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The influence of biological soil crusts on dew deposition in Gurbantunggut Desert, Northwestern China

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SUMMARY

Dew is an important source of moisture for plants, biological soil crusts, invertebrates and small vertebrates in desert environments. In this paper, measurements were taken to investigate the effects of three different types of biological soil crusts (cyanobacteria, lichen and moss) and bare sand on dew deposition in the Gurbantunggut Desert. Dew quantities were measured using micro-lysimeters with a diameter of 6 cm and a height of 3.5 cm. The results showed that the total amount of dew deposited increased with the development of soil crusts, from bare sand to cyanobacterial crust to lichen crust to moss crust. The average amount of dew deposited daily on the moss crust was the highest of all and it was significant higher than the other three soil surfaces (lichen crust, cyanobacterial crust and bare sand) ($p < 0.05$). During the period of the study, for each type of crust studied, the maximum amount of dew recorded was several times greater than the minimum. Moss crust was characterized by having the greatest amount of dew at dawn and also the maximum amount of dew deposited, whereas bare sand yielded the lowest amount of dew, with lichen crust and cyanobacterial crust exhibiting intermediate values. However, this was not the case for dew duration, as bare sand retained moisture for the longest period of time, followed by cyanobacterial crust, moss crust and finally lichen crust. Dew continued to condense even after sunrise. Furthermore, the differences in dew deposition may be partially attributed to an effect of the biological soil crusts on surface area. This study demonstrates the important effect of biological soil crusts upon dew deposition and may assist in evaluating the role of dew in arid and semi-arid environments.

Introduction

Water availability is the most important limiting factor in arid lands where any additional source of water can have a positive impact upon the ecosystem. In arid and semi-arid areas, apart from precipitation in the form of rain or snow, dew and fog play a vital role in providing an essential source of water for plants, invertebrates, small vertebrates and biological soil crusts. This is especially the case in desert environments, where water resources are severely limited and dewfall and early morning evaporation are the most important processes affecting the daily water balance of the upper soil layer (Broza, 1979; Duvdevani, 1964; Jacobs et al., 1999; Moffett, 1985).

Dew and fog are features of many deserts (Kidron, 1999, 2000b; Zangvil, 1996). In Avdat, in the heart of the Negev Desert Highlands, 195 days of dewy and foggy mornings were recorded, providing a mean annual yield of 33 mm of dew and fog precipitation during 17 years of measurements (Evenari, 1981). Although supplying relatively small amounts of moisture, the fact that fog and dew provide a constant and stable water source may be of greater value in arid and semi-arid zones than ephemeral rainfall events. It has been suggested that the seed germination of annual plants in deserts is enhanced if dew occurs regularly (Gutterman and ShemTov, 1997) and droplets of dew that condense on the canopies of vascular plants can provide sufficient moisture to enable them to survive throughout the dry season. The role of dew as a factor in the stabilization of sand dunes has been recognized as an important meteorological factor in arid regions (Subramaniam and Kesava Rao, 1983).

Biological soil crusts which have extraordinary abilities to survive desiccation, extreme temperatures (up to 70 °C), high solar radiation, high pH, and high salinity, have been found in desert areas world wide and may constitute as much as 70% of the living ground cover of some plant communities (West, 1990). The presence of biological soil crusts, however, implies that some moisture must be available on a regular basis. Mosses, lichens, fungi and cyanobacteria, the components of biological soil crusts in arid

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areas, have evolved various mechanisms for desiccation tolerance, suspending metabolism during dry periods, then absorbing water rapidly and recommencing photosynthesis soon after precipitation events. Thus absorption of moisture from dew may be significant in determining the total period of potential net CO_2 uptake by biological soil crusts, providing relatively long phases of photosynthesis during the early morning daylight hours (Lange et al., 1998, 1992) before the moisture evaporates as the temperatures increase.

Dewfall is a process whereby atmospheric water vapour condenses and is deposited in the form of droplets on any cool surface, especially at night. During the night, free liquid water on the earth's surface can originate from three separate sources: the air (dewfall), the soil (dewrise) and plants (guttation) (Garratt and Segal, 1988). Deserts are characterized by low soil moisture and very low percentage of perennial vegetation cover, consequently moisture on the soil surface is primary due to dewfall (Jacobs et al., 2000). Numerous observations and simulations of dew deposition have been carried out in deserts, arid and semi-arid areas, humid tropical islands, rural areas, urban areas and forests (Clus et al., 2008; Jacobs et al., 1999, 2000, 2002; Kidron, 2000a; Liu et al., 2006; Malek et al., 1999; Moro et al., 2007; Richards, 2004; Zangvil, 1996). The amount of dew deposited varies with altitude, angle and aspect (Kidron, 1999, 2005). Some studies have found out that there were significant differences in daily dew amount among different kinds of soil surfaces (bare soil, gravel and sand mulches, and sandy soils with biological soil crusts) (Li, 2002; Liu et al., 2006; Ninari and Berliner, 2002).

Various dew-measuring devices are described in the literature, some measure the amount of dew deposited, some measure the duration of dew, and yet others are used to measure both the duration and the amount of dew (Agam and Berliner, 2006). There is no standard method or instrument that has been internationally accepted for measuring dew (Zangvil, 1996). Estimates of the actual amount of dewfall can be made by direct methods, for example, by using micro-lysimeters or the eddy correlation technique (Jacobs et al., 2000, 2002).

To quantify overnight dew deposition and evaporation during the early morning, measurements were made within an interdune area of the Gurbantunggut Desert, where different types of biological soil crusts are commonly found. This data will increase our understanding of the water balance in arid areas and provide valuable scientific information that can be utilized in policy-making for the management of desert ecosystem.

Study areas

The Gurbantunggut desert (44°11′–46°20′N, 84°31′–90°00′E) is situated in the center of the Jungger Basin, Xinjiang Uygur Autonomous Region of China. It is the second largest desert in China with an area of 4.88×10^4 km^2. The Himalayan Range to the south produces a "blocking effect" so that, moist air currents from the Indian Ocean fail to reach the area, resulting in a vast expanse of arid terrain. Mean annual precipitation is approximately 79.5 mm, falling predominantly in spring. In sharp contrast, the mean annual pan evaporation is 2606.6 mm. The average temperature is 7.26 °C. Wind speeds are greatest during late spring, with average 11.17 m s^{-1}, and are predominantly from the WNW, NW and N directions. The natural vegetation is dominated by *Haloxylon ammodendron* and *H. persicum* (Amaranthaceae subfamily Chenopodioideae), with vegetation cover of less than 30%. The area is covered by massive, dense semi-fixed sand dunes with stable moisture content. Biological soil crusts are abundant in the desert. Most growth occurs during cool, wet periods (fall and early spring) when moisture from dew, fog or ephemeral rainfall events can be utilized by the component species of the soil crusts (Kidron et al., 2002; Zhang et al., 2007). This study was conducted in the southern part of the Gurbantunggut Desert on biological soil crusts typical of those found throughout the desert (Zhang, 2005; Zhang et al., 2007).

In extremely dry conditions, much of the sand surface of this desert is covered by biological soil crusts, which grow as hard, rigid crusts (Fig. 1) dominated by the cyanobacterium *Microcoleus vaginatus*, with occasional lichen and moss patches in interdune areas. The dominant species of each type of biological soil crusts are shown in Table 1.

Materials and methods

In this study, the dewfall and early morning evaporation were measured using micro-lysimeters with a surface diameter of 6 cm and a height of 3.5 cm (Boast and Robertson, 1982). This method allows a soil core to be taken while leaving the surface intact, thus observations can be repeated using the same sample.

The observation areas were located in interdune areas of the Gurbantunggut Desert. The micro-lysimeters were pushed into the ground to collect undisturbed soil columns covered by representative biological soil crusts (cyanobacterial crust, lichen crust and moss crust respectively) and bare sand for control. The edges of the micro-lysimeters were close to the flat surface of the ground and their bases were covered. Each treatment was replicated five times. Crusts were not collected near shrub canopies in order to avoid any possible impacts shrubs might have on microclimate. During the experiment, there were 12 plots (1 m $\times$ 1 m) for each type of soil crust and five samples were taken from each plot every time.

The soil samples were weighted using a balance to a precision of ±0.01 g. The dew amount for each day was determined by calculating the difference between the weight in the morning and that at sunset of the previous day. In order to obtain a better insight into the time-course of dew deposition and dew duration, intensive measurements were carried out for several days on different samples. The weighing intervals are 2-h and 30-min for the time-course of dew deposition and dew duration respectively. The quantity of dew deposition (in millimeters) was calculated from these weights.

The soil temperature was measured by temperature sensor which was buried 5 cm below the soil surface covered with or without biological soil crusts. The soil temperature was recorded at 1 h intervals using a datalogger. For the whole observation period, the surface temperature and humidity were measured synchronously using a hygrothermograph (HC-520).

SPSS 11.5 statistical package was used to process the data. The effects of the biological soil crusts on dew condensation were compared using one-way ANOVA followed by post hoc LSD's honestly significant difference test.

Results

Dew amounts on different types of biological soil crusts

The variation in the dew amounts deposited on the different types of biological soil crusts and bare sand surface are shown in Fig. 2. Sixty-five records for dew amounts were obtained during the experimental period (7–23 May, September and October in 2008) (Fig. 2), when dew was recorded on almost every day other than on rain days. A general trend indicated the total amount of dew deposited increased with the developmental level of biological soil crusts, following the order: sand < cyanobacterial crust < lichen crust < moss crust (Fig. 2).

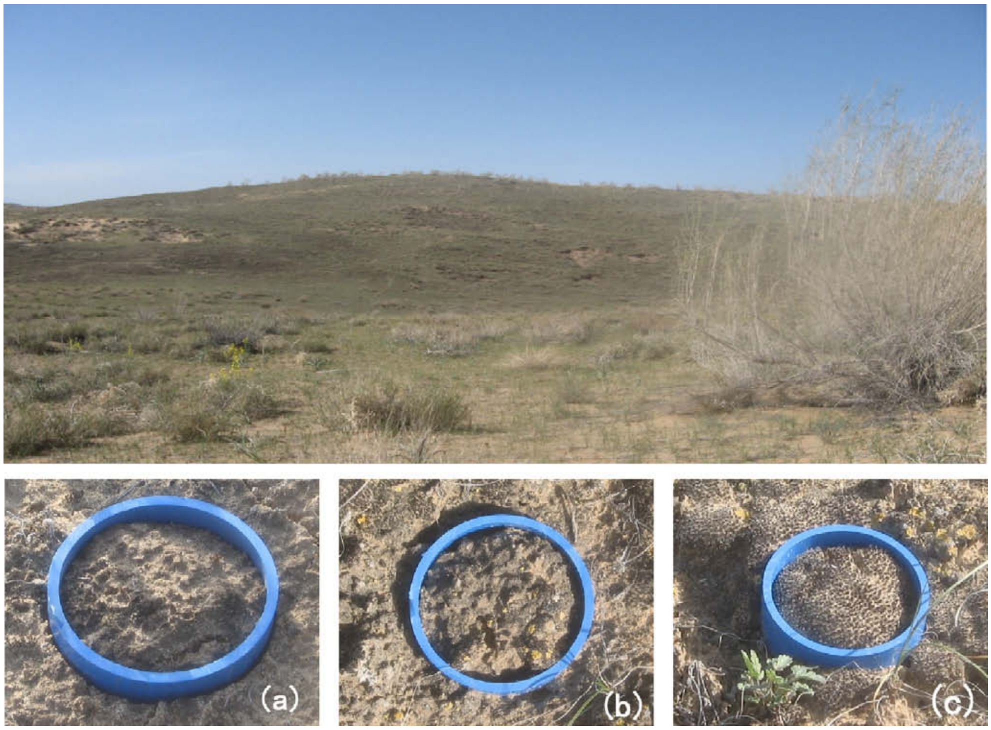

Fig. 1. Appearance of Gurbantunggut Desert and different types of biological soil crusts: (a) cyanobacterial crust, (b) lichen crust, (c) moss crust.

Table 1
The characteristics and distribution patterns of biological soil crusts developed in Gurbantunggut Desert.

	Crust type		
	Cyanobacterial crust	Lichen crust	Moss crust
Feature	Gray, primarily flat, lacking microtopography	Usually appears black, white, brown, yellow due to different species	It appears black in desiccated state, green in hydrated, living in the form of mat or cushion, the surface is somewhat rough and undulating
Average thickness (cm)	0.28	1.29	2.2
Compression strengths (kPa)	32.29 ± 9.96	52.27 ± 8.34	57.28 ± 5.12
Distribution	Mainly distributed on the upper windward and leeward slopes of sand dunes, from the lower slope of sand dunes to the interduneareas, the cyanobacteria-dominated crust was replaced by lichen and moss crusts gradually	Generally, lichen-dominated biological soil crusts develop flakily and cover a large area, going from the slope of sand dunes to the interdune areas	Most mosses can be found only under the canopy of vascular plants, such as *Haloxylon persicum* and *Ephedra distachya*
Most common species composition	*Microcoleus vaginatus*, *Microcoleus paludosus*, *Anabaena azotica*, *Lyngbya martensiana*, *Xenococcus lyngbyge*	*Collema tenax*, *Psora decipiens*, *Xanthoria elegans*, *Acarospora strigata and Lecanora argopholis*	*Tortula desertorum*, *Bryum argenteum*, *Crassidium chloronotos*, *Tortula muralis*, *Bryum capillare*

The maximum dew amount was recorded on moss crust, while the minimum dew amount was recorded on cyanobacterial crust and bare sand. The minimum dew amount occurred on May 13, 2008 when the value for the moss crust was 0.01 mm, while the dew amounts for the lichen crust, cyanobacterial crust and sand were negligible, less than the minimum limits of measurement (equal to zero). For any given crust type, the maximum value for dew amounts was several times greater than the minimum.

Daily soil surface temperature and relative humidity measured synchronously with dew amounts at 8:00 in the morning are presented in Fig. 3. Average daily soil surface temperature was 17.8 °C, 11.0 °C and 4.9 °C for May, September and October respectively. Average daily relative humidity was 37.6%, 39.9% and 72.7% for the above three months respectively. Among the three months, October had the lowest average daily soil surface temperature and the highest average daily relative humidity, which was beneficial for the dew deposition.

Data analyses shown in Fig. 4 entailed a comparison of dew amounts for each type of soil surface cover, whether sand, cyanobacteria, lichen or moss. The average daily amounts varied among the different soil surfaces. In addition, the moss crust had higher dew deposition than the lichen and cyanobacterial crusts ($p < 0.05$) (Fig. 4).

Dew accumulation and evaporation pattern

The pattern of dew accumulation and evaporation was studied over eight mornings. Every morning condensation continued after dawn. This was clearly seen when the dew condensation and evaporation pattern was studied on May 8, 2008. Dew accumulation and evaporation graphs for moss, lichen and cyanobacterial crust as well as bare sand, are shown in Fig. 5. Dew patterns for the following days for each surface category were very similar, thus this graph is a good representation of the data recorded for each of the soil surface described.

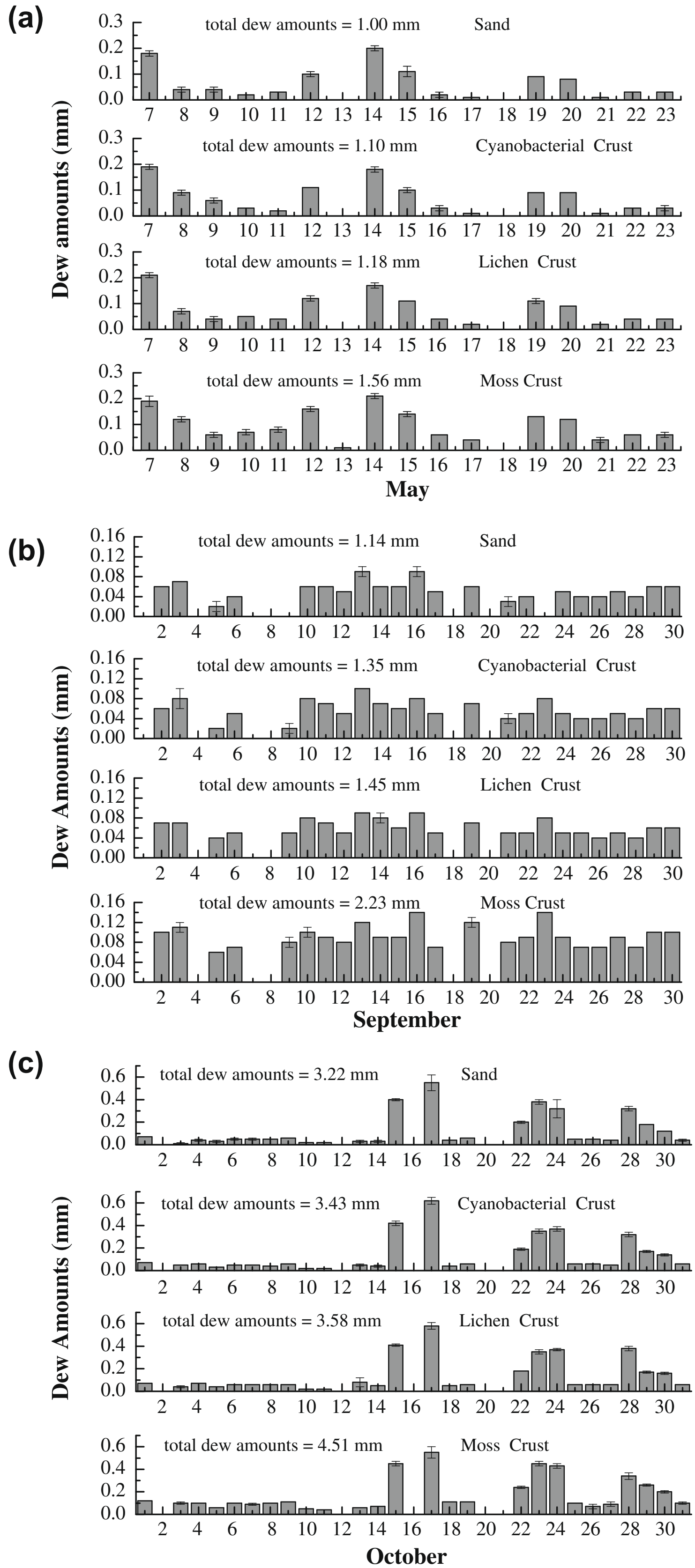

Fig. 2. Daily dew amounts on biological soil crusts and sand surface at the experimental site during May (a), September (b), October (c), 2008. Bars represent one standard error ($n = 5$).

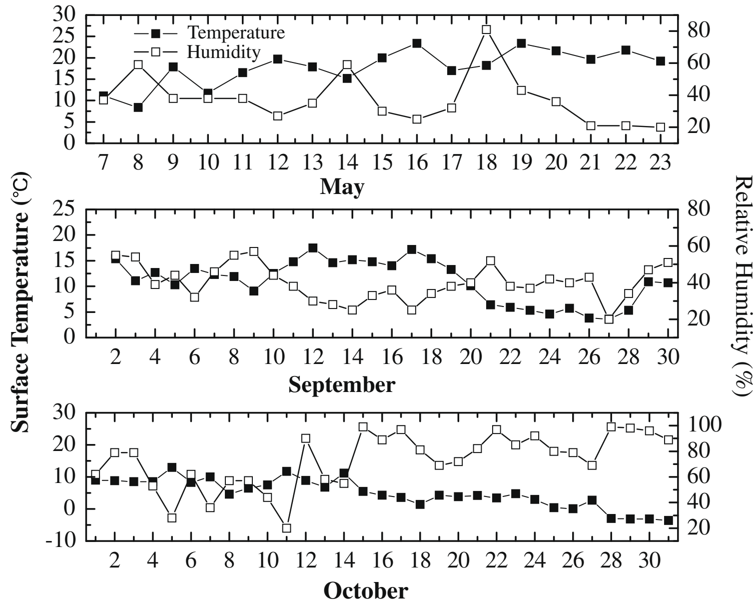

Fig. 3. Daily soil surface temperature and relative humidity measured synchronously at 8:00 in the morning during the experiment.

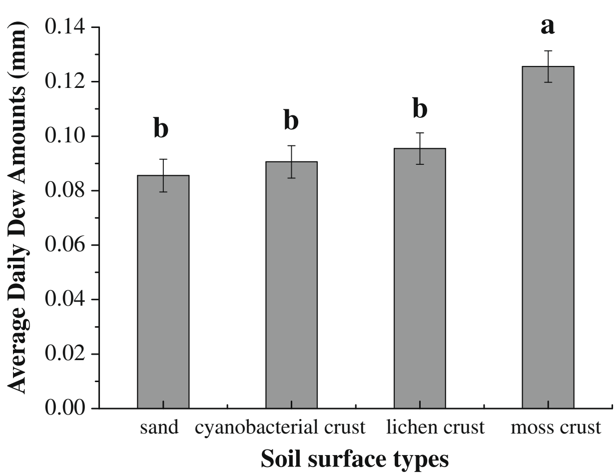

Fig. 4. Average daily dew amounts on different soil surfaces. Similar letters indicate non-significant differences among soil surface types at the 5% level. Bars represent one standard error (n = 315, 325, 325 and 330 for sand, cyanobacterial crust, lichen crust and moss crust, respectively).

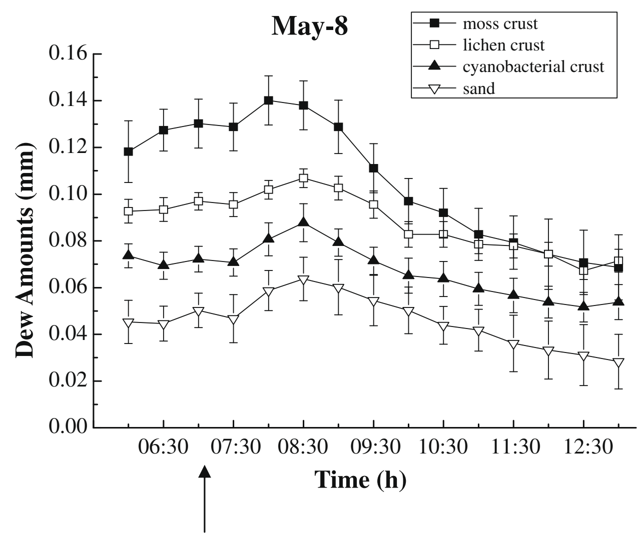

Fig. 5. Patterns of dew accumulation and evaporation on different kinds of soil surfaces during a typical morning. Bars represent one standard error (n = 5). Arrow indicates the sunrise.

To obtain a better insight into the time-course of dew deposition, two periods, 21–22 May and 25–26 October 2008, which are representative of many of the nights during the measurement period, are presented for detailed analysis here. The days selected were mainly clear with very few clouds and low wind speed.

A clear trend was noted. The moss crust accumulated the greatest amount of dew, and then there was a substantial decrease in dew amounts for lichen and cyanobacterial crusts for which dew accumulation figures were similar, and finally a moderate decrease to the amount of dew accumulated by bare sand (Fig. 6).

Dew duration

Dew deposition at dawn, maximum dew amounts, the average time from dawn to maximum accumulation of dew and the total daylight duration time of dew on different soil surfaces on May 8, 2008 were shown in Fig. 7. As can be seen from Fig. 7, moss crust yielded the highest dew amounts at dawn and maximal dew amounts, while sand surface yielded the lowest, lichen and cyanobacterial crusts exhibited intermediate values. In terms of dew duration, the situation was different as moisture from dew was retained by the sand surface for the longest period of time with the highest mean value of (4.30 ± 0.26) hours followed by the cyanobacterial crust (3.70 ± 0.12) hours, moss crust (3.40 ± 0.19) hours and finally lichen crust (3.30 ± 0.20) hours. For a given soil surface type, the differences between dew amounts at dawn and maximum dew amounts were different or significantly different (Fig. 7a, Paired-Samples T-test). Similarly, significant differences were observed between time from dawn to maximum and the total daylight dew duration (Fig. 7b).

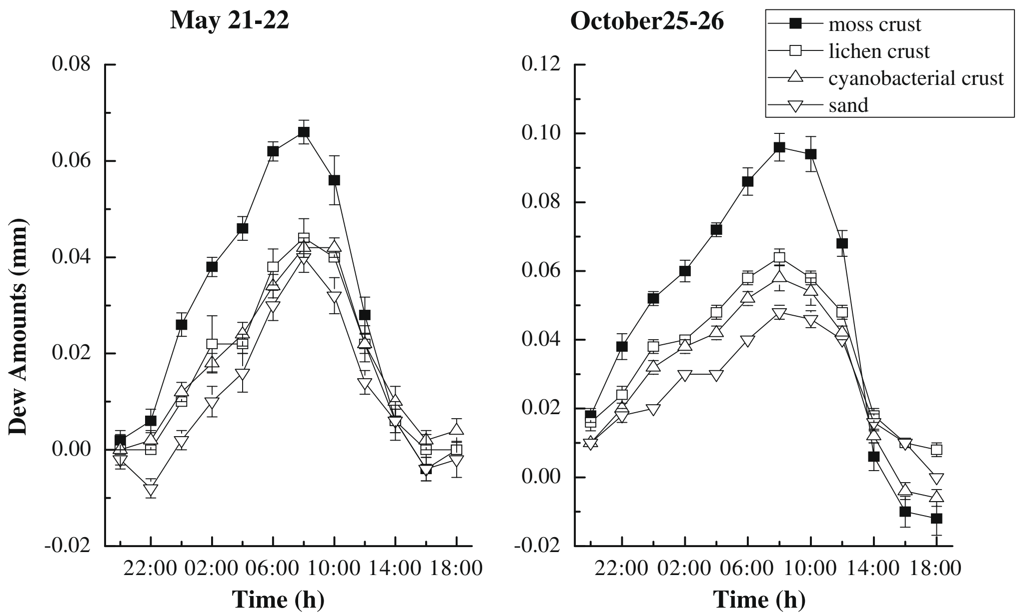

Fig. 6. Measured cumulative dew deposition and evaporation on different soil surfaces. The measurements were taken at two hourly intervals from late evening, May 21 and October 25, 2008 to late afternoon, May 22 and October 26, 2008 separately. Bars represent one standard error ($n = 5$).

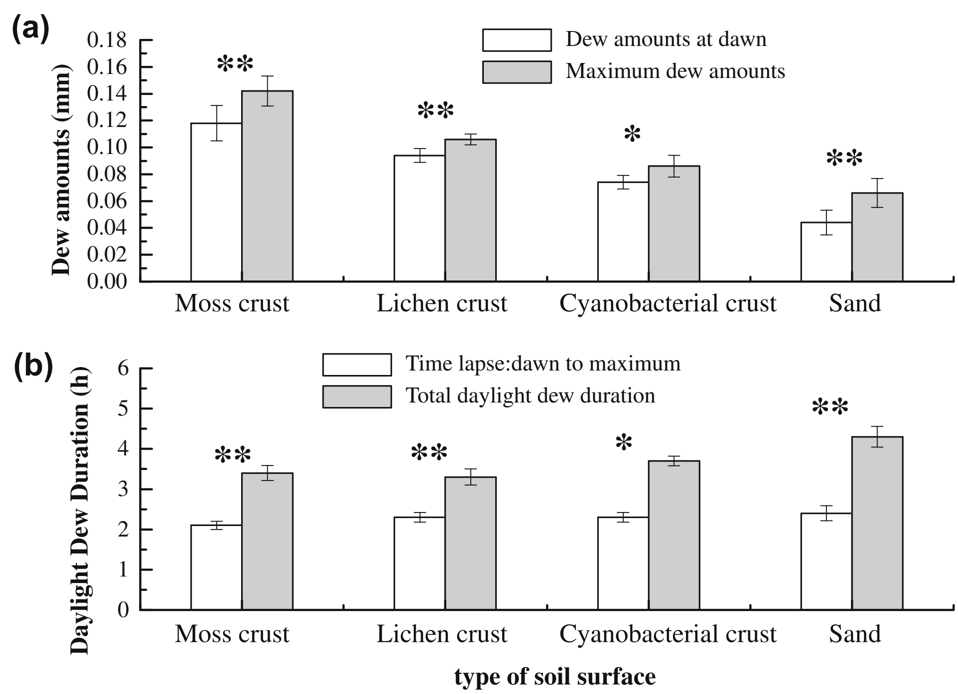

Fig. 7. (a) Average values of dew amounts at dawn and maximum dew amounts; (b) Time from dawn to maximum dew deposition and total daylight duration of dew, recorded on different soil surfaces on May 8, 2008. Bars represent one standard error ($n = 5$). ** indicating greatly significant difference ($p < 0.01$); * indicating significant difference ($p < 0.05$).

Comparison of soil temperature

In a comparison of an area covered by biological soil crusts (dominated by mosses and lichens) and an area devoid of biological soil crust (sand surface), the surface temperatures on the biological soil crusts were higher by day and lower at night than that of the sandy surface (Fig. 8).

Discussions

The effect of soil surface temperature on dew deposition

Soil surface temperature is believed to be one of the key factors affecting the dew amounts (Kidron, 1999, 2000b). At night, dew can be absorbed by soil, sand or biological soil crusts. After sunrise, this

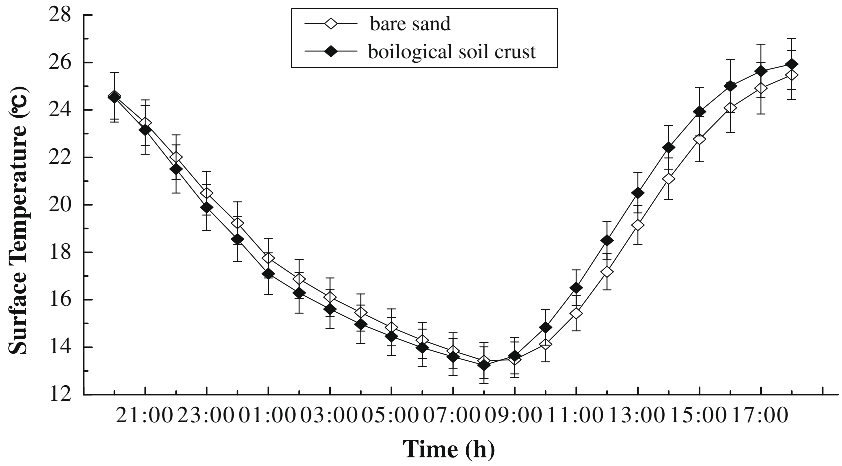

Fig. 8. Comparison of surface temperatures between an area covered by biological soil crusts and an area devoid of crusts. Bars represent one standard error ($n = 24$).

water evaporates rapidly, especially on slopes which face the sun. In this study, the moss crust warmed more rapidly during the day than bare sand but cooled more rapidly at night. This is consistent with the findings of Liu et al. (2006). The cooler overnight temperatures of the moss crust enhanced dew formation, resulting in deposition of higher dew amounts on moss crust than on bare sand.

During the day, the situation was reversed, with the temperature of the moss crust rising faster than that of the sand surface, increasing the rate of evaporation with a corresponding rapid decrease in dew amounts after 10:00 am (Figs. 5 and 6).

Taking into consideration the dew amounts at dawn, maximum dew amounts, time elapsed between dawn and maximum dew amounts, there was a general increase in dew amounts which corresponded with an increase in the developmental level of soil crusts from sand < cyanobacterial crust < lichen crust < moss crust. However, this was not the case for dew duration time, where dew was retained by bare sand surface longer than it was retained by any of the biological soil crusts. The results indicated a negative link between dew amounts and duration time, contrary to other observations (Kidron, 2000a,b). In this study, it can be explained by the fact that the surface temperature of moss crust was higher than that of sand surface, resulting in a much higher evaporation rate from the moss crust than from the sand surface.

Some moisture that has originated from dew can be retained by the soil surface layer for at least 12 h, i.e. from near sunset until well after sunrise, when all moisture has completely evaporated. During the short days of winter, this retention period can be considerably longer. During the late summer and fall of 1992 in the Negev Desert, Kidron et al. (2002) found that dew and fog precipitation occurred on over 50% of the mornings (Kidron et al., 2002). The high frequency and reliability with which dew occurs in the Negev is an important factor in the growth and development of biological soil crusts in an extremely harsh environment (Zangvil, 1996). Although the total amount of moisture contributed by dew and fog is extremely low, it is nevertheless adequate for photosynthesis (Jacobs et al., 1999).

The effects of physical characteristics on dew deposition

The differences in dew amounts and dew duration can probably be related to the physical characteristics of the three biological soil crusts and the sand surface.

Moss crust

Mosses absorb water and nutrients directly through stems and leaves, from rain, cloud, fog and dew. The rapid absorption of moisture allows for quick return of cells to full turgor and metabolic activity (Proctor, 2000). Tuba et al. (1996) demonstrated that normal rates of net photosynthesis in *Tortula ruralis* began within 30 min of remoistening (Tuba et al., 1996). On mornings with heavier dewfall, which is likely during late summer and early autumn, the water content of *Tortula ruralis* could regularly reach the level needed for maximal photosynthetic activity (Csintalan et al., 2000).

Tortula desertorum and Tortula muralis, as desiccation tolerant mosses, can alter the position of their leaves, from widely outspread when fully turgid, to tightly wound round the stem when dry, leaving the glossy abaxial surfaces of midribs exposed and providing protection from both solar radiation and desiccation (Scott, 1982). Also, in dry conditions, mosses are tolerant of very high temperatures but for metabolically active plants, the combination of hot and wet conditions can be lethal (Proctor, 2000). In these experiments the temperature of the moss crust increased more rapidly during the morning than did that of the bare soil surface. As the temperature increased, there was a corresponding loss of moisture which would have the effect of slowing photosynthesis and metabolism until the plants returned to a state of metabolic inactivity before temperatures reached lethal levels. Thus moisture input from dew allows for a short productive period of photosynthesis in the early morning, followed by rapid evaporation as the temperatures increase to ensure a return to metabolic inactivity ensuring protection from destructive high temperatures.

Lichen crust

In desert environments such as the Gurbantunggut, crustose and squamulose lichens dominate the environment, growing closely appressed to the ground with very little in the way of raised surfaces. Lichens absorb water across the whole surface of the thallus, utilizing moisture from rain, cloud, fog and dew. Lange et al. (1992) showed that cyanobacterial crust, taken from the Hallamish dune field of the western Negev Desert, began to photosynthesize soon after hydration (Lange et al., 1992).The gelatinous lichens, such as *Collema*, survive in the driest desert soils, by having the ability to absorb vast quantities of water, up to 36 times their dry weight, but as they have no cortical development, and no waxy cuticle, also lose water rapidly although the rate of water loss is usually slower than the rate of water uptake (Rogers, 1977). The ability of desert lichens to harvest dew water for maximum early morning photosynthetic activity, then to lose water rapidly to return to a state of metabolic inactivity as daytime temperatures increase, guarantees protection from lethal high temperatures and solar radiation.

Cyanobacterial crust

Cyanobacterial crust in the Gurbantunggut is dominated by the cyanobacterium *Microcoleus vaginatus* that lives in the upper soil surface layers. The filaments of *Microcoleus vaginatus* are bundled together into mucilaginous sheaths. When moistened, moisture first condenses on the crust surface, and then is absorbed into the soil and finally into the network of cyanobacterial sheaths and filaments, in a phototactic reaction, the filaments move out of the sheaths, towards the soil surface (Belnap et al., 2001). As temperature increases, the filaments dry out and withdraw underground. Moisture captured from dew and retained by the cyanobacterium in mucilaginous sheaths is protected from further desiccation, possibly explaining longer dew duration time.

Sand

Sandy soils can be characterized by having large pore spaces, poor water holding capacity, and rapid downward movement of moisture. When compared to moss and lichen crust, sandy soils appear to be limited in terms of the total surface area on which moisture can condense. Kidron (2000a) in a study of dew precipitation in the Negev Highlands of Israel commented that although dew was visible on plants and artificial surfaces, there was no evidence of moisture on bare soil surface. The observed capacity of sandy soils to retain moisture for longer than moss, lichen or cyanobacterial crust can be probably explained by that coarse sand allows deep penetration of moisture and impedes capillary movement to the surface, thus conserving moisture by reducing evaporation (Eriksson et al., 1989; Noy-Meir, 1973).

Thus we suggest that moss crust and lichen crust that predominantly live above the soil surface have the most complex morphology and soil roughness, which can offer increase in the amount of soil surface area available for condensation of dew from water vapour in the atmosphere. These same characteristics also permit rapid water loss as heat increases during the day, ensuring return to metabolic inactivity before temperatures reach lethal levels. In contrast, cyanobacterial crust which live predominantly below the soil surface and have the least surface area exposed to water vapour in the atmosphere, together with bare sandy soil, are the least successful in accumulating dew but moisture is retained for longer periods of time. Evaporation is reduced (dew duration) because there are few surfaces exposed to the atmosphere and the underground environment remains cooler allowing for potentially longer periods of metabolic activity.

Conclusions

Based on the data analyses, the present study showed that the total amount of dew deposited increased with the developmental level of biological soil crusts. Further analysis indicated that the moss crust warmed more rapidly during the day than bare sand but cooled more rapidly at night. The cooler overnight temperatures of the moss crust enhanced dew formation, resulting in deposition of higher dew amounts on moss crust than on bare sand. Contrary to other observations (Kidron, 2000a,b), a negative link between dew amounts and duration time was observed in our study. The differences in dew amounts and dew duration could probably be related to the physical and physiological characteristics of the three biological soil crusts and the bare sand.

Further investigation of the significance of dew and fog in desert environments will have important implications for the disciplines of ecology, agriculture, air pollution and sustainable development. Understanding how the degree of development of biological soil crusts affects deposition of dew and the length of time dew is retained by soil crusts may contribute to our understanding of the importance of biological soil crusts in semi-arid, arid and desert environments.

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