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Effects of Earthworm Cast Application on Water Evaporation and Storage in Loess Soil Column Experiments

Yanpei Li [1,2], Mingan Shao [1,2,3,*], Jiao Wang [3,*] and Tongchuan Li [1]

[1] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China; liyanpei19@mails.ucas.ac.cn (Y.L.); litongchuan_xinong@163.com (T.L.)

[2] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

[3] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

* Correspondence: mashao@ms.iswc.ac.cn (M.S.); wangjiao@igsnrr.ac.cn (J.W.)

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Abstract: Earthworm cast is a common bio-organic fertiliser, which can effectively improve soil fertility and structure. However, only a few studies have focused on the effect of earthworm cast on soil water movement. In this study, loess soil was used to determine the effects of earthworm cast application on soil evaporation. The effects on water storage capacity and capillary upward movement were also investigated. A laboratory-based soil column experiment using earthworm cast with different particle sizes (1–3 × 1–2 cm and 3–5 × 2–4 cm) and three application doses (5%, 7.5%, and 10%) was carried out. The daily evaporation and volume of capillary ascension were monitored. The addition of earthworm cast clearly affected the soil evaporation by changing soil water storage capacity and capillary water upward movement. Compared with control soil, the application of 5% small-particle cast reduced the soil cumulative evaporation by 5.13%, while the cumulative evaporation was higher in all large-particle cast treatments. The upward capillary water movement increased with increasing dose of earthworm cast, but decreased with increasing particle size. Overall, the addition of earthworm cast clearly enhanced the water storage capacity of the soil, with the small-particle cast having greater effects than the large-particle cast. We concluded that the application of 5% small-particle earthworm cast can enhance soil water retention and reduce soil evaporation.

Keywords: earthworm cast; particle size; evaporation; water storage capacity

1. Introduction

Soil moisture has been shown to be a key factor that influences soil quality in northwest China [1]; it affects soil physical properties [2] and restricts the dissolution and transfer of nutrients and microbial activities [3]. Soil moisture is also a key factor in soil fertility and a necessary element for crop growth [4,5]. As an important component of continental water balance, evaporation directly affects the soil moisture use efficiency of plants and the growth and development of terrestrial vegetation [6,7]. In the arid and semi-arid areas, the evaporation of soil water is intense, resulting in a lot of water loss [8,9]. Measures that reduce soil moisture evaporation, such as the application of water retaining agents and ground cover [10–12], are key to improving water use for sustainable agricultural development.

Soil water movement processes are closely linked to soil organic matter content. Organic matter can reduce evaporation and improve water conservation and water supply performance [13–15]. Organic matter also significantly affects moisture retention [16], the characteristic curve of soil moisture [17], and thermal conductivity [18], which contribute to evaporation. Improvement of the soil organic matter content using organic fertilisers has become a common agricultural practice [19].

Application of organic fertilisers can improve the soil physical properties [20], increase porosity [21], and improve the conservation of water and crop yield [22,23]. The application of organic fertilisers can improve water use efficiency [24] and increase the content of soil macroaggregates and reduce bulk density, which increases the water storage capacity [25,26]. Varela et al. demonstrated that soil water repellency is closely related to the organic matter content [27]. However, there is no specific conclusion about the functions of organic matter on the water repellency of soil particles. Some studies show that earthworm cast can effectively increase the water holding capacity because of its high organic matter content [27,28].

Earthworm casts are the by-product of the biodegradation of soil organic matter by earthworms. Earthworms could produce up to 5–10 times their own weight in casts in one day [29]. The quantity of earthworm casts in temperate soils is 75–250 t ha^{-1} yr^{-1}, and even larger in tropical grasslands [30]. The beneficial effects of earthworm cast utilization have been proven in agriculture and horticulture [31,32]. In recent years, earthworm cast has been widely used in agricultural production due to its advantageous physical and chemical properties. As earthworm cast is rich in humus and nutrients, it has a high capacity for adsorbing and releasing fertilisers [33,34]. Various studies have shown that earthworm cast can significantly increase soil structural stability [35,36]. Lim et al. noted that earthworm cast is apparently uniform and porous in structure, with a large surface area and deep dark colour [21]. When earthworm cast is applied to the soil, the colour of the soil becomes darker and the soil temperature increases as a result of increased absorption of light energy from sunlight [37]. Furthermore, earthworm cast usually has a lower bulk density than the surrounding soils [38,39]. As a result of earthworm cast application, the abundance and activity of microorganisms in the soil are considerably enhanced and soil aggregates form easily, thereby increasing the total porosity, and decreasing the bulk density of the soil [40]. These facts suggest that the application of earthworm cast may affect soil-water movement. Therefore, we hypothesise that the application of earthworm cast can reduce evaporation from loess soil, but the effect of earthworm cast depends on the application rate and cast size. To test these hypotheses, herein, we conducted column experiments to investigate the effects of the application rate and size of earthworm cast on soil evaporation, water storage capacity, and capillary rise.

2. Materials and Methods

2.1. Soil Preparation

Loamy soil, sampled from fallow farmlands in Yangling in the Shaanxi province and representative of the main soil type in the Guanzhong Plain in northern China, comprised silt-clay soil (5.9% sand, 62.8% silt, and 31.3% clay) of anthrosols with terric horizon derived from manure and loess materials. Undisturbed soil was collected using cutting ring for the determination of bulk density. Disturbed soil samples were air-dried and then passed through a 2-mm mesh sieve. The organic matter content of the soil was 5.36 g kg^{-1} (calculated using the Smith-Weldon method) and the total nitrogen (N) content was 0.81 g kg^{-1} (calculated using the Kjeldahl method).

2.2. Earthworm Cast Source

The earthworm cast used in this study was produced by *Pheretima guillelmi* (Michaelsen) earthworms. A total of 40 adult earthworms were placed in a plastic cylindrical container (inner diameter, 35 cm; height, 30 cm) filled with grated leaves and pomace mixed with 15 kg of corn stalks. The containers were maintained at 20 °C and the water contents of the media were maintained at 10%–15%. Casts were collected from the surface of the substrate every 7 days for 1 month, and numbered according to the date of collection. Cast diameter was measured using a digital calliper and all collected earthworm casts were sorted into two groups: 1–3 × 1–2 cm (diameter × height), or 3–5 × 2–4 cm (diameter × height). The cast size was characterised using diameter × height, which was determined by measuring the width of the bottom and side face five times and calculating the average of the values. All batches of collected earthworm casts (throughout the 1-month collection period) were mixed thoroughly prior to analysis and experimental application. The mechanical composition of the earthworm cast was 19.8% sand, 59.7% silt, and 20.5% clay; the organic-matter content was 18.92 g kg^{-1}; and the total N content was 8.77 g kg^{-1}. The pore characteristics of the earthworm cast and soil samples were determined using a Surface Area and Pore Size Analyzer (BELSORP-mini II, Japan). The weight and volume of randomly selected earthworm casts were measured to calculate the bulk density. Earthworm cast volume was determined by a "drainage method". Firstly, earthworm cast samples were wrapped with melted wax. After the wax was cooled and concreted, the wrapped cast samples were put in a container filled with water. The volume of drained liquid was then determined using a measuring cylinder. Based on the pre-measured weight and density of the wax, earthworm cast volume can be easily calculated. The details of the earthworm cast samples are presented in Table 1.

Table 1. Pore characteristics and bulk densities of earthworm cast and soil used in this study.

	Micro Porosity/%	Effective Porosity/%	Total Porosity/%	Bulk Density/g cm^{-3}
Earthworm cast (1 cm < diameter ≤ 3 cm)	3.6 ± 0.8	57.4 ± 1.6	61.1 ± 2.3	0.73 ± 0.06
Earthworm cast (3 cm < diameter < 5 cm)	5.9 ± 1.1	51.1 ± 1.3	57.4 ± 1.7	0.65 ± 0.05
Soil	1.8 ± 0.7	48.2 ± 1.2	50.3 ± 1.9	1.34 ± 0.08

Note: Micro porosity refers to the pore with equivalent diameter < 0.002 mm. Effective porosity refers to the equivalent diameter of soil pore > 0.002 mm.

2.3. Experimental Design

The evaporators used in the experiment comprised of plexiglass columns (20 × 35 cm, diameter × height) with graduated depth markings, and the inner wall was coated with petroleum jelly to reduce the effects of the wall on water infiltration. A piece of nylon gauze was placed at the bottom of the column to prevent finer soil particles from blocking the bottom holes. Air-dried soil samples and earthworm cast were mixed thoroughly and then packed into each column to a depth of 25 cm. Both the application rate and earthworm cast size were analysed to determine their effects on soil evaporation. In addition to the control, three different application rates were used in the present study, according to farming practices in China. The total amount of soil and earthworm cast used per treatment was 7854 g. The quantity of soil per treatment was 7854 g for the 0% control group (no cast), 7461 g for the 5% (M1) group, 7265 g for the 7.5% (M2) group, and 7069 g for the 10% (M3) group. The bulk density of each treatment is shown in Table 2. In addition, two sizes of pre-sorted cast were used for the different treatments (1–3 cm diameter: S1; and 3–5 cm diameter: S2). The study included a total of eight treatments with three replicates. The surface of each soil column was covered with a piece of filter paper to prevent crust formation during watering.

The soil samples were then cultured at 22 ± 3 °C and a relative humidity of 35% ± 3% for 1 month. The capillary rise test was carried out during the culturing of the soil columns. Water was applied using Mariotte bottles (65 × 10 cm, height × inner diameter) connected to the bottom of the soil column via a rubber hose, with a head height of 3 cm. At the beginning of the water input test, the water-stop clamp of the Mariotte bottle rubber hose was opened and the surface of the sample column was covered with a plastic film to prevent soil water evaporation. Based on the time interval between the initial dense water content and the final sparse water content, the volume of supplied water from the Mariotte bottle was recorded at short time intervals for the early period and longer time intervals for the later period, e.g., the volume was recorded every 10 min within the first hour, then every hour from 2 h to 16 h, and finally, every 4 h from 16 h onwards. Meanwhile, the height of wetting front in each column was also recorded and used as an index of capillary rise. When the soil surface layer was wet, the water supply was stopped, and the water storage capacity was calculated as the difference in the weight of the soil column before and after the test. The quantity of absorbed water is equal to the soil water storage when water moves from the bottom to the surface of the soil column. Following this, the columns were left undisturbed for 12 h with no further water supply, then weighed again to determine the soil water content following the different treatments (Table 2). Afterwards, all columns were moved outdoors for an evaporation test. Plastic films were used to cover the soil surface when it rained. Daily evaporation was measured by weighing the columns at 8:00 a.m. every day for 15 consecutive days using an electronic scale with a measurement range of 0–30 kg at a precision of 1 g (Zhujiang Weighing Apparatus Co., Ltd., Zhejiang Province, China). These measurements were used to estimate the cumulative evaporation and daily evaporation rates. On-site atmospheric evaporation was also measured using an evaporation pan at the same time. In addition, soil samples were collected from the 0–10 cm and 10–25 cm layers of each column at the end of the evaporation experiments to measure the water content at the different layers.

Table 2. Basic properties of different treatments at the beginning of evaporation experiment.

		Application Dose			
		0%	5%	7.5%	10%
Earthworm cast (1 cm < diameter ≤ 3 cm)	Initial soil water content (%)	21.1 ± 1.2	22.4 ± 1.7	23.2 ± 1.4	24.6 ± 2.1
	Bulk density (g cm^{-3})	1.34 ± 0.07	1.22 ± 0.05	1.19 ± 0.09	1.17 ± 0.06
	Total porosity (%)	50.3 ± 1.9	52.6 ± 1.7	53.5 ± 1.6	55.2 ± 2.4
	Organic matter content (g kg^{-1})	5.36 ± 0.32	6.12 ± 0.42	6.35 ± 0.47	6.88 ± 0.53
Earthworm cast (3 cm < diameter < 5 cm)	Initial soil water content (%)	21.1 ± 1.2	21.9 ± 1.5	22.8 ± 1.7	24.1 ± 1.2
	Bulk density (g cm^{-3})	1.34 ± 0.07	1.18 ± 0.03	1.15 ± 0.04	1.10 ± 0.04
	Total porosity (%)	50.3 ± 1.9	53.3 ± 1.1	54.1 ± 2.3	55.7 ± 2.7
	Organic matter content (g kg^{-1})	5.36 ± 0.32	6.08 ± 0.37	6.31 ± 0.41	6.83 ± 0.43

2.4. Data Analysis

The cumulative evaporation and ratio of soil evaporation to atmospheric evaporation (SEAE) were used to determine the effect of application dose of earthworm cast and cast particle size on soil evaporation, which was calculated using the following equation:

$$\text{SEAE} = \text{Es}/\text{Ea} \quad (1)$$

where Es is the daily evaporation of soil and Ea is atmospheric evaporation.

We also examined the effects of soil water storage capacity, soil water content, and earthworm cast on anastatic water to evaluate the effects of earthworm cast on soil water properties. Data were tested using two-way analysis of variance, with the amount of earthworm cast application and cast particle size, as well as the interaction between them, as the factors. A least significant difference test was used to determine the effects of application dose and particle size on soil evaporation. Differences were regarded as significant at p-values < 0.05, using SPSS 20 to fit the statistical data. Fisher's least significant difference (LSD) test was used to evaluate the significant differences between the treatments ($p < 0.05$). All findings were obtained using Origin 8.0 software (Origin Lab, Northampton, MA, USA).

3. Results

3.1. Soil Evaporation Characteristics

The SEAE ratio was used to determine the differences in evaporation rates in the different treatments. In all cases, the SEAE ratio declined over time (Figure 1). As water was sufficient during the early stage of evaporation, the SEAE ratio exceeded 0.75 for the first 6 days of the experiment. After this time, the evaporation intensity weakened as the water in the soil column gradually decreased. At 7–15 days, the minimum SEAE ratio was only 0.21. The SEAE was significantly affected by earthworm cast size, the amount of cast added, and their interaction ($p < 0.05$; Table 3). Among the S1 treatments, the SEAE ratio followed the order of 5% earthworm cast < 7.5% earthworm cast < pure soil (control) < 10% earthworm cast for the first 10 days of the evaporation experiment. However, the ratio of SEAE was significantly higher ($p < 0.05$) in the 7.5% earthworm cast treatment than in pure soil on the 11th day, and the daily evaporation of soil in the 7.5% treatment was greater than that in pure soil after this point. Among the S2 treatments, the daily evaporation in the soil samples treated with earthworm cast was significantly higher than that in untreated soil ($p < 0.05$). The SEAE ratio increased with increase in earthworm cast application dose. In the 5% and 7.5% samples, the SEAE ratio was significantly lower in the S1 than in the S2 treatments, while the 10% application dose showed no significant difference among the treatments with different particle sizes.

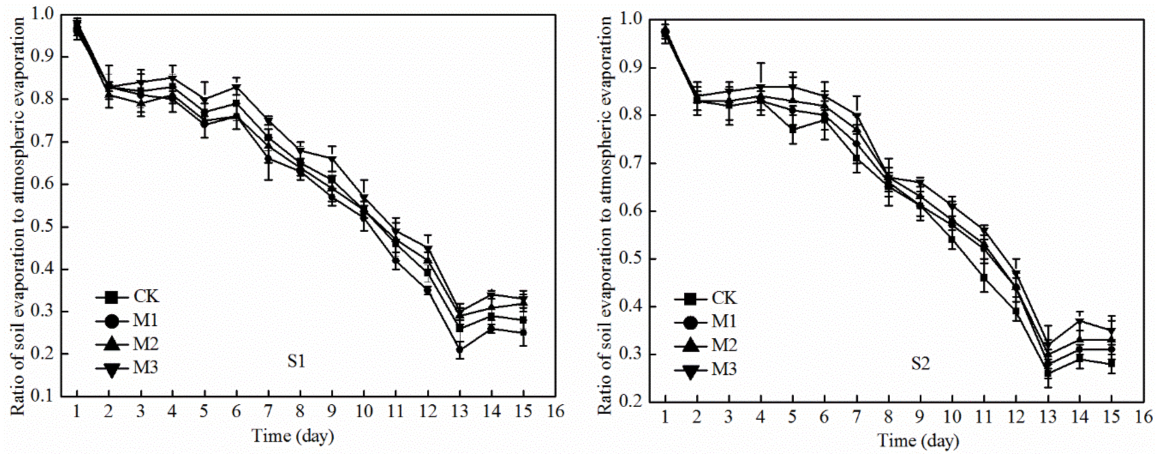

Figure 1. Effects of earthworm cast application on the ratio of soil evaporation to atmospheric evaporation. S1 and S2 represent applications with earthworm cast particle size classes of 1 cm < diameter ≤ 3 cm and 3 cm < diameter < 5 cm, respectively.

Table 3. Main and interactive effects of earthworm cast application dose on several indexes related to soil evaporation.

Parameters		SEAE	Soil Cumulative Evaporation	Deep Water Recharge	Soil Water-Holding Capacity	Soil Water Content
Size	*p*	0.043	0.036	0.015	0.023	0.033
	F	15.23	27.75	17.62	34.39	23.52
Dose	*p*	0.028	0.045	0.023	0.017	0.031
	F	7.86	11.25	21.34	43.57	29.33
Size × Dose	*p*	0.037	0.043	0.067	0.083	0.029
	F	7.15	10.34	2.15	1.73	7.42

The temporal variations in soil cumulative evaporation relative to different earthworm cast application doses during the first 15 days of the experiment are shown in Figure 2. Earthworm cast size, application dose, and their interaction had significant effects on soil cumulative evaporation ($p < 0.05$; Table 3). For the S1 treatments, cumulative evaporation for the 7.5% and 10% doses was 1088.9 and 1156.3 g, respectively, and significantly higher than that for the 5% dose (1010.7 g) or for pure soil (1062.6 g) ($p < 0.05$). In the S2 treatments, cumulative soil evaporation was 1062.6 g in the pure soil treatment at the end of the evaporation experiment, compared to 1126.2, 1156.6, and 1207.5 g under the M1, M2, and M3 treatments, respectively. The earthworm cast application treatments also showed significantly higher cumulative evaporation than that of pure soil ($p < 0.05$). A comparison of the cumulative evaporation of the same earthworm cast dose indicated that large-sized (S2) earthworm cast led to significantly higher degrees of evaporation than small-sized (S1) earthworm cast ($p < 0.05$).

These findings demonstrated that soil evaporation was enhanced regardless of cast size and dose, with the exception of the 5% application dose under S1 treatments.

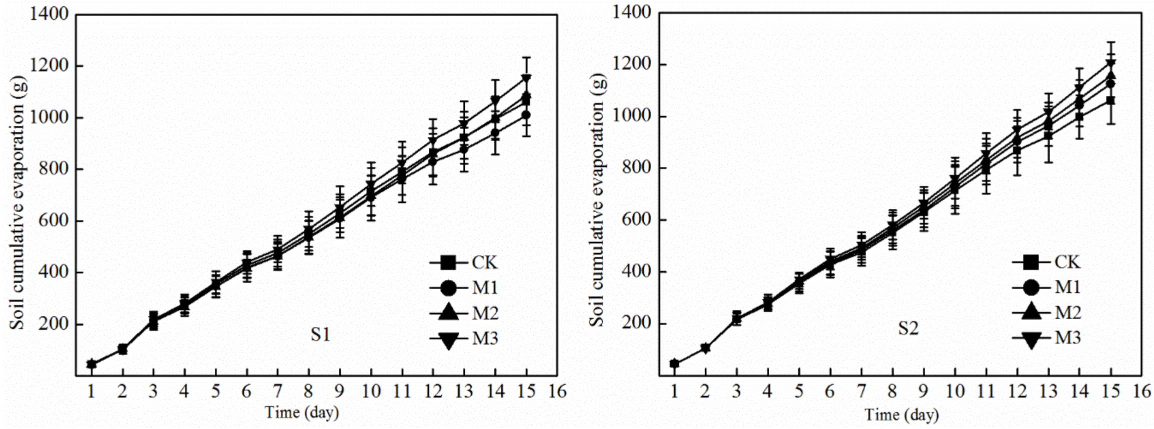

Figure 2. Effects of earthworm cast application on the temporal variation in cumulative soil evaporation. S1 and S2 represent applications with earthworm cast particle size classes of 1 cm < diameter ≤ 3 cm and 3 cm < diameter < 5 cm, respectively.

3.2. *Capillary Water Upward Movement*

The effects of earthworm cast treatments on capillary water upward movement in the first 32 h of the experiment (during which the wetting front did not reach the soil surface in any of the treatments) are plotted in Figure 3. The ordinate represents the scale value of the Mariotte bottle, which reflected the quantity of upward-moving capillary water. Earthworm cast particle size and dose had significant effects on upward capillary water ($p < 0.05$; Table 3), but their interaction did not affect upward water ($p > 0.05$; Table 3). In all experiments, the anastatic water followed the order of 10% earthworm cast > 7.5% earthworm cast > 5% earthworm cast > pure soil. Among the S1 treatments (Figure 3S1), the volume of upward capillary water in the control group was significantly lower than in the cast-treated groups ($p < 0.05$). The maximum rise was measured in the treatment with the highest earthworm cast dose at 10%. However, no significant differences in upward moving capillary water were observed among the treatments with earthworm cast. In the S2 treatment group (Figure 3S2), the volume of upward moving capillary water did not differ significantly between the control and the 5% earthworm cast dose, but was significantly higher in the 7.5% and 10% application doses ($p < 0.05$). The volume of upward moving water driven by capillary force was significantly higher ($p < 0.05$) in treatments with the same dose but with the smaller-sized cast particles than with the larger-sized cast particles. For example, at the beginning of day 28, capillary water movement upward in soils treated with small-sized earthworm cast particles was 1.0 cm (M1), 0.6 cm (M2), and 1.7 cm (M3) higher than that in soils treated with large-sized cast particles.

The application of earthworm cast increased the upward capillary water. During the process of evaporation, the moving rate of water to the surface soil also affected the evaporation intensity. The volume of upward capillary water increased with increasing earthworm cast application, but the rate of increase reduced over time (Figure 3). We define upward rate as the volume of upward capillary water per unit time and used a power function to fit the temporal variation in the upward capillary water:

$$I\,(t) = Kt^{-n} \tag{2}$$

where $I\,(t)$ represents the upward rate of water from the bottom, t represents the time, and K and n are empirical constants. In order to evaluate the fitting effect, the determination coefficient R^2 and root mean square error (RMSE) were determined. The fitting effect increases with the increase of R^2 and decreases with the increase of RMSE. The range of RMSE and R^2 for the model fit was 0.0033–0.0039 and 0.996–0.998, respectively, which indicated a strong goodness-of-fit. The fitted parameters are shown in Table 4. The exponential *n* reflects the attenuation degree with the upward rate. The *n* values for all earthworm cast application treatments were lower than that for the control treatment. As the application dose of earthworm cast increased, the index *n* apparently decreased. Under the same application dose of earthworm cast, the index *n* was higher under the S2 treatment than the S1 treatment, suggesting that the application of larger earthworm cast could slow the degree of attenuation. As the evaporation process proceeded, the application of earthworm cast significantly improved the upward rate of capillary water from the bottom compared to the control treatments. In addition, the anastatic water was greater in the S1 treatments than in the S2 treatments.

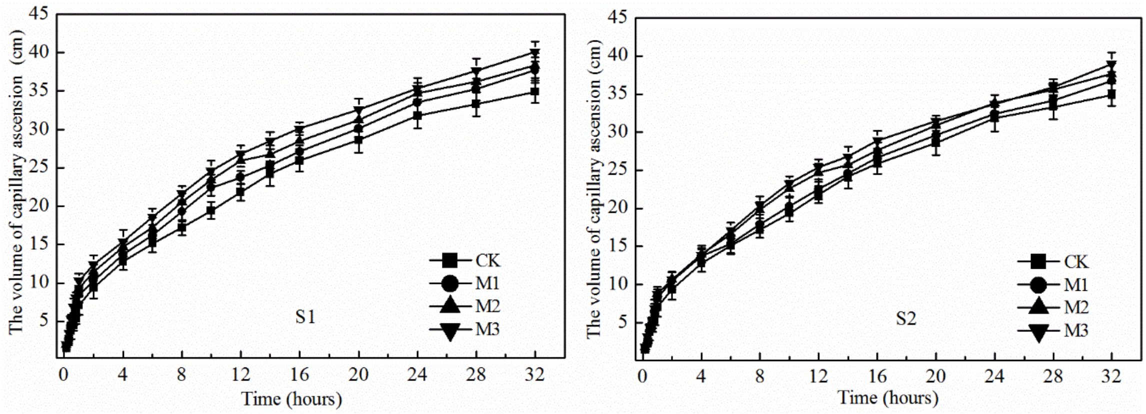

Figure 3. Effects of different earthworm cast applications on the upward capillary water. S1 and S2 represent earthworm cast particle size classes of 1 cm < diameter ≤ 3 cm and 3 cm < diameter < 5 cm, respectively.

Table 4. Fitted parameters of upward rate of capillary water under different applications of earthworm cast to the soil.

Treatment	S1				S2			
	K	n	R^2	RMSE	K	n	R^2	RMSE
CK	1.14624	0.50955	0.996	0.0038	1.14624	0.50955	0.996	0.0037
M1	1.93526	0.4912	0.996	0.0039	1.47256	0.5036	0.998	0.0033
M2	2.64726	0.47331	0.997	0.0036	2.26941	0.48022	0.996	0.0038
M3	2.91617	0.44612	0.996	0.0038	2.46439	0.47865	0.996	0.0037

Note: K and *n* are empirical parameters and R^2 is the determination coefficient. RMSE is the root mean square error.

3.3. Soil Water Storage Capacity and Water Profile Distribution

Earthworm cast particle size and addition rate had significant effects on soil water storage capacity ($p < 0.05$; Table 3), but their interaction had no significant effect on soil water storage capacity ($p > 0.05$; Table 3). The application of earthworm cast will affect the physico-chemical properties of soil as shown in Table 2. The initial water content, total porosity, and organic matter content of soil increased with the increase of application doses, while the bulk density decreased with the increase of application doses. The soil water storage capacity of the control soil samples was significantly lower than that of the soil samples treated with earthworm cast. Significant differences were also observed among the earthworm cast application treatments ($p < 0.05$; Figure 4), whereby the soil water storage capacity increased with the increase in earthworm cast dose. Under the same application doses, the soil water storage capacity of the S1 treatments was higher than that of the S2 treatments. At the end of the capillary water upward movement experiment with the S1 treatment, the soil water storage capacities of the 5%, 7.5%, and 10% application doses were 22.9%, 34.1%, and 48.9% higher, respectively, than that in the control (0.4248 L/kg). The effects of earthworm cast dose on the soil water storage capacity under the S1 treatment was similar to those seen under the S2 treatment, in which the water contents were 19.2%, 28.1%, and 34.5% higher than the control treatment for the 5%, 7.5%, and 10% earthworm cast application doses, respectively.

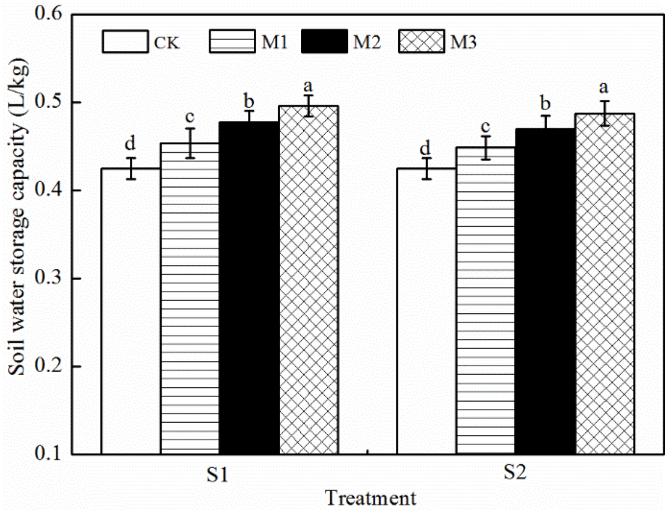

Figure 4. Effects of earthworm cast applications on the soil water storage capacity. S1 and S2 represent earthworm cast particle size classes of 1 cm < diameter ≤ 3 cm and 3 cm < diameter < 5 cm, respectively.

The water content in the layers at different soil depths under different earthworm cast application doses at the end of the evaporation are shown in Figure 5. Earthworm cast particle size, addition doses, and their interaction had significant effects on the soil water content ($p < 0.05$; Table 3). Water content in the different soil layers under the earthworm cast application treatments decreased initially before increasing with increasing soil depth. For the same application doses, the water contents in the soil layers at different depths under the S1 treatment were significantly higher than those under the S2 treatment ($p < 0.05$). Among the S1 treatment groups, the soil water content of each layer for the 5% earthworm cast application dose was higher than those of the 7.5% and 10% application doses and pure soil. Soil water content eventually increased to the depth of 10 cm. Significant differences were observed in the soil water content at different depths among the treatments with earthworm cast. Among the S2 treatment groups, the water content in the 0–10-cm and 10–25-cm layers decreased with increasing earthworm cast application. The water content increased to the depth of 15 cm after the application of 5% earthworm cast, as well as to 10 cm soil depth after the application of 7.5% and 10% earthworm cast, but no significant difference was found among the treatments at the depth of 10 cm. Compared with pure soil, all treatments had higher water content in the 10–25-cm soil layer, regardless of the cast application dose and particle size. Additionally, the increase in water content with the increase in soil depth was higher following the earthworm cast treatments than in the pure soil. This suggests that the application of earthworm cast to soil could increase the water content of deep soil.

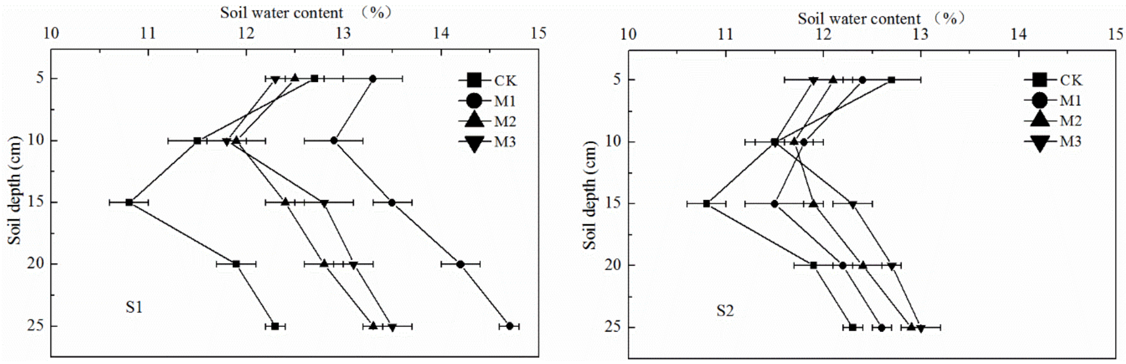

Figure 5. Effects of earthworm cast applications on the soil water content at different soil depths. S1 and S2 represent earthworm cast particle size classes of 1 cm < diameter ≤ 3 cm and 3 cm < diameter < 5 cm, respectively.

4. Discussion

4.1. Effects of Earthworm Cast on Soil Evaporation

Soil evaporation is a critical component of the hydrological cycle, and is affected by soil structure, soil surface characteristics, soil temperature, and atmospheric evaporation factors [41,42]. In this study, earthworm cast application significantly increased soil cumulative evaporation ($p < 0.05$), except in the 5% application treatment with small-sized earthworm cast particles. The promotion of soil evaporation increased with increasing earthworm cast dose, which is consistent with the findings of Wang et al., who demonstrated that there is a significant correlation between the application dose of earthworm cast and water availability [43].

As shown in Figure 2, the application of large-sized earthworm cast and soil treated with 7.5% and 10% small-sized earthworm cast particles promoted soil evaporation, while soil treated with 5% small-particle size cast showed inhibited soil evaporation. The effects of earthworm cast depend on the interaction of cast size and application rate. Compared with the application of large-particle earthworm cast, small-particle cast is smaller in volume and more dispersed in the soil. Therefore, the effect of small-particle cast was greater in improving soil organic matter than porosity, which led to higher soil water capacity (Table 2). Broadly, the application of earthworm cast may change the quantity and spatial arrangement of aggregates of different-sized soil grains as well as the hydraulic characteristics of the soil [44]. Under the same application dose, the specific surface area and porosity of small-particle earthworm cast were higher (Table 1). A highly porous structure and a large specific surface area improve the soil water retention ability [45], and therefore, inhibit soil water evaporation, i.e., by promoting the accumulation of more moisture (Figure 2S1). The 7.5% application of small-particle cast inhibited soil water evaporation at the early stage of the experiment. Nevertheless, compared with the effects of earthworm cast on the water storage capacity and soil water evaporation, soil macropores and temperature under treatments with small-particle earthworm cast had a greater effect on soil water evaporation. Aksakal et al. also concluded that earthworm cast contains a large number of particles that are less than 53 μm in size, which can increase the specific surface area of the soil particles [35]. Smaller-sized cast particles usually have larger external surface areas, which increases the potential for interaction with microorganisms, and thus, improves their ability to absorb water. Therefore, the application of the 7.5% small-particle cast was shown to improve the soil evaporation at the later stage of the experiment.

4.2. Effects of Earthworm Cast on Upward Capillary Water, Soil Water Storage Capacity and Water Profile Distribution

Intense soil evaporation in arid areas leads to surface water loss and therefore, water moves upward continuously from subsurface soil [46]. Soil water storage capacity and capillary water upward have important effects on the evaporation process. The evaporation of soil moisture decreases with increased water storage capacity and increases with the volume of capillary water [47,48]. The application of earthworm cast could significantly increase upward capillary water (Figure 3). Many studies have described earthworm cast treatment as a possible means to enhance soil permeability and improve soil hydraulic conductivity [49,50]. This could explain our findings that stated that increased earthworm cast application led to increased upward capillary water levels. Furthermore, organic matter plays a key role in soil moisture variation [15]. Earthworm cast is rich in polysaccharides, with an organic matter content as high as 30% [51,52]. Kumar attributed the increase in water retention capacity of soil to the absorbent organic matter in earthworm cast [53]. In our experiment, the application of earthworm cast increased the content of soil organic matter; this was presumably the main reason for our findings whereby the soil water storage capacity increased with the increasing cast treatment, as well as for the fact that the water storage capacity of small-particle cast was better than that of large-particle cast (Figure 5). Similarly, as a major component of organic matter, humus consists mostly of hydrophilic colloid, which is effective for improving soil water retention performance [31,54]. In addition, soil water storage capacity has an effect on soil water evaporation rate [55]. Similarly, we found that the initial soil moisture content increased with water storage capacity at the beginning of the experiment. Xiao et al. reported positive correlations between the soil water content and evaporation rate [11]. Our findings indicate that soil evaporation tends to increase with the initial water content in the same cast particle size treatments (Figure 2). Similarly, Li et al. observed that soil evaporation was proportional to the initial water content [56]. Therefore, the water storage capacity and initial water content may better explain the effect of application doses on soil evaporation.

As shown in Figure 5, the soil water content significantly increased under higher doses of earthworm cast (7.5% and 10%). As a cementing agent in the soil, polysaccharides are favourable for the formation and maintenance of agglomerates [21]. Additionally, the application of earthworm cast can increase the total porosity and effective porosity (the equivalent diameter of pore > 0.002 mm) of soil [57], and thus promote the upward movement of capillary water. The effective porosity of the soil and upward capillary water increases with decreasing particle size of earthworm cast in the soil. Therefore, the initial penetration rate under small-particle cast treatments would have been higher than that under treatments with large-particle cast, which could explain the observed difference in the water storage capacity between the cast particle sizes. Under the same application doses, small-particle earthworm cast has a higher abundance of pores and larger specific surface area [21], which may enable the growth of beneficial micro-organisms in the soil [58]. Under this scenario, large amounts of mucopolysaccharides could bind to organic colloids in the soil to form crumb structures and improve soil water retention [59]. Therefore, the water storage capacity of soils treated with small-particle earthworm cast was greater than that of those treated with large-particle earthworm cast (Figure 4).

5. Conclusions

Our findings suggest that the application of earthworm cast has both positive and negative effects on soil water evaporation. The impacts were closely correlated with the application rate of earthworm cast and the particle size of the cast. Soil evaporation can be enhanced after applying earthworm cast in most cases, except for the use of small-size cast at a very low application rate. Earthworm cast influences soil evaporation by altering soil water storage capacity and capillary upward movement; these effects were greater for higher application rates and smaller cast size. Based on these findings, we suggest that the application of small-particle earthworm cast will improve soil water retention and inhibit soil water evaporation.

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