A bench-scale assessment of the effect of soil temperature on bare soil evaporation in winter

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ABSTRACT

To quantitatively evaluate in the laboratory the effect of soil temperature on bare soil evaporation, this study uses two indoor soil columns and homogenized sand as an example to carry out the experimental study of soil temperature on bare soil evaporation in winter. The results show that the soil temperature directly affects the change in bare soil evaporation and that the effect decreases as the soil temperature decreases. Because of the influence of soil temperature, the soil water movement accelerates, and the soil water content increases. At a depth of 50 cm, the average difference in soil water content between groups A and B was 7.61%. The soil evaporation when considering the soil temperature was obviously greater than that without considering the soil temperature. This shows that in a laboratory environment where the soil temperature is higher than the room temperature in winter, the effect of the soil temperature on bare soil evaporation is significant. Soil temperature directly affects soil water movement and distribution, which is one of the important influencing factors affecting bare soil evaporation.

Key words | bare soil evaporation, bench-scale, soil temperature, soil water content

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HIGHLIGHTS

- Soil temperature is higher than the atmospheric temperature in the winter, and the soil evaporation when considering the soil temperature is increased by 34.78% compared with when the soil temperature is not considered.
- When the groundwater depth is larger than the supporting capillary water rise height, the soil temperature has a greater influence on soil evaporation and soil water content and cannot be ignored.

INTRODUCTION

Soil evaporation is one of the main sources of land surface evaporation and regional evapotranspiration, one of the main factors in the consumption of groundwater resources, an important part of the hydrological cycle, and one of the main driving forces for soil salinization. If the soil is salinized, it will lead to a series of problems, such as decreased soil-related performance, plant growth failure, and deterioration of ecological environment quality. Therefore, there is an urgent need to conduct research on soil evaporation.

Many factors affect soil evaporation. At present, research on the factors affecting soil evaporation is focused on the depth, lithology of the aeration zone, vegetation, temperature, etc. On one hand, soil texture is one of the important factors affecting soil evaporation. Hao *et al.*

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(2011) analyzed the phreatic evaporation and hydrometeorological observations of two typical soils (lime concretion black soil and fluvo-aquic soil) from 1995 to 2008 in the Wudaogou Experimental Station and found that under the same external conditions, the soil evaporation of the fluvo-aquic soil was much larger than that of the lime concretion black soil. On the other hand, even with the same soil quality, different depths will have different effects on the soil evaporation. Different experimental studies have shown that within a certain depth of burial, the evaporation of different soils will decrease with the increase in depth. The rate of decline in soil evaporation at different depths of the same soil is different. Generally, the deeper the depth, the slower the rate of decline in the soil evaporation (Mengistu Achamyeleh *et al.* 2018). However, even when the depth is very deep, there is still the possibility of evaporation, although it is sometimes weak. For example, Li & Wang (2014) used the arch shed method to monitor the water evaporation in the Gobi Cave of Dunhuang Mogao Grottoes with a depth of approximately 200 m and found that water under the sand can enter the surface through the sand layer, which can form a small amount of evaporation. In addition, evaporation will change with changes in climate and temperature. At the same time, the growth of crops will significantly increase the soil evaporation due to the water absorption of the roots under conditions where the control of submersible depth, soil quality, temperature and other natural conditions are the same. The root development of crops in different growth stages is different; therefore, the effect of crop growth on soil evaporation varies with the depth (Di *et al.* 2019). Furthermore, because soil evaporation will cause problems such as soil salinization, the laws of soil salinity under different evaporation conditions are different, and the feedback effects of different solute potentials on evaporation rate are also different. Therefore, it will further affect the soil salinization process (Rosa *et al.* 2016).

In addition to the abovementioned influencing factors, soil evaporation will also be affected by soil temperature. Although there is currently only a small amount of literature on the effects of soil temperature on soil evaporation, soil temperature is usually ignored. In the 1950s, Philip & De Vries (1957) established a coupled equation for soil water-thermal migration to explain the mechanism of the temperature gradient on soil water movement. Seyed *et al.* (2018), by using heat and water transport experiments in the presence of an osmotic gradient in the soil column, found that nearly 96% of the steam transfer was caused by a temperature gradient. In addition, the heat transferred by the steam flux is significant, and further analysis shows that the evaporation can be estimated directly from the soil temperature, soil heat flux and net radiation. Changes in temperature can cause changes in shallow groundwater levels and shallow ground temperature, and cause potential energy imbalances. So steam transport caused by temperature gradient changes plays a key role in soil mass and energy transfer (Bittelli *et al.* 2008). At the same time, for different soil types, the effect of heat dispersion on soil water flux estimation is also different. Generally, the effect of heat dispersion in fine-grained soil on soil water flux is more pronounced than that of rough-textured soil (Lu *et al.* 2018). In addition, for relatively special soil such as frozen soil, the temperature gradient during the freezing and thawing process will have a significant impact on soil moisture movement (Yang & Wang 2019). For example, Merlin *et al.* (2018) used seven different initial and boundary conditions to study the coupling process in unsaturated frozen soil and found that the main factor affecting the freezing position is the temperature gradient. The temperature field is the main factor affecting the gas phase distribution, and the steam content distribution is also related to the temperature distribution. Therefore, the influence of the temperature gradient on soil water movement is extremely obvious.

The temperature gradient will not only affect the soil water movement but also further affect the joint migration process of water, gas and heat during the evaporation process. In other words, soil hydrodynamics are closely related to temperature changes (Bittelli *et al.* 2008). Du *et al.* (2018) used the Hydrus 1D model to simulate the coupled transport of water, steam and heat in the Gobi Desert and found that soil temperature significantly affects the movement of steam and that soil temperature gradients are the main driving factors affecting desert steam transport. Certainly, soil temperature is connected to soil properties and many numerical modelings are used to characterize the relationship and model the migration process of water, gas and heat (Ondřej *et al.* 2016; Hoogland *et al.* 2017). Seitz *et al.* (2020) used a numerical model to model the influence of porosity changes during thermochemical heat storage and found that the porosity influences the shape of the reaction front and the amount of released (or consumed, depending on charge or discharge) heat and then affects the entire migration process. Therefore, it can be suggested that the current correlation between soil hydrodynamics and temperature changes is mainly concentrated in the stage of simulation and theoretical analysis. There is still little actual data or research examples to further verify the influence of temperature changes on soil water movement.

In bare soil areas, when the groundwater depth is shallow, solar radiation is the main source of energy required for phreatic evaporation. The greater the intensity of sunshine, the greater the thermal power, so the greater the bare soil evaporation (An *et al.* 2018; Olivier *et al.* 2018). However, when the groundwater is buried below the surface, the groundwater temperature and the surrounding soil temperature are lower than the atmospheric temperature; in contrast, in winter, the groundwater temperature and the surrounding soil temperature are higher than the atmospheric temperature. At this time, the influence of solar radiation weakened, and the influence of groundwater temperature increased. The temperature directly affects the movement pattern of water, the mutual conversion of liquid water and gaseous water, and the movement process of water vapor, which affects the evaporation of bare soil. However, the study of bare soil evaporation at the hydrological test station at this stage does not focus on the influence of soil temperature on bare soil evaporation, and its influence mechanism has not yet seen public results. Therefore, to quantitatively assess the effects of soil temperature on bare ground evaporation, this paper takes homogeneous sand (homogeneity refers to the uniform distribution of particles of different particle sizes in the soil, and the permeability coefficient is equal at each point) as an example in the winter context where the soil temperature is substantially above the atmospheric temperature and studies the influence of winter soil temperature on bare land evaporation through the construction of an indoor soil column test device in the laboratory, which is expected to further promote research on the mechanism of the effects of bare soil evaporation and provides a scientific basis for determining under laboratory conditions the effect of soil temperature on the evaporation of bare soil.

MATERIALS AND METHODS

A bench-scale setup

As shown in Figure 1, the bench-scale setup consisted of a Plexiglass cylinder with a diameter of 35 cm and a height of 100 cm. Initially the bottom was sealed, and the top was open. Four TP-SR-1 (www.top17.net/company.html) soil water content sensors were installed on the left side of the setup at 20, 40, 60, and 80 cm from the bottom, and four TP-ST-1 (www.top17.net/company.html) soil temperature sensors were installed at the same positions on the right side. The measurement range of TP-SR-1 is 0–100%, and the measurement accuracy is ±2%; the measurement range of TP-ST-1 is -40 to $100\,^{\circ}$C, and the measurement accuracy is $\pm 0.5\,^{\circ}$C. They can record soil water content and soil temperature at any point at any one time. These sensors are only a little inside the column (much smaller than the size of the column) and mainly rely on the probe to determine the relevant parameters and respond quickly, so there is no influence on the results. During the test, the groundwater depth was kept at 80 cm. The groundwater depth is controlled according to the principle of the connected machine, so a valve is installed on each side of the cylinder 5 cm from the bottom and connected to a Marriott bottle which controls a

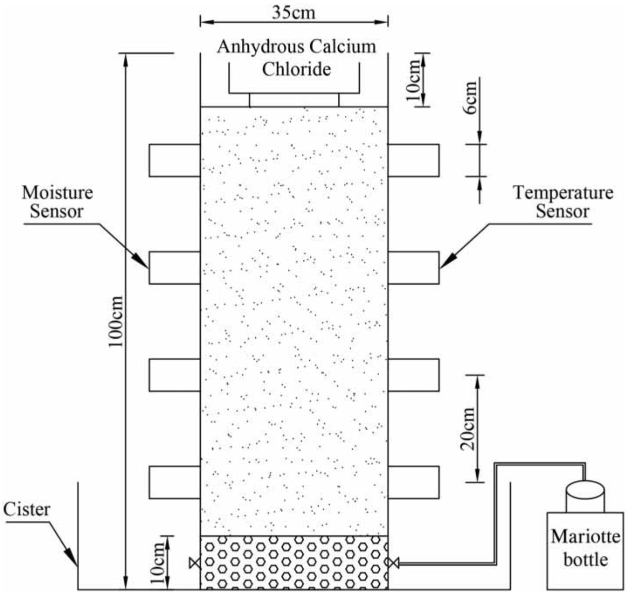

Figure 1 | Bare soil evaporation column test device.

constant water level of 10 cm. To reduce the fluctuation in groundwater depth caused by soil evaporation, an 8 cm-thick sandy gravel layer is placed at the bottom of the device, and a 2 cm-thick water filter plate and filter screen are installed on the upper part of the sandy gravel layer to prevent fine sand with a smaller particle size from flowing into the bottom. The upper part of the water filter plate is filled with an 80 cm-thick layer of sand with a diameter of 400 mesh.

In order to exclude the influence of climates, soil textures, vegetation and other common factors on bare soil evaporation, the test was conducted mainly in the laboratory. This paper focuses on the effect of soil temperature on bare soil evaporation, so the soil temperature is simulated in the laboratory by means of a heating rod. First, two sets of the same experimental test were set up and placed in a pool 100 cm in diameter and 30 cm in height. Then, a heating rod was placed in one of the pools and the heating rod was set to a continuous heating status so that there was water circulation in the pool to homogenize the temperature distribution. The temperature of the heating rod ranged from 5 to 30 °C. The experimental set number was named A, considering the effect of soil temperature. The other pool was not heated with a heating rod, and the temperature varied with the environmental temperature. This test set number was named B, regardless of the effect of the soil temperature.

A mercury thermometer was placed near the two tests to monitor atmospheric temperature changes. The test process lasted from December 1, 2018 to December 23, 2018. It was winter in China, and the atmospheric temperature was between 0 and 12 °C. Under normal conditions, the soil temperature is higher than the atmospheric temperature (Merlin *et al.* 2018). Therefore, the temperature of the heating rod is set to 20 °C, which means that the soil temperature is 20 °C when monitoring bare soil evaporation.

Analytical methods

Soil evaporation was usually determined by the weighing method (Yuan *et al.* 2009; Ren & Huang 2014), vapor method (Guido *et al.* 2018; Di *et al.* 2019), heat balance method (Balugani *et al.* 2018) and water balance method (Wei *et al.* 2015). The weighing method is simple, practical and widely used. However, owing to the heavy test device of approximately 100 kg and the low accuracy of the weighing scale of only 0.1 g, the weighing method is not used in this study. The soil evaporation per day is small, in the order of 10^{-2}–10^{-1} g per day. If the weighing method is used, the error will be large. The measurement accuracy requirement cannot be met. Therefore, this test measurement method of soil evaporation does not use the weighing method but the anhydrous calcium chloride method. The measurement principle of the anhydrous calcium chloride method is to adsorb water vapor through anhydrous calcium chloride. Anhydrous calcium chloride will form $CaCl_2{\cdot}6H_2O$ after water absorption and has strong water absorption performance. Then, the weight before and after water absorption is measured using an electronic scale with high precision. It can indirectly obtain soil evaporation by calculating the difference in the weight of calcium chloride before and after water absorption.

Before the start of the test, the anhydrous calcium chloride particles were spread in a dry paper cup, which was fixed to the top of the sand sample with a bracket (Figure 1). To ensure that the water evaporated by the soil can be absorbed as much as possible by the calcium chloride, many evenly spaced holes are arranged in the bottom of the paper cup. In addition, the top of the cylinder is sealed with plastic wrap to prevent calcium chloride from absorbing moisture in the air. The reaction in the column can still be changed by the temperature in the air. In addition, the characteristics between plastic wrap and glass column are different, so the effect on evaporation results is slight. The weight of the calcium chloride paper cup was measured with an electronic scale (accuracy of 0.01 g) at 8am every morning, and then the weight of soil evaporation was obtained by the difference from the previous weight. Temperature and weather conditions were recorded simultaneously. Because the evaporation in winter was small, the anhydrous calcium chloride was replaced once in about three observation periods. To make the initial water content the same in the two sand columns, at first they were fitted with the same dry sand to the same depth, then placed in a water container to be fully saturated, and then the test was carried out.

According to the weight of soil evaporation, the corresponding soil evaporation can be obtained from Equation (1):

$$E = \frac{m}{\rho \cdot A} \tag{1}$$

where E is soil evaporation (mm); m is the weight of soil evaporation (g); ρ is water density (g/cm^3); and A is evaporation area (cm^2).

RESULTS AND DISCUSSION

Characteristics analysis of soil temperature change

Theoretically, the ground temperature directly affects the change in soil temperature of different depths and the degree of the change at different positions is different. According to the mercury thermometer and the TP-ST-1 soil temperature sensors, the temperature values of the atmospheric temperature and the A and B devices at depths of 10, 50, and 70 cm were obtained, as shown in Figure 2.

Figure 2 shows that the soil temperature changes with the fluctuation in atmospheric temperature at different depths with the same trend. However, because the water temperature is increased by the heating rod to simulate the soil temperature and the specific heat capacity of the water is larger, compared with the temperature change, the change in water temperature shows a certain hysteresis. On the observation dates of December 4th to 5th, December 10th to 11th, and December 20th to 21st during the test, the temperature appeared to cross in Figure 2. The heat capacity of soil is greater than air and when the heat balance is re-established in the sand column, the soil heat capacity also changes. Therefore, under the same conditions, the soil temperature change was less than the air temperature change. So even if the atmospheric temperature was close to zero on December 19th, no significant condensation formed in the sand column and the water on the surface of the pool did not freeze. Overall, it can be suggested that at the same depth, the temperature considering the soil temperature is significantly higher than the temperature without considering the soil temperature. It is mainly because the bottom of the sand column considering the soil temperature is heated at a constant temperature and forms a temperature gradient with the top of the sand column. Then the heat in the sand column is redistributed until the temperature of each layer of the sand column gradually stabilizes to reach a new thermal equilibrium.

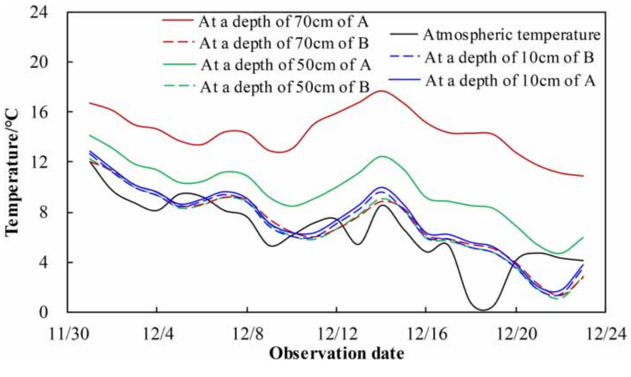

Figure 2 | The changes in soil temperature.

In addition, as the depth increases, the soil temperature influence is more obvious. For example, the maximum soil temperature difference at a depth of 70 cm is 9.86 °C, with an average difference of 7.37 °C; when the depth is reduced to 50 cm, the average temperature difference is reduced to 2.79 °C, which is 4.58 °C less than the difference at a depth of 70 cm, accounting for 62.14%. At the depth of 10 cm, the temperature considering the soil temperature is slightly higher than the temperature without considering the soil temperature. The difference is between 0.17 and 0.47 °C. This is mainly because the heat in the sand column is transferred from the bottom of the sand column to the surface of the sand column, forming a temperature gradient. Then the heat is transferred along the direction of the temperature gradient, which causes the different changes of soil temperature at different depths.

Analysis of change in soil water content

According to the TP-SR-1 soil water content sensors, the soil water content of the A and B devices at depths of 10, 50, and 70 cm were obtained, as shown in Figures 3 and 4. Figure 3 shows the variation in soil water content with depth. At a depth of 10–70 cm, the soil water content increases with increasing depth. At the same depth, the soil water content under the soil temperature condition is obviously higher than the soil water content regardless of the soil temperature, and the difference first increases and then decreases with increasing depth (Figure 4). The average soil water content of the A and B devices at 10 cm depth is 4.28 and 1.37%, respectively, with a difference of 2.91%, accounting for 67.99%. At the depth of 50 cm, the average difference in soil water content between the A and B devices increased to 7.61%; however, at the depth of 70 cm, the soil water content fluctuated between 26.10 and 26.40%, and the difference between the A and B devices decreased to only 0.30%. At this time, the soil moisture content was considered to be saturated, and the soil moisture content at 80 cm was not further determined. In addition, in the latter part of the test (beginning from December 19th), the change in the soil temperature of B fluctuated between 0 and 2 °C. The overall temperature was low and the change was not obvious, so the soil moisture content at 10 cm was close to 0 and there was almost no change.

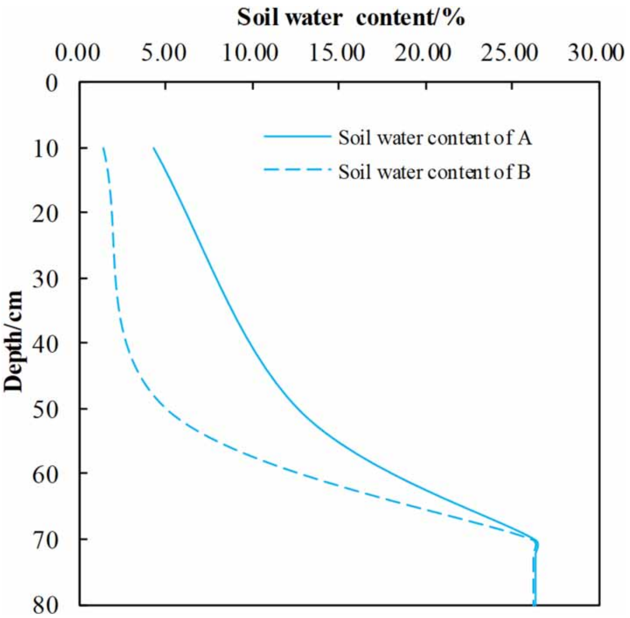

Figure 4 | Variation in soil water content with depth.

According to the analysis of Figure 2 and the soil temperature change characteristics, the soil temperature increases as the depth increases. Because the test was conducted after the sand column was fully saturated, and the Mariotte bottle is used to control the constant water level, it can be considered the soil was not disturbed and the structure was not damaged, therefore, soil moisture can change sensitively with soil temperature. It is can be suggested that the movement of soil moisture was accelerated mainly because of the increase in soil temperature. When a significant temperature gradient was formed in the column, the water vapor flux in the soil changed significantly along the path, that is, a larger temperature gradient accelerated the diffusion of water vapor. Therefore, under the influence of soil temperature, the soil water content in the A device is greater than that in the B device at the same depth. When the depth is increased from 10 to 50 cm, the difference in the soil temperature is gradually increasing, and the difference in the soil water content is also increasing. However, the difference in the soil water content between the A device and the B device from 50 to 70 cm began to gradually decrease. The groundwater level depth is 80 cm. Under the action of capillary forces, water rises from

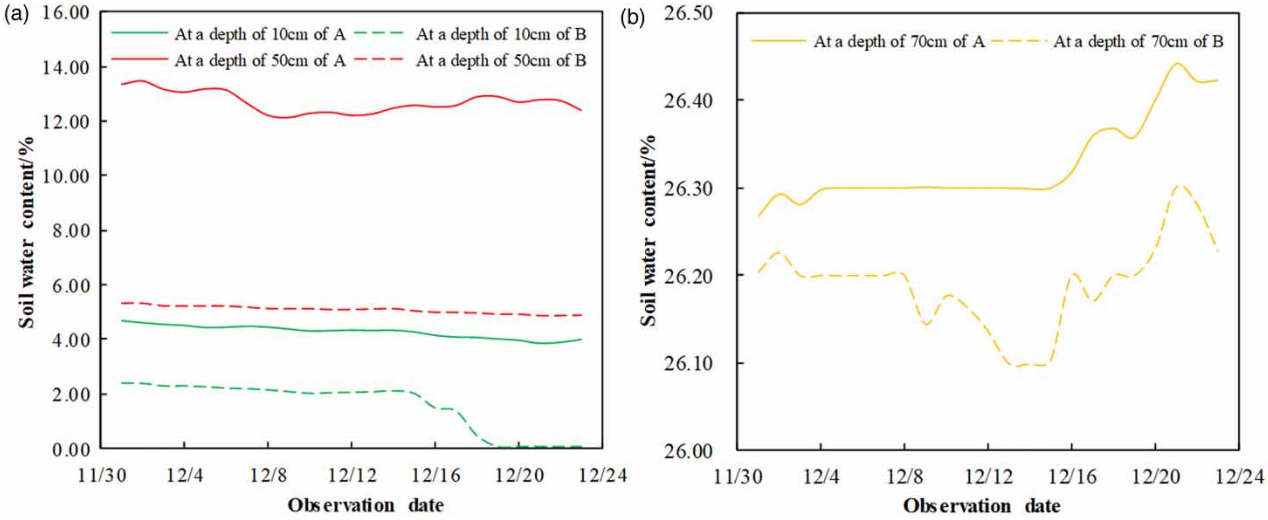

Figure 3 | The changes in soil water content.

the water table to form a capillary water belt. According to the research results (Schulz *et al.* 2015), the capillary height of the fine sand is approximately 200 cm. Therefore, the soil water content is mainly affected by the capillary action in the range of 50–70 cm, and the influence of the soil temperature is gradually weakened. Therefore, the difference in the soil water content between the A device and the B device at 50–70 cm began to gradually decrease. It can also be seen from Figure 2 that the difference in the soil temperature between the A device and the B device at 70 cm is the largest. However, due to the saturation of the soil water content at 70–80 cm, the soil water content at 70–80 cm is no longer affected by the soil temperature, and the soil water content of the A and B devices is the same at 70–80 cm.

According to the above analysis, it can be concluded that the soil temperature directly causes the soil temperature to rise, accelerates the soil water movement, and increases the soil water content. However, due to the influence of the groundwater level depth and capillary, the increase in the soil temperature caused by the soil temperature is different. As the depth increases, the magnitude of the increase in the soil water content first increases and then decreases.

The effect of soil temperature on soil evaporation analysis

By measuring the weight of calcium chloride, the soil evaporation of the A device and the B device was calculated by Equation (1). The process of soil evaporation is shown in Figure 5 during the test. Figure 5 shows that the fluctuations in the soil evaporation of the A device and the B device are basically the same, but the soil evaporation of the A device is significantly higher than the soil evaporation of the B device. In the 23 days of the experimental observations, the cumulative soil evaporations of the A and B devices were 1.24 and 0.92 mm, respectively, with a difference of 0.32 mm, which accounted for 34.78% of the total evaporation of the B device. In addition, on the 20th day, the difference between the atmospheric temperature and the soil temperature was relatively large, and the difference in the daily soil evaporation reached 0.02 mm, accounting for 60% of the soil evaporation of the B device, which is the largest proportion. It is concluded that the influence of soil temperature on soil evaporation is very significant and is an important factor affecting soil evaporation. Under the action of soil temperature, the density of water vapor in the soil was changed; when the temperature gradient was formed, the direction of water movement was determined, and the soil water movement rate was accelerated, more liquid water becomes vaporized water at the same time, which increases the amount of soil evaporation. The soil evaporation when considering the soil temperature is obviously greater than that without considering the soil temperature, and the difference in evaporation increases as the temperature difference increases.

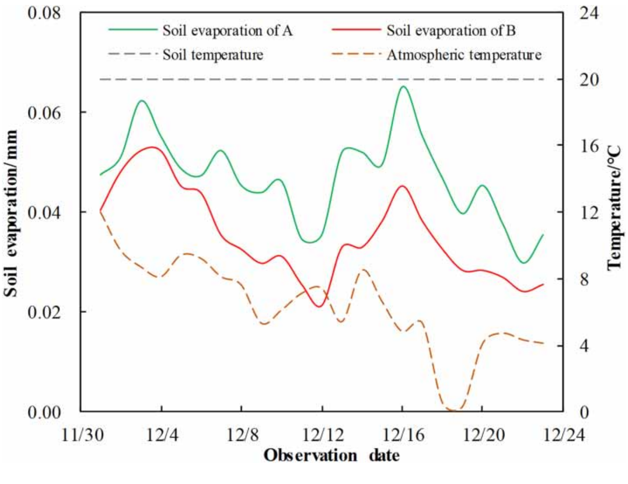

Figure 5 | The process of soil evaporation during the test.

The test environment is in the laboratory. Regardless of the influence of solar radiation, the driving force for changing the soil moisture distribution pattern is only the soil temperature. Because the atmospheric temperature is low in winter and the specific heat capacity of the soil is greater than the specific heat capacity of the air, under the influence of the soil temperature, the lower soil temperature is higher than the upper soil temperature; that is, the soil temperature increases with increasing depth. When the depth is small, the soil temperature is mainly controlled by the atmospheric temperature. The influence of the soil temperature is relatively weak, which also reveals the reason why the difference in soil temperature between the A and B devices is small at the observation point of 10 cm. At increasing depth, the effect of soil temperature on soil evaporation gradually increases, and the degree of influence of the atmospheric temperature on soil temperature becomes correspondingly weaker. Especially at a depth of 70 cm, the maximum soil temperature difference between the A and B devices was 7.37 °C. The increase in soil temperature causes the soil water movement speed to increase. This is the reason why the average difference in the soil water content at the depth of 50 cm between the A and the B devices is significantly larger than that at 10 cm. However, at 70 cm deep, only 10 cm from the groundwater surface, the 70 cm observation point is in the range of supporting capillary water. The soil water content is close to saturation, so the soil temperature has no significant effect on the soil water content at this point. It is concluded that in the bare soil area, when the groundwater level depth is larger than the supporting capillary water rise height, the soil temperature has a greater influence on soil evaporation and soil water content and cannot be ignored; otherwise, the soil temperature has little effect on soil evaporation and water content.

CONCLUSIONS

In this paper, the effects of soil temperature on soil evaporation, soil temperature and soil water content were discussed by conducting indoor bare soil evaporation experiments. The influence of soil temperature on water movement is directly reflected in the physical characteristics and existing forms of water and ultimately in the direction of water movement. The increase in soil temperature directly causes the soil water temperature to rise, which accelerates the conversion of liquid water to gaseous water in the vadose zone, accelerates the water vapor movement, promotes the escape of water vapor, and then affects the amount of soil evaporation. Therefore, since the soil temperature is higher than the atmospheric temperature in the winter, the soil evaporation when considering the soil temperature is increased by 34.78% on average compared with when the soil temperature is not considered. The effect of soil temperature on bare soil evaporation is very significant.

This paper carried out an experimental study on the effect of soil temperature on soil evaporation in bare soil areas in winter. Previous studies only suggested that soil temperature will influence soil evaporation. In this paper, the influence of soil temperature on soil evaporation is quantitatively studied around the winter weather conditions. However, the weather conditions change with the seasons. Especially in summer, the change of soil temperature is opposite to that in winter. The soil temperature in summer is lower than the atmospheric temperature, and the soil temperature shows a reverse stratification with the increase in the depth. This is the opposite of the temperature distribution in soil in winter. Is the resulting effect on soil evaporation the opposite? Further experimentation and research work are needed, which is the focus of our next study. Besides, affected by test errors, environmental changes and other factors, the experimental results in this paper have certain uncertainties. The influence of these uncertain factors on the reliability of experimental results will be the next step to be studied.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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