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Characteristics of Soil Moisture and Evaporation under the Activities of Earthworms in Typical Anthrosols in China

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Abstract: Earthworms have an important influence on the terrestrial ecological environment. This study assesses the effect of different earthworm densities on soil water content (SWC) and evaporation in a laboratory experiment. Four earthworm densities (0 no-earthworm, control [C]; 207 earthworms m^{-2}, low density [LDE]; 345 earthworms m^{-2}, medium density [MDE]; and 690 earthworms m^{-2}, high density [HDE]) are tested in soil columns. Results show that cumulative evaporation occurs in the decreasing order of densities: C (98.6 mm) > LDE (115.8 mm) > MDE (118.4 mm) > HDE (124.6 mm). Compared with the control, earthworm activity decreases cumulative soil evaporation by 5.0–20.9%, increases soil temperature to 0.46 °C–0.63 °C at 8:00, and decreases soil temperature to 0.21 °C–0.52 °C at 14:00 on the soil surface. Temperature fluctuations reduce with increasing earthworm densities. A negative correlation is found between cumulative soil evaporation and earthworm density ($R^2 = 0.969$, $p < 0.001$). Earthworms significantly ($p < 0.05$) decrease the surface SWC loss (0–20 cm) soil layer but increase the subsoil SWC loss (60–100 cm) by adjusting the soil temperature and reducing soil water evaporation. Earthworm activities (burrows, casts . . .) improve the soil water holding ability by adjusting soil temperature and reducing soil water evaporation. Thus, the population quantity of earthworms may provide valuable ecosystem services in soil water and heat cycles to save water resources and realize sustainable agricultural development.

Keywords: cumulative soil evaporation; soil water content; soil temperature; earthworm

1. Introduction

The frequency of extreme weather events is expected to increase worldwide in the 21st century [1]. Agriculture and ecosystems are experiencing new ecological, economic, and social demand challenges for sustainable development. Improving the effective rate of water resource usage is urgently required for ecologically sound agriculture and the sustainable development of ecological environments. The storage and evaporation of soil water are major forms of soil water consumption in the water cycles of agricultural production and ecosystems. These processes are mainly affected by soil water content (SWC), soil texture and structure, and soil organic matter, excluding meteorological factors. However, the actions of various soil-dwelling animals can affect soil structure. Analysis of the influence of soil macro fauna, particularly earthworms, ants, and termites, on runoff and infiltration increasingly attracts soil scientists [2–4]. These organisms increase water flow [5], improve soil fertility quality and the aboveground biomass in agroecosystems [6] and water infiltration [7], and increase crop yield [3].

Earthworms are "ecosystem engineers" because their feeding behavior and habitat affect soil structure [2,8,9]. Earthworms are categorized into three functional groups: epigeic, endogeic, and anecic species [10]. Their different ecological functions are due to their varied habitats and feeding preferences. Anecic earthworms, for example, mainly live in soil, create unique cave structures, and mix organic matter with soil by eating soil rich in organic matter. The feeding and casting activities [11,12] of earthworms largely affect pedogenesis [13], soil structure development [14], water regulation, nutrient cycling [15,16], primary production, soil microbial communities [17], climatic regulation, and the degradation and transformation of pollutants in soil [18,19]. Earthworms can increase porosity and decrease or increase bulk density, both of which increase water infiltration into the soil, reduce surface water flow, prevent soil erosion, and influence soil water storage [20–22]. Ehlers [23] showed that the water storage reaches 25% higher 10 years after the introduction of earthworms in a temperate climate. Emmerling et al. [24] found that the infiltration amount of irrigation in cultivated land increases 1.4–2 times under earthworm activities and that the infiltration degree of soil water is directly related to earthworm biomass. Capowiez et al. [25] observed that soil physicochemical properties and earthworm abundance may considerably affect earthworm burrows and water infiltration.

Earthworms also excrete a large amount of feces on the soil surface or within soil profiles. Casts not only increase soil organic matter [26], but also exhibit good water stability. Some researchers found the casts could improve soil microbial activity [27] and the soil water holding capacity [28], thereby affecting soil nutrient cycling [29,30]. Earthworms redistribute organic materials and influence ion transport in soils by their feeding and burrowing behavior. Amossé [26] suggested that earthworm activity increases the soil organic matter turnover (carbon and nitrogen mineralization) and soil structure and accelerates bio-physicochemical processes in soils. Thus, earthworms have similar functional roles to ants and termites for agriculture sustainability in the future [3,31]. Earthworms affect soil structure, water infiltration, and nutrient cycling in natural ecosystems. However, the effects of earthworms on soil heat and soil evaporation are unclear. Thus, this investigation aims to (1) evaluate the influence of the activities of burrowing earthworms on soil temperature and SWC in typical anthrosol soil profiles and (2) clarify the characteristics of soil water evaporation under earthworms and the effects of its main factors. This study provides an important step toward the prediction of the long-term effects of earthworm activities on the agriculture ecosystem hydrologic cycle.

2. Materials and Methods

2.1. Site Location and Soil Preparation

This study was conducted at the experimental station of the Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi Province, China (34°17′ N, 108°00′ E; 534 m a.s.l.) on the Southern Loess Plateau. This region has a temperate sub-humid continental monsoon climate. The mean annual temperature and precipitation are 13 °C and 550 mm, respectively. The soil type is a typical anthrosol (Lou soil) developed from silt loam. The soil contains 6.3% sand, 68.4% silt, and 25.3% clay. The field capacity is 21–23%, and the saturated water content is 32%. The soil bulk density is 1.32 g·cm^{-3}. Variations of the daily air temperature during the experiment are shown in Figure 1.

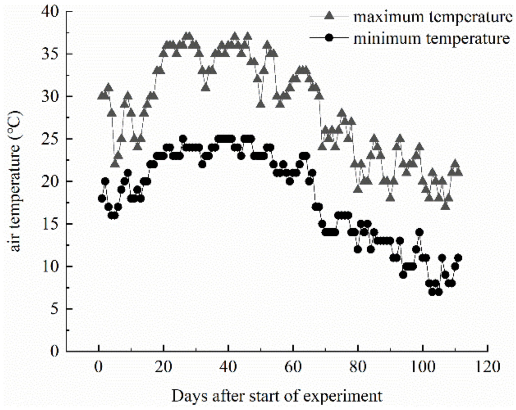

Figure 1. Daily maximum and minimum temperature during the experiment period.

Soil samples were collected from the upper 30 cm of farmland topsoil near Yangling. The samples were air dried, sieved to <2 mm particles, and then packed into 25 cm-diameter and 110 cm-high polyvinyl chloride (PVC) cylinders in 5 cm layers. A PVC screen was glued to the bottom of the cylinders to retain the soil. Drainage was not possible. The dry bulk density was controlled at 1.39 $g \cdot cm^{-3}$. The filled cylinders were watered to 25% SWC (gravimetric) and placed 110 cm deep underground to simulate the conditions of farmland soil. All soil cylinders were placed outside and covered with a canopy to avoid rainwater inputs. Finally, the center soil of the cylinder was removed by a hollow soil drill with the same diameter as that of the outer pipe of PR2-6 (Cambridge, UK, Delta-T Device Ltd.). The outer pipe of PR2-6 (100 cm long and 2.8 cm in diameter) was installed in the soil. The PR2-6 probe was inserted into the pipe to measure SWC of the soil every time.

2.2. Experimental Design and Source of Test Earthworms

An anecic species of earthworm (*Metaphire guillelmi*) was selected for this study [32]. *M. guillelmi* is the dominant local species, and it was collected in large numbers by shovel from grassland in Yangling. Sexually mature earthworms were transferred to the laboratory, washed, and then weighed. Similar-sized earthworms were inoculated into the soil columns. Occurring at the beginning of the experiment, cow manure (10 g per soil column) was added to the soil surface to feed the earthworms, including the controls (C). Each cylinder was covered with net containing small holes to prevent escape. Dead earthworms from the soil surface were timely removed and replaced. The earthworms were taken out by electrical extraction, and the numbers of living earthworms were counted after the experiment finished. Ultimate mortality was calculated in each column. The earthworm mortality was 10–20% during the experimental period.

We evaluated the effects of the earthworms on SWC and evaporation by varying the number of earthworms introduced into each column. We tested high (HDE, 10 earthworms), medium (MDE, 5 earthworms), and low (LDE, 3 earthworms) numbers of worms and a C column with no earthworms, with corresponding densities of 690, 345, 207, and 0 earthworms ind. m^2. The settings of the density were developed by referring to Holden et al. [33]. Each treatment included five replicates, with a total of 20 columns. The experiment ran from 29 June 2018 to 17 October 2018. During the experiment, the earthworms dug several burrows in the soil and simultaneously excreted cast on the soil surface, forming natural mulching materials. The casts were collected manually, and the dry weight was recorded at the end of the experiments. The cast quantities on the soil surface differed given the varied earthworm densities used in the experimental treatments (Figure 2).

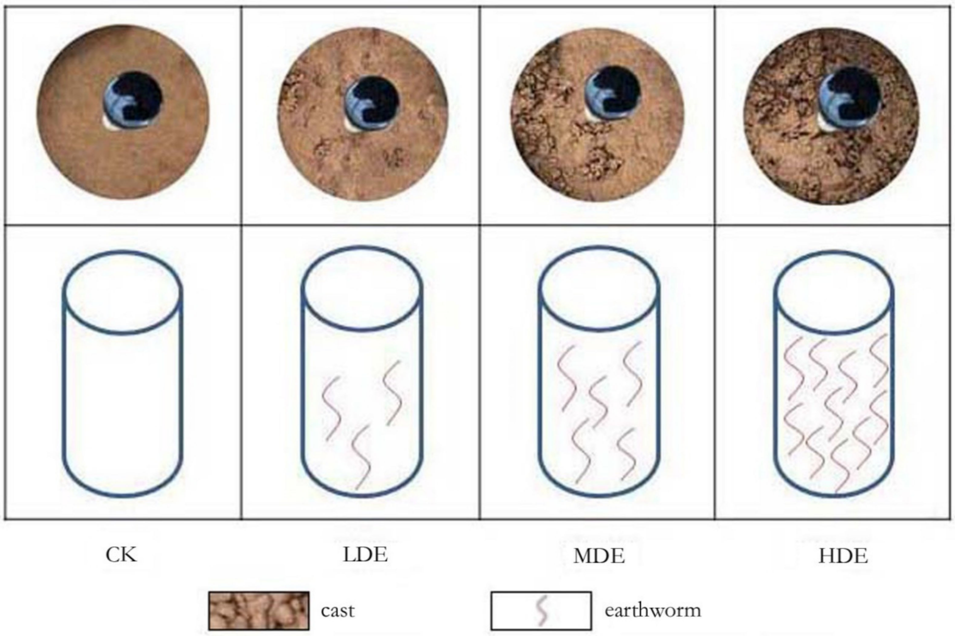

Figure 2. Different earthworm densities: HDE (10 earthworms), MDE (5 earthworms), LDE (3 earthworms), and CK (no earthworms) in the experiment column and the casts from different earthworm densities covering the soil surface.

2.3. Measurements of Evaporation, SWC and Temperature

Each cylinder with a soil column was weighed at 19:00 daily using an electronic scale with a range of 0–150 kg and a precision of 1 g to estimate cumulative soil evaporation and soil evaporation rate (E). SWC was measured at the depths of 10, 20, 40, 60, and 100 cm using PR2-6 probes every other day. Soil temperature for each column was measured at 8:00, 14:00, and 19:00 every 2 days by soil thermometers (with 0.1 °C precision) (Haoyu Electronic Technology Co., Ltd. in Shenzhen City, Guangdong Province, China) installed at 5 and 10 cm deep in the soil in each cylinder.

2.4. Statistical Analysis

One-Way ANOVA in SPSS 19.0 (IBM Corp., Armonk, NY, USA), followed by a least significant difference test ($p < 0.05$), was conducted to compare the SWC and temperature under different densities of earthworms. Stepwise regression analysis (SPSS 19.0) was conducted to examine the effect of the main factors of soil evaporation. Correlations were determined using the sample coefficient of determination (R^2). An R^2 close to 1 indicated a high simulation accuracy. The root mean square error (RMSE) was calculated to evaluate model precision.

3. Results

3.1. Variation of SWC with Earthworm Density

The SWC during the 111-day experimental period followed the order HDE > MDE > LDE > C (Figure 3a). The SWC varied in three stages during the experimental period. The SWC decreased rapidly in the first stage (days 1–23) when the average SWC in the C decreased from 25.43% to 16.50%. The SWC was 3.9–6.1% higher in the earthworm treatments than in the control. The SWC decreased slowly in the second stage, that is, from day 24 to day 103, when the average SWC in the C decreased from 16.50% to 11.59%. The SWC was 10.6–26.2% higher in the earthworm treatments than in the C. The SWC was extremely low in the third stage (days 104–111). The soil dried, and the SWC in each treatment was similar to that in the C. The SWC in the third stage was 0.7–18.9% higher in the earthworm treatments than in the control.

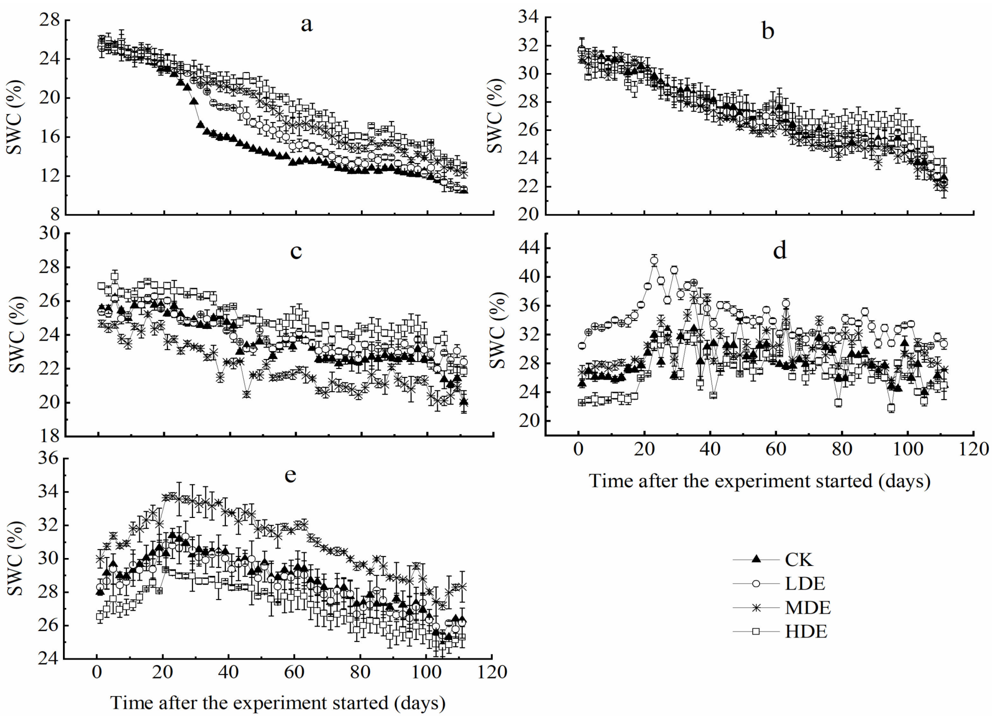

Figure 3. Variation of SWC (% cm^3/cm^3) in the column for CK (without earthworm), LDE, MDE, and HDE at depths of 10 (**a**), 20 (**b**), 40 (**c**), 60 (**d**), and 100 (**e**) cm.

Seen in Figure 3, the SWC of the soil at the 0–20 cm depth significantly decreased during the experimental times. The soil water of the C decreased from 25.4% to 10.4%, which had the largest descent range among the earthworm treatments. The SWC was significantly different between earthworms and the C ($p < 0.05$) at 0–20 cm. The introduction of earthworms was beneficial for storing water at the soil surface from 0 cm to 20 cm relative to the C. The SWC in the 30–60 cm layers was higher in the HDE than in the lower-density treatments and the C (Figure 3b–d). Seen at the 60–100 cm soil layer, no significant difference was found between the earthworm treatments and the C, but the SWC ($p > 0.05$) showed an increasing trend at the first stage and then decreased in the later stage. The casts of the HDE (1422.6 g) were more than those of the MDE (871.8 g) and the LDE (543.6 g) on the soil surface during the experiment times (Figure 1). The earthworms significantly decreased the SWC loss in the 0–20 cm soil layer and increased the SWC loss in the 60–100 cm layer. These results may be due to the notably larger earthworm casts on the soil surface in the HDE than in the other treatments. The casts benefitted the storage of soil water by forming a protective layer on the soil surface. However, the HDE produced additional cavities in the soil, which increased connectivity in the soil profile and benefitted soil water movement to the upper layer soil by evaporation. Thus, the SWC, at the depth of 100 cm, was lower in the HDE than in the MDE and the LDE under evaporative conditions (Figure 3). The MDE had fewer casts than the HDE and contained more burrows than the LDE and the C. The higher burrow density and lesser number of casts in the MDE than in the other treatments increased the amount of water lost by evaporation. The lowest SWC in the 30–40 cm layer was observed in the MDE. However, the more burrows in the MDE, the higher was the infiltration of water to deep soil. Thus, the SWC was the highest at 100 cm. The average SWC in the 0–100 cm profile was lower in the LDE than in the C.

3.2. Variation of Soil Temperature with Earthworm Density

Seasonal temperature fluctuations beneficially affected the soil surface temperature. Thus, soil temperatures at 5 and 10 cm depths were investigated. The results are shown in Figure 4. Soil temperature showed no significant difference between the earthworm treatments and the C at 8:00 (Figure 4a,c). However, the soil temperature of the earthworm-treated soils was higher than that of the

C when solar radiation was the highest (14:00; Figure 4b,d). No significant difference in temperature was observed among the four treatments during the experimental period (Figure 4). Occurring at 14:00, the highest soil surface temperature (35.2 °C) was observed in the C in June, followed by that in the LDE (34.86 °C), the MDE (34.58 °C), and the HDE (34.1 °C). When the air temperature at 8:00 was lower than the soil temperature, the temperature of the C decreased more rapidly than that of the earthworm treatments. However, a high air temperature was noted at 14:00. Occurring at 8:00, the lowest soil surface temperature (13.3 °C) was observed in CKN in October. Seen in the 0–5 cm layer, compared with the C, the earthworm treatments exhibited an increasing and decreasing average soil temperature at 0.46–0.63 °C and 0.52–0.46 °C at 8:00 and 14:00, respectively. Seen in the 5–10 cm layer, the average soil temperature of the earthworm-treated soil was higher by 0.28–0.55 °C than that of the no-earthworm soil at 8:00 and was lower by 0.39–0.21 °C than that of the C at 14:00. Earthworm activity effectively regulated soil temperature, and the effects increased with earthworm density.

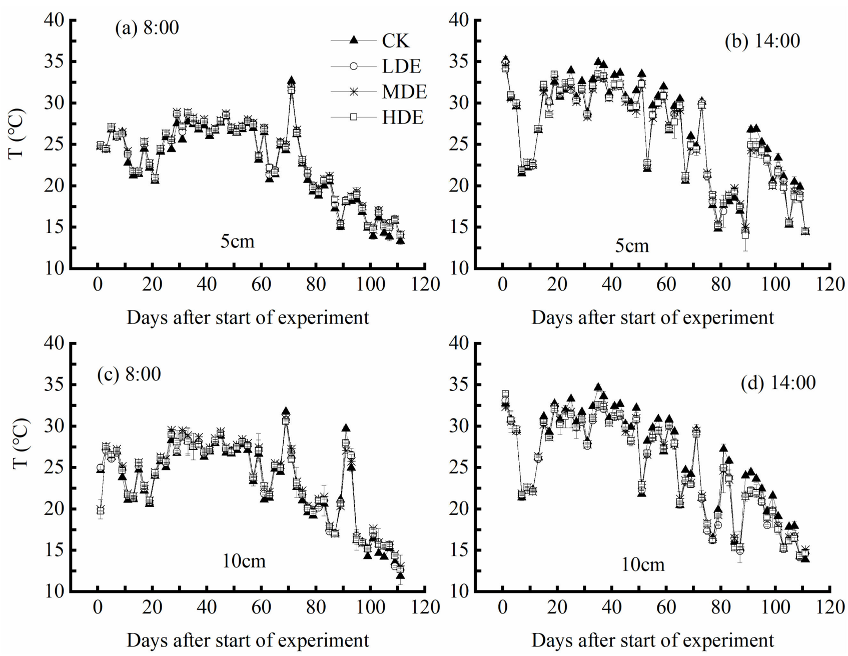

Figure 4. Variation soil temperature with earthworm density at 5 cm (**a**,**b**) and 10 cm deep (**c**,**d**) at 8:00 (**a**,**c**) and 14:00 (**b**,**d**) in the column for CK (without earthworm), LDE, MDE, and HDE.

3.3. Variation of Evaporation Rates and Cumulative Evaporation with Earthworm Density

The SWC in all treatments decreased as the soil evaporation time was prolonged (Figure 3). The rate of evaporation from the soil surface was notably higher in the C than in the earthworm treatments. The evaporation process could be divided into three stages (Figure 5a). The rate decreased slowly in the first stage (days 0–23) and differed significantly ($p < 0.05$) among all earthworm treatments. The rate was remarkably higher in the C than in the earthworm treatments. The rate of evaporation decreased rapidly in the second stage (days 24–103) but showed no significant difference among the four treatments. The rate decreased slowly in the third stage (days 104–111) and exhibited a consistent trend in each treatment. Shown in Figure 5b, cumulative soil evaporation during the experimental period was the highest in the C (124.6 mm), followed by the LDE (118.4 mm), the MDE (115.8 mm), and the HDE (98.6 mm). Earthworm activity decreased evaporation by 5.0–20.9%. During the successive evaporation process during 111 days of natural conditions, the logarithmic function relationship between cumulative soil evaporation and time under different earthworm densities was obtained with high determination coefficients (Table 1).

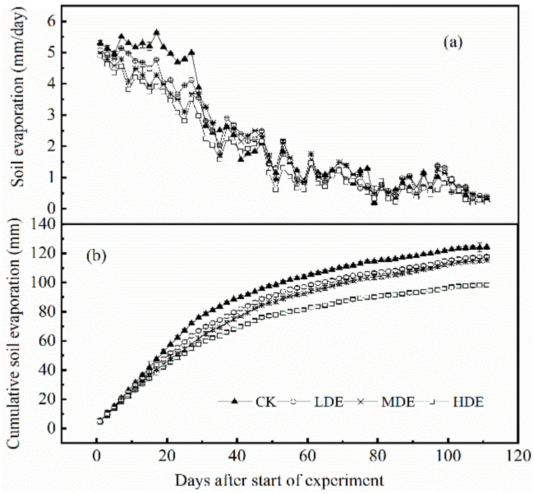

Figure 5. Variation of the rate of soil evaporation (**a**) and cumulative soil evaporation (**b**) in the column for CK (without earthworm), LDE, MDE, and HDE.

Table 1. Fitted equations †, determination coefficients (R^2) and root mean square error (RMSE) of cumulative evaporation over time in the soil under the four earthworm densities (CK, LDE, MDE, and HDE) tested.

Treatment	Fitted Equation	R^2	RMSE
CK	Ec = 33.673 ln(t)–35.338	0.948	7.61
LDE	Ec = 31.784 ln(t)–34.821	0.943	7.55
MDE	Ec = 31.319 ln(t)–36.373	0.934	8.04
HDE	Ec = −26.212 ln(t)–26.722	0.948	5.95

† Ec is the cumulative soil evaporation, g; t is experiment time, day.

3.4. The Relationship between Soil Evaporation and Earthworm Treatments

Soil evaporation and earthworm casts can differ depending on the earthworm species and densities. Found in this experiment, the cumulative soil evaporation showed significance ($p < 0.001$) with earthworm density. Cumulative soil evaporation was linearly correlated with earthworm density (Figure 6). The cumulative soil evaporation decreased with the increase in earthworm numbers. Earthworm activity decreased evaporation by 5.0–20.9%. Our findings also suggest that the population quantity of earthworm activity is an important factor that affects the terrestrial ecohydrological cycle.

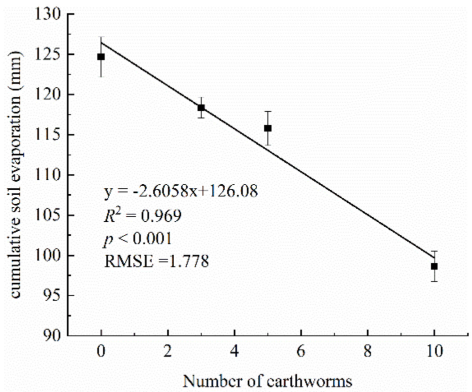

Figure 6. Relationship between cumulative soil evaporation and the number of earthworms.

4. Discussion

4.1. Impact of Earthworm on Temperature and Evaporation

The main factors influencing soil evaporation include soil structure, temperature, and moisture. Regarding traditional agricultural production, several artificial mulch methods are used to preserve soil moisture and temperature [34,35]. During the present experiment, the earthworms dug several burrows in the soil and simultaneously excreted cast on the soil surface, forming natural mulching materials. The cast quantities on the soil surface differed given the varied earthworm densities used in experimental treatments (Figure 2). Li et al. [4] found that the aggregated mulches of ants exert important effects on soil temperature and evaporation. Usually, earthworms excrete casts on the surface and in underground soil [36]. The coverage of earthworm casts on the soil surface varied from 10% to 90% in different earthworm densities during the experiment (Figure 2). The cast mulching on the soil surface formed a physical barrier that could prevent water and heat exchange between the soil and the atmosphere, change the microenvironment of the soil and the evaporative conditions of soil surfaces, and affect the SWC [37,38]. Ernst et al. [39] reported an increase in soil water holding capacity in the casts of epigeic earthworms from laboratory experiments. Thus, the storage of soil water can vary with earthworm activity [12]. Additionally, temperature is an important factor affecting evaporation. Found in the 0–5 cm layer, the average soil temperature of the earthworm-treated soils was higher by 0.28–0.63 °C than that of the C at 8:00 and was lower by 0.52–0.46 °C than that of the C at 14:00. Temperature fluctuations reduced with increasing earthworm densities. The result is similar to that obtained by Wang [40], who showed that mulch treatment can effectively regulate soil temperature. Li et al. [30] also suggested that aggregates of earthworms could form a new soil layer that positively reduces evaporation. During this experiment, the HDE (1422.6 g) had more casts than the MDE (871.8 g) and the LDE (543.6 g) mulching on the soil surface. The more cast mulching helped adjust the soil temperature, which could explain the high earthworm density with low evaporation.

4.2. Impact of Earthworms on SWC

Typical anthrosols (Lou soil) are an important agriculture soil type based on cinnamon soil formed by heaps of human dung and ripening for a long time on the Southern Loess Plateau [41]. The temperate soil is rich in organic matter which is beneficial to earthworm population increases. Earthworms generally live in farmlands and orchard lands. This soil has strong viscosity and poor ventilation and water permeability. However, earthworms could improve soil ventilation and water permeability by changing soil macropores, soil density, and soil aggregates, thereby increasing crop yield [42,43]. However, the soil type does not influence the burrow characteristics of earthworms [44]. During the present study, the average soil bulk density of the surface decreased from 1.39 $g \cdot cm^{-3}$ to 1.27 $g \cdot cm^{-3}$. The soil macropores from earthworm (*M. guillelmi*) burrows were 3–5 mm in diameter. The earthworm burrows can reopen, close, and re-connect pores and produce coatings at the pore surface, which can change the biopore wall [14]. Capowiez et al. [25] studied the burrow systems of earthworms using X-ray tomography and found the burrow system characteristics increase significantly with time and earthworm density. Those soil macropores form a special water channel that would affect soil infiltration. Shipitalo et al. [45] reported that soil water could infiltrate into a 1 m depth of the subsoil through earthworm burrows in a clayey soil. The infiltration rates are positively correlated with the number of earthworms. Fan [46] observed that the infiltration rates of no-tillage are 1.4–2.0 times larger than moldboard plough due to the larger earthworm biomass in the former than in the latter. Soil infiltrability affects the effective utilization of precipitation and irrigation water, soil water storage, nutrient cycle, and plant growth [47]. During our experiment, earthworm activity effectively regulated soil temperature and changed the SWC. The SWC of the earthworm-treated soils was significantly greater than that of the C ($p < 0.05$)) in the surface 0–20 cm of soil. The averages of the SWC were in decreased order with the earthworm density in all the experiment times, namely, HDE > MDE > LDE > C. Li et al. [30] suggested that earthworm casts are a natural water-retaining material. The majority of studies consider that the casts of earthworms are better water stabilizing aggregate [38]. It significantly modifies the soil aggregation and porosity, which affects water flow in the soil [44,48]. Our results showed the earthworms significantly decreased the SWC loss in the 0–20 cm soil layer and increased the SWC loss in the 60–100 cm layer. Earthworm activities can enhance the stability of soil aggregates and promote the formation of large aggregates. Gilot et al. [48] found that a tropical geophageous earthworm (Megascolecidae) can increase the content of >2 mm aggregates by 17.6%. Those large aggregates could improve soil porosity and soil water holding capacity. However, the quantities of large aggregates were determined by the numbers of the same species of earthworms (Figure 1). Hallam and Hodson [28] also reported that *Lumbricus terrestris* and *Allolobophora chlorotica* earthworms significantly increase soil water capacity by 7–16% due to more water stable aggregates. However, earthworms take the soil and litter mixtures as food and excrete them as casts. Arai et al. [49] found that increased organic matter input by crop residues through fertilization can enhance earthworm activities. Thus, soil organic matter content is an important factor affecting the burrow and cast behavior of earthworms. Soon, attention should be focused on the effects of earthworm activities on evaporation and soil water content under different fertilizers to improve water-use efficiency and sustainable crop yields.

5. Conclusions

Earthworms not only created numerous soil macropores in the soil profile, but also excreted casts on the soil surface that acted as mulch, forming a good insulating layer, which influenced soil structure, adjusted soil temperature, and reduced soil water evaporation. The average soil bulk density decreased from 1.39 $g \cdot cm^{-3}$ to 1.27 $g \cdot cm^{-3}$. Cumulative soil evaporation was lower in the earthworm-treated soils than in the no earthworm soil during the whole experimental period. Earthworms decreased cumulative evaporation by 5.0–20.9%. Earthworms decreased the surface SWC loss and increased the subsoil SWC loss by adjusting the soil temperature and reducing soil water evaporation. The SWC and evaporation varied with earthworm density. A negative relationship was found between cumulative evaporation and earthworm density. The population quantity of earthworms may provide valuable ecosystem services in soil water and heat cycles to save water resources and realize sustainable agricultural development.

Author Contributions: Methodology, Investigation, Resources, Formal analysis, Data Curation, Writing—Original Draft Preparation, Review and Editing, L.M.; Project Administration, Supervision, M.S.; Software, Investigation, T.L. All authors have read and agreed to the published version of the manuscript.

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