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Communication

Evaporation Process in Soil Surface Containing Calcic Nodules on the Northern Loess Plateau of China by Simulated Experiments

Soil containing calcic nodules is widely present on the northern Loess Plateau of China owing to soil genesis under local climate conditions. In most studies, little attention is payed to the effect of calcic nodules on soil evaporation and ecoenvironment, resulting in inaccurate evaporation estimation in this kind of soil and further improper field water management measures and irrigation effects. In this paper, soil column experiments were conducted in order to investigate evaporation process in soil containing calcic nodules and the effect of calcic nodules on soil evaporation was determined. The results indicated that evaporation reduction was positively related to calcic nodule content (CNC = mass of calcic nodules/total mass), and could be estimated by the experiential equation: $E_{soil} = E_0$ (1 − 0.4 CNC) (E_{soil} = actual evaporation, E_0 = theory evaporation in soil without calcic nodules). When CNC was below 0.2, the impact could be neglected. While, as CNC exceeded 0.2, the impact needed to be considered during soil evaporation estimation. As CNC reached 0.5, soil evaporation could be reduced by 7.5 mm, accounting for around 10% of the total soil water. Water balance calculation in soil columns showed that water absorbed by calcic nodules was partially available to evaporation. Water available to evaporation was positively related to CNC, and this water could not exceed 63% of the water absorbed by calcic nodules. Generally, evaporation behavior was dominated by calcic nodule quantity and its water absorption. These results provide new ideas for irrigation measures in arid areas of the globe.

Keywords: Calcic nodules; Northern Loess Plateau of China; Soil evaporation; Soil surface; Soil water cycle; Water absorption and balance

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1 Introduction

Soil evaporation plays an important role in soil-water process as well as land water cycle in arid and semiarid regions, which influences irrigation measures seriously. Through evaporation, soil water comes into the atmosphere to form cloud, which is a significant source of atmospheric water. At the same time, soil evaporation can lead to soil water loss [1–6]. According to the estimation, this water loss can amount to 50% of the total soil water or more during a normal growing season [7, 8]. Hence, accurately estimating soil evaporation and detecting factors that affect evaporation are vital for quantifying water cycle and field water management in arid and semiarid regions.

Many factors including climate, surface features (vegetation, land cover), roots, and soil types can exert impacts on soil evaporation. Few relevant studies pay attention to calcic nodules, an invaded body formed in soil genesis, which is widely present in the soils in arid and semi-arid regions. Calcic nodules are much different from soil particles in chemical and physical properties, resulting in the evaporation process in soil containing calcic nodules to be different from homogeneous soil [9–11]. First, calcic nodules can modify soil configuration and surface properties, leading to the changes of surface roughness and soil reflectivity that is closely linked to soil thermal property [12]. Second, calcic nodules have some effect on water allocation between soil and calcic nodules [12, 13], and finally initiates soil moisture [1, 2], which to some extent dominates soil evaporation [14]. In addition, calcic nodules can enhance soil water holding capacity and reduce water vapor sorption between soil surface and atmosphere especially as calcic nodules mulching soil surface [15]. In this case, soil evaporation is effectively repressed and soil water storage is improved in a long term view [16]. Furthermore, calcic nodules embedded in soil can decrease soil saturated and unsaturated conductivities [16–18], indicating the reduction of soil evaporation. Generally, the impacts of calcic nodules on soil evaporation

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Abbreviations: CNC, calcic nodule content (calcic nodule mass/total mass, kg/kg^{-1}); **EW,** evaporated water; **SW,** saturated water; **WAE,** water that participated into evaporation

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are confused, some positively and others negatively, which depend on calcic nodule's size, chemical composition and its position in the soil profile.

The northern Loess Plateau of China, located in the transitional zone from semiarid to arid region, is characterized by rare precipitation and severe soil erosion (wind and water erosion). The soil type of this region is mainly the loess with calcic carbonates. The carbonates can easily move down in the soil profile during wet years and deposit in deep soil layer during drought years. Along with wet and drought climate alternation in history, the deposited carbonates congregate around larger particle and gradually turn into calcic nodules. As top soil is eroded, the calcic nodules are exposed on the surface soil. Limited precipitation and relatively high evaporation induced from rare surface cover and high radiation, further result in the lack of soil water storage during most time in a year, which poses a great threat on natural vegetation restoration and crop production. Hence, it is urgently needed to quantify soil water loss caused by evaporation in order to further understand water cycle process, promote local vegetation restoration as well as filed water management. However, owing to difficulty in soil sampling and the limitation of water measurement methods, evaporation behavior in soil containing calcic nodules is still poorly understood [1, 2].

In this study, simulation experiments were conducted in soil columns by artificially mixing soil and calcic nodules with different ratios under the condition of controlling evaporation power. Its aim was to acquire evaporation process and primarily evaluate the effect of calcic nodules on soil evaporation.

2 Materials and Methods

2.1 Experimental Site Description

Experimental soil (containing calcic nodules) was sampled from the top of a hillslope in Shenmu County Shaanxi province, the northern Loess Plateau of China (Fig. 1). Local soil is rich in calcic carbonates. Under the condition of frequently wet and drought climate alternation in history, the carbonates move down with water, deposit in deep soil layer, and then form into calcic nodules. Severe soil erosion (erosion modulus $>1.5 \times 10^4$ t/km^2 a) in this region expose the calcic nodules in the topsoil. According to field survey, the mass percentage of calcic nodules in soil reaches 5–30% in this region.

2.2 Methods

The sampling soil was firstly passed through 2 and 75 mm sieves, respectively. Then, soil (<2 mm) and calcic nodules (2–75 mm) were air-dried. Soil particle composition and the physical properties of the calcic nodules were shown in Tables 1 and 2, respectively. According to the description in Table 1, the soil belongs to loamy sand. Experimental soil columns were made of PVC tube. The diameter and depth of soil column were 16 and 45 cm, respectively.

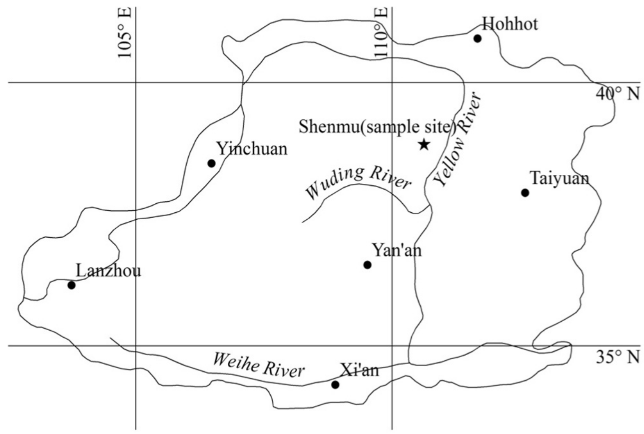

Figure 1. The location of experimental site on the northern Loess Plateau.

Table 2. Physical properties of calcic nodules.

Replications	Numbers	Volume (cm^{-3})	Density ($g\ cm^{-3}$)	SWC[a)] (%)	AWC[b)] (%)
1	26	200	2.16	7.05	0.48
2	21	200	2.07	8.62	0.72
3	38	225	2.08	7.20	0.52

a) SWC: saturated water content
b) AWC: air-dry water content

In the experiments, simulated calcic nodule contents (CNC = calcic nodule mass/total mass, kg/kg) were designed as 0, 0.05, 0.1, 0.15, 0.2, 0.3, and 0.5, respectively. As calcic nodule content exceeds 0.5, the soil can hardly fill the space between soil and calcic nodules, which will lead to larger system error.

In the experiments, soil bulk density was controlled at 1.33–1.35 g/cm. The requirements of soil and calcic nodules were calculated by calcic nodule density, soil bulk density, air-dry contents, and column volume. Then, soil and calcic nodules were mixed and loaded into soil columns. After loading, the top of the soil column was mulched by adiabatic material for a few days so as to make soil and calcic nodules contact tightly. All columns were watered initially with 1.5 kg water. After watering, soil columns were sealed to prevent evaporation and at the same time make water distribute evenly. The atmospheric evaporation power was controlled at around 10 mm/day. The soil columns were weighted at 20:00 every day at a day interval during 0–10 days, and two day interval after 10 days from the weighting start. The experiment was carried out from July 4th to August 14th, 2006. Each soil column included three

Table 1. Soil particle compositions.

	Particle sizes (mm)						
	Sand 2–0.5	0.5–0.1	0.1–0.05	Silt 0.05–0.025	0.025–0.01	0.01–0.002	Clay <0.002
Percentages (%)	3.42	47.03	35.84	9.59	2.78	1.03	0.31
	86.29			13.41			0.31

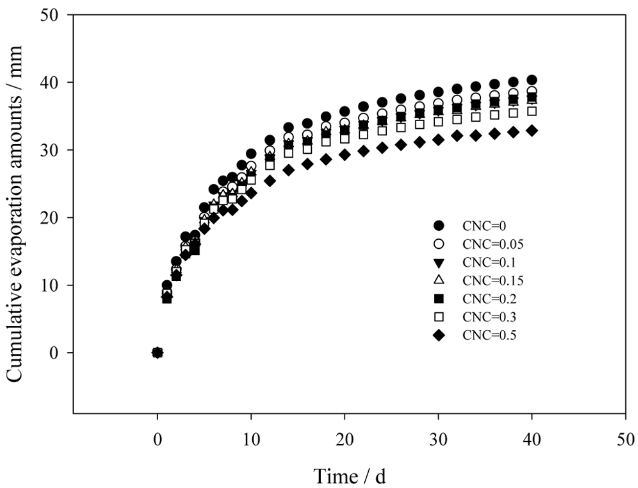

Figure 2. Cumulative evaporation with time.

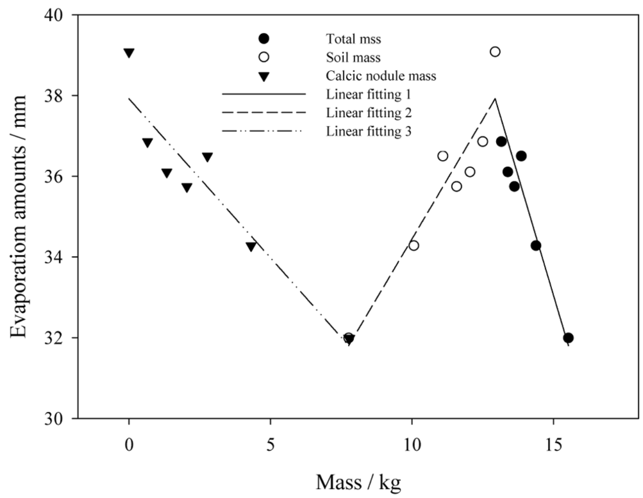

Figure 3. Soil evaporation amount versus total mass, soil mass and calcic nodule mass.

replications. The analyzed data was the mean values of the replications.

3 Results

3.1 Cumulative Evaporation

Each column was taken as a whole in the experiments. The evaporation amount can be calculated by Eq. (1):

$$E_{soil} = (M_{in} - M_{col})/(\rho A)\ 10 \tag{1}$$

Where E_{soil} is evaporation amount in soil containing calcic nodules (mm), M_{in} is initiate mass of the column (g), M_{col} is the mass of column when weighted (g), (ρ is intensity of water (=1 g/cm^3), A is the area of column transect (cm^2).

Figure 2 shows the changes of cumulative soil evaporations with time (days) in soil columns with calcic nodules. In the initial time (0–10 days), the difference in cumulative evaporations for experimental soil columns was tiny. After 10 days, there showed some differences between them. By the end of experiments, the total evaporation amount showed an order that negatively related to CNC. Simply, there was a linear relationship between cumulative evaporation amount and CNC as following Eq. (2):

$$E_{soil} = E_0\,(1 - 0.4\ \mathrm{CNC}) \tag{2}$$

Where E_0 is evaporation amount in soil without calcic nodules (mm), CNC is calcic nodule content (decimal).

This result was in accordance with other relevant experiments. While, in relevant studies the coarse invaded bodies mostly were rock fragments not calcic nodules. As all have known, there were obvious differences between calcic nodules and calcic nodules in roundness, water absorption and chemical composition. Most rock fragments are characterized by lower water absorption and high roundness. As this kind of rock fragments is present in soil, they can decrease evaporation transect and increase flow resistance. Consequently, soil evaporation is to some extent repressed. In our experiments, when soil column was taken as a whole, calcic nodules can also reduce soil evaporation. The reasons were on the one hand the same to that of rock fragments mentioned above. On the other hand, it could be attributed to calcic nodules absorbing water and at the same time restricting the movement of this water. This function is closely linked to high porosity and specific surface area of calcic nodules. These two aspects resulted in the reduction of soil evaporation.

In addition, it was needed to note that in our experiments the masses of soil and calcic nodules were changed with the CNC owing to the fixed volume of soil column. In this case, we had a simple analysis based on soil and calcic masses, and the result was shown in Fig. 3. In this figure, it could be seen that soil evaporation decreased with total mass of soil column and calcic nodule mass (could be expressed by the experiential Eq. (3):

$$y_1 = 37.9 - 0.79\ x_1 \tag{3}$$

where, y_1 = evaporation amount, x_1 = calcic nodule mass), increased with soil mass (could be expressed by the experiential Eq. (4):

$$y_2 = 22.6 + 1.2\ x_2 \tag{4}$$

where, y_2 = evaporation amount, x_2 = soil mass) inversely. This result indicated that soil evaporation was closely related to ratio of soil mass to calcic nodule mass in the columns. The water available to evaporation was mainly derived from soil. In other words, as for soil containing calcic nodules most of soil water distributes in soil and this water is the main resource for evaporation. The effect of calcic nodules on soil evaporation could not be neglected when soil contains large amount of calcic nodules. For instance, in our experiments when CNC reached 0.5, relative evaporation reduced by 7.5 mm compared with free-rock fragment soil, accounting for 10% of total soil water.

3.2 Evaporation Rate

Figure 4 shows the changes of soil evaporation rates with time (days). During the initial time (0–4 days) and time after 20 days, the evaporation rates in soils with difference CNCs were close to each other. This could be attributed to high soil moisture content in the

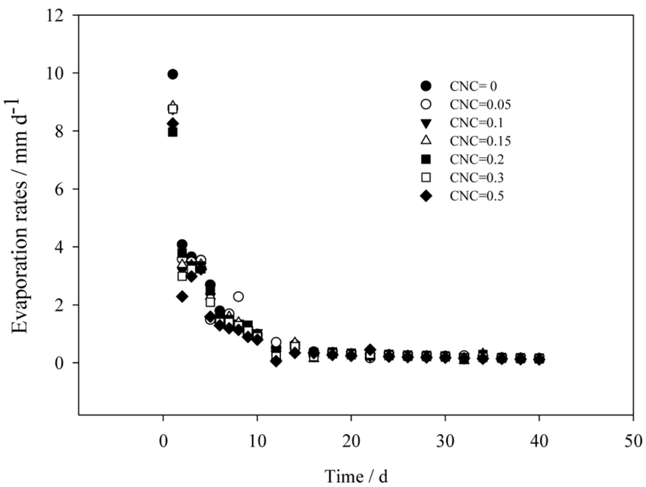

Figure 4. Evaporation rate with time.

initial time. In this stage, soil water supply was sufficient and the dominant factor of evaporation was evaporation power. After 20 days, soil moisture was considerably low for continuous evaporation, which resulted in insufficient soil water supply. At this stage, the dominant factor of evaporation was soil water supply capability. In both cases, the effect of calcic nodules was concealed. As a result, evaporation rate between soil columns was very close. During the middle stage of evaporation, soil water hydraulic conductivity was the dominant factor controlling evaporation, and hydraulic conductivity was closely linked to CNC. Calcic nodule exerted an impact on water hydraulic conductivity through reducing flow transects and channels. Hence, during this stage, there was some difference between soils with different CNCs. In other words, the effect of calcic nodules on evaporation mainly appeared over the middle stage of the evaporation.

According to previous studies on evaporation process, soil evaporation can be divided into three stages: constant-rate stage, falling-rate stage and low-rate stage [7, 10]. In our experiments, when atmospheric evaporation power was kept at 10 mm/day, the constant-rate stage was very short (less than 2 days). After two days, the evaporation basically transferred into falling-rate stage. After 20 days, the evaporation rates reduced to a stable low level and the differences were considerably little, suggesting the weak effect of calcic nodules on evaporation during this stage. In spite of the small differences in evaporation rate between soil columns, the total soil evaporation reductions were remarkable when soil contained a higher amount of calcic nodules.

3.3 The Effect of Calcic Nodules on Evaporation

Calcic nodules have a certain capacity of water absorption, which cause calcic nodules to absorb water. Whether this water could participate in soil evaporation was unknown. In order to analyze the effect of calcic nodules on evaporation, we calculated the water absorbed by calcic nodules assuming calcic nodules were water saturated. Figure 5 shows the calculated result. Figure 5a was the changes of water absorbed by calcic nodules as calcic nodules were saturated (SW) and evaporation water from SW (EW). Figure 5b was the relationship between SW and EW. It can be seen that both SW and EW were linearly positive to CNC (Fig. 5a) and EW is also positively related to SW (Fig. 5b). This result indicated water absorbed by calcic nodules could partly participate into soil evaporation. And this water was positive to CNC.

In order to determine the water available to evaporation, we calculated total water loss from soil column and SW. If total water loss plus SW exceeded total water, it indicated that water absorbed by calcic nodules participated in evaporation. According to this, we estimated water that participated into evaporation (WAE), and the result showed in Fig. 6. As CNC is between 0–0.2, the proportions of WAE linearly increase with rock fragment content. But, as rock content is between 0.2–0.5, the proportions keep at a level of about 63%. The proportion of WAE is not always increased with CNC though the potential evaporation water increases. The reasons may be: (i) as CNC is lower than 0.2, the total SW is limited and the SW is proportionally increase with CNC (for the water suction of calcic nodules reduces proportionally); (ii) as CNC more than 0.2, the water suction of calcic nodules keep stable and the excessive water is available to evaporation. Consequently, the proportion of WAE maintains at a stable level and no longer increases with CNC. However, further understanding of evaporation in soil containing calcic nodules is needed to consider the water distribution between soil and calcic nodules and water exchange between them.

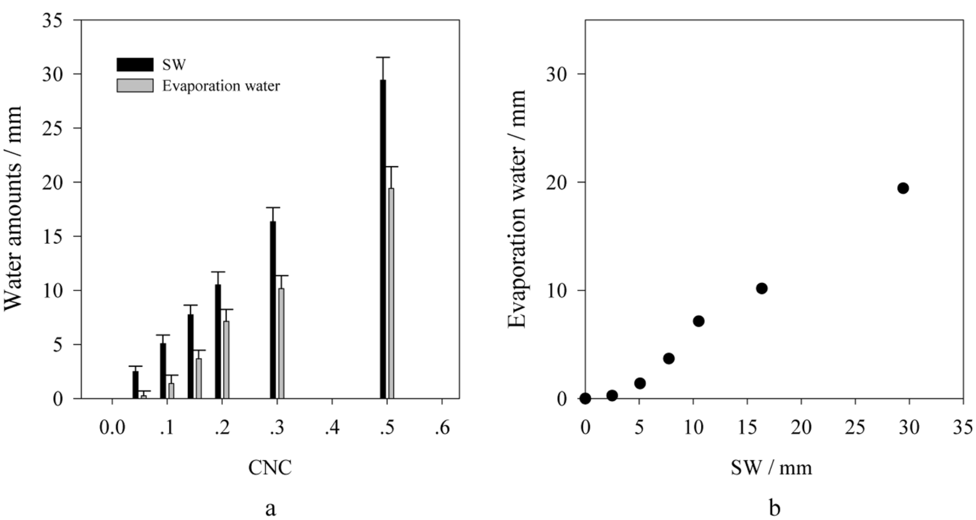

Figure 5. SW and evaporation water in soil columns.

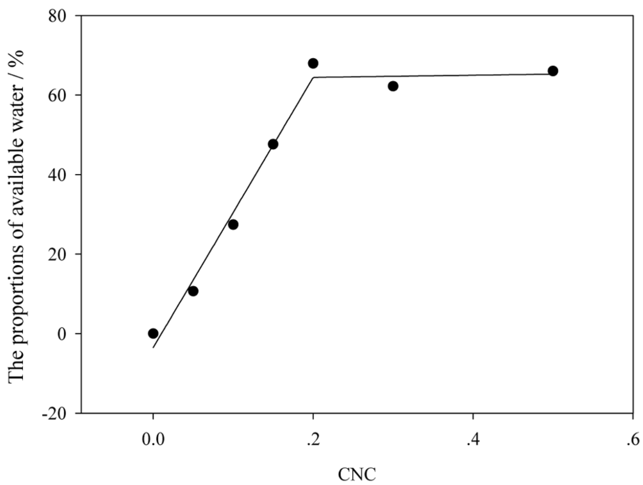

Figure 6. The proportions of WAE to SW.

4 Discussion

During a long time, studies related to calcic nodules affecting evaporation payed much attention to calcic nodules mulching as calcic nodules present at soil surface [19–21]. However, as for calcic nodules embedding in soil, few experiments are carried out [19]. Theoretical consideration, the effects of calcic nodules on evaporation in this case can be attributed to three aspects [19, 21]: (i) reducing evaporation area; (ii) changing soil hydraulic conductivity; (iii) altering soil water allocation.

The appearance of calcic nodules in soil changes not only the water allocation between soil and calcic nodules, but soil water hydraulic conductivity and surface features. In our experiments, the effect of calcic nodules on evaporation mainly occurred during the stage of falling-rate. This can be attributed to fact that calcic nodules are a dominating factor during this stage. As mentioned above, during this stage the evaporation is controlled by soil hydraulic properties, and soil hydraulic properties are negatively related to evaporation transect, resulting in soil hydraulic conductivity negatively related to calcic nodules. During the constant-rate and low-rate stages, atmospheric vapor power and soil water supply are dominant.

The reduction of evaporation caused by calcic nodules can be attributed to the following reasons. First, calcic nodules reduce the evaporation area. In theory, evaporation is positively related to evaporation area. Second, calcic nodules can exert impacts on soil hydraulic properties such as decreasing soil hydraulic conductivity and increasing tortuosity for water flow, which hamper the up-moving of soil water during evaporation [19].

In our experiments, total soil column volume is fixed; the increase of calcic nodules would result in the changes of soil water content (water in soil). If calcic nodules behave like soil or have no water absorption, the increase of calcic nodules would lead to the increase of soil water content as well. If calcic nodules are water saturated all the way, the increase of calcic nodules would cause the decrease of soil water content. Hence, the effect of calcic nodules on soil evaporation is dominated by water absorption of calcic nodules, the availability of this water to evaporation, and CNC. As calcic nodules behave like soil, they can be regarded as a whole [20, 21]. As calcic nodules are without water absorption, the total water distributes in the soil, causing the increase of soil water content owing to the increase of calcic nodules reducing the soil volume. In this case, the tendency of calcic nodules reducing evaporation rate is enforced. If calcic nodules are water saturated all the way, the relationship between evaporation rate and rock fragment content is closely related to invalid water absorbed by calcic nodules, CNC, and soil water response to calcic nodules.

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