteorological data of nights with and without dew were determined using a non-parametric MannWhitney *U* test. The t test was conducted to test the significance of the differences between dew-present and the dew-absent condition regarding both plant water relations and photosynthetic response. All the statistical analyses and figures were performed using the R 3.2.0 statistical software (R Core Team, 2017). Analysis of variance (ANOVA) and ggplot2 R packages were conducted to statistics and plot. The significance level was set as $\alpha = 0.05$ for all the tests.

3. Results

3.1 Dew frequency and amount

Rainfall was recorded on 26 days, and the total amount was 51.8 mm from June to October of 2016, whereas rainfall events of 5 mm or less were most frequent and comprised 92 % of the events (Fig. 3). The total number of dew days was 55 and varied depending on month. June and October had the fewest dew days at 9 and 8, respectively, while September had the most at 15 (Fig. 4). The total number of dew days and rainfall days accounted for 36 % and 17 % of total observation days, respectively. These results demonstrated that dew formation was more frequent during the growing season than rainfall.

The average dew amount for gravel surface was 0.06 mm d^{-1} ranging from 0.02 and 0.24 mm d^{-1}. Total recorded amount was 3.41 mm, representing 6.6 % of the rainfall from June to October (Fig.5). The results showed that the dew amount of $>$ 0.03 mm d^{-1} occurred on 45 days, which accounted for 82 % of the total dew events, and that, dew events with dew amount of $>$ 0.1 mm d^{-1} accounted for 16.4 % of the total dew events (Fig. 6).

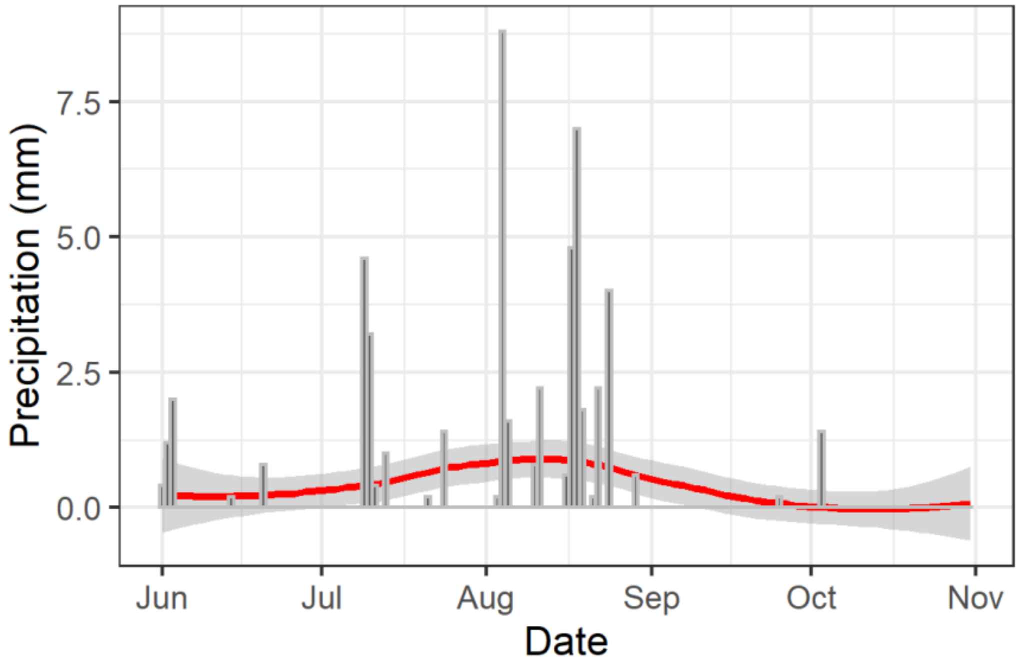

Fig. 3 Daily rainfall distribution in the study area from June to October of 2016.

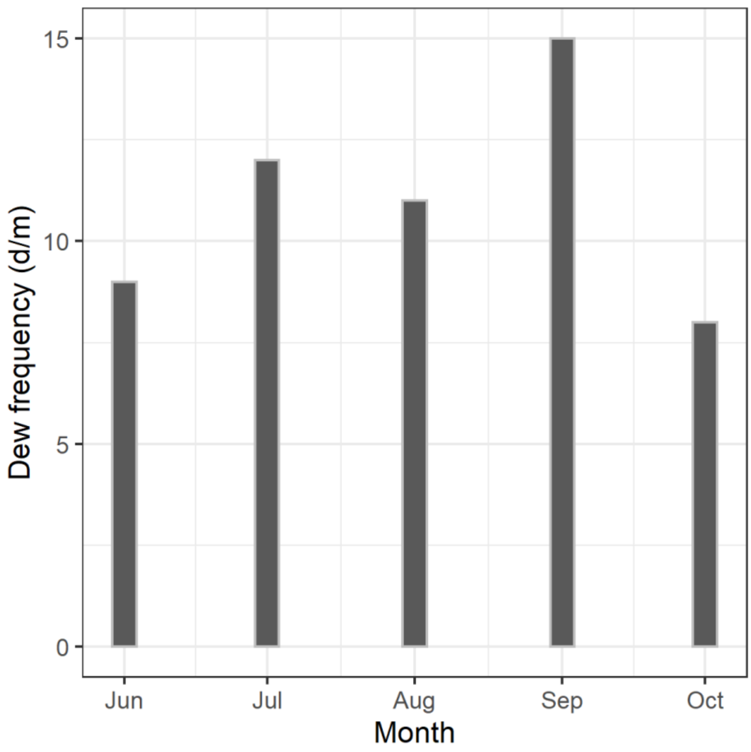

Fig. 4 The number of dew days from June to October of 2016.

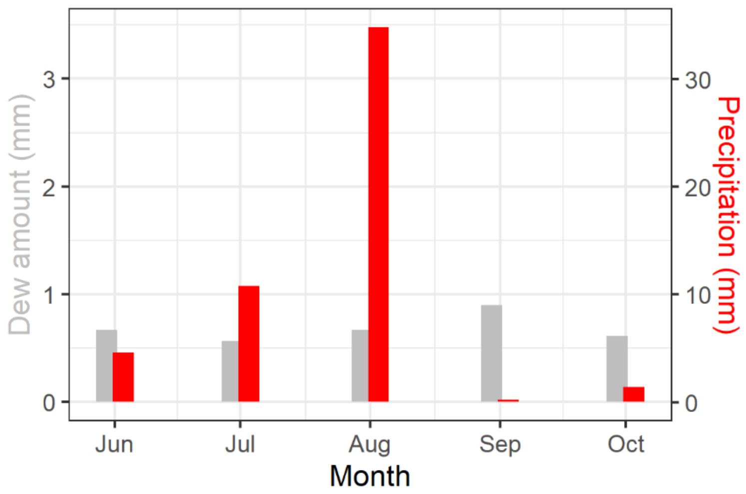

Fig. 5 Monthly total amounts of dew and precipitation from June to October of 2016.

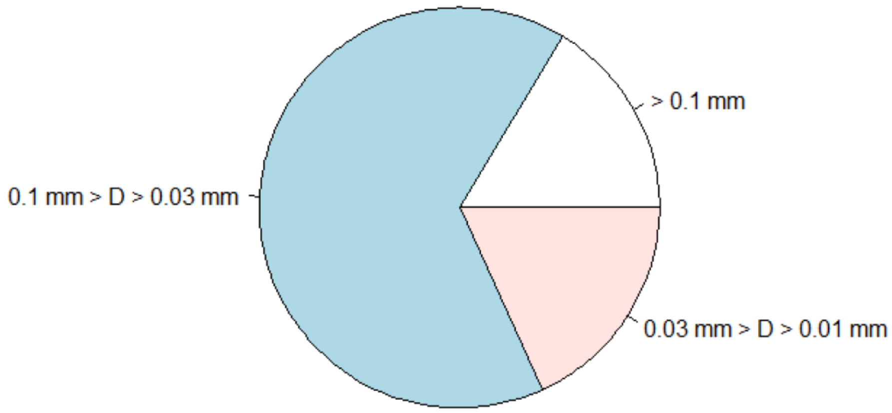

Fig. 6 Distribution of the number of dew days. The pie chart shows days with dew in three categories according to daily dew amount. The area of each category represents the percentage of total dew days.

3.2 Dew formation and meteorological factors

Dew formation is a complicated physical process, mainly influenced by the near surface meteorological parameters and surface properties (Kidron, 2000; Richards, 2005; Ye et al., 2007; Guo et al., 2016). During the observation period, usually, the soil surface temperature did not drop below the dew point, whereas an increase in soil surface moisture was observed. Data analysis of meteorological data indicated that nights with dew represented significantly higher relative humidity, higher mean temperatures difference between air and soil surface, lower mean wind speed, and lower means temperatures than nights without dew (Table 2). There was found to be a significant positive correlation between dew amounts and the relative moisture in the near-surface air when RH ≥30 % (Fig. 7a), a threshold of RH ≥30 % is taken to mark possible condensation in the gravel desert ecosystem. In addition, when RH ≥80 %, the dew formation was mainly controlled by air temperature in near surfaces. It was showed that there was a positive correlation between the dew amounts and wind velocity under the conditions of moderate wind velocity (1-1.8 m/s) (Fig. 7b). When wind velocity exceeded 1.8 m/s, the dew amounts decreased rapidly, and when wind velocity exceeded 5.47 m/s, there was no dew formation (Table 2).

Table 2. Meteorological data for nights with and without dew in the study area.

Variables		**Nights with dew (n=9)**	**Nights without dew (n=9)**	**Significance level**
Mean RH (%)	Min	19	9	
	Max	94	60	
	Mean	43.5	21.2	＜0.001
Mean DP (°C)	Min	0.11	0	
	Max	13.7	12.4	
	Mean	6.84	5.98	0.496
Mean T (°C)	Min	6.4	12.5	
	Max	31.5	39.8	
	Mean	19.7	24.5	＜0.01
Mean T_{soil}-T_{air}(°C)	Min	0.2	1.0	
	Max	29.3	18.5	
	Mean	10.2	6.24	＜0.05
Maximum wind speed (m/s)	Min	0	1.06	
	Max	5.47	9.6	
	Mean	1.84	5.04	＜0.001

9 Nights (dew amount ＞0.1 mm) with dew was choose. RH=relative humidity, DP=dew point, T=air temperature, T_{soil}-T_{air} =the temperature differences between soil

surface and air. Significance was determined at the 95 % confidence level by a non-parametric Mann-Whitney U test.

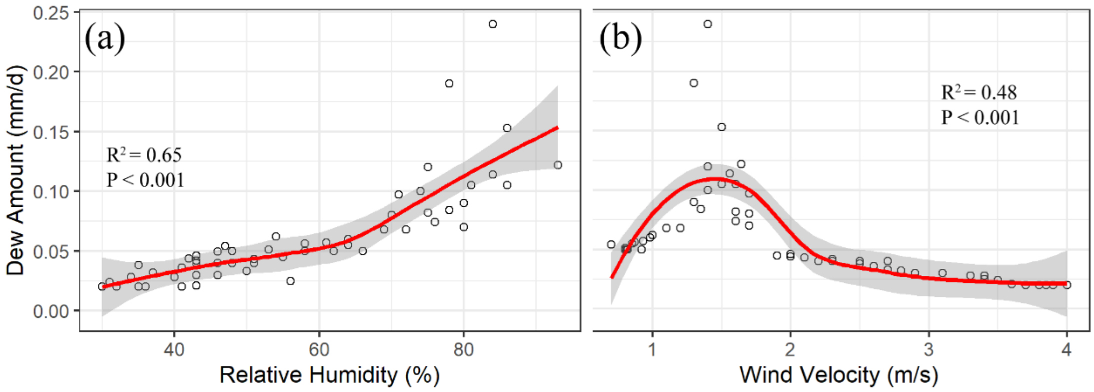

Fig. 7 Relationships between dew amount and relative humidity (a); dew amount and wind velocity (b).

3.3 The water status of *Reaumuria Soongorica* responses to dew

The relative water contents of *R. Soongorica* in the early morning increased from 49.2 % under dew-absent condition to 56.0 % after dew event. There was significant 13.8 % increase in the plants exposed to dew compared with those of no dew. In addition, the water potential of the species increased from -14.8 Mpa under dew-absent condition to -10.3 Mpa after dew event, with a significant 30.7 % increase. These results confirmed that the water status of *R. Soongorica* showed responses to the dew events significantly (Table 3).

Table 3 Water status variations of *R. Soongorica* in the early morning.

	Relative water contents (%)	**Water potential (MPa)**

Dew-present	56.0±5.0[a]	-10.3±1.1[a]
Dew-absent	49.2±3.1[b]	-14.8±1.6[b]

Different letters indicate significant differences between dew-absent and dew-present plants at $p < 0.05$ level.

3.4 The diurnal photosynthesis and stomatal conductance of *Reaumuria Soongorica* responses to dew

A typical two-peaked diurnal pattern of net CO_2 (*Pn*) assimilation rate was observed under dew-absent condition through the study period, achieving a maximum daily peak rate at 10:00 in the morning and the second peak rate at 16:00, while an atypical bimodal curve of net CO_2 assimilation rate was observed under dew-present condition, with a maximum peak rate at 9:00 and the second peak rate at 14:00 (Fig. 8b). The diurnal average net CO_2 assimilation rate and the maximum peak rate significantly increased under dew-present condition ($P < 0.05$). The daily mean value of stomatal conductance (*Gs*) increased from 75.55 mmol m^{-2} s^{-1} under dew-absent condition to 90.07 mmol m^{-2} s^{-1} after dew event, with a maximum value 110.4 mmol m^{-2} s^{-1} and 158.8 mmol m^{-2} s^{-1} at 8:00, respectively (Fig. 8a). The dew events significantly increased the stomatal conductance rate from 8:00 to 10:00 ($P < 0.01$).

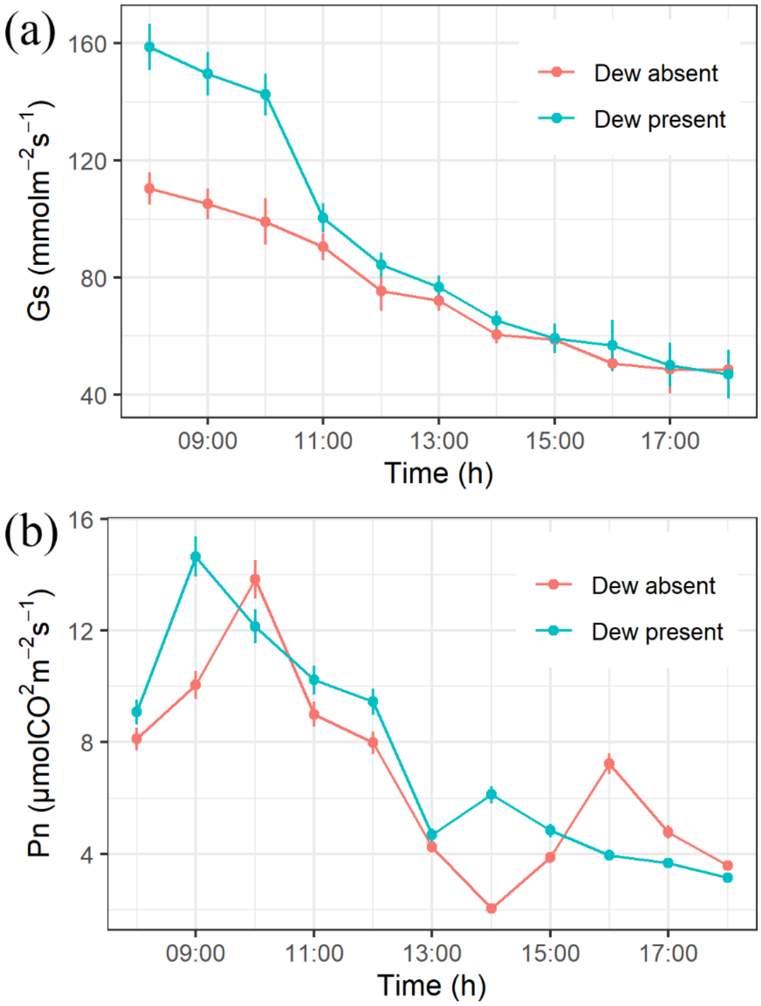

Fig. 8 The diurnal variation of stomatal conductance (*Gs*) (a) and CO_2 assimilation rate (*Pn*) (b) of *R. Soongorica* under the dew-absent and dew-present condition, respectively.

4. Discussion

4.1 The dew formation characteristics

Very few studies have noted the dew variability in the gravel desert ecosystems, which are widely distributed throughout the arid area of northern China. Current results showed that although soil surface temperature did not drop below the dew point temperature in many observation days, soil moisture content at uppermost layer still increased, which was accordance with the measurement performed in the Negev Desert, Israel (Agam and Berliner, 2004), in the Tengger Desert, China (Pan et al., 2010), and in the desert riparian forest, China (Hao et al., 2012). These results also indicated that the increase of surface soil moisture was not only due to the dew formation in the case of no rainfall. The surface soil moisture in the study area was extremely low (Table 1) under the condition of no rainfall and the water vapor content at the soil pores was less than that of air, demonstrating that water adsorption arises easily during the late afternoon and night, rather than through capillary condensation (Philip and De Vries, 1957; Kidron and Kronenfeld, 2020). Water adsorption is still an important hydrological process in the gravel desert ecosystems. A recent study conducted in sandy desert ecosystem also showed that water vapor absorption by soil was a typical characteristic of dew formation (Zhuang and Zhao, 2017). Likewise, it is confirmed that the dominant mechanism is still water adsorption in the gravel desert ecosystems. However, regardless of dew formation or water absorption, a diurnal cycle of latent heat flux is involved in the process (Agam and Berliner, 2006). Thus, in this paper, dew amounts consisted of dew formation and water absorption. Our study showed that the dew amounts and the frequency were lower in the gravel desert ecosystems than that in the sandy desert ecosystem (0.13 mm/d) (Zhuang and Zhao, 2017), which may be explained by the two different substratums. It is suggested that there are different thermal conductivity effects and the reaction of the air to temperature and humidity distribution to the two surfaces, which is important to dew formation (Kidron, 2000; Li, 2002). The previous study showed that the soil temperature with gravel cover is 1-4 °C higher than under sand cover during daytime (Li, 2002). The gravel acts as an insulator and helps to retain soil heat at night, in addition, the gravel cools slower than sand in the late afternoon, thus the higher soil temperature inhibits vapor condensation. Another reason for lower dew amounts of gravel may be attributed to higher surface roughness in the gravel habitat, increasing the turbulence degree of the airflow. It was suggested that the sandy soil can reduce the evaporation rate much more than the gravel, especially at the higher wind speed (Hanks and Woodruff, 1958; Li, 2002). The dew variability is primarily controlled by micrometeorological factors. Many studies have documented that the clear skies, moderate winds, high relative humidity, strong inversions of temperature from the soil surface to the atmosphere and the low surface temperatures were usually beneficial to dew formation (Kidron, 2000; Pan et al., 2010; Guo et al., 2016; Zhuang and Zhao, 2017). In our study, we confirmed that RH, T_{air}, T_{soil}- T_{air}, wind were key factors that influenced the dew formation in the gravel desert (Table 2). The results indicated that water vapor absorption occurred when RH ≥30 %, and dew amounts increased with increasing RH, suggesting a threshold of RH is 30 % for dew formation in the study area. Moreover, dew amounts were also controlled by wind speed and its influences on dew formation was complicated. Lower wind speed was not favorable to vapor diffusion and higher wind accelerated evaporation processes (Beysens, 2016). Our study also showed that the moderate wind velocity (1-1.8 m/s) was favorable to dew formation, whereas wind velocity less than 1 m/s and exceeded 2.5 m/s inhibited the dew formation. It is indicated that moderate winds increased the transport of water vapor and prevented the air mixing at the surface with air above (He and Richards, 2015). Other studies have shown that a wind speed of 5.7 m/s is the upper limit for dew formation (Nilsson, 1996; Muselli et al., 2009; Lekouch et al., 2011). The determination of key micrometeorological parameters in different desert environments could provide important reference for the calculation of dew models.

4.2 The positive effects of dew on *Reaumuria Soongorica*

Dew may play an important role in maintaining plant water status by foliar uptake of moisture (Wang et al., 2016).Vegetation dew uses have been noted for shrubs in different regions. It has been shown that an improvement in CO_2 assimilation rates, 72 % and 138 % increasing of relative leaf water content and shoots water potential of *Lavandula stoechas* (MunnÉ-Bosch et al., 1999) in Mediterranean filed condition. Hill et al. (2015) found that *Artemisia sieberi* and *Haloxylon scoparium* used 63 % and 46 % of their water from dewfall in Negev desert, respectively. Such information is still lacking for super-xerophytic desert plant where dew may potentially play a critical role in vegetation survival. In this study, we studied the dominant shrubs *R. soongorica* in the gravel desert habitat at the edge of a desert oasis, Northwestern China. The species showed responses to dew, as indicated by the significant increases in their predawn relative leaf water content and shoots water potential after the dew events. In a previous study, by conducting a series of observations of dew deposition in the dominant annual plant *Bassia dasyphylla* with leaf hairs and *Agriophyllum squarrosum* without leaf hairs at the sandy desert habitat, we found that dew improved water status and photosynthetic performance of *B. dasyphylla* in the early morning, whereas there was no significantly effects on *Agriophyllum squarrosum* (Zhuang and Ratcliffe, 2012*)*. It was also suggested that the anatomical characteristics may play a major role in foliar uptake. Using energy dispersive X-ray spectroscopy (EDS) analysis with a scanning electron microscope, Wang et al. (2016) found water-absorbing scales in the leaves of *R. soongorica* could absorb unsaturated water from the air. They showed that a complex cellular structure of water-absorbing scales, surmounted by four to seven valves that formed in inverted cone pore. The valves contracted and formed a more or less impermeable lid under low RH, while the valves absorbed unsaturated atmospheric water and swelled, gradually expanding and forming a larger central opening. Moreover, our results showed that an increase in average CO_2 assimilation rates and stomatal conductance, especially from 8:00 to 10:00, which indicated another mechanism that might be critically associated with physiology and water available. These results suggested that the dew events may have potential role in avoiding irreversible damage that the photosynthetic apparatus may suffer when RWC falls below 30 % (Kaiser, 1987). Therefore, dew may play a critical role in improving plant water status and ameliorating the adverse effects of plants exposed to prolonged drought.

4.3 Ecological significance of dew formation in the gravel desert ecosystem

Dew, as an additional source of water, may have a positive impact on the vegetation functions, microbes and animals, as well as on sustaining biogeochemical dynamics during rainless period (McHugh et al., 2015; Wang et al., 2017). In the present study, we found that although the dew is a small percentage of total precipitation and only about 6.6 % of total rainfall, it is a constant and stable water source and thus plays a significant role in the gravel desert environments with scarce water. Frequent dew formation improves the rate of seed germination and moistens desert plant and the soil crust. Generally, plant canopy condensation was greater than ground condensation (Hao et al., 2012). Plant canopy directly absorbs the dew condensed on their surface. Foliar absorption of dew could be particularly important in dryland ecosystems because plants commonly undergo periods of water stress. In our study area, the landscape of vegetation is commonly distributed in patches and low vegetation cover and the main vegetation type is desert vegetation dominated by super-xerophytic shrubs such as *R. soongorica*, which exhibit strong adaptability to drought and the gravel desert habitats, and have important roles in soil water conservation and wind erosion prevention. It was found that water-absorbing scales in the leaves of *R. soongorica* were critical role in dew foliar uptakes, which improved the water status during the drought period. On the other hand, inorganic salts in or on the valves of water-absorbing scales can contribute the atmospheric water molecules to condense on the leaf surface and penetrate them into the leaves of *R. soongorica*. Moreover, although the amount is little compared to the root water uptake, the indirect effect of dew is also important. Dew can wet the leave surface, reduce the temperature of plant leaves, and adjust the photosynthesis and stomatal conductance. The higher relative humidity on leaf surface layer and around the plants decreases the evaporation of soil moisture beneath, which makes for the storage of soil moisture in the gravel desert. The present study is important for identifying certain underlying principles that might be of use in the hyper-arid region where precipitation is very limited and top soil is often dry. Future study would be valuable to explore the different vegetation dew water use pathways and its mechanisms by stable isotope techniques.

5. Conclusions

Despite the increasing attention of dew formation and its effects on vegetation water status in dryland areas, we still have limited understanding on the roles of dew formation and its uses by super-xerophytic shrubs. It was concluded that water adsorption was a primary pathway of dew formation in the gravel desert ecosystem. Relative humidity, wind speed, air temperature, the difference between soil surface temperature and air temperature played important roles in dew formation. A threshold of RH ≥30 % is taken to mark possible condensation. In addition, the moderate wind velocity (1-1.8 m/s) was favorable for dew formation, whereas wind velocity less than 1 m/s or exceeding 2.5 m/s inhibited the dew formation in the gravel desert ecosystem. Dew significantly improved the relative water content, water potential, and photosynthetic performance to *R. soongorica* growing in the extremely dry environments, likely indicating that they could take up dew water through particular water-absorbing scales in the leaves. This study showed that strong response of plants and soil to dew, emphasizing the potential importance of dew in ecohydrological processes in the gravel desert environments. The study also provides a comprehensive evaluation of the effects of dew on plant water status in the gravel desert ecosystem and significantly enhances our understanding of vegetation dew water use in such systems. The present study has important implications for other arid regions and fills an important knowledge gap in dryland ecohydrology.

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