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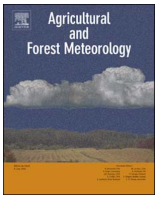

Research Paper

Dew formation and its variation in *Haloxylon ammodendron* plantations at the edge of a desert oasis, northwestern China

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ABSTRACT

Dewfall may be a critical source of moisture in desert environments and may determine sustainability of sand-stabilizing planted vegetation. However, little is known about factors responsible for dew formation, the relative importance of dew as a source of water, and its variability in plantations. During June and October of 2013, the dew amounts and duration were estimated by using the Bowen ratio energy budget technique (BREB), and the dew variability on sand dunes planted with *Haloxylon ammodendron* 5, 20, and 40 years before were measured by microlysimeter. We quantified dew formation characteristics in a sand-stabilizing *H. ammodendron* plantation at the edge of a desert oasis, northwestern China. The results indicated that the average daily amount of dew in the *H. ammodendron* plantations during the observation period based on BREB was 0.13 mm, and the dew duration lasted from 1 to 9.5 h. Dew occurred on 77% of growing season days, the number of days with dew amounts of > 0.03 mm comprised 95% of the total dewfall days, and the cumulative amount of dew for those days was 16.1 mm. Air temperature, relative humidity, the difference between air temperature and dew point, and wind speed had significant effects on dew formation. The thresholds of the dew formation were RH $> 50\%$ and wind speed < 4.27 m/s. As a result of larger canopy area and lower Sky View Factors to 20- and 40-year-old *H. ammodendron*, the accumulated amount of dew was always significantly greater, and its night-time variability was almost 3 times greater for 5-year-old than for 20- and 40-year-old shrubs. In addition, near-ground dew amounts at the inter-space of three ages of *H. ammodendron* exhibited higher values than that under the canopy, while dew formation lagged and the maximum cumulative amount of dew was observed 2 h later under the canopy of shrubs. The Bowen ratio method estimated actual dew reasonably well. It is concluded that dew may be a frequent and stable water resources in *H. ammodendron* plantations at the edge of a desert oasis, and there is a mutually reinforcing effect between dewfall and the sand-fixing vegetation system.

1. Introduction

Arid and semi-arid areas in China span 53% of land area, and are expanding per year. Measures to curb desertification and alleviate its impacts on crops, pastures, and human life have been developed and successfully implemented in China (Liu et al., 2013; Zhang et al., 2004). Cultivating sand-stabilizing plants is among the most important and widely-used sandbreak systems, and cultivated sandbreaks total 47,600 km^2 (Liu et al., 2013). *Haloxylon ammodendron* Bunge, as a typical desert shrub, has physiological and morphological traits that allow it to survive frequent aridity, torridity, and other environmental stresses (Xu and Li, 2008). The shrub is native to desert ecosystems of central Asia, and plays a significant role in the maintenance of structure and function of arid ecosystems (Xu and Li, 2008). *H. ammodendron* decreases wind speed, intercepts drift sand, and reduces air temperature (Jia et al., 2008). Since the mid-1970s, *H. ammodendron* plantations have been established on desertified sandy lands in the middle of the Hexi Corridor near the Badain Jaran Desert, northwestern China, with the goal of sand stabilization.

Dew is the result of water from atmospheric humidity condensing on a substrate that has sufficiently cooled via emission of radiation (Beysens et al., 2007; Maestre-Valero et al., 2011). Dew is often cited as a “common” or a “significant” source of water in many of the world deserts (Baier, 1966; Hill et al., 2013; Kidron, 2005; Kidron et al., 2002; Monteith, 1963). In desert environments, characterized by very low soil moisture, the air (“dew”) is the predominant source of such moisture, and the active layer of dew formation is mainly limited to the upper 0–3 cm of soil (Zhuang and Zhao, 2014). Dew is also an important water source for animals (Steinberger et al., 1989), plants (Barradas and Glez-Medellín, 1999; Ben-Asher et al., 2010; Munne-Bosch et al.,

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1999; Stewart, 1977; Stone, 1957a,b; Zhuang and Ratcliffe, 2012), and biological soil crusts (del Prado and Sancho, 2007; Lange et al., 1977; Pintado et al., 2005) in arid environments.

The role of dew in the stabilization of sand dunes has been recognized as an important meteorological factor in arid regions (Subramaniam and Rao, 1983; Zhang et al., 2009). Understanding the formation, the amount, and the duration of dewfall is important when managing the shifting sand dune environments. Knowing if and how dewfall is affected by a vegetation-restoration practice is critical for managing sand-protecting vegetation systems and for curbing sand-dune migration. The formation mechanism of dew has been studied in arid and semiarid environments because of its significant role in the water budget (Beysens, 2016; Jacobs et al., 1999; Tomaszkiewicz et al., 2017; Ucles et al., 2013). However, little is known about how dew formation is regulated in a sand-stabilizing plant community on sand dunes.

Dew formation is a natural physical process, described in some arid areas, humid tropical islands, and in cold alpine areas (Beysens, 1995; Jacobs et al., 1999; Jacobs et al., 2000; Kidron, 2000; Richards, 2004; Richards, 2005). The most important factors affecting dew formation are related to the near-surface meteorological parameters. Temperature and wetting properties of the substrate are two key parameters that control dew formation (Beysens, 1995). Thus, low air and soil surface temperatures, high relative air humidity, and moderate wind speed have been found to be the most favorable conditions for dew formation (Monteith, 1957; Zangvil, 1996). Substrate properties may also affect dew formation. In addition, the dew amount and dew duration are determined by the habitat and plant characteristics (Kidron, 1999; Kidron, 2000; Kidron, 2005; Zangvil, 1996; Zhuang and Zhao, 2014).

A major limitation in evaluating the ecological role of dewfall is difficulty of measurement, especially for assessing long-term variability of dewfall. Although dewfall has attracted great interest and various dew-measuring devices have been developed, a standard, internationally-accepted method or an instrument for dew measurement is lacking (Zangvil, 1996). An artificial-condensation surface has been used to measure the amounts of formed dew (e.g., Cloth-Plate method, plywood, glass plates, and polyethylene plates) (Kidron, 1998; Kidron, 1999; Kidron, 2000; Kidron et al., 2002; Lekouch et al., 2012; Ye et al., 2007). However, results obtained by such methods were often influenced by the composition of the artificial surface, and were not easily-comparable across studies. An effective and widely-used approach to monitor dew was that with the use of microlysimeters (Fritschen and Paul, 1973; Jacobs et al., 1999; Meissner et al., 2007; Richards, 2004). This method is considered the most accurate. Dewfall is estimated by direct weighing at the beginning and at the end of the condensation process. However, manual collection and evaluation of the microlysimeters is required early mornings, and it is difficult to obtain continuous and long-term data. More effective approaches for dewfall measurements include micrometeorological techniques such as Eddy Covariance (EC) or Bowen Ratio (BREB-Bowen Ratio Energy Balance), which are based on the energy-balance principle (Hao et al., 2012; Kalthoff et al., 2006; Moro et al., 2007). These techniques have the advantages of measuring surface energy fluxes over relatively large areas, and capturing continuous data (Moro et al., 2007) to facilitate further simulation. For this study, we chose the BREB combined with microlysimeters as a practical approach to dewfall quantification.

Previous field observations obtained in controlled experiments and with the cloth-plate method (CPM) showed that dew may play an ecologically significant role in the physiological activities of annual desert plants. Such activities included priming of seed germination, increasing rates of photosynthesis, and relieving water stress (Yang et al., 2011; Zhuang and Ratcliffe, 2012; Zhuang and Zhao, 2014; Zhuang and Zhao, 2016) in sand dunes near the Badain Jaran Desert. Therefore, the ecological implications of dew as a supplementary water resource in desert ecosystem cannot be overlooked. In China, little work has been done to determine the function of planted shrubs in dew formation. Using the Bowen ratio technique, we measured *LE* and the corresponding meteorological factors in a revegetation-stabilized desert ecosystem dominated by *H. ammodendron* from June to October of 2013. In addition, using the microlysimeter, we chose representative artificial *H. ammodendron* with different development stages to explore a variation of dew formation characteristics, which is induced by different microhabitats. The objective of the present study were: (1) to address dew amount and duration during the growing season in a sand-stabilizing *H. ammodendron* plantation based on measurements from a weather station, (2) to illuminated the relationship between dew formation and weather data, (3) to clarify the effects of microhabitats on the characteristics of dew formation in re-vegetated stabilized desert ecosystems of northwestern China using the microlysimeter method. The results will help us understand the characteristics of dew formation in different microhabitats, and the role of dew in desertification control and vegetation restoration.

2. Materials and methods

2.1. Study area

The study was conducted in *H. ammodendron* plantations, near the Linze Inland River Basin Research Station, Chinese Academy of Sciences (39°21′N, 100°07′E, 1374 m a.s.l.), located at the southern edge of the Badain Jaran Desert in northwestern China (Fig. 1). The climate in the region is temperate continental, characterized mainly by aridity, high temperatures, and frequent strong winds. The mean annual temperature is 7.6 °C. The average annual precipitation is 117 mm (1965–2000), of which 65% falls from July to September. The mean annual potential evaporation is 2390 mm, and the annual duration of sunlight totals 3045 h. Wind speed is greatest (21 m/s) in spring, and wind direction is predominantly from the northwest. The soil is characterized by coarse texture and loose structure, and is very susceptible to wind erosion. The textural composition is 89.52% sand, 5.97% silt and 4.51% clay (Su et al., 2007). Dew occurs most frequently in late summer or early autumn (Zhao and Liu, 2010). Plant species are dominated by shrubs, including *H. ammodendron*, *Calligonum mongolicum*, *Nitraria tangutorum, Hedysarum scoparium,* and annuals such as *Suaeda glauca, Bassia dasyphylla, Halogeton arachnoideus, Agriophyllum squarrosum*.

Before sand-fixing vegetation was planted, most of the area was covered by shifting sand dunes and lightly-undulating interdunal lowlands. To stabilize shifting sand dunes, the Lanzhou Institute of Desert Research, Chinese Academy of Sciences conducted a desertification-control project to restore vegetation and rehabilitate desertified land in 1975 (Su et al., 2007). *H. ammodendron*, as a typical sand-fixing species, was established in the form of protective forest belts at the fringe of an oasis. Subsequently, similar projects were conducted in adjacent rehabilitated areas. The area of shifting sand declined from 54.6% pre-treatment to 9.4% post-treatment (Su, 2010). Experimental plots established during different planting periods provided ideal conditions for the present study. We selected study sites which included three *H. ammodendron* plantation ages (5-, 20-, and 40-year-old), corresponding to plantation establishment years of 2010, 1995, and 1975 (Fig. 2a–c). The structure and quantitative characteristics of *H. ammodendron* plantations are shown in Table 1.

2.2. Experimental design and data collection

During June and October of 2013, the dew amounts and duration were estimated by using the Bowen ratio energy budget technique (BREB), and the dew variability on sand dunes planted with *H. ammodendron* 5, 20, and 40 years before were measured by microlysimeter. A meteorological tower was equipped to apply the Bowen ratio technique in the experimental field in the *H.* plantation. The measured meteorological variables included relative humidity, air

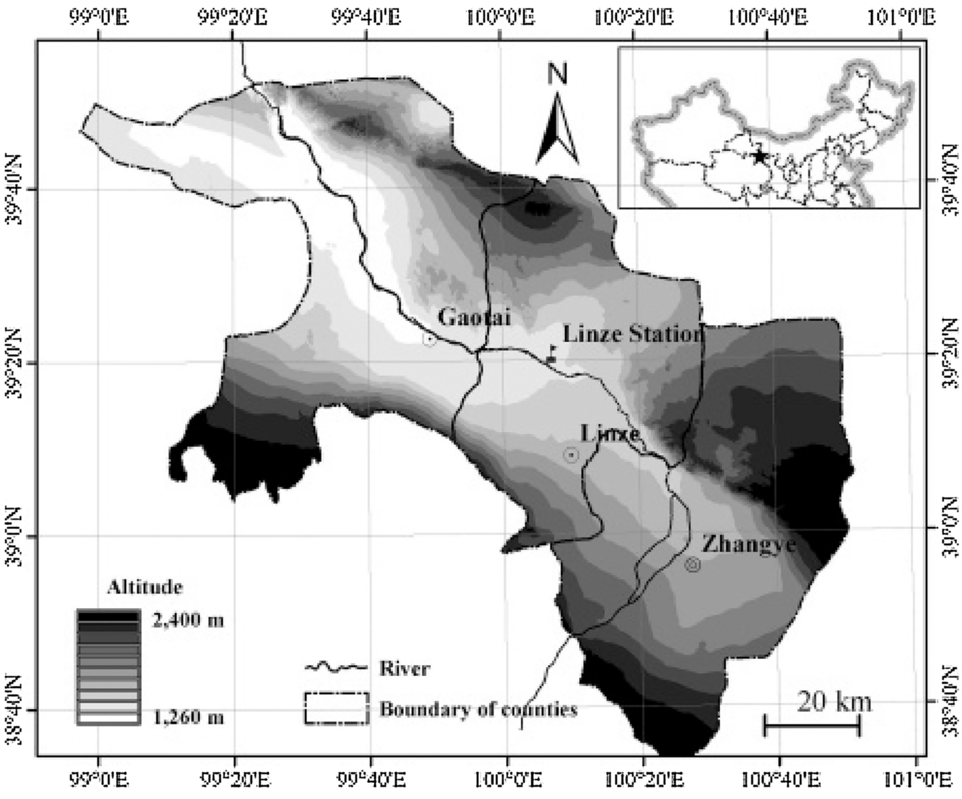

Fig. 1. Schematic map of the study area.

temperature, wind speed, components of the radiation balance (e.g. net radiation, incoming (atmospheric) and outgoing (terrestrial) long wave radiation, incoming and outgoing shortwave (solar) radiation), soil heat flux, soil surface temperature, and atmospheric pressure. These parameters were measured using an AG 1000 automatic weather station (Onset Computer Corporation, Pocasset, MA, USA). The sensors were installed at 1 and 2 m above canopy in the 20-year-old *H. ammodendron* plantations. Meteorological data were measured at a frequency of 10 Hz and recorded every 5 min using a CR1000 datalogger (Campbell scientific Inc., Logan, UT, USA); they were stored as 30-min averages.

Dew was measured in experimental plots in the planted 5-, 20- and 40-year-old *H. ammodendron* stands. Cylinders made of PVC (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 5 different sites in each habitat, 90 PVC containers were

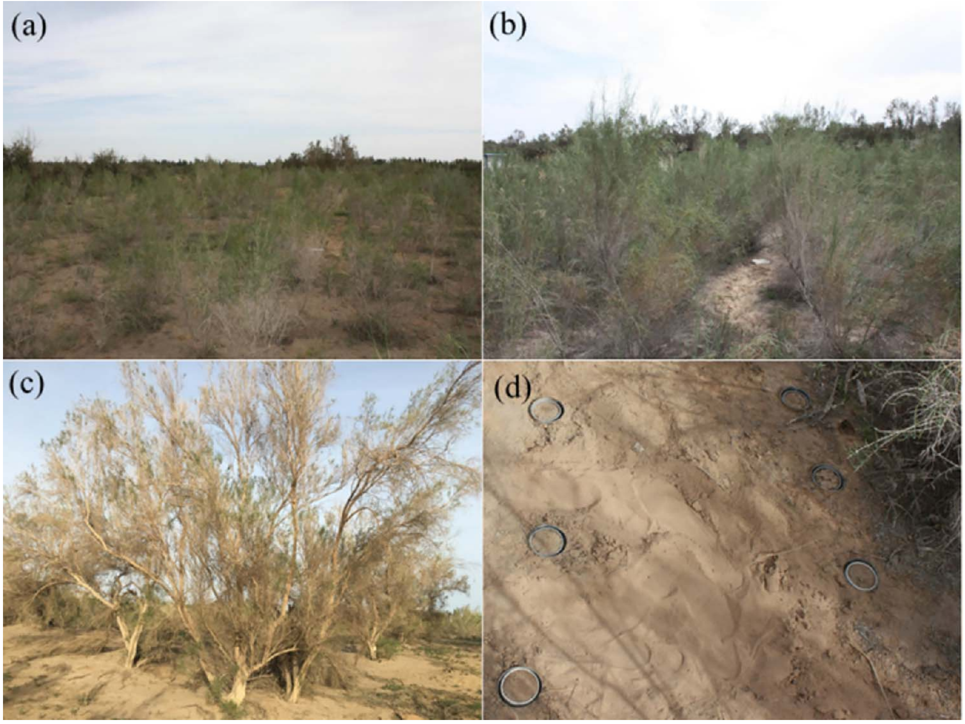

Fig. 2. The graph of *Haloxylon ammodendron* plantations at the edge of a desert oasis in Linze area, northwestern China. (a) 5-year-old; (b) 20-year-old; (c) 40-year-old; (d) Lysimeters shown.

Table 1
Characteristics (Mean ± SD) of *Haloxylon ammodendron* plantations.

Age	Stand density	Height	Basal diameter	Crown area	Vegetation cover
	(stems/ha)	(m)	(cm)	(m^2)	(%)
5-year-old	2812 ± 20	1.05 ± 0.05	4.03 ± 0.15	0.88 ± 0.2	13.2 ± 3.47
20-year-old	1125 ± 28	4.66 ± 0.24	20.35 ± 0.94	16.84 ± 0.75	98.5 ± 7.49
40-year-old	602 ± 18	6.05 ± 0.54	35.8 ± 3.24	26.22 ± 4.36	70.8 ± 6.64

used at all (Fig. 2d). PVC cylinders were weighed with soil with an electronic balance (precision: ± 0.01 g) 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. In order to obtain the variation trend of dewfall amount in the whole night under the canopy and inter-space of 5-, 20-, and 40-year-old *H. ammodendron* plantations, the microlysimeters were weighed every hour.

There were differences between the dew input once the soil was wet or dry. It was found that the onset and end time of condensation were controlled by surface soil water content, which was significantly correlation with the onset time of dew formation in our study area (Fang and Ding, 2017). Furthermore, according to a result from Guo et al. (2016), the dry soil is beneficial to the formation of dew as a result of rapid decrease in soil surface temperature and easily to reach dew point, whereas the higher soil moisture content, the less likely to reach the dew point. Clearly, low soil water content led to low thermal conductivity, thus leading to higher soil temperature difference between day and night, facilitating dew formation. For excluding the effect of rain, measurements were carried out only when the surface soil moisture content was less than 1.5% and therefore the values represent dewfall only.

2.3. Analysis methods

The Bowen ratio technique was successfully applied before to other semi-arid regions to calculate evapo-transpiration and dew formation (Malek et al., 1999). By assuming equality between the turbulent diffusion coefficients of sensible (K_h) and latent (Kw) heat fluxes$(\partial T/\partial z)/(\partial e_\alpha/\partial z) \approx \Delta T/\Delta e_\alpha$), the latent heat fluxes (LE, in W m^{-2}), based on Bowen ratio ($\beta = H/LE \cong \Delta T/\Delta e_\alpha$), was obtained by (Mastrorilli et al., 1998):

$$\lambda ET = \frac{R_n - G_{surf}}{1 + \gamma \Delta T/\Delta e_\alpha}$$

where λ (2.501 MJ kg^{-1}) was the latent heat of vaporization, G_{surf} was soil heat flux (W m^{-2}), R_n net radiation (W m^{-2}), γ the psychrometric constant (kPa $°C^{-1}$), and ΔT and Δe_a were the temperature (°C) and vapor pressure differences (kPa) at two levels above canopy (1 and 2 m), respectively. The latent heat flux (λET) was divided by λ to obtain the evapotranspiration (mm day^{-1}) and dew amount (mm day^{-1}). The evapotranspiration and dew formation were then calculated according to

$$ET = LE/L \text{ if } LE > 0,$$

$$D = LE/L \text{ if } LE < 0$$

Where D was the dewfall amount; LE was the latent heat flux; L was the latent heat of water vaporization, and summed up for each day.

Dew amount (I), in millimeters, was calculated with the following formula:

$$I = \frac{10 \times (Wr - Ws)}{S}$$

where I was the dew amount (mm); W_r was the weight of the condenser before sunrise (g); W_s was the weight of the condenser after sunset (g); S was the surface area of the condenser (cm^2); and 10 was a conversion factor.

2.4. Statistical analysis

Meteorological data determining the occurrence of dew was determined by comparing nights with and without dewfall. Significance of differences in meteorological data of nights with and without dewfall was determined at 95% confidence level by a non-parametric Mann-Whitney *U* test. Regression analysis was used to examine the relationship between Bowen ratio estimates and microlysimeter measurements of dew amount. Root-Mean-Square Error (RMSE) was used to evaluate the goodness of fit of the Bowen ratio technique. All the statistical analyses were performed using the R 3.2.0 software.

3. Results

3.1. Dewfall frequency and duration

Rainfall events in study area were characterized as rainfall pulses with discontinuous, highly variable and largely unpredictable frequency and intensity (Zhao and Liu, 2010). It was shown that the rainfall was recorded on 29 days, and the precipitation was 95.2 mm from June to October of 2013, whereas rainfall events of 5 mm or less were most common and comprised 86% of the events (Fig. 3). The measured nocturnal latent flux was negative, indicating that dewfall events were frequent during the growing period. The number of dewfall days varied depending on month. Thus, June and July had the fewest dew days at 21 and 22, respectively, while October had the most at 27 (Fig. 4). The total number of dewfall days and rainfall days accounted for 77% and 19% of total observation days, respectively. These results indicated that dew formation was more frequent and stable during the summer than rainfall, and thus the dew was the most common and important supplementary water sources in arid environments.

Ecologically, the duration of dewfall may have a higher significance for natural vegetation than dewfall amounts (Hanisch et al., 2015; Munne-Bosch et al., 1999). Our data analysis by BREB showed that dewfall began after sunset, continued until 7:30 am even after sunrise, and that all dew evaporated before 10:30 am (Fig. 5). Although it was assumed that the maximum of dewfall occurs at dawn or sunrise, dew

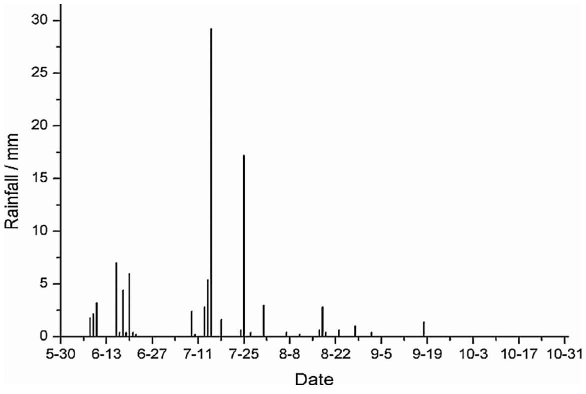

Fig. 3. Daily rainfall distribution in research area from June to October of 2013.

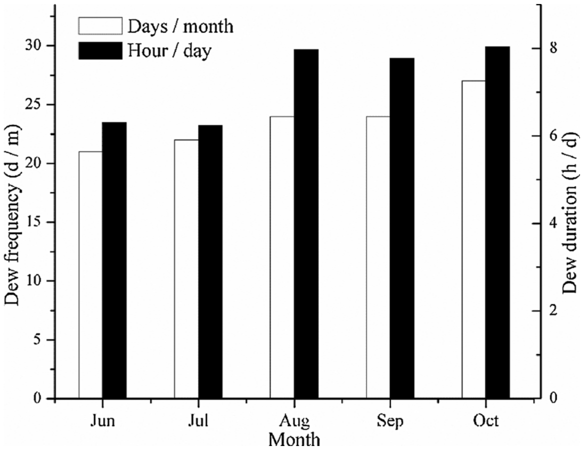

Fig. 4. Dewfall duration and the number of dewfall days from June to October in *H. ammodendron* plantations. Data were calculated by BREB.

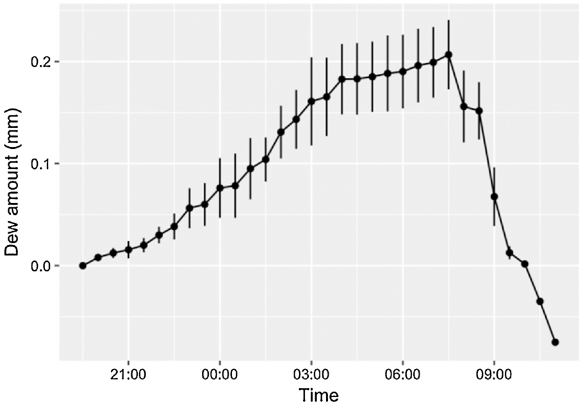

Fig. 5. Dew accumulation and evaporation process measured by BREB for days with dewfall > 0.1 mm ($n = 87$) in the study area.

continued even after sunrise. Dew accumulation continued for as long as 36–44% of the total daylight duration, and there were the greatly significant differences between the period from dawn to maximum (1.1 h) and the total daylight dew duration (2.9 h) ($p < 0.01$). In addition, daylight accumulation amounts of dew accounted on an average for 11–17% of the total dewfall amounts, and there were the significant differences between average dew amounts at dawn and maximum dew amounts ($p < 0.05$). Therefore, the condensation period of dew after dawn may have important implications for dew formation, and substantial amounts of dew formed during that period. A similar result from Kidron (2000) indicated that a continuous condensation was due to a slight turbulence, which was caused by early sunlight. Mean daily dew duration also varied depending on month and the entire process of dew formation was not continuous throughout the night, and exhibited large variability. Daily dew duration was longest in August, and shortest in June and July, moreover, most variable in August (from 1 to 9.5 h), and the least variable in June (from 4 to 7.5 h). Overall, the mean daily duration of dew was 7.6 h, with the maximum and minimum of 9.5 and 1 h, respectively (Fig. 4). It was found that although the duration of dew in one day was very short, more than 20 days in each month from June to October occurred dew. Therefore, a dew event consisted of a brief process in a day for the scales, but with a large probability event in a month for the scales.

3.2. Quantity of dew

Total monthly quantity of dew ranged from 2.7 to 4.0 mm, with a daily mean of 0.13 mm. Total recorded amount was 16.1 mm, representing 16.7% of the rainfall from June to October and 15.1% of rainfall for the year 2013 (Fig. 6). Kappen et al. (1979) demonstrated that 0.03 mm of dew was the threshold amount of dew availability for microorganisms. We found that amounts of dew totaling > 0.03 mm day^{-1} occurred on 112 days, which accounted for 95% of the total dewfall days. Moreover, dewfall days with dewfall amount of > 0.1 mm accounted for 80.5% of the total dewfall days (Fig. 7).

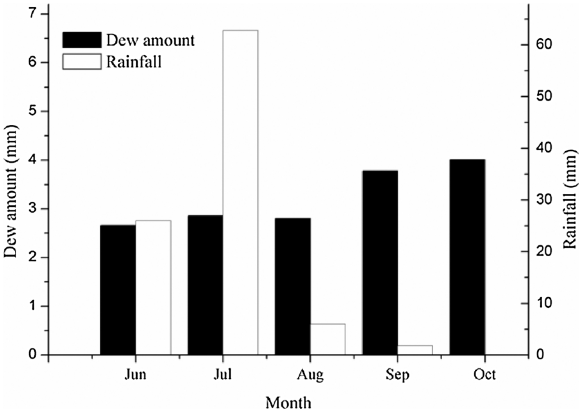

Fig. 6. Monthly total amounts of dew and precipitation from June to October in the study area. Data were calculated by BREB.

3.3. Dew formation and meteorological factors

During the observation period, we observed only 7 days with the soil surface temperature equal to or lower than the dew point. In addition, the relative humidity of soil was lower than that of air, demonstrating that an increase in soil surface moisture resulted from nighttime adsorption of water vapor. Analysis of meteorological data revealed that nights with dew exhibited significantly higher relative humidity, lower mean wind speed, lower mean difference between air and dew point, and lower means temperatures than nights without dew (Table 2). These results were consistent with those of Hanisch et al. (2015). It is clear that the average relative humidity during the nights with dewfall was 58.3%, while the maximum of the average RH was no more than 50% in the nights without dew (Fig. 8a). Surface temperature of soil was always significantly lower ($P < 0.001$) and declined noticeably during the late afternoon and the night with dew (Fig. 8c). High relative humidity and low surface temperature benefited to approximate dew point. The average wind speed during the nights with dewfall was 1.5 m/s (Fig. 8b). This was similar to the results of He and Richards (2015), who determined that wind speed of 1–2 m/s benefitted the formation of dew.

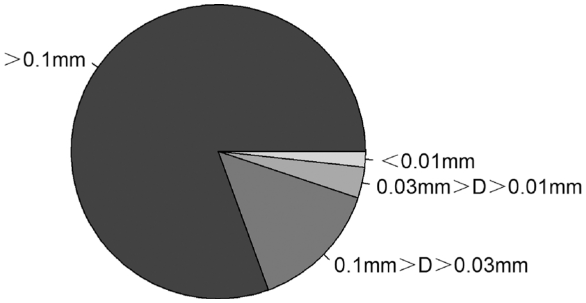

Fig. 7. Distribution of the number of dewfall days. The pie chart shows days with dewfall in four categories according to daily dewfall amount. The area of each category represents the percentage of total dewfall days. Data were calculated by BREB.

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

Variables		Nights with dew	Nights without dew	Significance level
		(n = 112)	(n = 35)	
Mean RH (%)	Min	27	11	< 0.001
	Max	98	89	
	Mean	62.3	45.4	
Mean DP (°C)	Min	4.3	2.6	0.286
	Max	17.6	16.5	
	Mean	10.73	9.47	
Mean T (°C)	Min	7.2	10.9	0.001
	Max	33.8	34.7	
	Mean	18.9	21.7	
Maximum T_{air}-T_{dp} (°C)	Min	0.3	1.7	< 0.001
	Max	27.7	32.8	
	Mean	8.18	13.27	
Maximum wind speed (ms^{-1})	Min	0	0.84	< 0.001
	Max	4.27	8.2	
	Mean	1.52	3.8	

RH = relative humidity, DP = dew point, T = air temperature, T_{air}-T_{dp} = the differences between air and dew point.
Significance was determined at the 95% confidence level by a non-parametric Mann-Whitney *U* test.

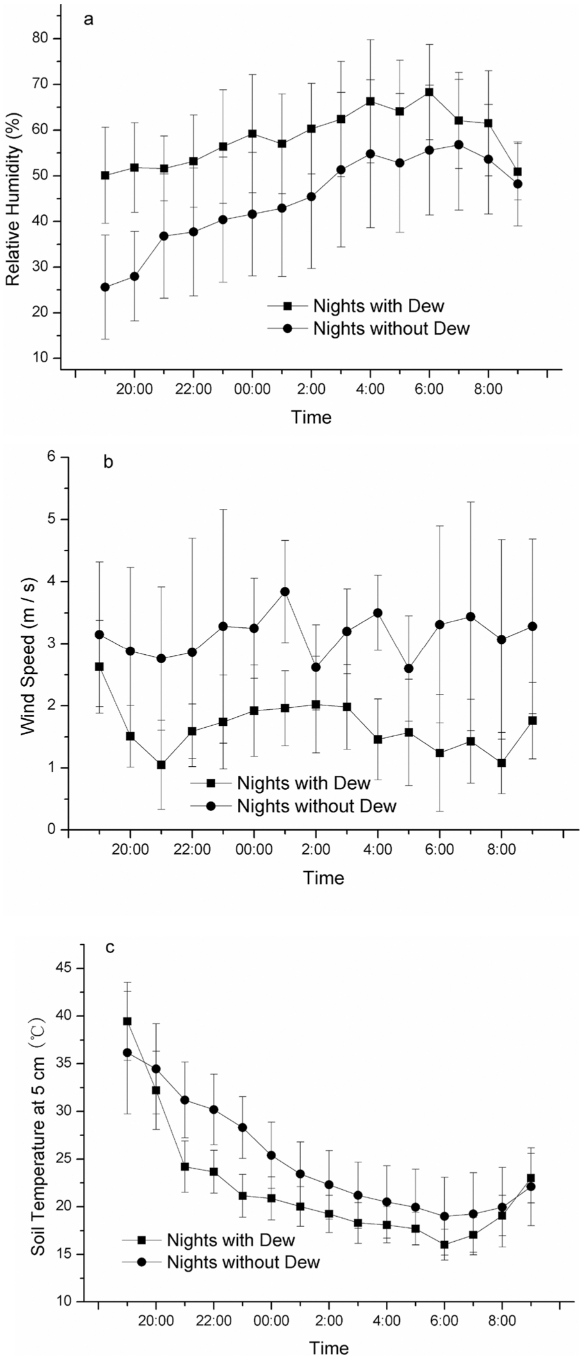

Fig. 8. Average weather conditions on nights with (n = 87, dewfall amount > 0.1 mm) and without dew formation (n = 10). (a) relative humidity; (b) wind speed; (c) soil temperature at 5 cm depth.

3.4. *The influence of H. ammodendron age on dew formation*

Dew formation in *H. ammodendron* plantations started at 19:00 h and accumulated gradually through the night, although the air temperature was higher than the dew point from 19:00 to 05:00 the following morning. From 05:00 to 08:00, the air temperature was lower than the dew point, relative humidity was saturated, and the accumulated dewfall amount increased sharply to a maximum at 07:00 the following day (Fig. 9a). Air temperature increased after 09:00, and the accumulated dew declined gradually via evaporation. The results indicated that dew accumulation through a day included water absorption process, condensation process and evaporation process. The timing of dew formation was almost simultaneous in 5-, 20-, and 40-year-old *H. ammodendron* plantations. The accumulated amount of dew was always much greater and its variability was almost 3 times higher for 5-year-old than for 20-, and 40-year-old *H. ammodendron*. The cycle of evaporation and condensation was distinct at 08:00, and the evaporation rate of dewfall was also higher for 5-year-old shrubs than for 20-, and 40-year-old shrubs. The maximum accumulated amounts of dew were 0.184 mm, 0.084 mm, and 0.07 mm for 5-, 20-, and 40-year-old *H. ammodendron*, respectively (Fig. 9b). After reaching a maximum amount of dew, the evaporation rate of dew was lower and the decline of soil moisture was slower for the 20-, and 40-year-old shrubs than for the 5-year-old ones. These results demonstrated that the denser canopy of 20-, and 40-year-old shrubs blocked the absorption and condensation of water vapor, and slowed down the subsequent evaporation.

Dew-formation characteristics for the inter-space and under the canopy of the 5-, 20-, 40-year-old *H. ammodendron* plantation indicated that the increase in cumulative dew amount was caused by water vapor absorption because the air temperature was higher than the dew point during the observation (Fig. 10a). The cumulative dew amount in the inter-space in 5-, 20-, 40-year-old *H. ammodendron* plantations was always greater than that under the canopy in the evening, and the difference increased gradually toward the maximum, and then declined rapidly. At the same time, the cumulative amount of dew under the canopy of the shrubs underwent a slow evaporation process. The maximum cumulative amount of dew was observed 2 h later under the canopy of the 5-year-old *H. ammodendron* plantation than in the inter-space (Fig. 10b). Dew formation lagged under the canopy of shrubs compared to the inter-space because the microhabitats formed by shrubs delayed the formation of favorable weather conditions. Moreover, the canopy itself partially captured the water vapor, which decreased the amount of water reaching the ground.

4. Discussion

4.1. *Conditions of dew formation*

The formation of dew is a complex physical processes, influenced by micrometeorological conditions (Ye et al., 2007). During the observation period in the Linze area, soil moisture content increased although

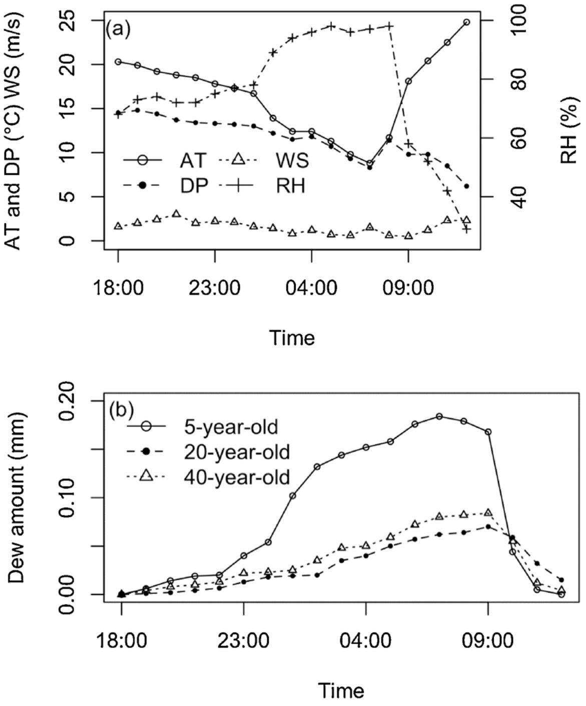

Fig. 9. Dew variability for three ages of *H. ammodendron* plantations measured by microlysimeters and the corresponding meteorological data. The meteorological data were given at the same with the dewfall amounts, 28-29 August, 2013–29August, 2013 H. ammodendron. RH, releative humidity; AT, air temperature; DP, dew point; WS, wind speed.

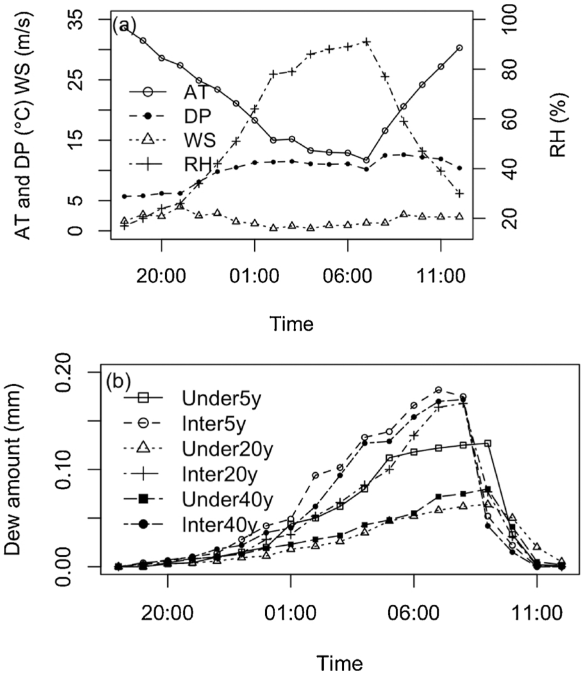

Fig. 10. Dew variability for three ages of *H. ammodendron* plantations measured by microlysimeters and the corresponding meteorological data.The meteorological data were given at the same with the dewfall amounts. (a) 25–26August, 2013; (b) The variation trend of dewfall amount in the whole night under the canopy and inter-space of 5-, 20-, and 40-year-old *H. ammodendron* plantations. RH, relative humidity; AT, air temperature; DP, dew point; WS, wind speed.

relative humidity was not saturated. This was a result of water vapor adsorption by top soil, a type of molecular condensation formed by the combination of molecular attraction of dry sand and capillary condensation (Agam and Berliner, 2006). Water-vapor absorption by soil is a typical feature of dew formation at the edge of desert oases. Similar results were also reported for the steppe desert, and for a desert riparian forest ecosystem (Hao et al., 2012; Pan et al., 2010).Also, dew formation is largely dependent on moisture provided from the atmosphere. Our study site, which lies at the edge of desert oasis, is 5 km from Heihe River. Also, the main vegetation in the desert oasis includes crops, fruit trees, and artificial protection forest, which are characterized by strong evaporation and high water consumption. Clearly, the river and plant transpiration would supply moisture. Analysis of all days measurements by BREB indicted that the highly average maximal dew of 0.2 mm was obtained, which occur mainly on clear days and after crop irrigation. The diurnal variability in dewfall is controlled by meteorological factors. It was shown that clear skies, moderate winds, strong inversions of temperature from the ground surface to the atmosphere, low surface temperatures, and high relative humidity were favorable for condensation of water vapor (He and Richards, 2015). The present study showed that high air relative humidity was a precondition for water vapor absorption and condensation, and that 50% was the lowest value of relative humidity at which dew formed at the edge of the desert oasis. In addition, dew was also controlled by WS and the effect of wind on dew formation was complex. Observations in the Linze area indicated that the maximum night-time wind speeds and the night-time mean wind speeds with dewfall were 4.27 m/s and 1.52 m/s, respectively. It is suggested that moderate winds enhanced the transport of water vapor and prevented the mixing of air at the surface with air above (He and Richards, 2015), while high wind speeds (> 4.57 m/s) inhibited dew formation (Monteith, 1957). Other studies have also shown that a wind speed of 5.7 m/s is the upper limit for dew formation (Lekouch et al., 2012; Muselli et al., 2009; Nilsson, 1996).

4.2. Comparison between measured dewfall by microlysimeter and estimated dewfall by BREB

Fig. 11 displays the course of dew amounts gathered with the microlysimeter and calculated with the Bowen ratio energy balance (BREB) for one selected night (4–5 August 2013). The selected night is the representative of the measurement night, highlighting the good consistency between the microlysimeter measurement and the calculated dew. It was indicated that measured and calculated value follow a similar tendency, but Bowen ratio estimates were consistently lower than microlysimeter values. Moreover, the onset time of dew, the time to reach the maximum condensation and the total dew duration were also similar. Comparisons between Bowen ratio and microlysimeter daily estimates of dewfall amounts for 50 nights were made during the observation period (Fig. 12). It was demonstrated that the Bowen ration

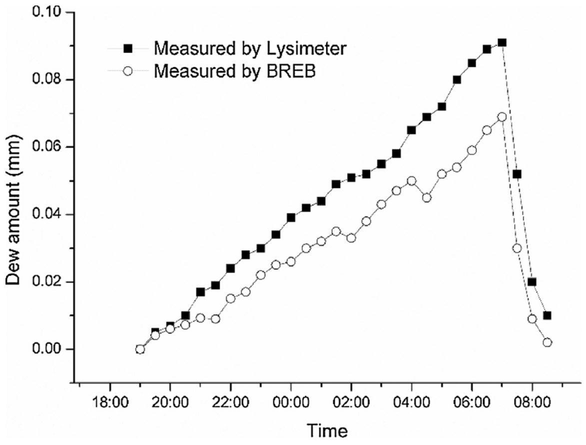

Fig. 11. Course of the cumulative dew amounts measured by microlysimeters and the Bowen-ratio methods on 4–5 August 2013.

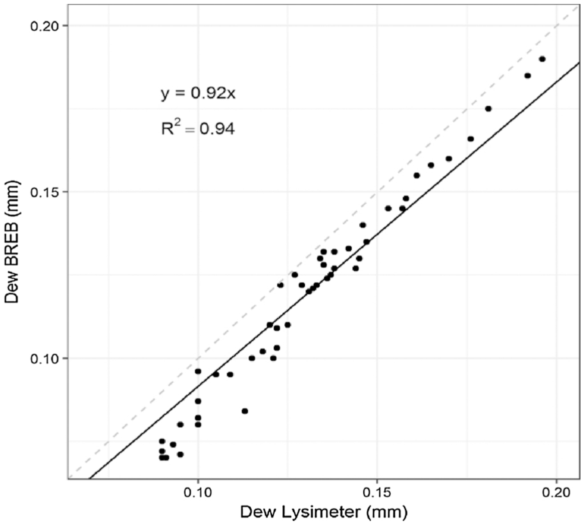

Fig. 12. Correlation between measured dew amount by microlysimeters and by Bowen-ratio methods during 50 nights from June to October 2013.

estimates of daily dew amount were closely correlated with the measured values by microlysimeter (Fig. 12; $R^2 = 0.94$). The fitted lines were considerably close 1:1 line, with a slope of 0.92. The RMSE were small, with values of 0.01 mm. As the calculated dew results agree well within 10% with the microlysimeter data, the Bowen ratio method was considered acceptable for nighttime dew assessments in the study region. The above results were similar to those reported by Atzema et al. (1990), and Jacobs et al. (1994); Jacobs et al. (1990), who applied successfully the Bowen ratio technique to determine dewfall of crop canopies. In addition, the majority of comparisons between the Bowen ratio technique and microlysimeter have been conducted within crop canopies and differences of less than 10% between the two methods have been reported (Denmead and McIlroy, 1970; Prueger et al., 1997; Tanner, 1960). Some studies had also shown that the largest difference between the two methods occurred on the day following irrigation, when the Bowen ratio underestimated the lysimeter λE by 8% (Bausch and Bernard, 1992). Therefore, these data provide confidence in using the Bowen ratio method to obtain accurate estimates of dew at the edge of a desert oasis, northwestern China.

4.3. *The influence of H. ammodendron age on dew formation*

Although the formation of dew was dependent primarily on meteorological conditions, the relevant meteorological conditions partly depended on landscape factors. Therefore, the landscape was also a key element in triggering the formation of dew. Existing vegetation changed the microclimate of the soil surface, and interrupted the migration of water vapor. Our results demonstrated that high variability in dew amounts characterized the three microhabitats formed by *H. ammodendron* plantations and microhabitats formed by *H. ammodendron* shrubs of 3 different ages (5-, 20- and 40-year-old) affected how dew formed; thus, microhabitat conditions caused a lag in the timing of onset, increased the length of time to maximum cumulative amounts of dew, and extended the duration of dewfall under the canopy. These observations were consistent with those of Pan et al. (2010). These effects were more notable under the thicker canopy of the 20-year-old plantation than elsewhere, where the influence of the dense canopy was more significant than that of tall but 40-year-old shrubs. Our data also indicated that the accumulated amount of dew was always greater and its variability at night almost 3 times larger for 5-year-old than for the 20- and 40-year-old shrubs. The lower near surface dew amounts at 20- and 40- year old *H. ammodendron* may be explained by low ‘Sky View Factor (SVF)’, that is, the proportion of sky seen by the deposition surface (Oke, 1978). It has been observed that higher canopy area and vegetation cover resulted in low SVF, which caused the less efficient long wave radiational cooling at 20- and 40- year old *H. ammodendron*, and thus hinder near-ground the formation of dew. As a result of higher SVF in 5 year old *H. ammodendron*, and its well-ventilated location, the dew-point temperature may be reached earlier, resulting in earlier dew condensation and consequently higher dew amounts. This result was consistent with those reported by Kidron (2000) and Kidron et al. (2000) at an arid drainage basin in the Negev Highlands, Israel, which indicated that the lower near surface dew amounts at the wadi beds, resulting from the lower SVF at the narrow wadi. Also, wind is seen to be responsible for greater amplitude of variation at 5 year old *H. ammodendron* plantations than 20- and 40- year old *H. ammodendron*.

During most mornings, near-ground dew amounts at the inter-space of three ages of *H. ammodendron* exhibited higher values than that under the canopy. The research of Pan and Wang (2014) also found the accumulated dew formation amount was larger at open spaces as compared to under the canopy. Surface temperatures and ventilation may also explain the present findings. The inter-space of shrubs location, which is fully exposed to the cooling effect of the afternoon winds, will also experience a more efficient long wave radiation cooling, which may result in high dew amounts. In addition, the difference of air temperature under the canopy was less in comparison with the location of inter-space of shrubs, with a consequent reduction in dew formation. The results from Monteith (1957), Duvdevani (1964) and Kidron et al. (2000) also demonstrated that the important role of temperature difference in controlling the dew formation. Furthermore, the difference of soil surface moisture for different microhabitats may be also another major factor affecting the variations of dew amounts. It was noted that soil moisture at 5-cm depth decreased during the observation period in the order of: under the canopy, 20-year-old shrubs > under the canopy, 40-year-old shrubs > under the canopy, 5-year-old shrubs > inter-space, 5-year-old shrubs > bare sand dunes. The higher soil moisture under the shrub canopy slowed the decrease in soil temperature more than in the open space at night, and thus the soil surface is usually warmer under the canopy of shrubs than inter-space of shrubs location. Due to a slower decrease of surface temperature under the canopy of shrubs and its relatively wind-sheltered location, near-ground dew condensation under the canopy of shrubs was delayed, consequently resulting in lower dew amounts. The evaporation processes of dew were slower under the canopy of shrubs, which was explained by the relatively sheltered from the early morning sun rays, and the slower rose of surface temperature at this location.

4.4. *Ecological implications of dew formation in temperate desert ecosystems*

Dewfall is an important supplementary source of water in desert environments. It effectively provides supplementary moisture for animals, plants, and biological crusts that can contribute to the stabilization of sand dunes, especially in extreme drought season (Lange et al., 1977; Munne-Bosch et al., 1999; Shachak and Steinberger, 1980). As part of water and heat exchange, dewfall plays a significant role in the desert ecosystem. We showed in this study that dew frequently occurred in our study area, and the number of days with dew amounts > 0.03 mm accounted for 95% of the total dew days. Many studies showed that condensation of dew on plant leaves enabled direct absorption through foliage even in conditions of small amounts and short duration of dew (Boucher, 1995; Jacobs et al., 2000; Zhuang and Ratcliffe, 2012). A previous study on *Bassia dasyphylla* in our study area showed that the presence of dew significantly enhanced plant water status, photosynthetic accumulation, and total biomass (Zhuang and Ratcliffe, 2012). Further, water absorption or condensation on the soil surface improved the percentage of seed germination of annual desert plant species (Zhuang and Zhao, 2016). Dew is also an important source of moisture for microbiotic soil crusts in deserts, arid and semi-arid areas

(Jacobs et al., 1999; Kidron, 1999; Kidron et al., 2000; Kidron et al., 2002, Zhang et al., 2009). It has been found that there was mutually beneficial relationship between microbiotic soil crusts and dew. On the one hand, the occurrence of microbiotic crust benefited formation of dew. Microbiotic soil crust can absorb much more dew with the development of soil crusts, from bare sand to cyanobacterial crust to lichen crust to moss crust (Kidron et al., 2000; Kidron et al., 2009; Kidron et al., 2008; Zhang et al., 2009), and this may be especially important for the total period of potential net CO_2 uptake by these crusts, providing relatively long phases of photosynthesis from a low moisture supply during early morning hours (Lange et al., 1998). Lange et al. (1992) has reported that 0.1 mm of dew is the threshold of dew availability for net photosynthesis of microbiotic soil crusts. On the other hand, the increasing amount of dew nourished the microorganisms and thus promotes the growth and development of microbiotic soil crust, which accelerated the stabilization of moving sand dunes (Jacobs et al., 2002; Zangvil, 1996). In China, Pan et al. (2010) conducted experiments in revegetation stabilized arid desert ecosystem in Shapotou area, which indicated that biological soil crusts had higher capability of absorbing and holding water, and they could utilize dew to enhance the biology and chemical activity of microorganisms and spore plants. Tao and Zhang (2012) in Gurbantunggut Desert demonstrated that patches moss (*Syntrichia caninervis*) with awns accumulated more dew, and increased their ability to adapt to arid environments. However, there were no biological soil crusts in the research site. The phenomena may be explained by two reasons. Firstly, lower precipitation and higher evaporation in the study area were unfavorable to formation of biological soil crusts. Secondly, *H. ammodendron* had apparent ‘Salinity Island ’effect (Liu et al., 2009; Zhang et al., 2016), unfavorable for survival of microorganisms and establishment of annual desert plant species under the canopy. It was observed that physical crusts of 3 cm covered on the artificially vegetated sand dunes had a high salt content and a hard texture, which play an important role in sand dune stabilization. In addition, dew may have a significant contribution to formation of physical crusts in our research area. In the end of summer or beginning of autumn, the assimilating branches of *H. ammodendron* gradually fell off and formed a deciduous layer on the sand dune, which had a high salt content of 10–15%. The occurrence of dew caused the formation of hard salt crusts, thereby effectively alleviating the movement of the sand dunes. Future study would be valuable to explore the role of dew as a moisture source for physical crusts in the research area. Clearly, the changed microhabitat influenced the dew formation and the increased level of dew formation in the inter-space of the sand-fixing shrubs is important to the microorganisms and herbaceous plants, favoring the stabilization of moving sand dunes. The dew formation plays important ecological roles in promoting the restoration of vegetation and curbing the desertification.

5. Conclusions

It is concluded that dew formed frequently, and that water adsorption was a major pathway of dew formation at the edge of the desert oasis. Air temperature, relative humidity, the difference between air temperature and dew point, and wind speed played important roles in dew formation. The thresholds of the dew formation were RH $>$ 50% and wind speed $<$ 4.27 m/s. Changes in microhabitat resulting from different ages of *H. ammodendron* had an influence on the quantitative characteristics of dew in arid desert ecosystem. As a result of larger canopy area and lower Sky View Factors to 20- and 40- year-old *H. ammodendron*, the accumulated amount of dew was always significantly greater, and its night-time variability was almost 3 times greater for 5-year-old than for 20- and 40-year-old shrubs. Due to the blocking effects of the shrub stands itself, the near-ground dew amounts at the inter-space of three ages of *H. ammodendron* exhibited higher values than that under the canopy. Dew formation lagged and the maximum cumulative amount of dew was observed 2 h later under the canopy of shrubs. However, the evaporation of dew after sunrise was slower under the canopy due to the shading effects of shrubs, thus extending the duration of dew on the soil surface. The present study has important implications for establishment of sand-fixing vegetation and sand-dune stabilization. Understanding the characteristics of dew formation and its variability in artificially regenerated ecosystems will help explore the role of dew in desertification control and vegetation restoration.

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