Effects of straw size in buried straw layers on water movement in adjacent soil layers

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Abstract: Deeply buried straw retention can improve the soil content of organic matter, its capacity for moisture preservation, the agroecological environment utilization efficiency of water resources, ensuring a stable crop yield; at the same time, the quantitative effects of deeply buried straw retention on soil moisture have a direct influence on the promotion and application of the technology. Using an infiltration and evaporation experiment of a one-dimensional soil column, the effects of straw size on the water content of the straw and the adjacent soil were evaluated when the straw was deeply buried in soil; the infiltration and evaporation features of different sized straw and its adjacent soil were analyzed; the hydraulic conductivity, sorptivity and saturated water content of the straw were obtained; in the end, the water distribution laws of straw and adjacent soil under the same conditions were concluded. The experiment was comprised of rod-shaped straw (RS), segment-shaped straw (SS) and filament-shaped straw (FS) to control treatment (CK). The results indicated that from the perspective of infiltration, the infiltration rate of filament-shape straw was the lowest at the stage of straw unsaturation. The hydraulic conductivities of rod-shaped, filament-shaped and segment-shaped straws are 4.01 mm/min, 1.33 mm/min and 0.03 mm/min at the stage of straw and adjacent soil saturation, respectively. There is a strong effect on preventing infiltration from segment-shaped straw; with the help of the Philip model of long duration, the sorptivity of the soil with rod-shaped, filament-shaped and segment-shaped straws was 12.31 $mm/min^{0.5}$, 11.02 $mm/min^{0.5}$ and 24.26 $mm/min^{0.5}$ at the unsaturation stage, respectively. The segment-shape straw improved the water absorption capacity of the soil and straw column. The water retention capacities indicated that the saturated water contents of sandy loam, filament-shaped straw, segment-shaped straw and rod-shaped straw were 0.38 cm^3/cm^3, 0.29 cm^3/cm^3, 0.26 cm^3/cm^3 and 0.13 cm^3/cm^3, respectively. Additionally, the evaporation rate indicated that the soil moisture content of soil below different straw layers retained approximately 30%; that the more crushed the straw was, the more moisture the straw layer lost; and that the cumulative evaporation of rod-shaped straw, filament-shaped straw and segment-shaped straw within 120 days was 1.5 mm, 13.5 mm and 25.5 mm, respectively.

Keywords: deeply buried straw, straw size, soil moisture, infiltration, evaporation, water retention

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1 Introduction

Northeast China is one of the most important maize-producing areas of China, accounting for 31% of the national maize area and 34% of the total maize produced nationally[1]. Spring maize is one of the most popular grain crops cultivated by local farmers in this region[2]. China produces approximately 640 million tons of straw every year[3]. A large number of harmful gases, such as nitric oxide, black carbon, carbon monoxide, carbon dioxide, etc., is generated by the burning of approximately 23% of these straws in the open air[4]. According to the 2010 Global Burden of Disease Study, approximately 1.2 million people in China died prematurely and 25 million disability-adjusted life years were lost due to air pollution in 2010[5]. Air pollution could become the greatest threat to the health of the

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Chinese public[6]. It is a challenging problem to contend with a large amount of straw in a reasonable, economical, unpolluted and highly practical way. In northeast China, long-term continuous maize cropping in combination with improper fertilization management has resulted in soil organic content (SOC) loss and associated yield suppression[7]. The SOC content in cultivated soils was shown to be 39.9% lower than in uncultivated soils[8]. These effects are reinforced by current conventional tillage (CT) practices, which include the post-harvest removal of crop residues and moldboard or rotary plowing[9]. This type of practice has caused SOC reduction, soil structure degradation and extensive wind-water erosion[10].

Crop straws are often incorporated into soils or mulched on the soil surface as a natural supplement to increase the SOC in sustainable agriculture; meanwhile, decreasing the amount of straw that is burned in the open air[11,12]. Improvements in soil ecological processes are often reported after straw incorporation or mulching, including SOC enhancement, nutrient availability, microbial activity, soil water moisture and crop yield[13-26]. These methods not only mitigate the environmental pollution resulting from straw burning but also improve the soil.

However, some reports indicate that these return methods have drawbacks. For example, existing straw incorporation methods cannot utilize all of the straw produced[27]. The emissions of CO_2 significantly increase because of straw incorporation and mulching[28-30]; furthermore, there are negative effects on seedling emergence after conventional straw retention due to a large amount of fragmented straw retention on the surface of the soil or in the plough horizon[31-33].

Therefore, a novel straw return method (deeply buried straw retention or ditch-buried straw retention; DBSR) has been developed to overcome these problems in China[34,35]. Under the conditions of DBSR, after harvesting in the autumn, the soil is tilled to create deep furrows filled with straw that are backfilled to form ridges by machinery[36]. One special straw layer is constructed under every ridge. Some researchers have indicated that DBSR might be a better straw retention method for increasing SOC, N retention, and crop yields, as well as for improving soil quality[37-40]. DBSR is also advantageous for the vertical infiltration of water and salt leaching[41]. The soil moisture content within the 0-40 cm soil layer increases significantly when mulching straw is combined with deeply buried straw[42].

Obviously, most previous research has focused on the influence of DBSR on soil improvement and soil fertility retention. However, only a few scholars have researched the effect of DBSR on water movement in adjacent soil layers, and less research has been conducted on the effect of straw size on the function of DBSR. Using straw size as a factor and a test of one-dimensional soil column infiltration and evaporation in the laboratory, this research studied the effects of straw of different sizes on the infiltration and evaporation of moisture in the straw and in the adjacent soil to quantitatively describe the capacity for storing and retaining moisture in the deeply buried straw layer in soil. Therefore, this research provides a theoretical basis for the scientific application of deeply buried straw in the soil in both greenhouses and under field agricultural production.

2 Materials and methods

2.1 Experimental conditions

The experiments were conducted in the laboratory of comprehensive testing at Shenyang Agricultural University (41°46′N, 123°27′E, 44.7 mASL) in northeast China. The experimental soil and straw were collected from the Jianping County in the northwest of Liaoning, which is a province in northeast China. The organic C, total N, total P_2O_5 and total K_2O in the maize straw were 42.90%, 0.86%, 0.38% and 1.35%, respectively. The organic matter, total N, total P and total K in the sandy soil were 1.69%, 0.11%, 0.17% and 2.3%, respectively. The detailed physical parameters of the soil and corn straw are listed in Tables 1 and 2.

Table 1 Bulk density and initial moisture content of the different shaped corn straw and soil

Parameters	Treatments			
	RS	SS	FS	CK
BD of soil layer/g cm^{-3}	1.26	1.26	1.26	1.26
BD of straw layer/g cm^{-3}	0.11	0.08	0.07	
IMC of soil layer/cm^3 cm^{-3}	0.02	0.02	0.02	0.02
IMC of straw layer/cm^3 cm^{-3}	0	0	0	

Note: BD means bulk density, IMC means initial moisture content

Table 2 Particle size density of sandy loam

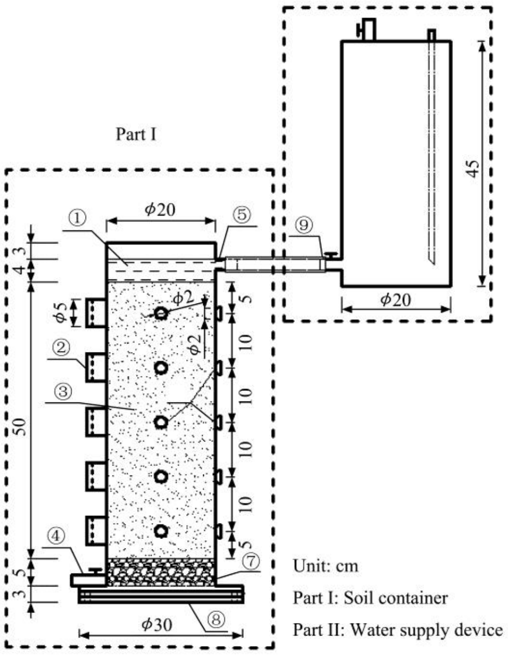
Soil texture	Sand/%	Silty/%	Clay/%
Percent	59.50	30.30	10.20

2.2 Experimental design

The experiment was comprised of four treatments with three replicates. The four treatments were as follows: a control treatment without corn straw (CK); a treatment with rod-shaped straw (RS); a treatment with segment-shapes straw (SS); and a treatment with filament-shaped straw (FS). The crushed extent of corn straw was FS>SS>RS. RS refers to rod-shaped corn straw with a length of 1 cm to 20 cm, SS is segment-shape straw of 1 cm in length cut by a crushing machine, and FS is filament-shaped corn straw of 40-50 cm in length and 0.1-0.2 cm in width crushed by a rubbing machine.

2.3 Experimental soil and corn straw packing

A handmade micro-lysimeter was used in the experiment, consisting of two parts: a soil container and a water supply device (Figure 1).



① Constant head ② TDR monitoring hole ③ Soil and straw ④ Outlet ⑤ Inlet ⑥ Sampling hole ⑦ Crushed gravel inverted filter ⑧ Flange plate ⑨ Outlet

Figure 1 Handmade micro-lysimeter

(1) There was a crushed gravel inverted filter, comprised of 5 cm of gravel on the bottom of the soil container, to supply conditions with unobstructed air for water infiltration. A nylon filter with a 0.1-mmdiameter mesh was paved on the inverted filter to prevent small grains of soil from entering the inverted filter. (2) Sandy loam was added to the column at different layers in equal amounts and a set bulk density of 1.26 g/cm^3. After a 5-cm thick layer of soil was compacted and brushed, another layer of sandy loam would be added to the column to ensure that the bulk density reached the set criteria. (3) The total height of the samples was 50 cm, and they were comprised of three layers: sandy loam, corn straw and sandy loam, with a height of 20 cm, 15 cm and 15 cm, respectively, from bottom to top. The CK sample was only comprised of sandy loam of 50 cm in height, and there was a nylon filter on top of the sample to prevent soil from being scoured by water flow; at the same time, there was a nylon filter between the soil and straw to prevent small grains of soil from entering the corn straw.

2.4 Index monitoring and monitoring methods

2.4.1 Monitoring of the infiltration index

The infiltration experiments were conducted on August 8th, 2014. The vertical soil column was put on lower shelves, while the bottle was put on top shelves. A rubber pipe was attached to the column and the bottle, which made the column inlet and the outlet of the Markov bottle remain on the same level. A stopwatch was attached to the water evapotranspiration device, and water was ponded at the top of the column at a depth of 5 cm. One-dimensional vertical ponding infiltration was implemented to determine the infiltration properties of the soil and corn straw; meanwhile, the data of the water level in the Markov bottle and the position of front wetting in the column per unit time were recorded. After the end of infiltration, the rubber pipe was taken off, and the outside of the column was wrapped in tinfoil to prevent direct sunlight from influencing the water evaporation in the soil. Finally, the top of the column was also sealed by plastic film to achieve the same goal.

2.4.2 Monitoring of the soil and corn straw moisture

Forty-eight hours after the infiltration experiments (August 10th, 2014), the plastic film was taken off, and then, the evaporation experiments were conducted. The volumetric water content of corn straw was obtained using a TDR probe and an oven-drying method; the soil's volumetric water content was measured at depths of 5 cm, 15 cm, 35 cm and 45 cm. Soil samples were taken with a small soil auger 12 times during the 120 days of evaporation.

2.5 Calculation of the saturated hydraulic conductivity of the soil and corn straw

1) The saturated hydraulic conductivity of the homogeneous soil, as well as that of the mixture of soil and corn straw, was obtained with the Darcy Equation, improved by Darcy and Dupuit in the 1950s[43]:

$$J_w = -K_s \frac{\Delta H}{L} \quad (1)$$

where, J_w is the flow rate of water per unit of cross-sectional area, mm/min; ΔH is the distance from the water surface to the soil bottom, mm; L is the soil thickness, mm; and K_s is the saturated hydraulic conductivity of the soil (mm/min).

2) The saturated hydraulic conductivity of the corn straw obtained with Equation (2) based on that of layered soil.

Steady flow through a layered soil can be described by making an analogy between water flow and the flow of an electric current. It would be useful to know the flux through a soil column with N layers of thickness $L_1 ... L_N$ and the saturated hydraulic conductivity $K_1 ... K_N$. Using an analogy between Darcy's and Ohm's laws, the effective saturated hydraulic conductivity, a single value that will have the same effect on flow as all layers combined[44], can be shown as follows:

$$K_{eff} = \frac{\sum_{j=1}^{N} L_j}{\sum_{j=1}^{N} \frac{L_j}{K_j}} \quad (2)$$

where, L_j is the thickness of j layered soil, mm; K_j is the saturated hydraulic conductivity of j layered soil, mm/min; and K_{eff} is the saturated hydraulic conductivity of the layered soil and corn straw sample, mm/min.

3 Results

3.1 Effects of straw size on the water infiltration rules of straw and adjacent soil

3.1.1 Effects of straw size on the cumulative infiltration of water

The water infiltration of the straw and the adjacent soil occurs in three stages based on the location of the moisture peak: an early stage (moisture peak occurs 30 cm under the soil surface), a middle stage (moisture peak occurs at 50 cm under the soil surface) and a stable stage (infiltration rate reaches stability). The dynamic changes of the cumulative infiltration of water under different treatments at different stages are listed in Figure 2.

1) Infiltration laws of water during the early stage

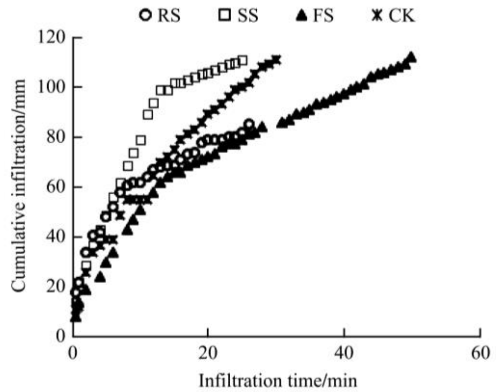
The dynamic changes of the cumulative infiltration of straw and adjacent soil under different treatments during the early stage are listed in Figure 2a, with the average infiltration rate ranging from SS (4.44 mm/min) > CK (3.70 mm/min) > RS (3.27 mm/min) > FS (2.24 mm/min). Therefore, the early stages of soil infiltration per unit time reaches its maximum when segment-shaped straws are buried in deep soil; whereas cumulative infiltration reaches its maximum (approximately 112 mm) with filament-shapes straw buried in deep soil and is a little bit higher than that of segment-shaped straw.

2) Infiltration laws of water during the middle stage

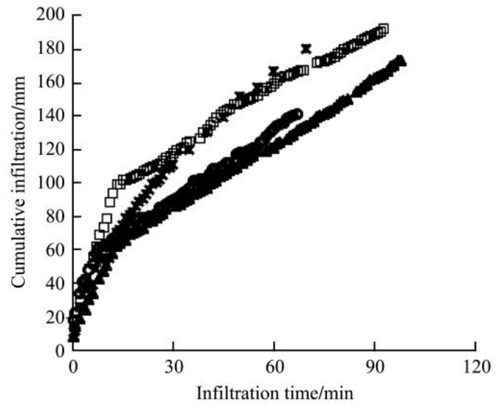
The dynamic changes of the cumulative infiltration of straw and adjacent soil under different treatments in the middle stage are shown in Figure 2b, with the average infiltration rate ranging from CK (2.57 mm/min) > RS (2.10 mm/min) > SS (2.06 mm/min) > FS (1.77 mm/min). Therefore, in the middle stage, the soil infiltration per unit time reaches its maximum without straw, whereas the cumulative infiltration reaches its maximum (approximately 191 mm) with segment-shaped straw buried in deep soil.

3) Infiltration laws of water during the stable stage

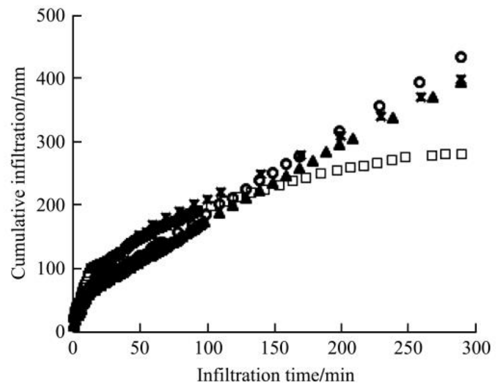
The water infiltration rate per unit of time under different treatments remains stable when infiltration lasts 290 minutes; the dynamic changes of the cumulative infiltration of straw and the adjacent soil under different treatments at this stage are listed in Figure 2c, with the cumulative infiltration ranging from RS (434 mm) > CK (399 mm) > FS (394 mm) > SS (281 mm), the average infiltration rate ranged from RS (1.50 mm/min) > CK (1.38 mm/min) > FS (1.36 mm/min) > SS (0.94 mm/min). Therefore, in stable stage soil, the infiltration per unit time reaches its maximum when rod-shaped straws are buried in deep soil, as does its cumulative infiltration.



a. Changes in the cumulative infiltration under different treatments during the early stage



b. Changes in the cumulative infiltration under different treatments during the middle stage



c. Changes in the cumulative infiltration under different treatments during the stable stage

Figure 2 The dynamic changes of the cumulative infiltration of soil-straw under different treatments during different stages

3.1.2 Effects of straw size on saturated hydraulic conductivity

The saturated hydraulic conductivity (Table 3) of straw of different sizes was obtained with Equation (2) based on the amount of water per unit area per unit of time when the infiltration of other treatments reached stability, with the supposition that the saturated hydraulic conductivity of the upper soil of straw is the same as that of subsoil.

The saturated hydraulic conductivity of sandy loam was obtained with Equation (1), based on the amount of water per unit area per unit time when the infiltration of treatment CK reached stability.

Table 3 shows that the saturated hydraulic conductivity of soil and straw of different sizes is RS>FS>CK>SS, whereas the saturated hydraulic conductivity of treatment RS was 4.3 times as much as that of treatment CK, and that of SS was 0.03 times that of CK, which indicates that under saturation conditions, the hydraulic conductivity of rod-shaped straw is apparently higher than that of sandy loam, whereas that of segment-shaped straw is apparently lower than sandy loam.

Table 3 Straw of different sizes and the saturated hydraulic conductivity of soil

Parameters	Treatment			
	RS	SS	FS	CK
K_{eff}/mm min^{-1}	1.2	0.09	1.02	0.93
K_s/mm min^{-1}	4.01	0.03	1.33	0.93

3.1.3 Effects of straw size on sorptivity in the Philip model of long duration

$$I(t) = St^{0.5} + At \tag{3}$$

where, $I(t)$ is the cumulative infiltration, mm; S is sorptivity, mm/min$^{0.5}$; A is final infiltration rate, mm/min, and t refers to time, min.

The fitting process was conducted with the Philip model of long duration for the actually measured value of filtration in straw and the adjacent soil under different treatments when the infiltration rate reached stability (290 min); the results are listed in Table 4.

Table 4 Filtration parameters under long durations

Treatment	Fitting parameters		R^2
	S/mm min$^{-0.5}$	A/mm min^{-1}	
RS	12.31	0.7	0.9865
SS	24.26	-0.44	0.9941
FS	11.02	0.67	0.9942
CK	18.57	0.25	0.9981

It can be seen from Table 4 that there is a high degree of fit for the Philip model of long duration, and there are changing laws of cumulative infiltration that vary with time under different treatments. All of the R^2 values are beyond 0.98, and the sorptivity of different treatments is SS>CK>RS>FS, which indicates that the sorptivity of segment-shaped straw is better than that of sandy loam. The final infiltration rate of different treatments is RS > FS > CK > SS, where only segment-shaped straw is negative, indicating that the sorptivity of soil and straw mainly constitutes the infiltration of segment-shaped straw in a 290 min treatment and that the Philip model of long duration is not suitable to describe water movement laws.

3.2 Effects of straw size on water retention capacity of straw and adjacent soil

Changing laws of volumetric water content 48 hours after the infiltration experiment are listed in Figure 3. The figure shows that soil moisture increases with increasing depth in the CK treatment, which has a linear distribution as a whole; the soil moisture first decreases and then increases with increasing depth under the RS, SS and FS treatments. The saturated water content of straw of different sizes and the adjacent soil indicate that CK (0.38 cm^3/cm^3) > FS (0.29 cm^3/cm^3) > SS (0.26 cm^3/cm^3) > RS (0.13 cm^3/cm^3).

Table 5 shows that the gross water storage capacity of the straw and the adjacent soil under different treatments is CK > FS > SS > RS, which indicates that the water retention capacity of the CK treatment is the best; the percentage of water retention in straw and the adjacent soil under different treatments is SS > CK > FS > RS, indicating that the water retention capacity of segment-shaped straw is most effective.

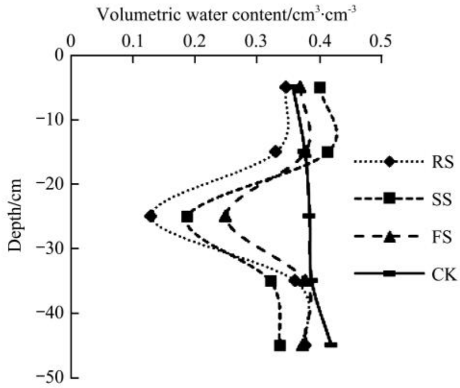


Figure 3 Changing laws of volumetric water content 48 hours after the experiment

Table 5 Percentage of water retained under different soil-straw layers

Treatment	Cumulative infiltration /mm	Impoundage /mm	Percentage water retention/%
RS	434	154.4	35.58Cc
SS	281	165.84	59.02Aa
FS	394	174.56	44.3Bb
CK	399	192.41	48.22Bab

Note: the same letter(s) in the different treatments are not significantly different at $p<0.05$.

The percentage water retention of different layered straw and adjacent soil 48 hours after the infiltration experiment, as well as the average volumetric water content of different layers, are listed in Tables 5 and 6.

It can be seen from Table 6 that the average volumetric water content of the straw layer is lower than that of sandy loam in the upper and lower layer without straw and that CK> FS> SS> RS, with the straw layer being 15 cm to 30 cm under the ground.

Table 6 Average volumetric water content in different layers

Treatment	Average volumetric water content in the 0-15 cm soil layer /cm^3 cm^{-3}	Average volumetric water content in the 15-30 cm straw layer /cm^3 cm^{-3}	Average volumetric water content in the 30-50 cm soil layer /cm^3 cm^{-3}	Average volumetric water content in the 0-50 cm soil layer /cm^3 cm^{-3}
RS	0.34	0.13	0.37	0.28
SS	0.40	0.26	0.33	0.33
FS	0.37	0.29	0.38	0.35
CK	0.36	0.38	0.40	0.38

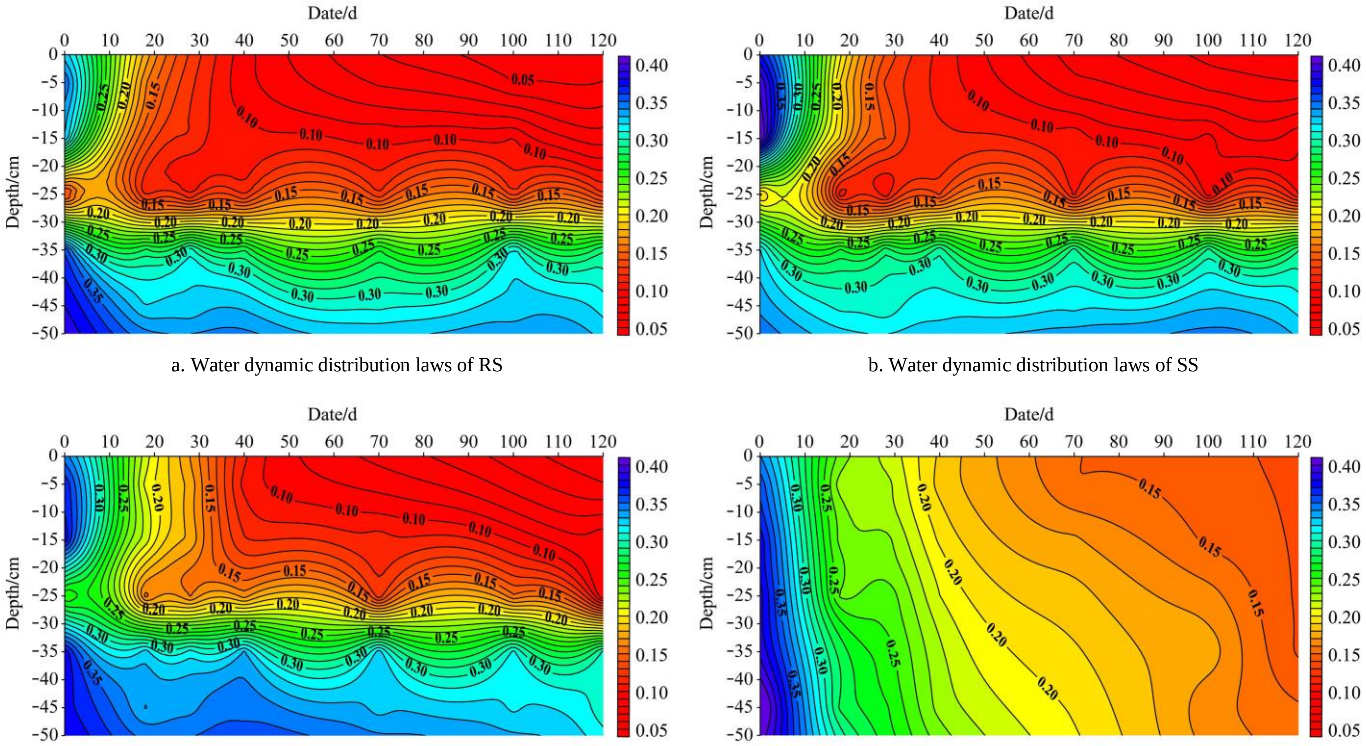
3.3 Effects of straw size on water evaporation laws of straw and adjacent soil

3.3.1 Water distribution laws of straw and adjacent soil during the process of evaporation

The volumetric water content of straw and soil that is 5 cm, 15 cm, 25 cm, 35 cm and 45 cm away from the soil surface were measured with a method of oven drying when evaporation continues for 0, 10 d, 20 d, 30 d, 40 d, 60 d, 80 d, 100 d and 120 d, and contour maps of the volumetric water content were generated with a method of Kriging interpolation (see Figures 4a, 4b and 4c).

Figure 4 shows that during evaporation over 120 days, there is a significant impact from deeply buried straw on soil moisture distribution; the average water content of soil with deeply buried straw in the 0 to 15 cm layer under the ground drops to 0.10 cm^3/cm^3 after 40 days of evaporation and gradually drops to 0.5 cm^3/cm^3 during evaporation from 40 to 120 days, while that for the CK treatment gradually drops to 0.11 cm^3/cm^3 after 120 days of evaporation. The average water content of soil with deeply buried straw in the 15 cm to 30 cm layer under the ground is significantly lower than that for treatment CK at the same depth. The average water content of the 30 cm to 50 cm soil layer under the ground with a straw layer above it retains approximately 0.30 cm^3/cm^3, whereas that for treatment CK gradually drops to approximately 0.15 cm^3/cm^3 within 120 days of evaporation. All of these data indicate that deeply buried straw effectively stops the water in the deep soil from moving upward.

During 120 days of evaporation, the average water content under the rod-shaped, segment-shaped and filament-shaped straws drops to below 0.10 cm^3/cm^3, with a decrease of 0.03 cm^3/cm^3, 0.09 cm^3/cm^3 and 0.11 cm^3/cm^3, respectively, and are respective evaporation duration of 35 d, 38 d and 40 d, which suggests that the more crushed corn straw is, the better the water retention capacity and the better the straw can supply water to the upper soil.



a. Water dynamic distribution laws of RS

b. Water dynamic distribution laws of SS

c. Water dynamic distribution laws of FS

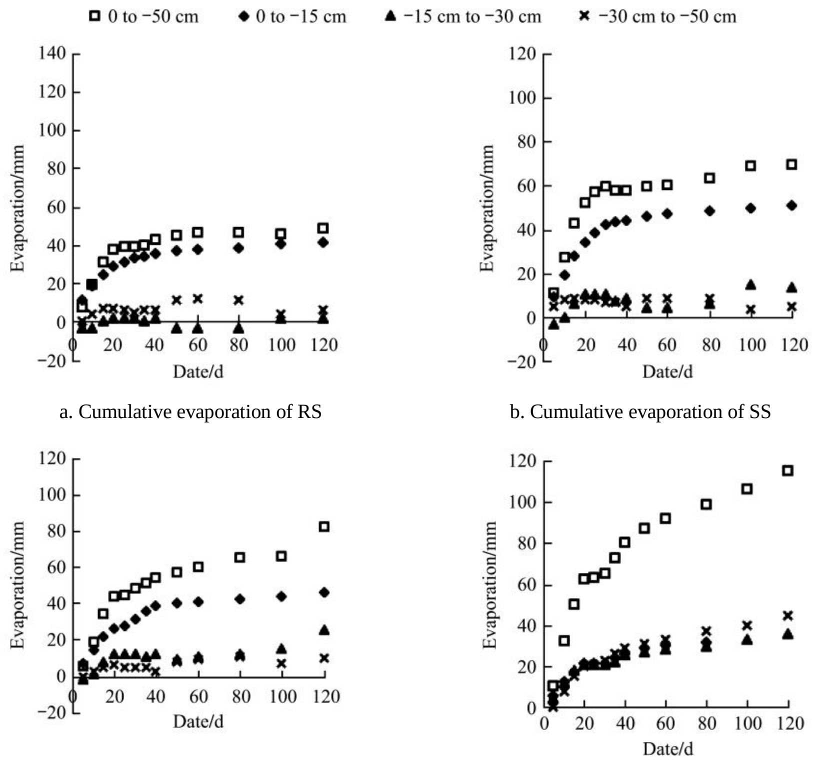
d. Water dynamic distribution laws of CK

Figure 4 Water dynamic distribution laws of soil and straw under different treatments

3.3.2 Effects of straw size on dynamic changes of cumulative evaporation

Moisture changes of straw and adjacent soil are caused by the evaporation of surface soil. The cumulative evaporation of straw and the adjacent soil in the 0 to 15 cm, 15 cm to 30 cm, 30 cm to 50 cm, and 0 to 50 cm under the ground, which were obtained with a water balance equation when evaporation continues for 0, 5 d, 10 d, 15 d, 20 d, 25 d, 30 d, 35 d, 40 d, 50 d, 60 d, 80 d, 100 d and 120 d, and the dynamic changes of cumulative evaporation are listed in Figure 5a, 5b, 5c and 5d.

Figure 5 indicates that after 120 d of evaporation, deeply buried straw can significantly decrease the water evaporation of straw and adjacent soil 0 to 50 cm under the ground, whereas there is strong evaporation in soil 0 to 15 cm under the ground and weak evaporation of soil 15 cm to 30 cm and 30 cm to 50 cm under the ground. The more crushed the straw, the higher the cumulative evaporation of straw and adjacent soil in the 0 to 50 cm soil layer, and the weaker the straw's function in preventing water from evaporating.



a. Cumulative evaporation of RS

b. Cumulative evaporation of SS

c. Cumulative evaporation of FS

d. Cumulative evaporation of CK

Figure 5 Dynamic changes of cumulative evaporation of soil and straw under different treatments

3.3.3 Effects of straw size on water retention capacity

Table 7 shows that deeply buried straw can significantly improve the average moisture content and relative water retention capacity of straw and adjacent soil in the 0 to 50 cm soil layer, and the more crushed the straw is, the lower the average moisture content and relative water retention capacity.

Table 7 Water retention amount in the straw and the adjacent soil from 0 to 50 cm under the ground

Treatment	Initial water content/mm	Evaporation /mm	Final water content/mm	Relative degree of water/%
RS	154.40	49.00	98.40	63.73
SS	165.84	69.50	85.50	51.56
FS	174.56	82.00	81.50	46.69
CK	192.41	115.00	71.00	36.90

4 Discussion

The saturated hydraulic conductivity of soil is one of its hydraulic characteristics and can reflect the vertical infiltration ability of water in soil. Before 2008, many researchers thought that it was difficult to determine the saturated and unsaturated hydraulic conductivity of soil because of the large amounts of macro-pores in the straw layer[31]. Researchers were then able to determine the saturated hydraulic conductivity of soil at a certain depth under a layer of straw mulching[32]. In our research, the saturated hydraulic conductivity of straw of different sizes was obtained with Darcy Equations (1) and (2) based on the assumption that the deeply buried straw and adjacent soil have hierarchical structures; the results indicate that the saturated hydraulic conductivity of rod-shaped straw, filament-shaped straw, sandy loam and segment-shaped straw are 4.01 mm/min, 1.33 mm/min, 0.93 mm/min and 0.03 mm/min, respectively. Based on the aforementioned results and Equation (2), a conclusion can be drawn that under the precondition of stable saturated hydraulic soil conductivity in other layers, the higher the saturated hydraulic conductivity of soil with hierarchical structures is, the better the effective saturated hydraulic conductivity of straw and adjacent soil. Our research indicates that deeply buried rod-shaped straw significantly improves the effective saturated hydraulic conductivity of straw and the adjacent soil, as well as water infiltration into deep soil, whereas deeply buried segment-shaped straw significantly improves the effective saturated hydraulic conductivity of straw and the adjacent soil decrease and prevents water from infiltrating into deep soil. Zhao Yonggan draws the conclusion through a field experiment that there is higher moisture content in soil in the 0 to 40 cm top layer of deeply buried segment-shaped straw and that the segment-shaped straw significantly prevents water from infiltrating into deep soil[29].

The saturated water content of soil is one of its water retention characteristics, and can reflect its maximum capacity to hold water. In previous studies, based on the assumption that the straw layer is an ecological mulching method with an interlayer of water movement, researchers have mainly discussed the variation of saturated moisture content in the soil below and above the straw layer and have neglected that of straw because they think the straw layer is too thin (approximately 5 cm). The results of our research indicate that the more crushed the corn straw is, the higher the saturated moisture content of straw of different sizes because there are many small pores that absorb a certain amount of water in the core of the corn straw, and it is difficult for the phloem outside the corn straw to absorb water. The saturated moisture content of rod-shaped straw decreases because it has a low degree of crushing and its cores are wrapped by outside phloem, whereas that of segment-shaped straw and filament-shaped straw increase because they have a high degree of crushing when more cores are exposed to water. The results also indicate that the saturated water content of straw of different sizes is significantly lower than that of sandy loam, but when the thickness of the straw layer reaches 15 cm, the saturated water content of straw significantly influences the maximum water-holding capacity of the straw and adjacent soil.

Reducing water evaporation and improving the water content in soil are major objectives of mulching and deeply burying straw. Previous researchers have found that through field experiments, the deeply buried straw significantly prevents water in soil below the straw layer from moving upward, compared with the moisture content in homogeneous soil, and the moisture in soil above and below the straw layer improves when straw is mulched and deeply buried[33]. Through evaporation experiments, we found the following: in contrast to homogeneous soil, all of the evaporated water in the straw and the adjacent soil is mainly derived from lost water in the soil above the straw layer and that there is a higher evaporation rate and more cumulative evaporation in the soil. The moisture in the straw layer decreases fast, the more crushed the straw is, the more cumulative the evaporation is, but the cumulative evaporation is still less than in homogeneous soil at the same depth; the moisture in the soil below the straw layer decreases slightly, retaining approximately 30 cm^3/cm^3; and there is a significant difference in moisture distribution in the straw layer and soil above or below the layer, and the distribution law is significantly different from that in homogeneous soil. The study of deeply buried straw of different sizes and its adjacent soil indicates that the cumulative evaporation of rod-shaped straw, segment-shaped straw, filament-shaped straw and homogeneous soil is 1.5 mm, 13.5 mm, 25.5 mm and 36.0 mm, respectively, indicating that the more crushed the straw, the more its cumulative evaporation. At the same time, our research indicates that the moisture content of deeply buried straw and its adjacent soil is higher than that of homogeneous soil, indicating that deeply buried straw and its adjacent soil has better water-holding capacity and that the more crushed the straw is, the less its overall moisture content and the lower its water-holding capacity.

5 Conclusions

This research indicates that straw of different sizes influences not only saturated hydraulic conductivity, saturated moisture content and water loss capacity of soil but also water infiltration, retention and evaporation when the straw is deeply buried in the soil. The saturated hydraulic conductivity of rod-shaped straw and filament-shaped straw is higher than that of sandy loam, and that of rod-shaped straw is the highest, whereas that of segment-shaped straw is significantly lower than that of sandy loam. The more crushed the straw is, the higher the saturated hydraulic conductivity and the larger the water loss. When deeply buried in soil, rod-shaped straw and filament-shaped straw, compared to sandy loam, can improve the water infiltration rate in soil, with rod-shaped straw being achieving the highest rate, while deeply buried segment-shaped straw significantly decreases the water infiltration rate in soil. The more crushed the straw is, the higher the upper limit of water-retention of deeply buried straw and the adjacent soil and the poorer the water-retaining capacity. In conclusion, the straw size has a significant influence on water movement laws in deeply buried straw and the adjacent soil.

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