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Formation and influencing factors of dew in sparse elm woods and grassland in a semi-arid area

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ABSTRACT

Dew is a significant source of available water in arid and semi-arid regions, and it is considered as being the primary water source that supports living things in extreme arid regions. The objective of the present study was to determine temporal and spatial variation and the influencing factors of dew in natural sparse elm woods and grassland in Hunshandak Sandland, Inner Mongolia. One of the goals of this study was to quantify dew accumulation and duration in different types of vegetation based ecosystems. Dew formation, duration, accumulation, and environmental factors were continuously measured from the end of July to early October, 2014 during the growing season utilizing the weighing method and condensation surface technique. Leaf surfaces of the natural ecosystem were used as the condensation surfaces and served as a tool to determine the atmospheric condensation water on the plant leaves. PVC tubes with undisturbed soil were weighed before being placed into the soil at night and were reweighed before sunrise the next morning to determine dew formation in the soil from both atmospheric and deep soil layer condensation. The experiment was conducted from July 22 to October 10, 2014 and there were 43 days of dew formation during this time. Daily dew duration was averagely 4.04 h and 5.69 h in sparse elm woods and grassland, respectively, and daily dew accumulation was 0.12 mm and 0.24 mm, respectively. The total dew accumulation was 1.44 mm in sparse elm woods and 5.95 mm in the grassland ecosystem. Dew accumulation was significantly higher in grassland than in sparse elm woods ($p = 0.029$). Daily dew accumulation was the highest in July, with a value of 0.11 mm, followed by 0.10 mm and 0.03 mm in August and September, respectively, for sparse elm woods, while the highest value for grassland was 0.26 mm in July, followed by 0.22 mm, 0.16 mm, and 0.12 mm in August, September, and October. Soil dew mainly depended on the water vapor arising from the deep soil layers, rather than atmospheric water vapor. The highest values occurred in September and were 0.29 mm and 0.35 mm in sparse elm woods and grassland. Soil displayed water vapor lost to the atmosphere and the evaporation of soil was larger than the amount of condensation even at night, which was due to higher soil temperature in the upper 5 cm soil layer than that of the air temperature. Soil water evaporation also provided a large amount of water vapor for atmospheric dew, and enhanced by increasing relative air humidity near the ground surface. Dew was largely affected by air temperature and relative air humidity in both sparse elm woods and grassland, followed by wind speed. Dew accumulation increased with rising relative air humidity. In conclusion, dew was a variable water source and was affected by multiple factors, not only climatic factors but also vegetation coverage. Dew accumulation and duration were lower under sparse elm wood canopies than in grassland.

1. Introduction

Dew comprises the drops of water formed on a cold surface of objects when warm water vapor in the air and soil becomes cool and the surface temperature of objects descends to the dew point. Dew is usually attached to the leaves of plants and the soil's surface or into shallow soil [1]. Dew is a natural phenomenon that occurs frequently in arid and semi-arid regions. Although supplying water in relatively low amounts, dew is constant in formation, is a stable available water source, and has great significance in arid and semi-arid zones. The earliest scientist to conduct research on dew was Stephen Hales, a British plant physiologist [2]. There has been limited progressive research on dew since his early efforts. A hundred years later, two papers, Boussingault [3] and Henslow [4], stimulated interest in research on the dew that plants can absorb from rain and the use of dew-originating

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water to relieve an insufficient water supply under certain conditions. These two studies confirmed that the plants can absorb and use dew [5]. In 1963, American scientist Edward C. Stone firstly explained the ecological significance of dew, and summarized the basic problems of research on dew in the field, such as what is dew, how can it be measured, where does dew form, and what are the physiological responses of plants to dew [5]. After that, research on dew again became a primary topic in different ecosystems of arid and semi-arid areas around the world [6–9]. As a result, methods have been developed to measure dew, factors influencing dew formation, and the ecological effects of dew.

Studies of dew in the Negev Desert, Israel, were initiated very early. Researchers studied dew under various natural conditions such as different slopes that were treated as sunny slope and shady slope and or different terrain conditions such as slope and lowlands in valley settings [10–11]. Studies of dew were primarily launched in arid areas, such as the edge of oases in desert and semi-arid sandy areas in China. One study measured the quantity of dew and environmental factors affecting the formation of dew on oases periphery [12]. The atmospheric source of dew condensed in the shallow soil in desert settings was examined and [8], and the quantity of dew in soil was measured in different land types, *i.e.* stationary sand dunes, shifting sand dunes, farmland and in forest habitat dominated by *Pinus sylvestris* var. *mongolica*, in Inner Mongolia's Horqin Sands [13]. A study in the Mu Us Desert elaborated the process of dew formation in the canopy of *Sabina vulgaris* [14]. The relationship between the soil dew and micro-meteorological conditions were explored through indoor controlled experiments [15]. In addition to formation of dew, the significance of dew on plants eco-physiological traits was also explored. The leaves of *Sequoia sempervirens* can absorb dew to alleviate water stress, and the leaf water content increased 2% to 11% [16]. Dew formed during at night and increased relative water content and total biomass of branches of *Bassia dasyphylla*. It improved the water potential, stomatal conductance, and the photosynthetic rate, which reached the maximum value when these plants suffered from drought stress [17]. In summary, dew as a water source plays an important role in the survival and growth of plants in arid and semi-arid regions [18–20,4].

Hunshandak Sandland is a typical semi-arid area in northern China, with an average annual precipitation between 370 and 400 mm and an average annual evaporation of 1740 mm, which is 4 times more than the amount of precipitation. Although it is such a stressful environment, the sparse elm forest ecosystem is able to survive. Elm (*Ulmus pumila*) has strong adaptability and is the primary timber tree species. A large number of elm trees are naturally distributed in a diversity of habitats in Hunshandak Sandland. They form a unique woodland landscape with grass and shrubs in sandy soils [21]. The ecological processes and the mechanisms of survival for such a diversity of plant species are important to understand in an environment with a limited water supply, ameliorated primarily by dew. In the field, we observed that there was dew on the leaves of plants throughout most of the growing season in the morning, but it was still unclear which micro-climate conditions allow the formation of the dew and condensation. The dew varies greatly with the change of environmental conditions in different ecosystems. Therefore, it was necessary to conduct a comprehensive study of the Hunshandak Sandland habitats. Study of the formation of dew and condensation volume is the first step to deeply understand the contribution of dew in Hunshandak Sandland ecosystem, but also is an important basis for further studies of the influence of dew on plant eco-physiology. This study investigated the meteorological and vegetational factors affecting the formation of dew. It provides identifiable grounds for vegetation protection and ecological restoration in Hunshandak's sandy lands and for exploring the adaptation strategy of plants in semi-arid region in drought environments within the context of global change.

2. Materials and methods

2.1. Study area

The study was conducted in Hunshandak Sandland (116°31.75′E, 42°4.36′N), located in Duolun County, Inner Mongolia. The elevation is approximately 1318 m. The prevailing climate is the temperate continental climate, with the annual average temperatures being 1.6 °C, and with a frost-free period of about 100 days. The area receives an annual precipitation about 385 mm, with uneven distribution throughout the year. Rainfall fluctuates between years, from 150 mm in a drought year to 480 mm in the wettest year. The annual average wind speed is 3.6 m/s. The type of soil is sandy soil, low in phosphorus and nitrogen, and with an organic matter content of about 3%. The landscapes of the study area are sparse elm woods and grassland. The vegetation cover is 70–80%. Grass species in the study area are primarily *Agropyron criststum*, *Leymus chinensis*, *Cleistogenes squarrosa*. Other herbs are *Plantago asiatica* and *Potentilla chinensis*, and woody plants are mainly *Ulmus pumila*. Elm seedlings are present, but only a small number of elm biennial seedlings were found.

2.2. Sampling

2.2.1. Study plots

In sparse elm wood habitat a 20 m × 20 m plot was selected, and in a 10 m × 10 m fenced area, grass plot was established. The two plots were 100–150 m from each other, so the soil and climate conditions in both plots were the same. The canopy density of the sparse elm woods site was about 0.4. Understory vegetation cover was 70%–80%, and in the grassland habitat, cover by vegetation was 70%–80% as well. The experiment was conducted from July 22, 2014 to October 10th.

2.2.2. Dew condensation

The condensation surface and weighing methods were used to measure atmospheric dew in both of the sparse elm woods and grassland plots. The condensation surface method measured dew on plant leaves, and the soil moisture absorption dew was measured by weighing. To quantify dew on the leaves of plants, 10 leaves of herbaceous plants were selected and marked in each of the two plots. To avoid the curvature of the leaves resulting from nocturnal water loss, flat leaves were selected. A piece of dried absorbent paper sealed in a bag was weighed using an electronic balance with precision of 1/10000. The dried absorbent paper of known mass was used to accept dew on leaf surfaces approximately 30 min before sunrise daily, then the absorbent paper was returned to the sealing bag, and weighed. The difference of total mass for both paper and sealing bag before and after dew absorption represents the net amount dew formed on the leave during the night.

The mass of dew can be converted to the amount of condensation in mm by the following formula:

$$H_{\text{dew}} = 10 \times \Delta m/(\rho \times A) \quad (1)$$

H_{dew} is the condensation in unit mm, Δm is the difference of weight of absorbent paper before and after dew absorption (g), ρ is the density of water ($\rho = 1.0$ g/cm^3), A is the area of condensation surface (cm^2).

The weight method is the one most commonly used for determining dew in soil. It not only can elucidate the atmospheric dew formed on the soil surface condensed from atmospheric water vapor but also can be used to measure the soil moisture absorption of dew formed on the soil particle's surface. This component of dew is condensed from water vapor from deep soil. Previous studies have shown that soil dew occurs mainly in the upper soil layer within 5 cm of the surface [8,22]. Dew in the soil layer within 0–5 cm was measured in this experiment and two types of PVC tube were employed. Tubes with sealed bottoms were used to record the total dew in soil. Tubes with a lid at the top and bottom sealed by nylon netting through which water vapor can