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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