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Effects of biological soil crusts on water infiltration and evaporation, Yanchi Ningxia, Maowusu Desert, China

Abstract: Biological soil crusts serve as a vanguard for improving the ecological environment in arid, semi-arid desertification areas. It is a good indicator of the level of improvement which the local ecological environment is undertaking. In desert areas, water condition is a key factor of improving the ecological environment. As a first layer protection, biological crusts play an important role in local vegetation succession due to their abilities to conserve and maintain moisture. Using Maowusu desert in Yanchi of Ningxia province as an example, after three years of research, this paper chooses three kinds of biological crusts including lichen, moss and cyanobacterial which are under the cover of Artemisia ordosica as research objects. The results of this study indicate that, the closer biological crusts are to Artemisia ordosica vegetation, the thicker they become. In the same position of Artemisia ordosica vegetation, the thickness of moss crusts is the highest, followed by lichen crusts, and the thickness of cyanobacterial crusts is the lowest. Biological soil crusts coverage protects the natural water content of soil layers from 0 to 5cm. Also, it effects falling water to infiltrate deeper, and cannot prevent the surface water content from evaporating effectively. The effect of biological crusts blocking water infiltration decreases with the increase of rainfall. At the same rainfall level, moss crusts provide the strongest water infiltration blockage, followed by lichen crusts and cyanobacterial crusts. With the increase of rainfall, the depth of water infiltration increases. At the same rainfall level, the relationship of water infiltration depth is as follows: cyanobacterial crusts> lichen crusts> moss crusts. With the increase of biological crusts thickness, they blocking water infiltration capacity is stronger, and the depth of water infiltration is smaller. Analysis on the characteristic of simulated rainfall process on biological crusts shows that sandy land can be fixed by applying appropriate artificial biological crusts to build a sustainable forest protection system and to create a stable ecosystem in desertification area.

Key words: Lichen crusts; Moss crusts; Cyanobacterial crusts; The thickness of biological crusts; Simulated artificial rainfall; Desertification area.

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1.Introduction

Biological soil crusts are widespread ranging from desert to polar region in many ecosystems (Thomas et al., 2010). Desert has the characteristics of low productivity and substantial unvegetated space (Cable & Huxman, 2004). Biological soil crusts are composed of cyanobacteria, green cyanobacterial, mosses, fungi and lichens covering the first millimeters of the topsoil (Belnap & Lange, 2001), and are the first colonizers of new ecosystems and after large scale disturbances (Vest, 2005). Biological crusts play an important role on the formation of biochemistry and landform in arid area (Eldridge & Greene, 1994; Evans & Johansen, 1999). These biological soil crusts reduce soil erosion (Belnap, 2003; Warren, 2003), promote the formation of organic carbon (Beymer & Klopatek, 1991), have nitrogen fixation (Cameron & Fuller, 1960), promote or retard the survival and growth of vascular plant seedling (Malam et al., 1999; Prasse, 1999). Filaments of cyanobacteria which exude sticky substance and the rhizoids and protonemata of mosses stick the bioses and soil particles together. This stabilizes the topsoil, reduces soil erosion, and enhances the organic matter in the first millimeter of the topsoil (Vest et al., 2001). When considering the impact of biological crusts on hydrologic processes, the function of green cyanobacterial and microfungi is similar to cyanobacteria, and the function of other bryophytes is similar to lichens, such as liverworts (Belnap, 2006). Consequently, this article only took cyanobacterial crusts, lichen crusts and moss crusts into consideration. In addition, simulated rainfall has been often applied to evaluate the infiltration properties of agricultural soil (Casenave & Valentin, 1992; Le´onard &Andrieux, 1998).

In the desert ecosystem, biological soil crusts play a key role in hydrological processes (Thomas et al., 2010; Belnap, 2006; Yair, 2008). However, effects of biological soil crusts on water infiltration and evaporation are far from conclusive. First of all, some of the studies on water evaporation argue that the presence of biological soil crusts favours water evaporation (Johansen, 1993; Eldridge et al., 1997b). The deep color of biological soil crusts lead to higher absorption of solar radiation. In addition, the sponge-like crusts can maintain water on the surface soil for a long time, so that the water cannot be used to vascular plants, which increases the probability of water evaporated (West, 1990). Also, some scholars believe that biological soil crusts seal the soil surface hence reduce water evaporation (Liu et al., 2005). While some studies remain neutral on this issue and argue that in lower rainfall (5mm) conditions, biological soil crusts promote water evaporation, however, in

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larger rainfall (10mm and 15mm) conditions, they cannot effectively block water evaporation, according to different trends shown by different types of biological crusts (Yan, 2008). Secondly, some studies on water infiltration indicate that the presence of crusts increases infiltration (Eldridge, 1993b; Perez, 1997; Seghieri et al., 1997; Belnap et al., 2005). Some scholars believe that the presence of crusts reduces infiltration(Dekker & Jungerius, 1990; Greene et al., 1990; Abaturov, 1993; Bisdom et al., 1993; Danin, 1996; Mazor et al., 1996; Kidron & Yair, 1997; Eldridge et al., 2000; Eldridge & Leys, 2003). However, other studies show no effect on this process (Belnap & Gardener, 1993; Dobrowolski & Williams, 1994; Eldridge et al., 1997a; Williams et al., 1999). In China, positive (Li et al., 2002), negative (Chen et al., 2002; Li et al., 2002; Xiao et al., 2007; Li et al.,2011)and neutral (Wei, 2005; Xu et al., 2003) functions of biological soil crusts were also reported.

Using Maowusu desert in Yanchi of Ningxia province as an example, after three years of research, this paper chooses three kinds of biological crusts including lichen, moss and cyanobacterial which are under the cover of Artemisia ordosica as research objects. Combined with shelter forest construction in desertification area, studying the biological crusts makes suggestions for the development of local agriculture, the study results are applied to ecological construction and pasture management.

2.Materials and methods

2.1 Site location and characteristics

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The study area is located at the Yanchi sandy land within the Ningxia province (37°04′ - 38°10′N, 106°30′ - 107°41′E) covering an area of 7130 km² (Figure 1). The north region of Yanchi County is connected with the Maowusu sandland. The landform is complex with undulating terrain. Its land type consists of mainly beach, flat ground, gentle slope, hilly and dune (He et al., 2009). The climate of Yanchi county is in a transition zone from semi-arid to arid areas, which is a typical temperate continental climate. The average annual rainfall is 280mm and the annual evaporation is 2100mm (Cui et al., 2009). The perennial dominant wind direction is northwest. Vegetation flora in Yanchi County is in a transition zone between Eurasian steppe, Central Asia sub-region and central China loess plateau. Vegetation in the county is short, scarce with no natural forest. Perennial wild herbs are widely distributed, along with semi-shrub and shrubs. The vegetation can be categorized into five types: grasslands, thickets, meadows, sand vegetation and desert vegetation. Shrubs, grasslands and sand vegetation are greater in number and also more widespread. Sandy vegetation mainly consists of bitter beans formations, bovine heart Puzih formations, Artemisia formations and sphaerocephala formations, along with white thorn formations, Splendens formations and Kalidium formations. Growth of biological crusts in the region is closely related to the rainfall, most of them are initial sand crust and biological crusts with fungi. The soil type mainly consists of sierozem, aeolian sandy soil, black loam and saline soil, of which sierozemand aeoilian sandy soil accounted for 75% of the total amount.

2.2 Research technique

2.2.1 Water evaporation

On the Maowusu sand land surface, there are mainly three types of biological crusts: cyanobacterial, lichens and mosses. Samples were collected as close to their natural state as possible, and were carefully placed in sealed plastic bags. Samples were taken back to Beijing Forestry University, state key laboratory of soil and water conservation to perform simulations to find out the effects of biological crusts on water evaporation.

The simulation was designed in the following way. Containers which are 4.3cm in diameter and 6cm in height were filled with 80 g of fluidized sand. Then the biological crusts were put into the containers in their natural state in such a manner that the crusts are just enough to cover the surface of the sand. Three replications were made for each type of crust with a container with no biological crust covers as the control. Finally, depending on the area (14.51 cm^2) of the plastic container mouth, three kinds of precipitation (5 mm, l0 mm and 15 mm) were designed, and slowly added to the plastic containers in a single time. Evaporation was simulated under laboratory conditions. Every day at 9pm, the evaporation loss for each sample was determined with 1/ 1000 electronic balance. Measurements were carried out until the evaporation loss stops reducing, the duration is 6d.

At the same time, a mixed sample of soils under the cover of three different types of biological crusts was collected in the study area, with soil samples from the plots. With no biological crusts covered as control, the natural moisture content was determined. The depths of sampling were 0-5 cm, 5-20 cm, 20-30 cm and 30-40 cm soil layers. The samples collected were put into aluminum cases and taken back to the laboratory to be weighed on analytical balance. Then they were put into a constant temperature oven, dried for 24 hours at 105℃. Then they were weighed again to calculate the natural moisture content of the soil.

2.2.2 Water infiltration

Experimental studies in Shaquanwan experimental base utilized random sampling method. A relatively flat area was selected, ignoring the effects of slopes. Typical sample Artemisia plots with moss, lichen and cyanobacterial biological crusts were selected (15 groups each), drawing 45 plots with a size of 4 m×4 m. The

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location and altitude of the plots were recorded.

Inside the plots, 45 strains of Artemisia ordosica were selected. Samples of lichen, moss and cyanobacterial crusts were taken out the cover of Artemisia ordosica, under the cover of Artemisia ordosica and near the root of Artemisia ordosica, respectively (15 groups each) (Figure 2). Employing vernier caliper measurement, the thickness of the 45 groups of biological crusts was measured. Coverages of biological crusts inside the plots were then estimated. If there was no crusts cover, the crust thickness was considered as 0 cm.

In their natural state, lichen, moss and cyanobacterial crusts which are covered by oil Artemisia were sampled 15 groups each. The relative sand below the crusts was also sampled into zip-lock bags. On top of the biological crusts, artificial rain were simulated using rainfall of 5 mm, 10 mm and 15 mm. Water used in the simulation were domestic life water. The area of rainfall was set to 40 cm×40 cm.The rainfall was set uniformly, and the intensity of rainfall was consistent. This procedure does not consider the effect of water evaporation on the experiment. The wet crusts and wet sand were taken utilizing aluminum case method into zip-lock bags. Together with the dry crusts and dry sand taken previously, samples were taken back to the lab to measure the moisture content. Depths of water infiltration of the three different types of biological crusts were measured.

Finally, an investment on vegetation was carried out in the plots, measuring vegetation types, height and crown, estimating the coverage vegetation within the plot.

2.3 Data analysis

Experimental data was analyzed using SPSS 20.0 (SPSS Inc., 1989-2011). Using one-way ANOVA to analyze the correlativity between lichen, moss and cyanobacterial crust thicknesses in the same location of Artemisia ordosica, the correlativity between the same biological crust in different locations of Artemisia ordosica, the correlativity between the moisture content of lichen, moss and cyanobacterial crusts, the correlativity between the moisture content of the lower soils under lichen, moss and cyanobacterial crusts, and the correlativity between the depths of water infiltration under lichen, moss and cyanobacterial crusts, respectively. Using Pearson correlation analysis to analyze the correlativity between the moisture content of biological crusts and the lower soils, and the correlativity between water infiltration capacity, biological crust thickness and the depth of water infiltration was also analyzed using Pearson correlation analysis. The figures were drawn using Origin 9.0 (OriginLab Inc., Northampton, MA, USA) and Surfer 8.0 (Golden Sofware, Inc., 2002).

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3.Results

3.1The thickness of biological crusts

In China, from the northern arid steppe to desert area, when the roughness of the flow sandy surface soil increased, mobile sandy land will naturally evolve to fixed sandy land after a period of time for the evolution (Chen & Duan, 2008). In this process, the thickness of biological crusts is one of the main characters which also marks a change in desert habitats (Li et al., 2011).

Figure 3 shows the thicknesses of biological crusts in different locations. The average thicknesses of lichen crusts outside, inside and at the root of Artemisia vegetation coverage are 0.67 cm, 0.81 cm and 1.07 cm respectively. The average thicknesses of moss crusts outside, inside and at the root of Artemisia vegetation coverage are 0.84 cm, 1.07 cm and 1.19 cm respectively. The average thicknesses of cyanobacterial crusts outside, inside and at the root of Artemisia vegetation coverage are 0.45 cm, 0.59 cm and 0.84 cm respectively. The thickness of the same biological crusts is locational ordered as the base of Artemisia vegetation> under the cover of Artemisia vegetation> outside the cover of Artemisia vegetation. At the same location related to the Artemisia vegetation, the average thicknesses of the three crusts are ordered by moss> lichen> algae. The three-dimensional drawing of biological crust thickness can be more intuitive indicated variation trend of biological crust thickness in the different locations of Artemisia ordosica (Figure 4). Using one-way ANOVA to analyze the relationship between biological crust thickness in the different locations of Artemisia ordosica, lichen, moss, cyanobacterial crust thickness are significantly different (at the 0.05 level).

In a certain extent biological crust thickness reflects how long the mobile sandy land has been fixed or biological crusts formed. So the thickness of biological crusts is consistent with the formation time and correlation with the enrichment of nutrient (Li et al., 2011). When the distance between biological crusts and the root of Artemisia ordosica is closer, the thickness is higher. This phenomenon is probably caused by the promotion that Artemisia ordosica provide to the growth of biological crusts (Liu, 2012). Artemisia ordosica can promote biological crusts produced which is conducive to fixed the mobile sandy land and accelerate the formation of soil, so it is very important for the sandy land ecosystem. However, Artemisia ordosica is deciduous subshrub with a short lifetime, hence provides weaker promotion to the occurrence of sandy soil nutrient "fertile island", compared to sandy vegetation with longer lifetimes, such as Sabina vulgaris Ant (Schlesinger et al., 1996). Artemisia ordosica is a semi-shrub plant, no obvious stem and many branches. In large evaporation areas like Maowusu desert, the thick foliage blocking out light is weaker, small climate phenomenon is more obvious, and more favorable to the development of biological crusts which is thicker. With the growth of sand fixing vegetation and the increase of sand fixation duration, biological crusts developed gradually. Generally, developmental stage can be divided into crisp powder crust, crispy thin crust, more

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closely flaky crust and closely flake, lump crust (Cui et al., 2004). The growth process of biological crusts probably evolve from sand crusts to cyanobacterial crusts, and then change to lichen crusts, finally evolve into the moss crusts or a symbiosis between moss, lichen and algae crusts. The relationship of biological crust thickness was shown that moss crust thickness is the highest, with lichen crust thickness being lower than moss crust and higher than cyanobacterial crusts.

3.2 Water evaporation

3.2.1 Natural water content

The biological crust covers directly affect the redistribution of moisture .In the results shown in Figure 5, the natural moisture content in 0-5 cm bare sand soil (including biological crust covers) is only 0.15%. The natural moisture content in 0-5 cm soil covered by moss crusts is 0.43%. The natural moisture content in 0-5 cm soil covered by lichen crusts is 0.36%. The natural moisture content in 0-5 cm soil covered by cyanobacterial crusts is 0.32%. This indicates that biological crust covers have a protective effect on the natural moisture content in surface soil. However, with the increase in depth, the natural moisture contents expand in different trends for the three types of crust covers.

In bare sand lands with no biological crust covers, the natural moisture content in the soil increase gradually with the increase of depth. The natural moisture contents for soil layers of 0-5 cm, 5-20 cm, 20-30 cm and 30-40 cm depth are 0.15%, 0.98%, 1.30% and 1.53% respectively. This indicates that dry bare sand inhibits the evaporation loss in lower-layer sand. This also indicates that bare sand layer has good moisture penetration abilities, allowing natural precipitation to penetrate into deeper parts of soil, hence has water conservation effect.

Under moss biological crust covers, there is a significant increase in natural moisture content in depths of 5-20 cm. As the depth of soil increases, there is a sharp decline in natural moisture content, even below the natural water content in depths of 5-20 cm. Lichens biological crusts act as moss crusts. This on one hand indicates that the moss and lichen biological crusts have high moisture absorption ability to intercept part of the precipitation to penetrate deep soil, resulting in low moisture content in deep (20 cm below the surface) soil. On the other hand, this reflects that the moss and lichen biological crusts have better water-conserving performances than those in lower-layer sand. In cases where moss and lichen crusts are relatively dry due to natural evaporation, the moisture loss due to evaporation is reduced, and the natural moisture content in the respective lower-layer sand can be maintained at a high state.

On the other hand, for soil covered by cyanobacterial crusts, the natural moisture content in different layers of soil mainly reduces with the increase of soil depth. This indicates that different types of biological crusts affect the natural moisture content and precipitation redistribution in soil differently. However, for soil below 20 cm depth, the case is contrary. Similarly, this indicates that cyanobacterial crust covers

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intercept part of the precipitation to penetrate into deep soil, leading the moisture content in deep soil at a low state.

3.2.2 Simulate 5 mm rainfall

As shown clearly by Figure 6, in 5 mm simulated rainfall, the interior evaporation processes of soil are different under different types of covers. Out of the three types of biological crusts, only moss crust had less evaporation loss than bare sand on the first day. Starting from the second day, the evaporation loss under all types of covers declined sharply, in which the evaporation loss for moss biological crusts is significantly higher than the other three groups. With the extension of the evaporation process (starting from the third day), dry sand layer formed in bare sand (starting from the second day of evaporation), with the evaporation loss of moss biological crusts higher than the other three groups. On the fourth day, all of the evaporation losses became zero. Starting from the fifth day, the samples began to absorb moisture from the air, in which the water absorption of moss biological crusts was significantly higher than the other three groups.

There is a clear turning point on the 5 mm precipitation evaporation process curve, showing that evaporation losses were drastically reduced after two days of dry sand layer formation. On the first and second day of the evaporation experiment, the moisture losses in bare sand, sand with moss crust covers, sand with lichen crust covers and sand with cyanobacterial crust covers were 3.53 g, 3.47 g, 3.67 g and 3.65 g respectively. On the third to fifth day, the accumulated losses in bare sand, sand with moss crust covers, sand with lichen crust covers and sand with cyanobacterial crust covers were 0.005 g, 0.04 g, -0.015 g and 0.005 g respectively.

Throughout the evaporation process, the accumulated losses in bare sand, sand with moss crust covers, sand with lichen crust covers and sand with cyanobacterial crust covers were 3.535 g, 3.51 g, 3.655 g and 3.655 g respectively. This indicates that in the case of low precipitation (5 mm), only moss biological crusts have a certain degree of effect on preventing evaporation. Lichen and cyanobacterial crusts cannot effectively prevent the evaporation of water. Instead they promote water loss. This also indicates that biological crust covers have high water absorption capacity. They can intercept precipitation to permeate into deep soil and lose by evaporation. The Chen (1992) study suggests that the presence of desert biological crusts shallows precipitation. Most of the precipitation are rapidly dissipated and lost through surface evaporation. In precipitations less than 5mm, biological crust covers cannot effectively prevent the evaporation process, and show different trends due to their difference in types (Chen, 1992).

3.2.3 Simulate 10 mm rainfall

Starting from the second day of the evaporation, the water loss was significantly reduced. During the evaporation process, once a dry sand or dry layer is formed on

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the surface, the evaporation of soil moisture will be significantly inhibited. On the first day of evaporation, moisture loss in bare sand was less than loss in sand covered by biological crusts. On the second to fourth day, loss in bare sand was higher than loss in sand covered by biological crusts. On the fifth day of evaporation, loss in bare sand was lower than sand covered by biological crusts (Figure 7). It can be observed that different types of biological crusts have different effects on soil moisture.

Observing the evaporation process curve in 10mm precipitation, on the first to second day of evaporation, the evaporation losses in bare sand, sand covered by moss crust, sand covered by lichen crust and sand covered by cyanobacterial crust are 6.395 g, 6.875 g, 6.795 g and 6.39 g respectively. This also indicates that under the experimental conditions for 10mm precipitation, the biological crust covers cannot effectively prevent the evaporation process. Different types of biological crusts act differently on soil moisture.

Throughout the evaporation process, the accumulated moisture losses in bare sand, sand covered by moss crust, sand covered by lichen crust and sand covered by cyanobacterial crust are 7.255 g, 7.16 g, 7.21 g and 7.225 g respectively. This indicates that when moisture is low (10 mm precipitation), biological crust covers can effectively prevent evaporation process and has certain effect in water conservation.

3.2.4 Simulate 15 mm rainfall

On the first day of evaporation, the moisture loss in bare sand is lower than all of the biological crusts, in which the loss in cyanobacterial crust was the highest, followed by moss biological crust and lichen biological crust. Starting from the second day of evaporation, the water losses in cyanobacterial and moss biological crusts decreased rapidly. Losses in lichens biological crust and bare sand followed a significant downward trend from the third day. This indicates that under the 15 mm precipitation conditions, bare sand and lichen biological crust cover is one day behind cyanobacterial and moss crusts to show a significantly reduction in evaporation loss (Figure 8).

Observing the evaporation process curve after 15 mm precipitation, on the first three days of evaporation, the moisture losses in bare sand, sand with moss biological crust cover, sand with lichen biological crust cover and sand with cyanobacterial biological crust cover are 10.175 g, 10.35 g, 10.21 g and 10.485 g respectively. On the last two days of evaporation, the moisture losses in bare sand, sand with moss biological crust cover, sand with lichen biological crust cover and sand with cyanobacterial biological crust cover are 0.71 g, 0.385 g, 0.61 g and 0.42 g respectively. This indicates that under the experimental conditions for 15mm precipitation, the coverage of biological crusts cannot effectively prevent the evaporation process on the first three days, and the coverage of biological crusts effectively prevent the evaporation process on the last two days. Different types of biological crusts showed different trends towards soil moisture.

Throughout the whole evaporation process, the accumulated moisture losses in bare sand, sand with moss biological crust cover, sand with lichen biological crust

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cover and sand with cyanobacterial biological crust cover are 10.885 g, 10.735 g, 10.82 g and 10.905 g respectively. This also indicates that the coverage of biological crusts cannot effectively prevent the evaporation process. Different types of biological crusts showed different trends towards soil moisture.

3.3 Water infiltration

The relationship between the moisture content of biological crusts and the lower soils are analyzed by Pearson correlation analysis. In natural state, the moisture contents of moss crusts and the lower soils are significant correlation (at the 0.01 level), and the moisture contents of cyanobacterial crusts and the lower soils are significant correlation (at the 0.05 level).Under simulate 5 mm rainfall, the moisture contents of biological crusts and the lower soils are not significant correlation (at the 0.05 level).Under simulate 10 mm rainfall, the moisture contents of lichen crusts and the lower soils are significant correlation (at the 0.01 level), the moisture contents of cyanobacterial crusts and the lower soils are significant correlation (at the 0.05 level). Under simulate 15 mm rainfall, the moisture contents of lichen crusts, cyanobacterial crusts and the lower soils are significant correlation (at the 0.01 level) (Table 1).

Compare the water content increased which are biological crusts relative to the lower soils (Figure 9). In the natural state, compared with the water content of the lower sand soil, the water content increased of lichen, moss, cyanobacterial crusts was 0.43%, 0.49% and 0.32% respectively. After simulated 5 mm, 10 mm and 15 mm rainfall, compared with the water content of the lower sand soil, the water content increased of lichen crusts was 0.67%, 0.61% and 0.6% respectively (Figure 9a). The water content increased of moss crusts was 1.17%, 0.764% and 0.761% respectively (Figure 9b). The water content increased of cyanobacterial crusts was 0.61%, 0.35% and 0.33% respectively (Figure 9c). In arid and semi-arid desert region, natural rainfall precipitation is usually small with short durations. With sunlight strikes directly onto the surface, the surface temperature raises suddenly. With small rainfalls, the water resistance of the biological crusts becomes stronger. Surface water does not penetrate into the crust and the underlying sand. Moisture will quickly evaporate into the air under sunlight. With large rainfalls, the rain may penetrate upper-level biological crusts. Moisture will penetrate into the sand, which is more conducive to vegetation moisture absorption.

When rainfall was increased from 5 mm to 10 mm, the water content of lichen crusts was increased from 12.61± 3.4% to 14.39± 8.9%, however, when rainfall was 15 mm, the water content was decreased to 14.21± 7.3%.When rainfall was increased from 5 mm to 15 mm, the water content of moss crusts was increased from 19.44± 5.7% to 22.64± 15.1%. When the rainfall were 10mm and 15mm, the water contents of cyanobacterial crusts were 12.06± 3.3% and 12.05± 3.1% respectively, which were lower than 12.41± 4.8% (when the rainfall was 5 mm). On the other hand, the water contents of the lower soils were increased in the whole process of simulated rainfall. The result indicates that when the rainfall increases, cyanobacterial crusts first reaches the saturated water content (less than 5 mm rainfall),

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followed by lichen crusts (from 5 mm to 10 mm rainfall), the water contents of moss crusts finally reaching the saturated capacity (more than 15 mm rainfall). The topsoil water-holding capacity of different Biological crusts was found to increase in the following order: cyanobacteria and algae crusts< lichen crusts< moss crusts (Li et al., 2010). The results are in accordance with the view of this paper. Cyanobacteria absorb up to 10 times their volume of water and 8-12 times their dry weight (Campbell, 1979; Verrecchia et al., 1995). Gelatinous lichens and mosses can expand their cover and biomass by up to 13 times or more when wetted (Galun et al., 1982). Cyanobacteria are less likely to clog pores than lichens and mosses, which are large enough to cover soil pores completely (Belnap, 2006).

3.4 The depth of water infiltration

After simulated 5 mm, 10 mm and 15 mm rainfall, the water infiltration depths of lichen crusts were 3.58 cm, 5.31 cm and 7.47 cm respectively, which of moss crusts were 2.29 cm, 4.05 cm and 5.58 cm respectively, and which of cyanobacterial crusts were 4.90 cm, 6.32 cm and 8.38 cm respectively (Figure 10). When the rainfall increased, the depth of water infiltration increased. The water infiltration depths of cyanobacterial crusts were the largest (when the rainfall was 15 mm), and which of moss crusts were the smallest (when the rainfall was 5 mm). The water infiltration depths of the same type biological crusts were significantly different (at the 0.05 level).

The depth of water infiltration and the thickness of biological crusts have a significant negative correlation at 0.01 level. The thickness of biological crusts and the water infiltration capacity have a significant positive correlation at 0.01 level. Moreover, the water infiltration capacity and the depth of water infiltration have a significant positive correlation at 0.01 level (Figure 11). The relationship between the depth of water infiltration，the thickness of biological crusts and the water infiltration capacity was shown by Table 2.

When the thickness of biological crusts becomes larger, their ability to hold water and blocking infiltration capacity become stronger. There was a linear positive correlation between biological crust thickness and water infiltration resistance. Under wetter conditions, a thick layer of biological crust develops in topsoil, and this layer is able to absorb large rain amounts (Almog & Yair, 2007). In drier areas, the thin crust can absorb only a limited amount of rain, resulting in surface runoff and deeper water infiltration at run-on areas (Yair et al., 2011). Most cyanobacterial crusts growth are mixed with the topsoil, they can cover on the surface of vegetation only when wetting. Most biomass of lichen and moss crusts grow on the soil surface, they protect the lower soil to prevent the impact of raindrops, and resist peeling off the soil particles in surface runoff (Belnap, 2006). The water infiltration depth is highly negatively correlated with soil water-holding capacity (Li et al., 2010). With the rainfall increased, the depth of water infiltration increasing (Yair et al., 2011).The water infiltration depth is also negatively correlated with biological crust thickness.

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4. Discussion

4.1 Water evaporation

In the past few decades, biological soil crusts were found with an astonishing variety of habitats throughout the world (Belnap & Lange, 2003), however, they were only recognized as one factor of major influence on terrestrial ecosystems (Williams et al., 1995; Belnap, 2002). In arid and semiarid environments, the potential effectiveness of Biological crusts in increasing water infiltration and decreasing overland flow, in turn impacting soil erosion and water storage, has attracted the interest of many ecologists and environmentalists, although their utility has also been questioned (Xiao et al., 2011).

Researches on the water content of natural state indicate that there is a quite difference in variation of biological crusts and bare sand layers. The dune profile is full of sands. The water content of dry sand layer is very low which resists the lower soil from losing water. Under dry sand layer the water content increased rapidly, due to the lack of absorption and transpiration of plants. Biological soil crusts are a long time to maintain the water on the surface of the earth, so that the water is not easy to be use to vascular plants, it raised the possibility of water evaporated (Eldridge et al., 1997; West, 1990). Biological soil crusts blocked the substrate surface hole, reduced water evaporation (Brotherson et al., 1983).The water content is higher than that of soil profile with vegetation growth, and shows the opposite trend (Yan, 2008).

In this paper, study on water evaporation of biological crusts indicated that different biological crusts showed different trends. Biological crusts prevented the formation of dry layer at soil surface (which could significantly slow down soil evaporation) and subsequently resulted in faster soil water evaporation rate and longer time at constant rate drying stage (Zhang et al., 2008; Xiao et al., 2010; Kidron & Tal, 2012; Chamizo et al., 2013). Better development of moss crusts resulted in relatively less invalid rainfall, but maintained higher evaporation rate for longer time. The initial development of dust crust and shifting sand cause more invalid rainfall, but due to water infiltration depth is relatively deeper, take longer to complete the evaporation process (Zhou & Lamusa, 2011). The surface soil can be coated with sand which can effectively reduce water evaporation of soil (Chen et al., 2005; Modaihsh et al., 1985). Increasing soil surface obstacles (such as stone) helps magnify vegetation canopy and avoiding direct sunlight hence can effectively reduce the loss of soil moisture. Protections should be provided in early stages of formation and development of biological crust. However, some amount of damage is beneficial after the crusts have developed to a certain extent. This can decrease the surface soil precipitation evaporation and increase water recharge (Zhou & Lamusa, 2011).

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4.2 Water infiltration

The influence of biological crusts on water infiltration is dependent on soil texture and structure, degree of cover, types of organisms in crusts, climate (mainly rainfall) and disturbance history (Belnap, 2006). The influence of biological crusts on infiltration can be negative (Li et al., 2011). The existence of biological soil crusts blocked the substrate surface hole, delayed water infiltration rate, reduced water infiltration, and water infiltration depth become shallow(Brotherson et al., 1983) . The reason of biological soil crusts blocking water infiltration is that biological soil crusts completely shut down the sand surface water gap (Li et al., 2001).In this paper, studies on water infiltration of biological crusts indicated that with the rainfall increasing, the capacity of biological crusts blocking water infiltration became smaller. When ponding depth increases, the ponded area increases also, integrating more and more of the area composed of structural crusts, which have higher infiltration rates. The apparent infiltration rate thus increases with rainfall intensity and ponding depth (Fox et al., 1998). Moisture accumulation is formed by larger rainfall on bio crust surface, resulting in increasing water infiltration capacity. After the 5mm rainfall simulation, biological crust water content increased sharply (compared with natural state). With the rainfall increased, the water content also increased slowly. The infiltration capability of a dry soil is initially high but decreases at a rapid rate to a more or less constant value (Liu et al., 2011). The rate of increase in cumulative infiltration was less under higher initial soil water contents, especially in the initial rainfall stage (Liu et al., 2011).The effect on infiltration among different crusts can be attributed to differences in the thickness of biological crusts and topsoil and the soil water-holding capacity. The latter is highly positively correlated with the thickness, which is dependent on the crust types (Li et al., 2010).

4.3 Construction of shelter forest

The development of surface crusts results in progressive flattening of the soil surface, and thus the more crusted is the soil, the less rough it becomes (Le´onard et al., 2006). Smooth crusts flatten the soil surface and thus reduce water retention times (Yair, 1990), reduce biomass (Belnap, 2006). Crust can affect ecosystem processes such as infiltration, erosion, and the development of physical soil crusts. This influence has a major impact on ecological processes such as germination and establishment of vascular plants (Harper & Marble, 1988; West, 1990; Eldridge & Greene, 1994; Danin, 1996; Zaady et al., 1997). Smooth crusts increase the probability that seeds will be blown or washed from plant interspaces to nearby obstructions (e.g. plants, large rocks) (Prasse, 1999). Seedlings are infrequently found in interspaces on the smooth crust type (Belnap, 2003).Therefore, tillage may increase infiltration rate and slow down runoff, preventing high erosion rates (Schiettecatte et al., 2005).Biological soil crust organisms are also sensitive to other types of disturbance, including air pollution, herbicides (Zaady et al., 2004; Belnap et al.,

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2003b), and climate change, including changes in precipitation (Belnap et al., 2004) and increased air temperatures (Belnap et al., 2006). Biological crusts are easily crushed, especially in dry conditions. Once buried, these photosynthetic organisms die (Belnap, 2006). Biological crusts are fragile structures that are vulnerable to disturbance, especially to human-driven impacts, such as trampling by livestock, burning or vehicle traffic, which usually causes the loss of mature BSCs and reversal to early cyanobacterial crusts (Barger et al., 2006; Housman et al., 2006). These disturbances simultaneously reduce soil surface roughness promoted by typical well-developed BSCs, causing soil compaction, and often sealing the soil surface (Chamizo et al., 2012). This leads to increased overland flow and reduced storage capacity for water and sediments (Abrahams et al., 1995). In arid and semi-arid area, nitrogen is the main limiting factor for plant growth, and the biological nitrogen fixation is poor, biological components in biological crusts are the most important nitrogen sources (Evans & Ehleringer, 1994). Nitrogen fixed by biological crusts is utilized by associated vascular plants (Belnap, 2003), and thus it likely results in greater plant biomass. Artificially propagated moss crusts significantly increase infiltration consequently decreasing overland flow (Xiao et al., 2011).Using appropriately artificial biological crusts to fix sand, to build sustainable protection forest system and to create a stable ecosystem in desertification area.

Many factors affect effects of biological soil crusts on water infiltration and evaporation, we found it has a close relationship with the biological soil crusts type and thickness in this paper. Effects of different types and thickness biological soil crusts on water infiltration and evaporation are not same. In the construction of protection forest system, we can appropriately break the biological crust structure mode, which could increase water penetration, reduce water evaporation, and increase the use of water by deep soil. It is much more conducive to the formation and growth of bushes and trees in desertification area. The relationships between effects of biological soil crusts on water infiltration and evaporation and physical, chemical properties of biological soil crusts, the surrounding vegetation characteristics will be further research in the future.

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5. Conclusions

Researches on biological crust thickness indicated that the closer biological crusts are to Artemisia ordosica vegetation, the thicker they become. In same positions related Artemisia ordosica vegetation, the relationship between the thicknesses of different biological crusts are as follows: moss crusts ＞ lichen crusts ＞ cyanobacterial crusts.

In their natural state, cover of biological crusts on surface soil water content has a protective effect, but due to absorption and transpiration of plants, apart from 5-20 cm sand layer, the water content is lower in deeper sand layers (0.15%- 1.53%) than the bare sand at same depth. Water status of biological crust covers was worse than the bare sand soil.

In low precipitation (5 mm), moss crusts can prevent water evaporation. Most of the moisture is stored in the moss crusts, enhancing water resistance, while blocking the infiltration of water at the same time. However, lichen and cyanobacterial crusts cannot effectively prevent water evaporation, instead they promoted moisture loss. In 10 mm rainfall simulation, biological crust covers can effectively prevent evaporation process and has certain effect in water conservation from the accumulated moisture losses. However, biological crusts cannot effectively prevent water evaporation in the evaporation process. Therefore, it is not a strong proof for that under conditions of 10 mm precipitation, biological crusts have obvious effect in preventing evaporation, which is the water retention effect. In 15 mm rainfall simulation, the coverage of biological crusts cannot effectively prevent the evaporation process. Different types of biological crusts showed different trends towards soil moisture.

After rainfall simulations, with small rainfalls, the water resistance of the biological crusts became stronger. At the same rainfall level, the water resistances of the three types of biological crusts are in the order of moss crusts＞ lichen crusts＞ cyanobacterial crusts. With the rainfall increased, the depth of water infiltration also increased. At the same rainfall level, cyanobacterial crusts showed the highest depth of infiltration, followed by lichen crusts and moss crusts. The thickness is strongly positively correlated to water resistance capacity. The water infiltration depth is highly negatively correlated to the thickness and water resistance capacity. With the increase of biological crust thickness, biological crusts blocking water infiltration capacity increase, the depth of water infiltration decreases.

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Tab.1 The relationship of the water content between biological crusts and the lower soils under different rainfall

Biological crusts species	Rainfall	Linear equation	R^2	F	P
Lichen crusts	Natural state	Y=0.282x+0.181	0.216	3.58684	0.08071
	5mm	Y=0.275x+4.239	0.119	1.75406	0.20818
	10mm	Y=0.405x+3.179	0.564	16.83783	0.00125
	15mm	Y=0.696x-0.783	0.725	34.27049	0.000056
Moss crusts	Natural state	Y=0.347x+0.208	0.538	15.11961	0.00187
	5mm	Y=0.260x+4.171	0.124	1.84319	0.19768
	10mm	Y=0.177x+8.012	0.077	1.08211	0.31719
	15mm	Y=0.248x+7.341	0.163	2.52972	0.13573
Cyanobacterial crusts	Natural state	Y=0.568x+0.090	0.386	8.1557	0.01351
	5mm	Y=0.283x+4.335	0.188	3.00242	0.10678
	10mm	Y=0.503x+2.965	0.375	7.79862	0.01524
	15mm	Y=0.396x+4.952	0.433	9.91087	0.0077

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Tab.2 The relationship between the thickness of biological crusts, the depth of water infiltration and the water infiltration capacity

Biological crusts species	Rainfall	The relationship	Linear equation	R^2	F	P
Lichen crusts	5mm	a and b	$Y=-0.0379x+0.9430$	0.730	35.21764	0.000049
		a and c	$Y=0.1573x+0.7038$	0.606	19.96264	0.000633
		b and c	$Y=-3.9113x+6.1537$	0.736	36.2149	0.000043
	10mm	a and b	$Y=-0.0369x+1.0091$	0.590	18.67109	0.000830
		a and c	$Y=0.2847x+0.6399$	0.904	121.86632	0
		b and c	$Y=-4.9227x+8.3108$	0.623	21.46007	0.000469
	15mm	a and b	$Y=-0.0459x+1.1560$	0.909	130.20575	0
		a and c	$Y=0.2227x+0.6789$	0.854	76.30473	0.000001
		b and c	$Y=-4.4835x+10.1583$	0.801	52.18768	0.000007
Moss crusts	5mm	a and b	$Y=-0.2491x+1.6409$	0.889	103.5954	0
		a and c	$Y=0.2357x+0.7972$	0.895	111.36806	0
		b and c	$Y=-0.8656x+3.2935$	0.844	70.16869	0.000001
	10mm	a and b	$Y=-0.1430x+1.6465$	0.856	77.49113	0.000001
		a and c	$Y=0.3025x+0.8362$	0.803	53.05631	0.000006
		b and c	$Y=-2.0589x+5.6228$	0.899	104.05576	0
	15mm	a and b	$Y=-0.1170x+1.7205$	0.760	41.05426	0.000023
		a and c	$Y=0.2459x+0.8744$	0.763	41.74214	0.000021
		b and c	$Y=-1.7300x+6.9402$	0.680	27.64528	0.000155
Cyanobacterial crusts	5mm	a and b	$Y=-0.0714x+0.9463$	0.797	50.99198	0.000008
		a and c	$Y=0.2129x+0.4667$	0.765	42.37513	0.000020
		b and c	$Y=-2.6398x+6.5096$	0.752	39.49204	0.000028
	10mm	a and b	$Y=-0.1071x+1.2752$	0.709	31.63092	0.000083
		a and c	$Y=0.2143x+0.5227$	0.596	19.15388	0.000749
		b and c	$Y=-1.7962x+6.9540$	0.677	27.27468	0.000165
	15mm	a and b	$Y=-0.0228x+0.7902$	0.428	9.74588	0.008100
		a and c	$Y=0.2198x+0.5255$	0.418	9.34401	0.009180
		b and c	$Y=-7.6688x+10.9578$	0.616	20.83015	0.000531

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Fig.1 Yanchi county geography position map and the samples location map

Fig.2 Biological crusts in the different positions of Artemisia ordosica

Fig.3 The thickness of biological crusts in the different positions of Artemisia ordosica. “out” is out the cover of Artemisia ordosica, “under” is under the cover of Artemisia ordosica, “root” is the root of Artemisia ordosica.

Fig.4 The three-dimensional drawing of biological crust thickness.

Fig.4(a) The three-dimensional drawing of lichen crust thickness,

Fig.4(b) The three-dimensional drawing of moss crust thickness,

Fig.4(c) The three-dimensional drawing of cyanobacterial crust thickness.

Fig.5 The effection on the water infiltration of the lower soil under the cover of biological crusts

Fig.6 The effection on moisture evaporation of biological crusts with artificial simulate 5mm rainfall

Fig.7 The effection on moisture evaporation of biological crusts with artificial simulate 10mm rainfall

Fig.8 The effection on moisture evaporation of biological crusts with artificial simulate 15mm rainfall

Fig.9 The water content of biological crusts and the lower soil（0-5cm）.
0mm is the water content in natural state.

Fig.10 The depth of water infiltration under the different simulated rainfall

Fig.11 The relationship between the thickness of biological crusts, the depth of water infiltration and the water infiltration capacity

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Figure1

Figure2

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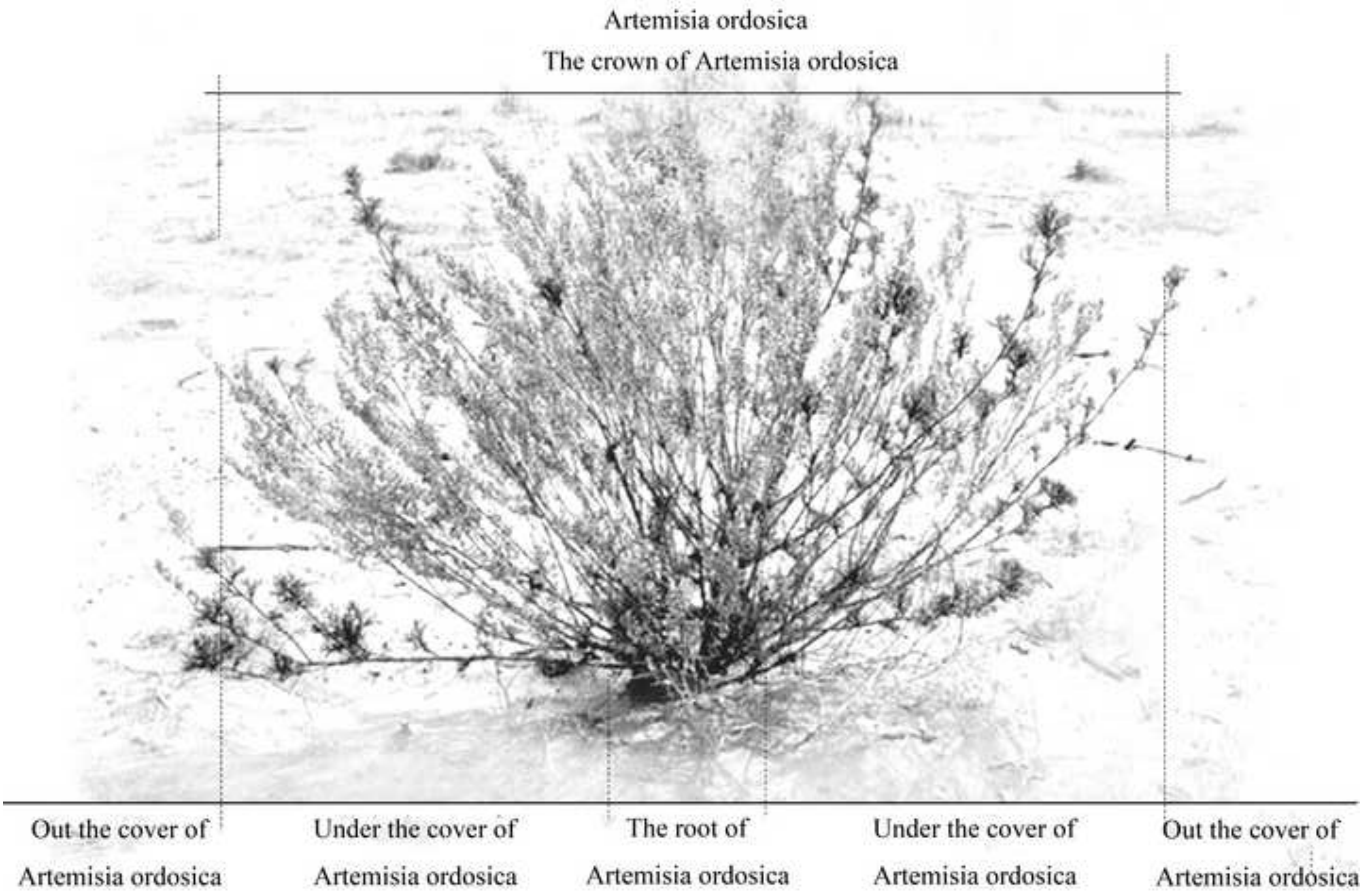

Figure3

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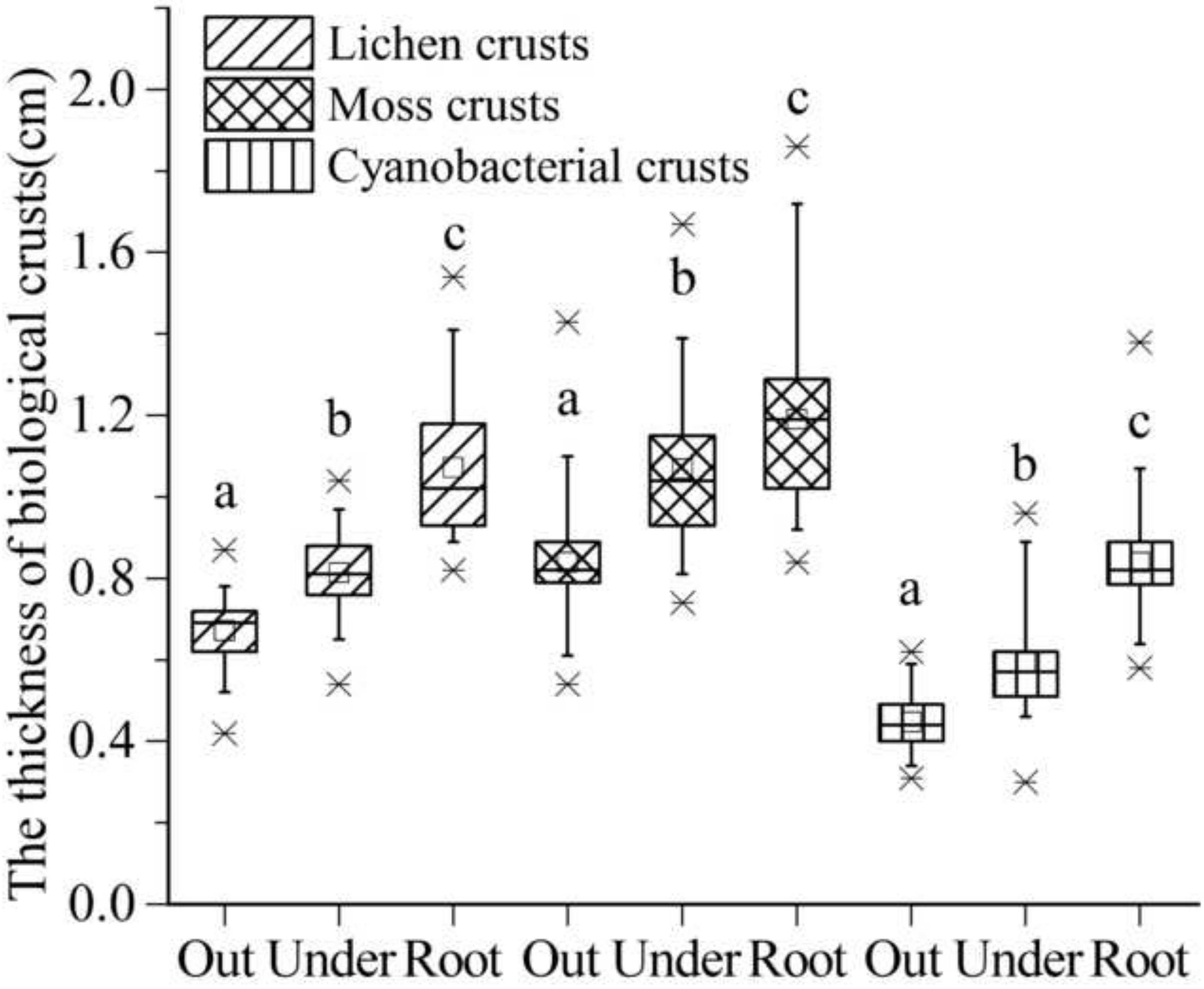

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Figure4a

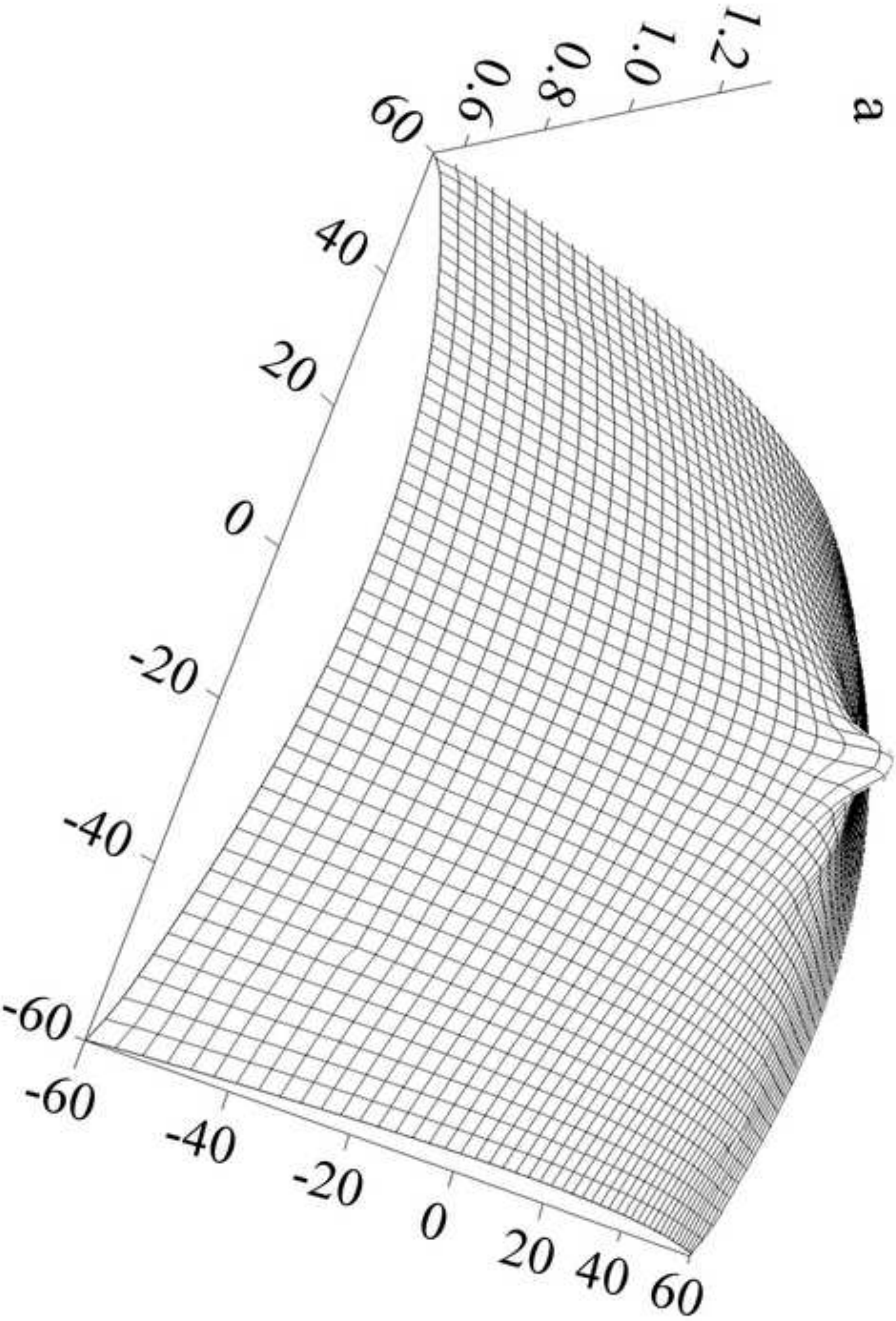

Figure4b

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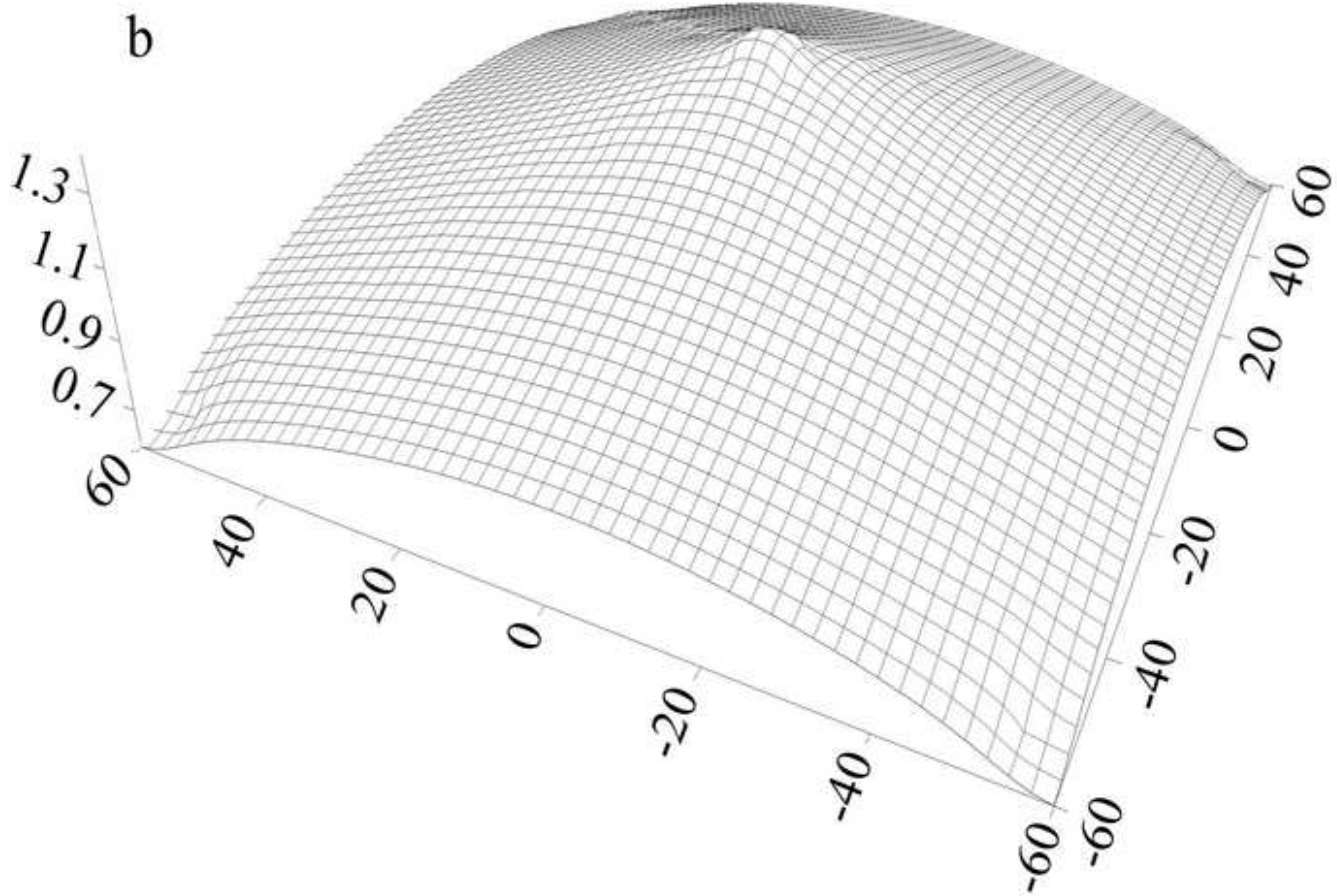

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Figure4c

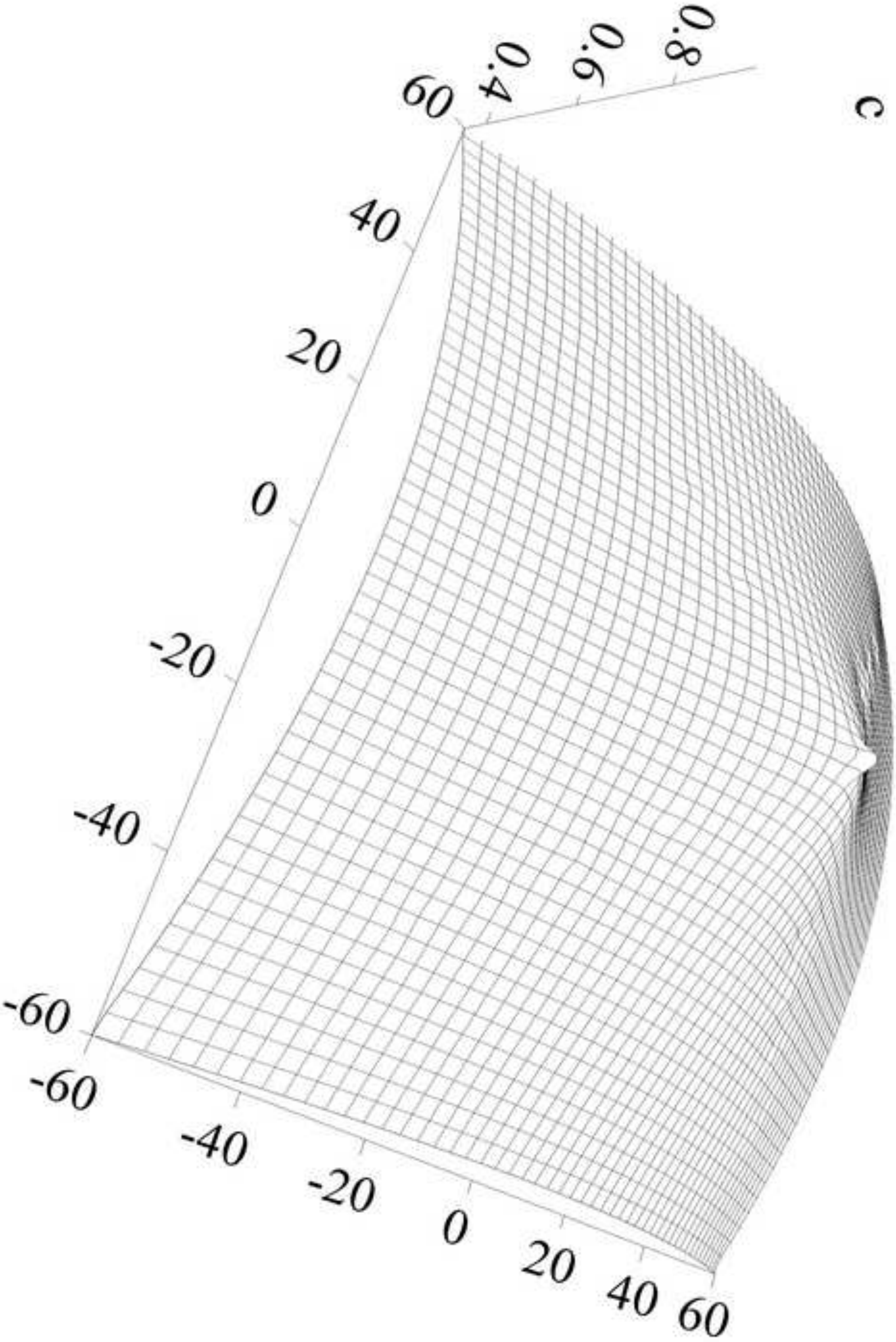

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Figure5

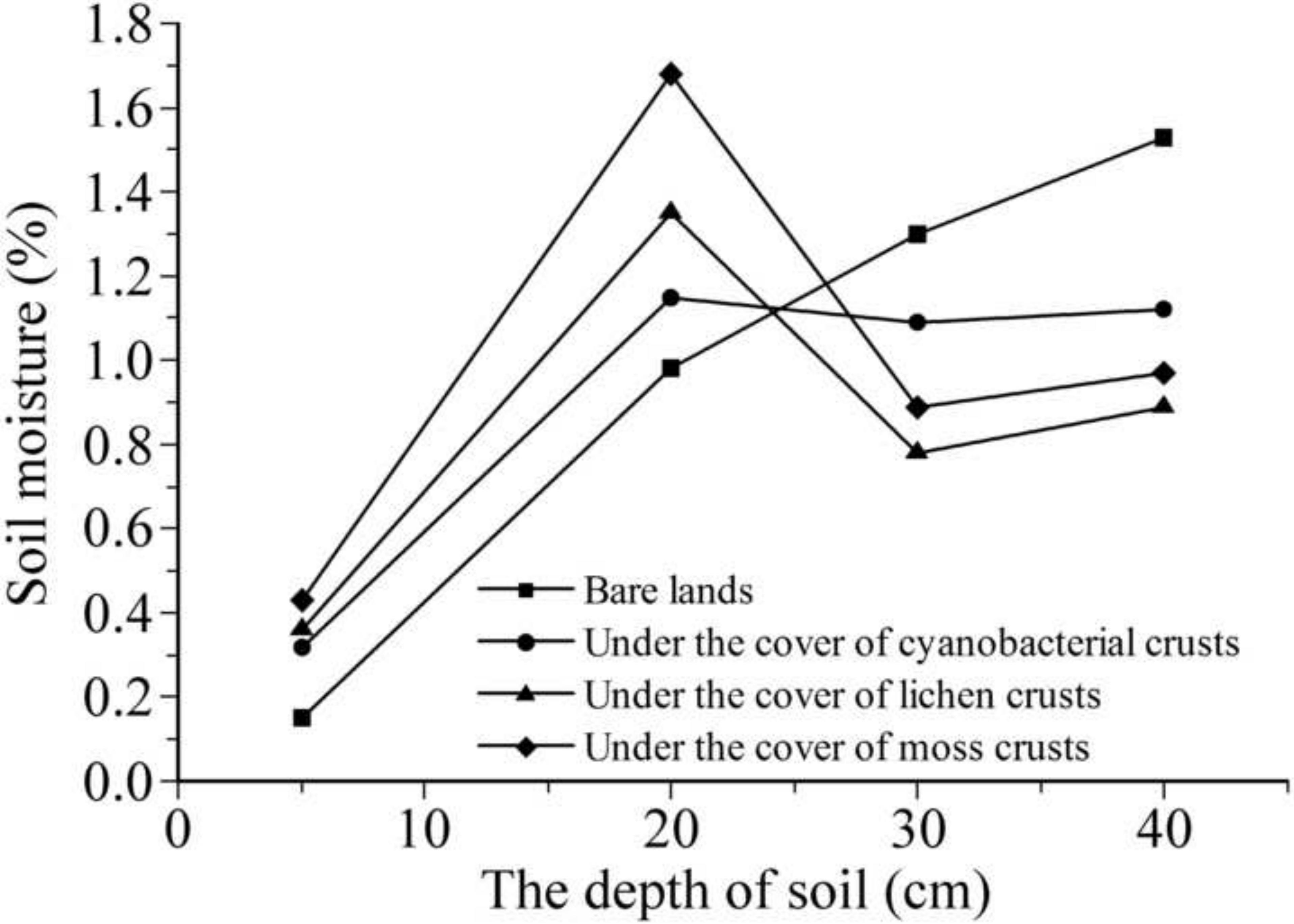

Figure6

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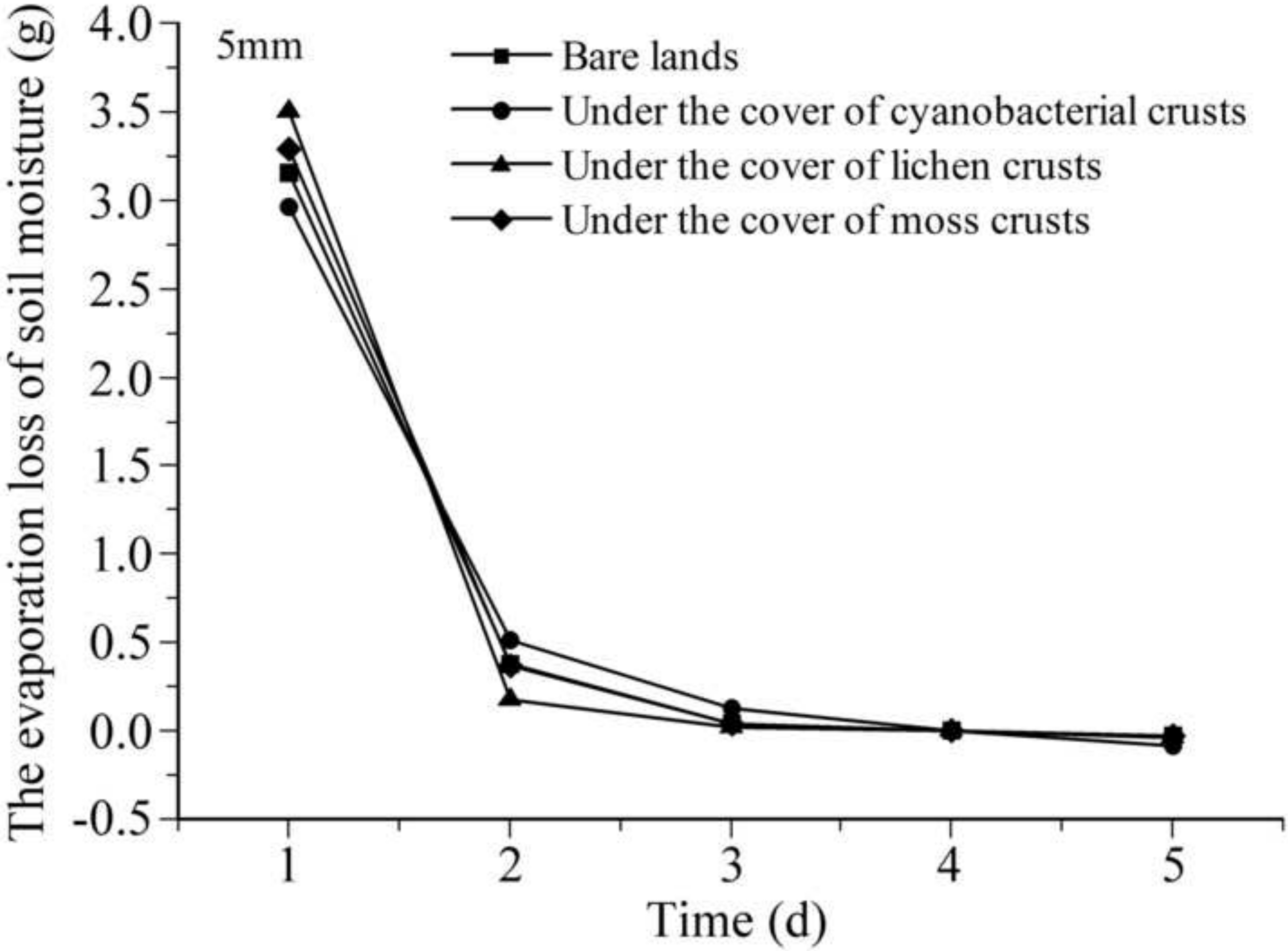

Figure7

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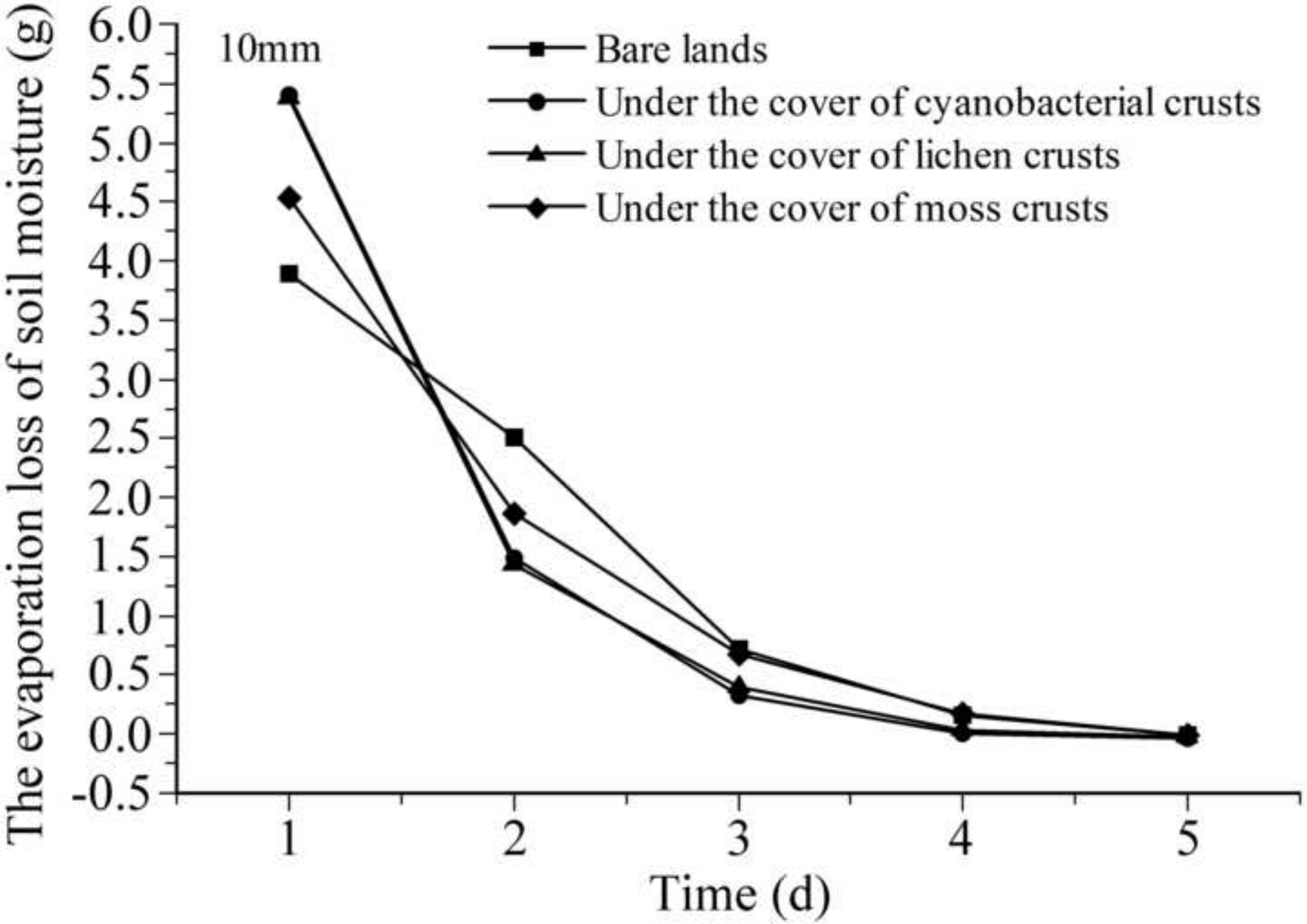

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Figure8

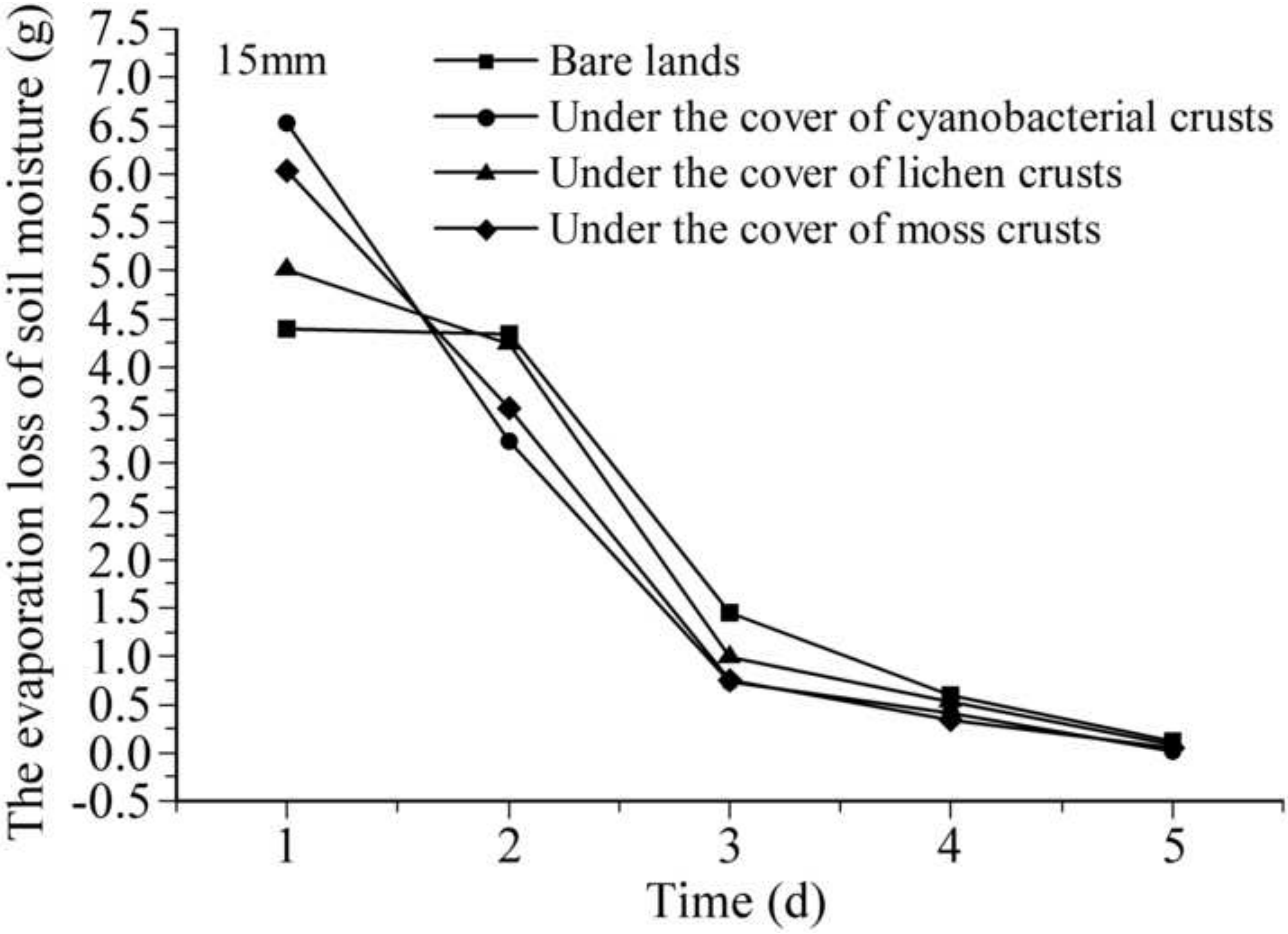

Figure9a

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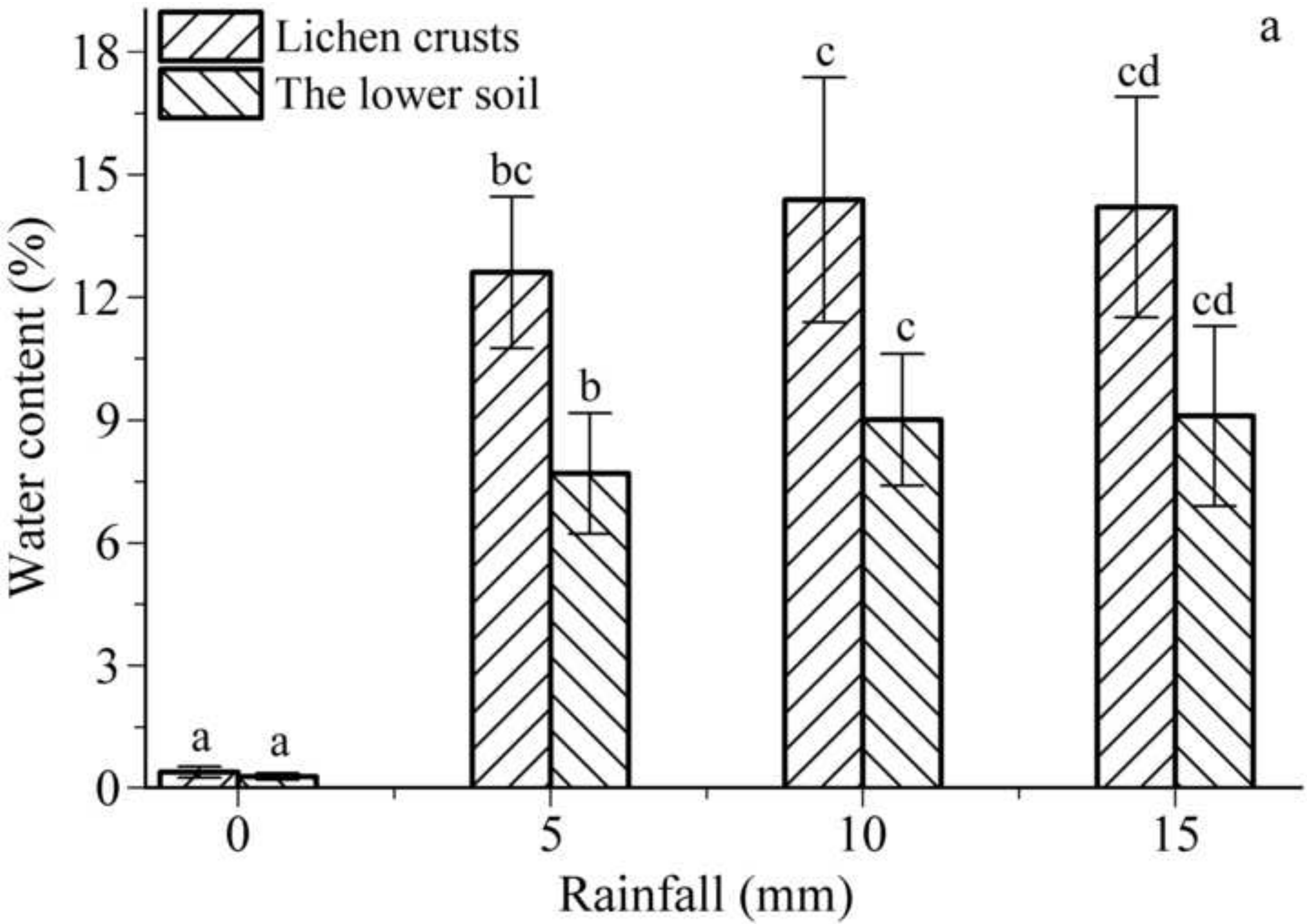

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Figure9b

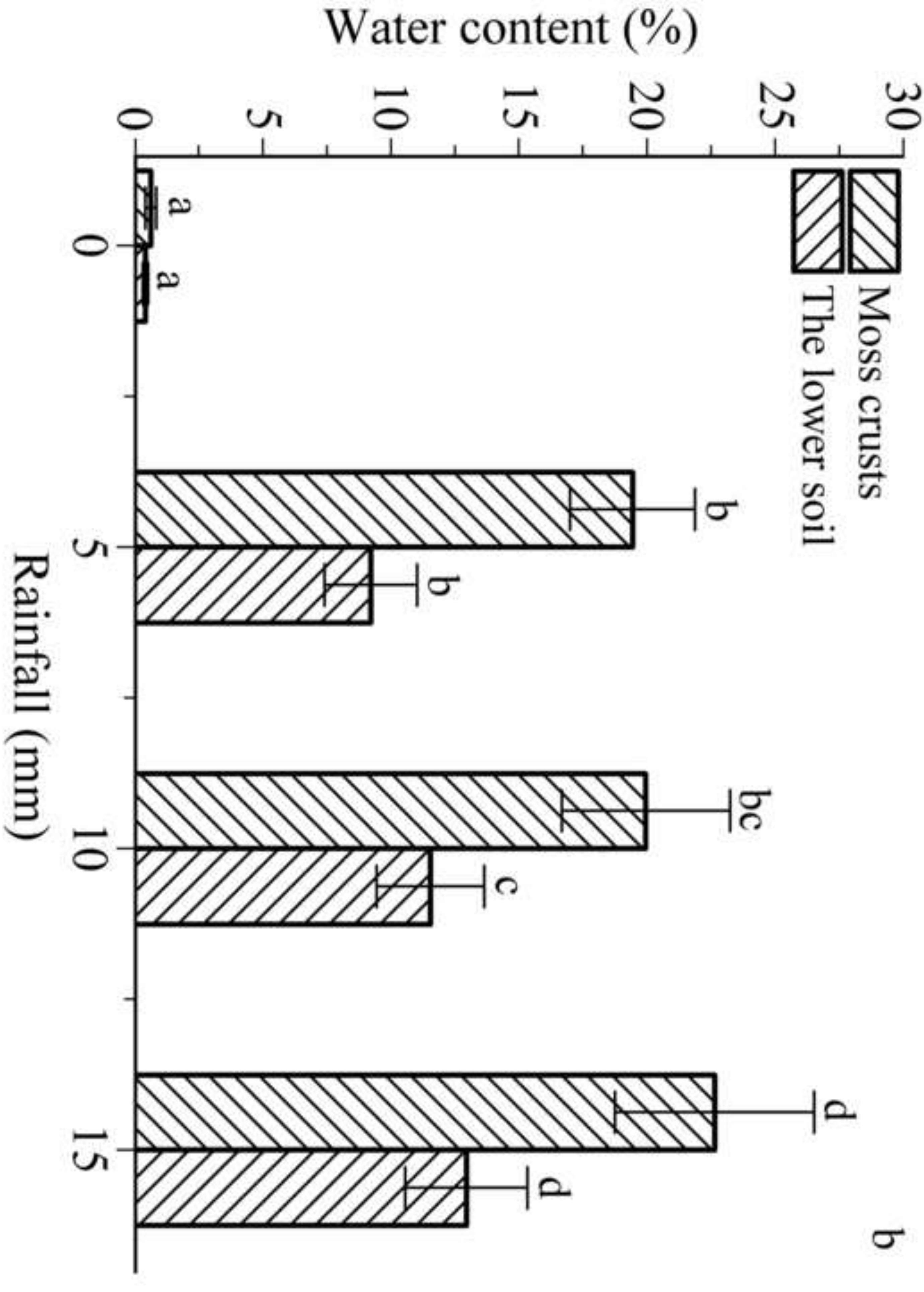

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Figure9c

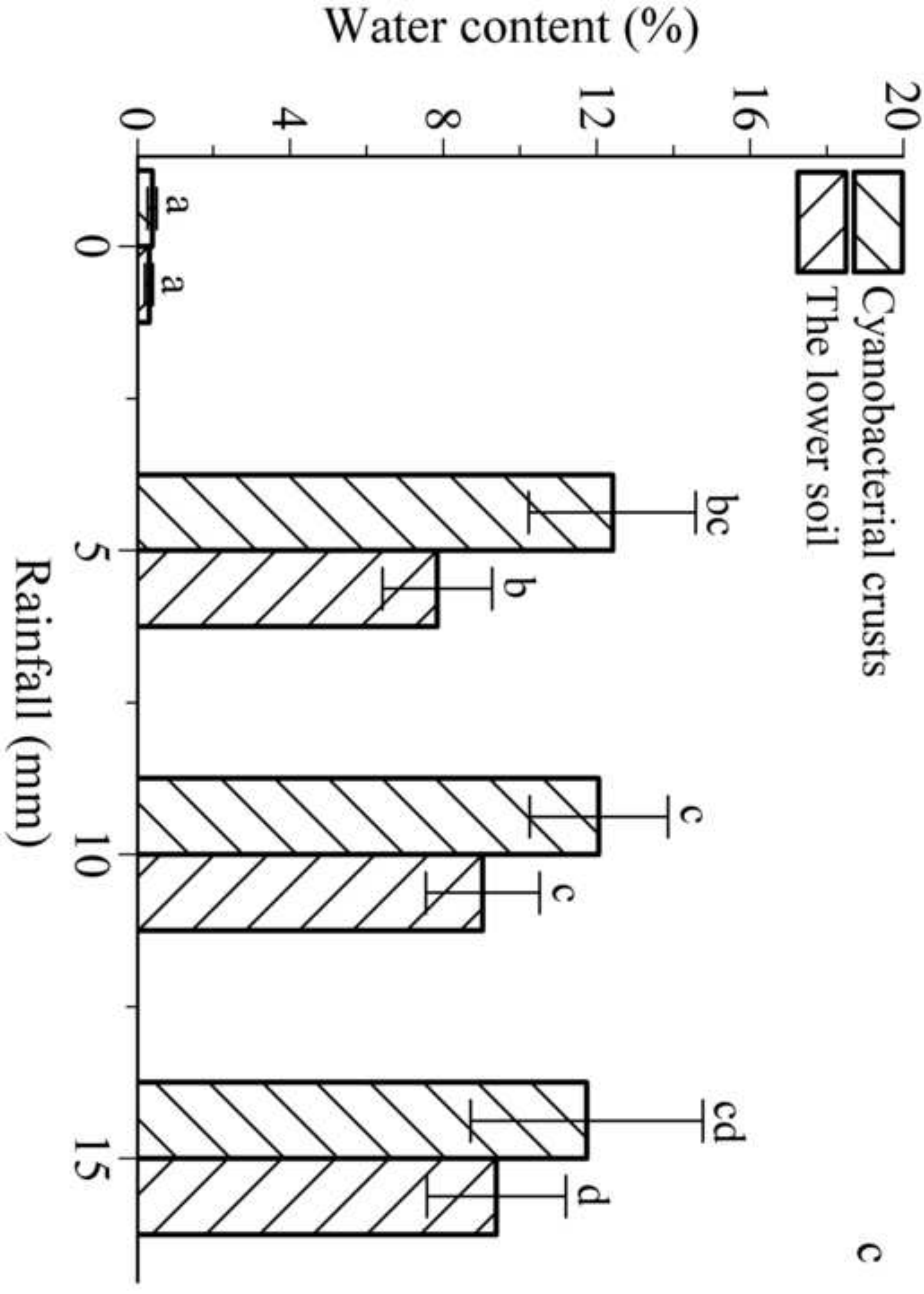

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Figure10

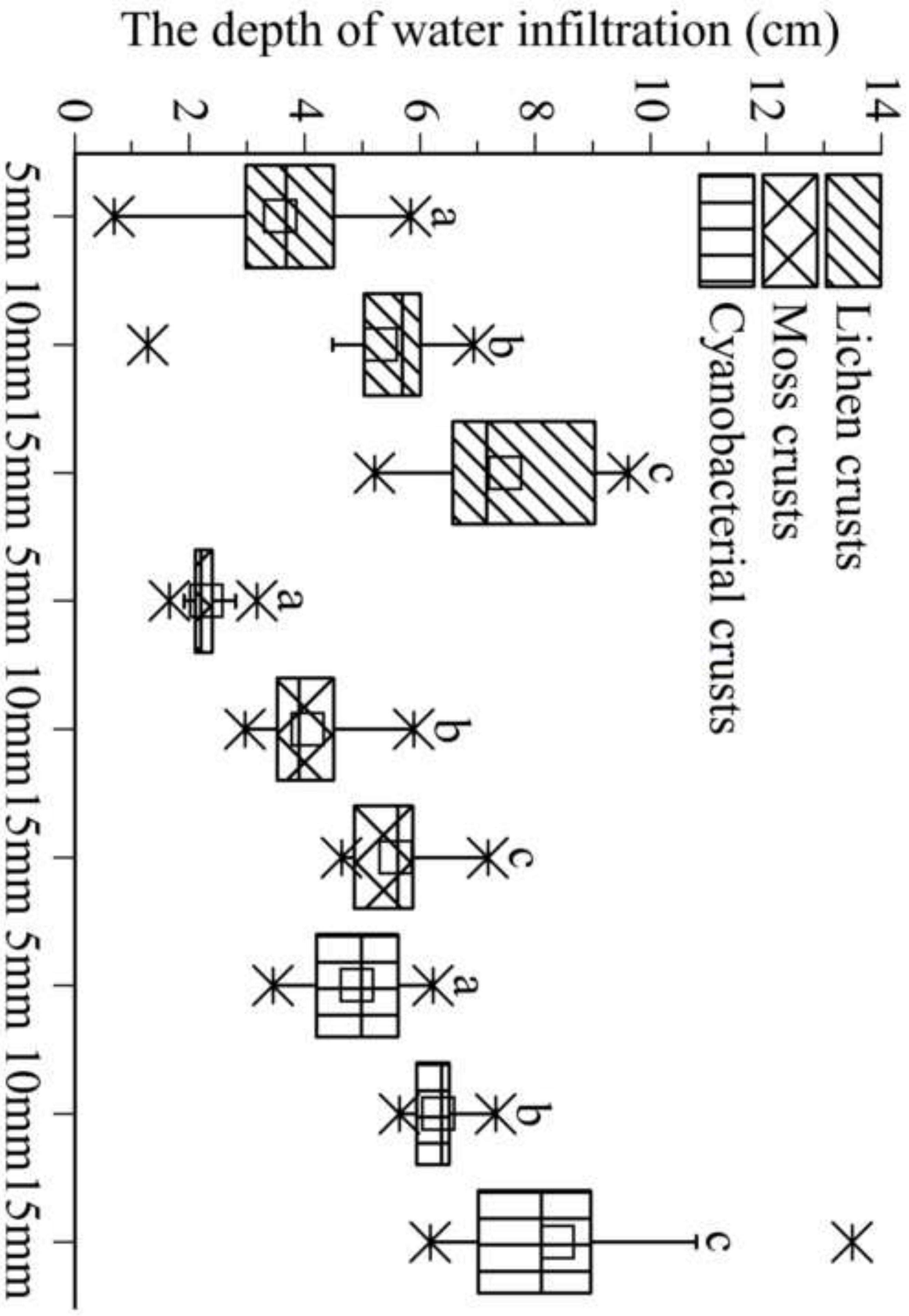

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Figure11-moss crusts

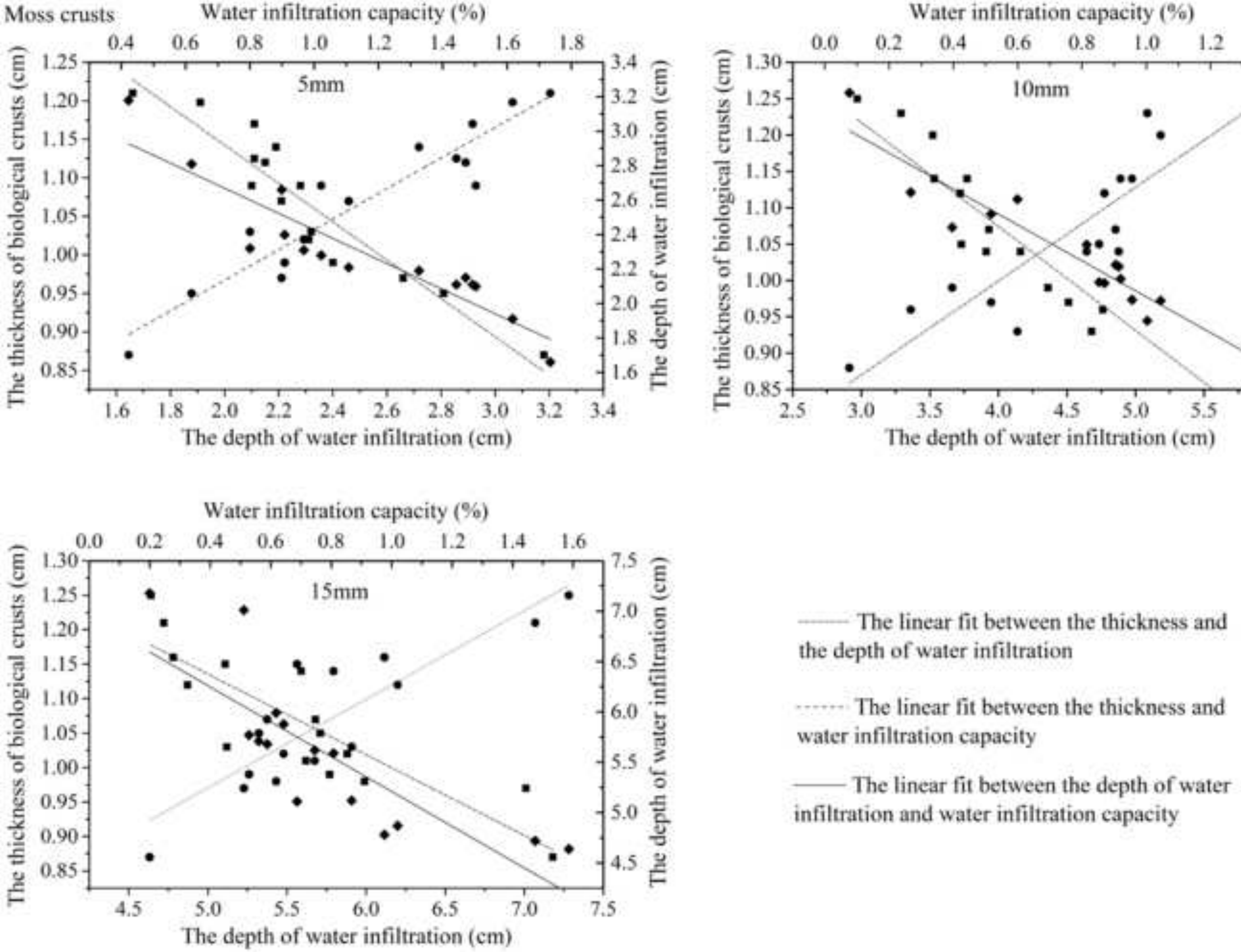

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Figure11-cyanobacterial crusts

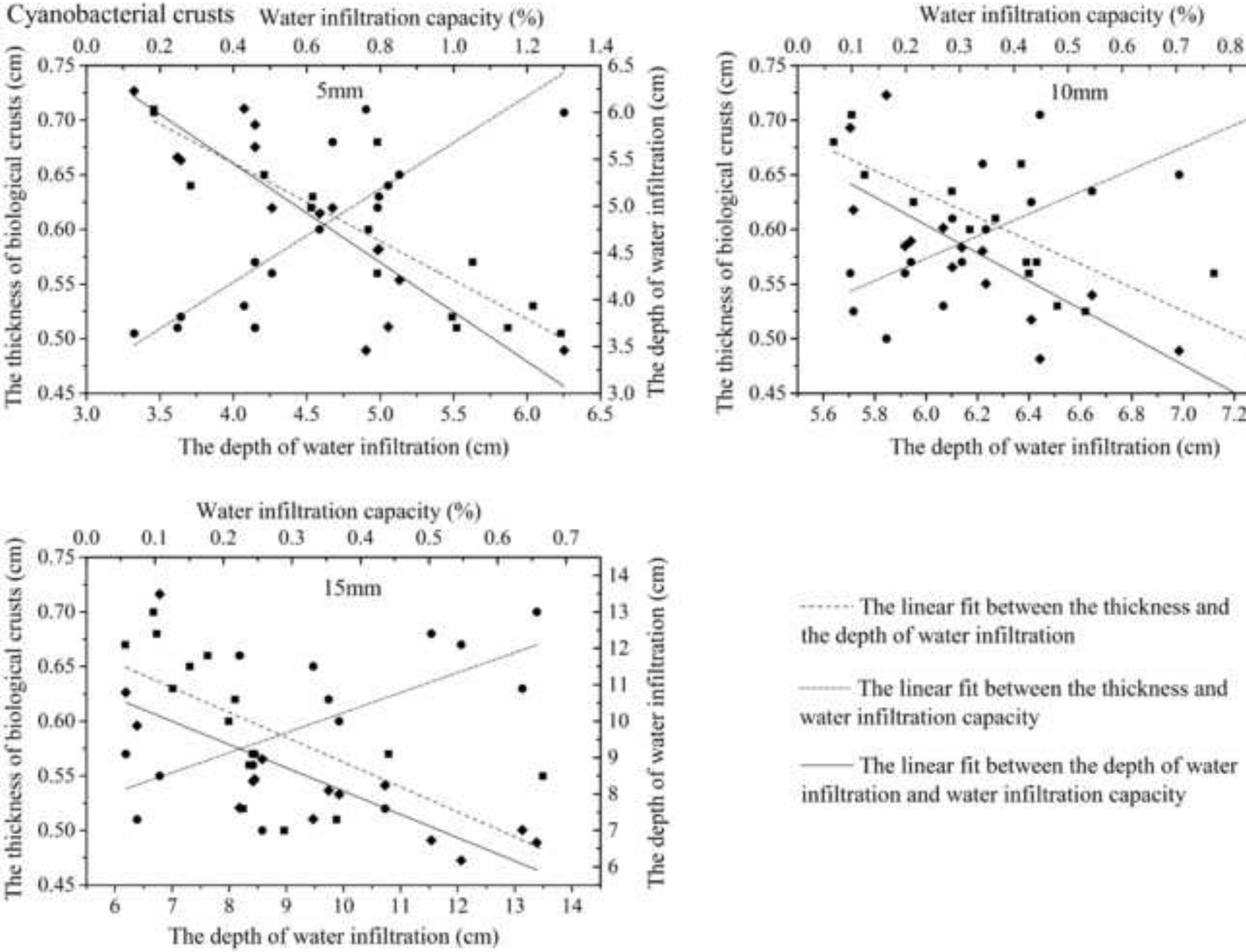

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Figure11-lichen crusts