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Effects of Straw Mulching on Near-Surface Hydrological Process and Soil Loss in Slope Farmland of Red Soil

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Abstract: Slope farmland is prone to soil erosion, especially in sub/tropical regions. However, our understanding of near-surface hydrology characteristics and their controlled factors in red soil sloping farmland remains limited. Here, we conducted simulated rainfall experiments to assess the impact of rainfall pattern, straw mulching, and soil structure on near-surface hydrological processes of red soil sloping farmland of southern China. Results showed that: (1) short duration-high intensity rain caused greater surface runoff and sediment production than did long duration-low intensity rain, whereas the variation pattern of subsurface flow exhibited the opposite trend; (2) tillage behavior could weaken the surface runoff intensity and promote the development of subsurface flow; (3) straw mulching increased the water infiltration rate and associated subsurface flow production (increased by 1.33~12.71 times), and thus reduced the surface runoff production (reduced by 99.68~100%). These findings highlight the crucial roles of rainfall pattern and straw mulching in regulating the spatial distribution pattern of rainwater and suggest that straw mulching can effectively reduce soil erosion via accelerating water infiltration and subsurface flow form in slope farmland of soil erosion in southern China.

Keywords: slope farmland; simulated rainfall; subsurface flow; soil structure; rape straw mulching

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1. Introduction

Cultivated land is a scarce resource for the survival of people in various developing countries, including China [1,2]. As an important part of cultivated land, slope farmland has attracted more and more attention. However, due to unreasonable land use, the soil and water loss of slope farmland has been aggravated, making slope farmland become an important source of soil and water loss in many regions [3–5], which has become an ecological environment and agricultural resource problem that has attracted much attention worldwide. To ensure the normal life needs of people in hilly areas of developing countries, it is urgent to control soil erosion in sloping farmland.

Soil structure is an important factor affecting the near-surface hydrology of sloping farmland. Some scholars had preliminarily discussed the influence of soil configuration in black soil [6], purple soil [7,8] and karst topography [9] on near-surface hydrology. For example, in the report of Zhang [9], the surface runoff in the karst area after rainfall was less, and it was usually characterized by full runoff. Subsurface flow and deep leakage are important hydrological processes in the region. Zhang [6] found that in the black soil region, the soil layer was thick, the vertical stratification was obvious, the upper layer was loose, the lower layer was dense, and the infiltration performance was poor. The special soil configuration was easy to form the upper stagnant water. Long [7] found that the purple soil area had steep slope, thin soil layer, high gravel content, large porosity and strong infiltration capacity. Subsurface flow occurs in the middle and late stages of rainfall after soil saturation, and the runoff yield was large. However, the response of near-surface hydrology to rainfall caused by special tillage soil structure was still unclear. Long-term tillage of red soil slope farmland makes the surface soil loose and permeable. The bottom soil of the tillage layer was compacted by tillage equipment, which increased soil density and thus reduced soil permeability. Porosity, especially the content of macropores, is low, and the permeability is significantly lower than that of the loose plow layer, forming a typical soil structure of "upper loose-lower tight" [10]. Under sufficient precipitation and special soil configuration, red soil slope farmland makes the development of subsurface flow more active. In some extreme rainfall events, the outflow of subsurface flow even exceeds the surface runoff, which dominates the rainfall-flow process on the slope [11]. Surface runoff and subsurface flow of sloping farmland are important components of watershed runoff, and directly affect the hydrological process of the whole watershed [12,13]. Both of them play an equally important role in soil erosion.

As one of the measures to control soil erosion, straw mulching cannot only improve soil properties but also play an active role in reducing the surface erosion of sloping farmland [14–16]. Some scholars had preliminarily discussed the hydrodynamic process of straw mulch. Compared with bare land, straw mulching can increase surface roughness [17], significantly reduce flow velocity [18,19], reduce runoff [20,21], and reduce sediment. For example, Prosdocimi [21] reported a significant decrease in soil erosion rates due to reduced surface runoff due to straw mulching. Straw can affect the process of surface runoff and sediment production by increasing the roughness of the surface. Mulumba [22] and Guo [23] showed that straw mulching could effectively reduce surface temperature and water evaporation. Straw mulching can reduce soil bulk density and significantly promote soil water use efficiency [24]. In addition, straw mulching can also protect the soil surface from the splashing effect caused by raindrops, prevent the crusting effect of the soil surface during rainfall, and reduce the surface runoff and the amount of sediment covered by runoff [25,26]. However, few studies have considered the interaction between straw mulching on surface runoff and subsurface flow.

The southern red soil region is an important food production area in China, and it is also one of the most densely populated areas. As an important cultivated land resource in the region, slope farmland accounts for 26.3% of the cultivated land area there [27]. However, due to the unique natural conditions (such as subtropical monsoon rainfall patterns and landforms, soil parent materials, etc.) and social factors, this region has become one of the regions with serious soil and water loss in China, and agricultural development is greatly restricted. In recent years the region has used a series of means to solve the problem of soil and water loss, and has achieved remarkable phased results. However, there is still insufficient research on the response of near-surface hydrology to rainfall under straw mulching on sloping farmland in this region. Because of this, the purpose of this study is (1) to explore the influence of different rainfall patterns on near-surface hydrology and soil erosion; (2) to explore the influence of slope farmland soil structure on near-surface hydrology and soil erosion; and (3) to explore the impacts of straw mulching on near-surface hydrology and soil erosion for different rainfall patterns.

2. Materials and Methods

2.1. Study Site

The experiment was performed in the simulated rainfall hall of Jiangxi Soil and Water Conservation Ecological Science and Technology Park (115°43′42″, 29°16′55″) from July to October 2020. The science and technology park is located in the south of Dean County, Jiujiang City, Jiangxi Province. The study site is located in the small watershed of Yangou and the west bank of Boyang River in the Poyang Lake system (Figure 1). This site belongs to the subtropical monsoon climate zone with abundant rainfall. The average annual rainfall is 865.6~1807.7 mm, accounting for nearly 50% of the annual rainfall from June to October. The annual average temperature is 16.7 °C, annual sunshine hours range from 650~2100 h, the frost-free period 245~260 d, the soil parent material is Quaternary red clay, and the zonal vegetation is subtropical evergreen broad-leaved forest. The landform in the region is shallow hilly land with an elevation of 30~100 m and a slope of less than 25°. The science and technology park is located in the red soil center of China, and the terrain and soil conditions are typically representative.

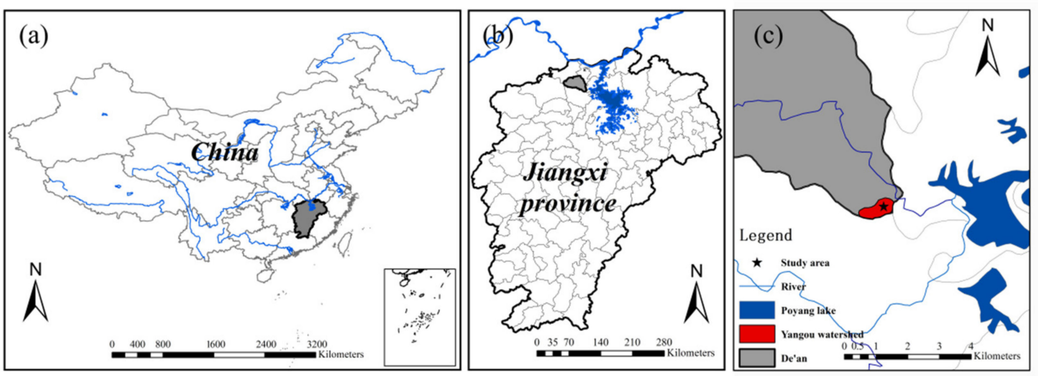

Figure 1. Location map of test area (**a**) Location of Jiangxi Province in China; (**b**) Location of De'an County in Jiangxi Province; (**c**) The location relationship between the test site and Yangou watershed, De'an County and Poyang Lake.

2.2. Test Materials

In this experiment, we used the steel soil tank with 1.5 m × 0.5 m × 0.5 m (length × width × height) to collect surface runoff, subsurface flow, and deep leakage in soils (Figure 2). According to the field investigation, the test slope was treated as 10° [28,29], representing the slope of most red soil slope farmland. The filling soil was a typically quaternary red soil collected from the study area (Table 1). The soil was naturally dried and screened to remove plant roots and gravel for standby. A layer of 5 cm thick graded gravel was filled at the bottom of the soil tank, and a layer of geotextile was covered on the gravel to prevent the loss of the upper soil and facilitate water permeability.

Table 1. Basic physical and chemical properties of soils.

Sand/(%)	Silt/(%)	Clay/(%)	pH	Organic Matter/(g kg^{-1})
13.700	53.055	33.245	5.533	13.24

Note: Sand (2.0 mm ≥ D > 0.02 mm). Silt (0.02 mm ≥ D > 0.002 mm). Clay (D < 0.002 mm).

In this study, the soils with the same bulk density were regarded as homogeneous soils (HoS) and filled uniformly to 5~45 cm of the soil tank. However, heterogeneous soils (HeS) were composed of two soil layers with different bulk densities. The details are exhibited in Table 2. For each treatment, soil was filled into the soil tank every 5 cm. And breaking the soil surface before filling the next layer. The soil moisture content of the soil tank test was controlled at 10 ± 1%, and the test was carried out after the completion of the soil tank filling.

Table 2. Backfilling bulk density of soil tank.

Soil Depth/(cm)	HoS/(g cm^{-3})	HeS/(g cm^{-3})	HeS + SM/(g cm^{-3})
0~15	1.10	1.10	1.10
15~40	1.10	1.45	1.45

Note: HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

Oilseed Rape (*Brassica napus* L.), as a common oil crop in the south of China, is widely planted in red soil sloping fields. Rapeseed leaves a large amount of straw after harvesting, which is an excellent material for straw mulching. The rape straw was taken from the rape planted in the slope farmland of the study area, and naturally dried after mature harvest. Before the experiment, the rape straw was crushed to 5~10 cm for covering. The covering amount was 10 t hm^{-2}, and the soil tank area in this experiment was 0.75 m^2. Straw laying thickness was about 3–5 cm.

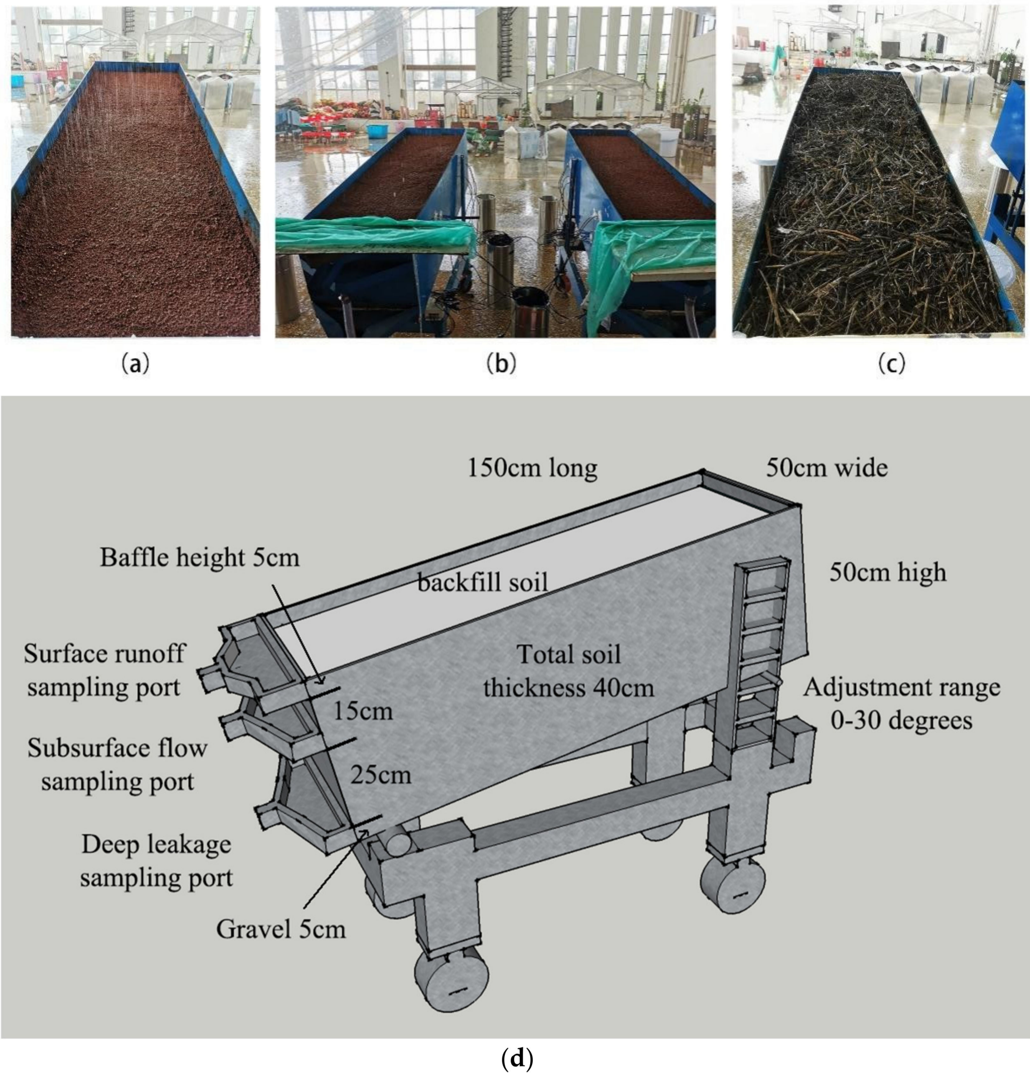

Figure 2. Experimental demonstration and soil tank schematic. (**a**) Uncovered soil tank. (**b**) Soil tanks during rainfall experiment. (**c**) Straw–covered soil tank. (**d**) Schematic diagram of steel soil tank.

2.3. Test Method

To simulate natural precipitation, this work was conducted in a rainfall hall, in which effective rainfall area, rainfall height, and rainfall evenness were 786 m^2, 18 m, and 0.85, respectively. The whole rainfall hall was divided into four independent rainfall test areas, of which areas 1, 2 and 3 were the lower spraying area, and area 4 was the side spraying area. The whole process of this test was completed in zone 2, which adopts FULLJET rotary down jet nozzle. The variable range of rainfall intensity in the spraying area is 10~200 mm h^{-1}.

Under the condition of consistent total rainfall control, two typical rainfall patterns in the southern red soil region were selected for the simulation test [30]. Rainfall pattern A was designed to simulate the rainfall with short duration-high intensity rain in summer, which lasts 1.5 h, and the rainfall intensity was 90 mm h^{-1}. Rainfall pattern B was designed to simulate the rainfall with long duration-low intensity rain in spring, which lasted for 4.5 h and the rainfall intensity was 30 mm h^{-1}. The designed rainfall field of this test was 3 (treatment) $\times$ 3 (repeat) $\times$ 2 (rain pattern) = 18. In the actual process of the test, there were 18 rainfalls, including 0 invalid rainfalls and 18 effective rainfalls. The test results were taken as the average of three repetitions.

In this experiment, water samples were collected every three minutes from the beginning of the rainfall and measured until the end of surface runoff. Among them, due to the mixed sediment in the surface runoff sample, the samples were weighed and filtered with a fast filter paper. The paper-wrapped sediment was put into the oven, the temperature of the oven was set to 105 °C, and the sediment was baked for more than 8 h and read after drying.

2.4. Analysis Method

All statistical analyses were performed with R version 4.1.1 [31], and the accepted significance level was set at $\alpha = 0.05$. A one-way ANOVA of Tukey's HSD comparison was used to determine the differences in the runoff, sediment yield, and subsurface flow among different treatments with the 'agricolae' package. Excel 2019 and Origin pro 2022 were used to process data and draw charts.

3. Results

3.1. Surface Runoff Generation Characteristics

Analysis of surface runoff start time and flow under straw mulching on red soil slope farmland is shown in Table 3. It can be seen that the surface runoff generation time of HoS (homogeneous soil) and HeS (heterogeneous soil) was similar under long duration-low intensity rain. The runoff generation time was ranked as HoS < HeS < HeS + SM from early to late. HoS and HeS began to produce runoff after 157.00 min and 160.42 min, respectively, and the HeS + SM with straw mulch did not produce surface runoff. The total surface runoff yields of HoS and HeS were 15.72 L and 9.83 L, respectively. The surface runoff of HoS was 1.6 times higher than HeS. The peak flow and average flow showed the same regularity. When the short duration-high intensity rain, the surface runoff of red soil slope land was faster, and the order was HoS < HeS < HeS + SM from early to late. HoS and HeS started runoff at 6.18 and 7.83 min after the beginning of rainfall, respectively. HeS + SM began runoff at 19.03 min. By comparing the two rainfall patterns, we can see that the short duration-high intensity rain causes early surface runoff generation, large total runoff, and high peak flow. Straw mulching significantly reduced surface runoff in red soil slopes.

Table 3. Effect of straw mulching on surface runoff of Red Soil Sloping Farmland.

Rain Pattern	Test Treatment	Runoff Generation Time/(min)	Total Flow/(L)	Peak Flow/(mL)	Average Flow/(mL)
Long duration -low intensity	HoS	157.00 ± 4.25 a	15.72 ± 1.60 a	740.00 ± 3.00 a	413.71 ± 21.05 a
	HeS	160.42 ± 3.35 a	9.83 ± 1.63 b	500.00 ± 45.00 b	265.54 ± 7.65 b
	HeS + SM	/	0	0	0
Short duration -high intensity	HoS	6.18 ± 0.03 c	81.41 ± 3.82 a	3300.00 ± 155.00 a	3015.19 ± 127.41 a
	HeS	7.83 ± 0.31 b	66.70 ± 7.52 b	2800.00 ± 55.00 b	2382.14 ± 90.60 b
	HeS + SM	19.03 ± 1.20 a	0.21 ± 0.02 c	18.00 ± 5.00 c	9.22 ± 0.84 c

Note: For the same column, different lowercase letters indicate significant differences among different treatments under the same rain pattern ($p < 0.05$). ± denotes standard deviation. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

It can be seen that the surface runoff intensity of HoS was greater than that of HeS under the long duration-low intensity rain (Figure 3a). Generally, the runoff intensity of Hos and HeS increased during rainfall. The runoff intensity reached its peak at the end of rainfall, and the runoff immediately ended after the end of rainfall. Differently, under short duration-high intensity rain (Figure 3b), the runoff intensity of soil tanks without straw mulching increased rapidly after runoff generation and formed superosmotic runoff. Between 20~25 min after the beginning of rainfall, the runoff intensity stabilized until the end of rainfall. Straw mulching leads to low surface runoff intensity and stable runoff yield on red soil slope.

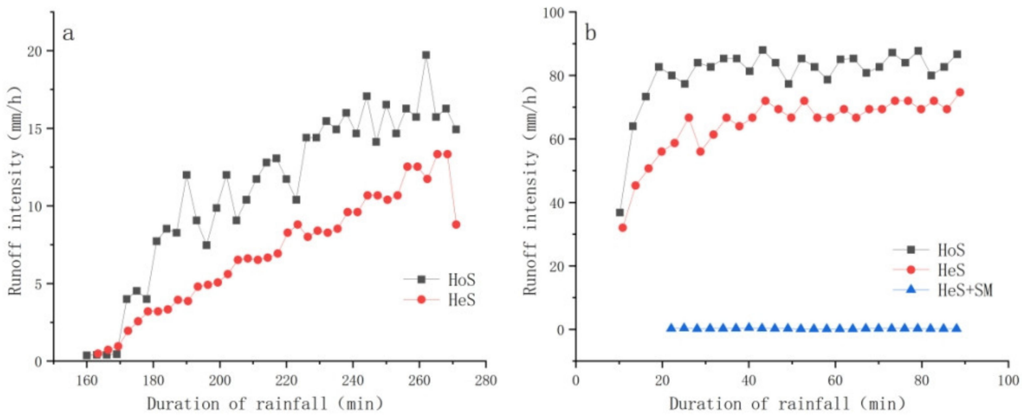

Figure 3. Surface runoff process under different rainfall patterns (**a**) Long duration-low intensity rain; (**b**) Short duration-high intensity rain. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

3.2. Sediment Yield Characteristics

The soil loss analysis of red soil slope farmland under straw mulching conditions was shown in Table 4. We can know that the total erosion of HoS was 1.4 times of HeS at long duration-low intensity rain. However, due to the large surface runoff of HoS, the sediment concentration was diluted, and the sediment concentration of HoS was 0.8 times that of HeS. Under short duration-high intensity rain, the total erosion amount was 1.2 times that of HeS. The sediment concentrations of the two were close, and HoS was 0.98 times that of HeS. It is worth noting that the total amount of soil erosion caused by short duration-high intensity rain was 12.12~12.39 times that of long duration-low intensity rain, and the peak erosion reached 35.29~44.29 times. In the case of constant rainfall, short duration-high intensity rain can form greater soil erosion.

Table 4. Effect of straw mulching on soil loss in red soil sloping farmland.

Rain Pattern	Test Treatment	Sediment Concentration (g L^{-1})	Total Sediment Yield (g)	Peak Sediment Yield (g)	Average Sediment Yield (g)
Long duration -low intensity	HoS	2.58 ± 0.06 [a]	40.43 ± 5.94 [a]	1.54 ± 0.05 [a]	1.19 ± 0.041 [a]
	HeS	3.23 ± 0.19 [a]	28.25 ± 3.17 [b]	1.19 ± 0.03 [a]	0.94 ± 0.039 [a]
	HeS + SM	0	0	0	0
Short duration -high intensity	HoS	5.96 ± 0.23 [b]	490.06 ± 20.08 [a]	54.35 ± 1.40 [a]	17.50 ± 1.07 [a]
	HeS	6.09 ± 0.02 [a]	406.52 ± 10.70 [a]	52.70 ± 0.95 [b]	14.52 ± 0.50 [b]
	HeS + SM	0	0	0	0

Note: For the same column, different lowercase letters indicate significant differences among different treatments under the same rain pattern ($p < 0.05$). ± denotes standard deviation. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

The analysis of soil loss processes caused by different rainfall patterns on sloping arable land was shown in Figure 4. We know that the erosion amount of red soil slope fluctuates with the continuous rainfall under the long duration-low intensity rain (Figure 4a). At the same rainfall time, the erosion amount generated by HoS was lower than that generated by HeS. Under short duration-high intensity rain, the trend of the HoS and HeS erosion process line was close (Figure 4b). Erosion of HoS and HeS increased rapidly from the beginning of runoff to peak in about 20 min and then decreased rapidly. The runoff intensity tends to level off until the end of the rainfall, about 50 min after the start of the rainfall.

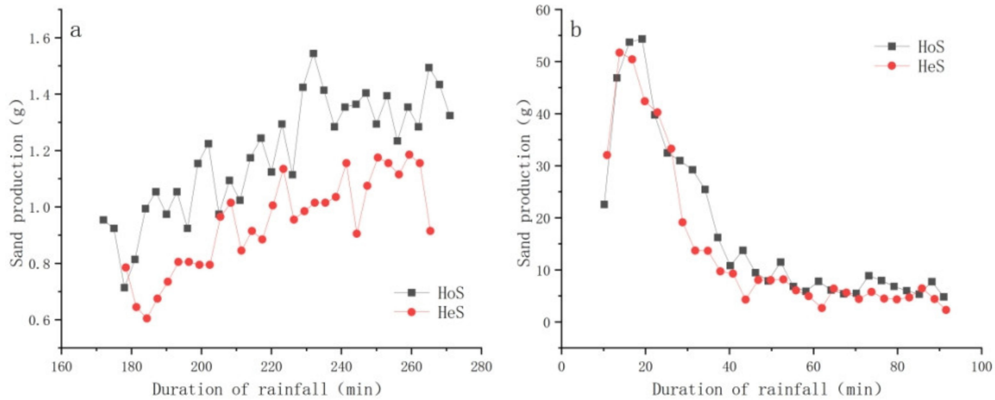

Figure 4. Surface sediment production process under different rain patterns (**a**) Long duration-low intensity rain; (**b**) Short duration-high intensity rain. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

3.3. Subsurface Flow and Deep Infiltration Characteristics

Analysis of the beginning time and flow rate of subsurface flow in red soil sloping farmland under straw mulching was shown in Table 5. It can be seen that under long duration-low intensity rain, the runoff generation time of subsurface flow of HoS and HeS was earlier than that of surface runoff. The subsurface flow of HoS was 14.5 min earlier than that of surface runoff, and the subsurface flow of HeS was 19.19 min earlier than that of surface runoff. The total flow in soil from high to low was HeS + SM > HeS > HoS, but the peak flow production was HeS + SM > HoS > HeS. Under long duration-low intensity rain, the beginning time of HoS leakage (40 cm) runoff was close to that subsurface flow. However, the leakage of HeS and HeS + SM was significantly different from the runoff generation time of subsurface flow. The time of subsurface flow and leakage of HeS + SM was earlier than that of HeS. We found that the total runoff showed HeS + SM > HeS > HoS in the long duration-low intensity rain. This indicates that the flow rate was positively correlated with the flow time. Under short duration-high intensity rain, the runoff generation time of subsurface flow was later than that of surface flow, and the runoff generation time from early to late was HoS < HeS < HeS + SM, which was opposite to that under long duration-low intensity rain. The total flow of subsurface flow was inversely proportional to the runoff generation time, which was HoS < HeS < HeS + SM. Straw mulch had a great influence on leakage. The leakage runoff of the soil tank covered by straw mulch started early and the runoff was large.

The response process of subsurface flow to different rainfall patterns in red soil sloping farmland under straw mulching was shown in Figure 5. We can see that the HeS + SM flow generation time was the earliest (Figure 5a). With continuous rainfall, the runoff intensity was increased. Runoff intensity was proportional to time. The runoff intensity was proportional to time until the peak intensity is reached at the end of rainfall, and then rapidly decreased to the end of runoff. The runoff generation time of HoS was close to that of HeS. After HoS began to produce runoff, the runoff intensity increased rapidly, reached the peak at 169.50 min, and then decreased rapidly. The runoff stopped at 208.5 min. The runoff intensity increased rapidly after the beginning of HeS runoff, remained stable at about 180 min, and gradually decreased to the end of rainfall after 210 min. Under the condition of short duration-high intensity rain, the runoff intensity of HoS and HeS was higher than that of HeS + SM at the beginning of runoff generation (Figure 5b). The runoff generation time of HeS + SM was relatively late. With continuous rainfall, the runoff intensity of subsurface flow increased and reached the peak intensity at the end of rainfall.

Table 5. Effects of straw mulching on subsurface flow and deep leakage in red soil sloping farmland.

Rain Pattern	Test Treatment	Subsurface Flow				Deep Leakage			
		Runoff Generation Time (min)	Lag Time Compared with the Surface (min)	Total Flow (L)	Peak Flow (mL)	Runoff Generation Time (min)	Lag Time Compared with the Surface (min)	Total Flow (mL)	Peak Flow (mL)
Long duration -low intensity	HoS	142.50 ± 1.75 [a]	−14.50 ± 2.50 [a]	1.55 ± 0.09 [c]	175.00 ± 7.00 [a]	141.50 ± 4.95 [b]	−15.5 ± 0.7 [b]	34.43 ± 2.30 [a]	1467.00 ± 75.00 [a]
	HeS	141.23 ± 1.52 [a]	−19.19 ± 1.83 [a]	3.92 ± 0.19 [b]	152.00 ± 11.00 [b]	168.75 ± 3.67 [a]	8.33 ± 0.32 [a]	23.24 ± 3.20 [b]	480.00 ± 56.00 [b]
	HeS + SM	101.50 ± 2.74 [b]	/	5.23 ± 0.30 [a]	180.00 ± 10.00 [a]	161.30 ± 2.12 [a]	/	29.03 ± 3.55 [ab]	600.00 ± 60.00 [b]
Short duration -high intensity	HoS	10.85 ± 0.37 [c]	4.67 ± 0.34 [b]	0.35 ± 0.04 [c]	130.00 ± 5.00 [b]	92.12 ± 11.28 [a]	85.94 ± 11.25 [a]	1.35 ± 0.11 [b]	30.00 ± 5.00 [b]
	HeS	13.00 ± 0.80 [b]	5.17 ± 0.49 [a]	2.18 ± 0.14 [b]	140.00 ± 4.00 [b]	/	/	/	/
	HeS + SM	23.02 ± 1.28 [a]	3.99 ± 0.08 [c]	27.71 ± 0.93 [a]	1790.00 ± 120.00 [a]	39.65 ± 1.75 [b]	20.62 ± 0.55 [b]	41.42 ± 5.03 [a]	1280.00 ± 80.00 [a]

Note: For the same column, different lowercase letters indicate significant differences among different treatments under the same rain pattern ($p < 0.05$). ± denotes standard deviation. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

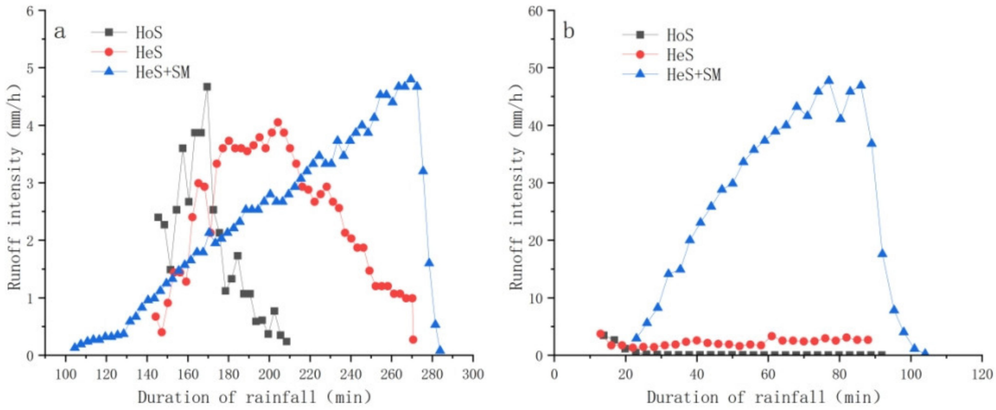

Figure 5. Subsurface flow process under different rainfall patterns (**a**) Long duration-low intensity rain; (**b**) Short duration-high intensity rain. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch.

4. Discussion

4.1. Effects of Rainfall Pattern on Near-Surface Hydrological Process and Soil Loss

In this study, the surface runoff generated by short duration-high intensity rain in uncovered sloping farmland was 5.18~6.79 times that of long duration-low intensity rain, and soil erosion was 12.12~14.39 times as much. For short duration-high intensity rain, the surface runoff accounted for 66~80% of the total rainfall water, and the surface runoff caused by long duration-low intensity rain accounted for only 10~16% of the rainfall water (Figure 6). Previous [32,33] studies showed that short duration-high intensity rain is an important rainfall pattern that causes erosion in various regions compared to long duration-low intensity rain. Ma [34] found that the mean runoff depth of short duration-high intensity rain was 3.4 times that of long duration-low intensity rain. Short duration-high intensity rain is the main pattern of rainfall that causes runoff development on purple soil slopes. Fang [32] analyzed natural rainfall and found that the total runoff caused by short duration-high intensity rain was the highest among all rainfall patterns in karst areas. Ma [33] reported that the rill erosion of red soil slope farmland occurred in the 33rd minute under the condition of heavy rain and heavy rain, and in the 160th minute under the condition of light rain and heavy rain. Generally, short duration-high intensity rain in a certain period rainfall, more than surface soil moisture infiltration rate to form surface runoff. The water not absorbed by the soil forms surface runoff, which takes away the surface soil and leads to soil erosion. Therefore, short duration-high intensity rain is more likely to cause soil erosion than long duration-low intensity rain under the same value of rainfall.

Different rainfall patterns have a great influence on subsurface flow beginning time and runoff yield. Specifically, the subsurface flow of long duration-low intensity rain started earlier than that of short duration-high intensity rain. Moreover, the subsurface flow produced by long duration-low intensity rain was 1.80~4.43 times that of short duration-high intensity rain in uncovered sloping farmland. Long duration-low intensity rain produced a subsurface flow of 2~4% of total rainfall, while short duration-high intensity rain produced 0~2% (Figure 6). We believe that in long duration-low intensity rain, the rainfall intensity per unit time is small, and the water has sufficient time to infiltrate, thus forming subsurface flow. In short duration-high intensity rain, the infiltration rate of surface soil was lower than that of rainfall intensity, forming infiltration excess runoff [35]. Moreover, short duration-high intensity rain forms surface crusts after raindrops hit the surface soil [36,37], further reducing the soil infiltration rate and subsurface flow. This is consistent with most previous studies [38]. These findings indicate that long duration-low intensity rain is more likely to promote the development of subsurface flow than short duration-high intensity rain.

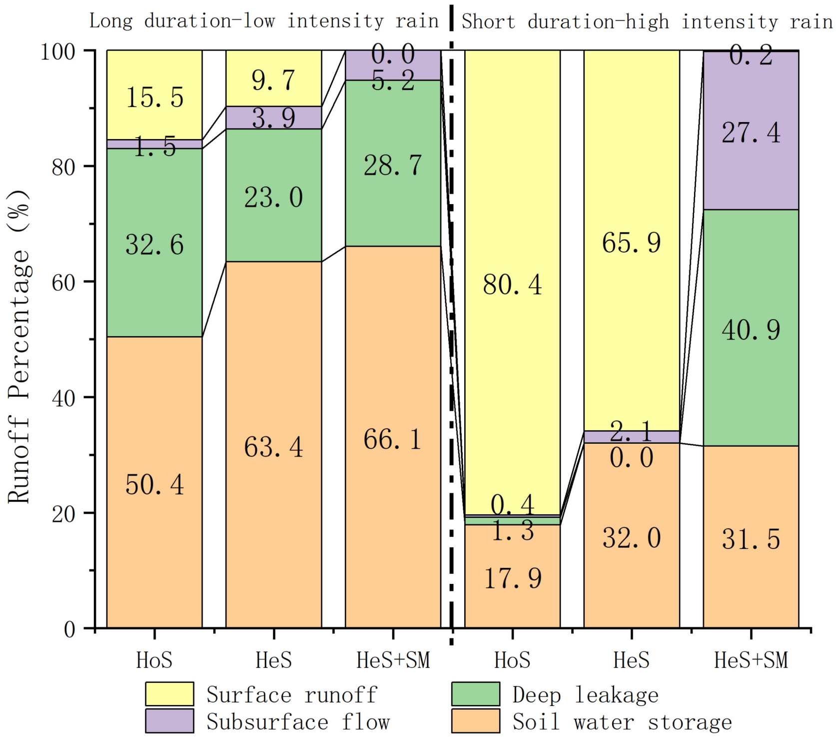

Figure 6. Surface runoff and subsurface flow under different rainfall patterns. HoS, Homogeneous soil. HeS, Heterogeneous soil. HeS + SM, Heterogeneous soil + Straw mulch. (The proportion is less than 1%, and the figure is not marked).

4.2. Effect of Soil Structure on Near-Surface Hydrological Process and Soil Loss

In red soil slope farmlands, soil structure is an important factor affecting surface runoff and erosion [39]. Our results showed that the surface runoff generated by HeS (heterogeneous) was lower than that done by HoS (homogeneous), regardless of rainfall pattern. Because the surface infiltration rate of soil with heterogeneous is higher than that of homogeneous soil. Part of the water was absorbed by the surface soil infiltration, thereby reducing the generation of surface runoff. This is consistent with previous research results [40]. Nanda [40] report that the spatial heterogeneity of soil properties affects the spatial distribution of runoff. Relatedly, less surface runoff can cause less erosion. This is consistent with our results that HeS has lower surface soil erosion than HoS. These phenomena indicate that the soil structure of red soil slope farmland can effectively reduce the yield of surface runoff and weaken the surface erosion caused by rainfall.

The subsurface flow is also affected by the soil structure. Different from surface runoff, the subsurface flow of HeS was 2.53~6.23 times of HoS under two rainfall patterns. Under HeS conditions, the proportion of subsurface flow in rainfall water increased by about 2%. Soil structure increases the flow of subsurface flow, which was consistent with previous studies [41]. Soil heterogeneity caused by long-term tillage of sloping farmland can effectively reduce the intensity of surface runoff [42]. When the water infiltrates into the heterogeneous soil, it encounters the plow pan with poor permeability, forming a lateral subsurface flow. This will reduce the water pressure in the surface soil, increase the water infiltration rate and reduce the surface runoff. Aldo [41] report that heterogeneity is more sensitive to rainfall inputs. The increase of subsurface flow and saturation is faster than that of a homogeneous case. In summary, the soil structure of red soil slope farmland can increase the water infiltration rate and increase the proportion of subsurface flow in the overall water. Therefore, soil structure can affect near-surface hydrology, reduce soil erosion, and achieve the effect of water and fertilizer conservation.

4.3. Effect of Straw Mulching on Near-Surface Hydrological Process and Soil Loss

Straw mulching is an effective means of dealing with soil erosion caused by rainfall. Straw mulching reduced 99.7% (Long duration-low intensity rain)~100% (Short duration-high intensity rain) surface runoff and 100% surface erosion under different rainfall patterns, respectively. Compared with bare land, surface runoff and erosion in straw mulching experiments decreased significantly, which was similar to the results of several authors [43–46]. Misagh [43] found that a higher straw application rate would produce less runoff and reduce soil erosion. Wang [44] also found that straw mulching had a significant effect on the average infiltration rate, cumulative runoff and cumulative sediment yield on the slope. We believe that the physical and biochemical properties of surface soil change when the straw is covered on sloping farmland. Straw mulching can reduce the impact of rainfall on surface soil and reduce surface crust. Straw mulching can also reduce surface soil temperature [47], decrease soil bulk density [48,49], increase soil porosity [50] and increase soil water storage. For example, Liu [47] proposed that soil porosity gradually increased with the continuous coverage of straw. Increasing soil porosity can improve soil infiltration, thus affecting surface runoff and subsurface flow. These results suggest that straw mulching can regulate the formation of surface runoff and reduce surface soil erosion.

In this study, the subsurface flow was significantly affected by straw mulching (Table 4). Specifically, in long duration-low intensity rain, the initial runoff time of subsurface flow caused by straw mulching was 39.73 min earlier than that without mulching, and the total subsurface flow runoff increased by 33.42%. After straw mulching, the proportion of total precipitation in subsurface flow runoff increased by 1~25%, and the amount of deep leakage also increased by 6~41% (Figure 6). These findings indicate that straw mulching can effectively promote the development of subsurface flow [38]. The report of Gao [46] suggested that straw mulching could significantly increase subsurface flow under various rainfall intensities. Duan [38] reported that straw mulching significantly reduced surface runoff and significantly increased subsurface flow at a depth of 30 cm. Different from the previous research results, in short duration-high intensity rain, straw mulching increased the total amount of subsurface flow runoff to 12.71 times, but the initial runoff time-lagged 10.02 min. We believe that heavy rainfall has compacted and splashed the surface of sloping farmland without straw mulching in this experiment. This leads to the change of surface micro-topography, and some surface soil forms a crust effect. Therefore, a large amount of water carried by rainfall cannot be infiltrated, forming runoff on the surface. Due to the large surface runoff water potential, the water rapidly infiltrates the large gap to form a preferential flow, and the subsurface flow is formed at the change of soil structure. Straw mulching reduced the splash erosion of raindrops on surface soil, resulting in loose surface soil and a high infiltration rate. Moreover, straw mulching reduced the flow velocity of surface runoff and made it infiltrate nearby. The straw mulching treatment made the surface soil moisture reach saturation before the formation of subsurface flow, resulting in the formation of subsurface flow later. Straw mulching enables the water carried by short duration-high intensity rain to be fully fixed by the surface soil. After the surface soil is saturated, subsurface flow is formed to recharge groundwater resources. This plays a positive role in water and fertilizer conservation and reduces soil erosion in slope farmland.

This study provides theoretical support for the application of straw mulching on red soil slope farmland. The protective effect of rape straw mulching on the surface soil of red soil slope farmland under short duration-high intensity rain was proposed, which was conducive to the popularization and application of this measure. However, the conclusion of this study was only obtained under the condition of single rape straw coverage and slope, which may vary with different coverage and slope. It will be the focus of our future research to select different coverage and find the optimal straw coverage of red soil slope farmland to expand the application scope and practicability of the research results.

5. Conclusions

In this study, the effects of rainfall pattern, soil structure, and straw mulching on near-surface hydrology and erosion were investigated in the sloping cropland of red soil. The main conclusions are as follows: (1) The intensity of surface runoff formed by short duration-high intensity rain is greater than that of long duration-low intensity rain, and the surface soil is more eroded. At the same time, short duration-high intensity rain is not conducive to the development of subsurface flow and cannot make full use of the water brought by rainfall; (2) Under the two rainfall patterns, the surface runoff intensity of HeS (heterogeneous) is smaller than that of HoS (homogeneous), while the subsurface flow runoff intensity is the opposite. This shows that the soil structure of red soil slope farmland can affect the development process of near surface hydrology, increase the infiltration of rainfall water, and reduce the surface runoff and erosion of the slope; (3) After mulching with rape straw, the intensity of surface runoff decreased significantly, and the intensity of subsurface flow increased significantly. The improvement of coverage on short duration-high intensity rain is particularly evident. Straw mulching can make the precipitation water fully fixed by the surface soil, which is conducive to the absorption and utilization of water by crops, and reduce the loss of soil. These findings will help to understand the impact of rainfall on the near-surface hydrology of sloping farmland in red soil and provide a theoretical basis for production practice.

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References

1. Tong, S.; Zhiming, F.; Yanzhao, Y.; Yumei, L.; Yanjuan, W. Research on Land Resource Carrying Capacity: Progress and Prospects. *J. Resour. Ecol.* **2018**, *9*, 331–340. [CrossRef]
2. Mishra, V. Review of Arable Land-Use Problems in Present-Day China. *AMBIO J. Hum. Environ.* **2009**, *38*, 110–112. [CrossRef] [PubMed]
3. Grum, B.; Assefa, D.; Hessel, R.; Woldearegay, K.; Kessler, A.; Ritsema, C.; Geissen, V. Effect of In Situ Water Harvesting Techniques on Soil and Nutrient Losses in Semi-Arid Northern Ethiopia. *Land Degrad. Dev.* **2017**, *28*, 1016–1027. [CrossRef]
4. Hacısalihoğlu, S. Variations of Measured and Simulated Soil-Loss Amounts in a Semiarid Area in Turkey. *Environ. Monit. Assess.* **2010**, *165*, 255–262. [CrossRef] [PubMed]
5. Wairiu, M. Soil Organic Carbon in Relation to Cultivation and Topsoil Removal on Sloping Lands of Kolombangara, Solomon Islands. *Soil Tillage Res.* **2003**, *70*, 19–27, (In Chinese with English Abstract). [CrossRef]
6. Zhang, G.H.; Yang, Y.; Liu, Y.N.; Wang, Z.Q. Advances and Prospects of Soil Erosion Research in the Black Soil Region of Northeast China. *J. Soil Water Conserv.* **2022**, *36*, 1–12, (In Chinese with English Abstract). [CrossRef]
7. Long, T.Y.; Liu, X.Z.; Liu, J. Modeling Spatial and Temporal Variation of Nitrate Loss via Interflow in a Sloping Field of Purple Soil. *J. Agro-Environ. Sci.* **2015**, *34*, 1973–1978, (In Chinese with English Abstract). [CrossRef]
8. Fu, Z.Y.; Li, Z.X.; Cai, C.F.; Guo, Z.L. Impact of boundary conditions on soil water and subsurface flow in shallow purple soil slope. *J. Hydraul. Eng.* **2011**, *42*, 899–907, (In Chinese with English Abstract). [CrossRef]
9. Zhang, X.; Wang, K.L.; Fu, Z.Y.; Chen, H.S.; Zhang, W.; Shi, Z.H. Hydrological characteristics of calcareous soil with contrasting architecture on dolomite slope of Northwest Guangxi, China. *J. Appl. Ecol.* **2017**, *28*, 2186–2196, (In Chinese with English Abstract). [CrossRef]
10. Lal, R.; Mahboubi, A.A.; Fausey, N.R. Long-Term Tillage and Rotation Effects on Properties of a Central Ohio Soil. *Soil Sci. Soc. Am. J.* **1994**, *58*, 517–522. [CrossRef]

11. Liu, Y.-J.; Yang, J.; Hu, J.-M.; Tang, C.-J.; Zheng, H.-J. Characteristics of the Surface-Subsurface Flow Generation and Sediment Yield to the Rainfall Regime and Land-Cover by Long-Term in-Situ Observation in the Red Soil Region, Southern China. *J. Hydrol.* **2016**, *539*, 457–467. [CrossRef]
12. Wilson, G.V.; Cullum, R.F.; Roemkens, M.J.M. Ephemeral Gully Erosion by Preferential Flow through a Discontinuous Soil-Pipe. *Catena* **2008**, *73*, 98–106. [CrossRef]
13. Wang, T.; Zhu, B. Nitrate Loss via Overland Flow and Interflow from a Sloped Farmland in the Hilly Area of Purple Soil, China. *Nutr. Cycl. Agroecosyst.* **2011**, *90*, 309–319. [CrossRef]
14. Getahun, G.T.; Kätterer, T.; Munkholm, L.J.; Rychel, K.; Kirchmann, H. Effects of Loosening Combined with Straw Incorporation into the Upper Subsoil on Soil Properties and Crop Yield in a Three-Year Field Experiment. *Soil Tillage Res.* **2022**, *223*, 105466. [CrossRef]
15. Wang, J.L.; Shi, X.X.; Li, Z.Z.; Zhang, Y.; Liu, Y.Q.; Peng, Y.X. Responses of Runoff and Soil Erosion to Planting Pattern, Row Direction, and Straw Mulching on Sloped Farmland in the Corn Belt of Northeast China. *Agric. Water Manag.* **2021**, *253*, 106935. [CrossRef]
16. Keesstra, S.D.; Rodrigo-Comino, J.; Novara, A.; Gimenez-Morera, A.; Pulido, M.; Di Prima, S.; Cerda, A. Straw Mulch as a Sustainable Solution to Decrease Runoff and Erosion in Glyphosate-Treated Clementine Plantations in Eastern Spain. An Assessment Using Rainfall Simulation Experiments. *Catena* **2019**, *174*, 95–103. [CrossRef]
17. Jordan, A.; Zavala, L.M.; Gil, J. Effects of Mulching on Soil Physical Properties and Runoff under Semi-Arid Conditions in Southern Spain. *Catena* **2010**, *81*, 77–85. [CrossRef]
18. Rahma, A.E.; Warrington, D.N.; Lei, T. Efficiency of Wheat Straw Mulching in Reducing Soil and Water Losses from Three Typical Soils of the Loess Plateau, China. *Int. Soil Water Conserv. Res.* **2019**, *7*, 335–345. [CrossRef]
19. Rahma, A.E.; Lei, T.; Shi, X.; Dong, Y.; Zhou, S.; Zhao, J. Measuring Flow Velocity under Straw Mulch Using the Improved Electrolyte Tracer Method. *J. Hydrol.* **2013**, *495*, 121–125. [CrossRef]
20. Jourgholami, M.; Abari, M.E. Effectiveness of Sawdust and Straw Mulching on Postharvest Runoff and Soil Erosion of a Skid Trail in a Mixed Forest. *Ecol. Eng.* **2017**, *109*, 15–24. [CrossRef]
21. Prosdocimi, M.; Jordán, A.; Tarolli, P.; Keesstra, S.; Novara, A.; Cerdà, A. The Immediate Effectiveness of Barley Straw Mulch in Reducing Soil Erodibility and Surface Runoff Generation in Mediterranean Vineyards. *Sci. Total Environ.* **2016**, *547*, 323–330. [CrossRef] [PubMed]
22. Mulumba, L.N.; Lal, R. Mulching Effects on Selected Soil Physical Properties. *Soil Tillage Res.* **2008**, *98*, 106–111. [CrossRef]
23. Guo, T.; Wang, Q.; Li, D.; Zhuang, J.; Wu, L. Flow Hydraulic Characteristic Effect on Sediment and Solute Transport on Slope Erosion. *Catena* **2013**, *107*, 145–153. [CrossRef]
24. Fan, W.; Wu, J.G.; Li, J.M.; He, R.C.; Yao, Y.Y.; Wang, D.C.; Sun, L.; Wang, C.Y. Effects of Straw Return on Soil Physico-chemical Properties of Chernozem in Northeast China and Maize Yield Therein. *Acta Pedol. Sin.* **2018**, *55*, 835–846, (In Chinese with English Abstract). [CrossRef]
25. Materechera, S.A. Aggregation in a Surface Layer of a Hardsetting and Crusting Soil as Influenced by the Application of Amendments and Grass Mulch in a South African Semi-Arid Environment. *Soil Tillage Res.* **2009**, *105*, 251–259. [CrossRef]
26. Gicheru, P.; Gachene, C.; Mbuvi, J.; Mare, E. Effects of Soil Management Practices and Tillage Systems on Surface Soil Water Conservation and Crust Formation on a Sandy Loam in Semi-Arid Kenya. *Soil Tillage Res.* **2004**, *75*, 173–184. [CrossRef]
27. Jiang, G.Y.; Zen, X.Y.; Shi, D.M.; Zhang, J.L. Minimal Date Set of Effect Evalutaion and Measure Classiflcation of Soil and Water Conservation on Slope Farmland in South of China. *Soil Water Conserv. China* (In Chinese with English Abstract). **2021**, 5, 56–59. [CrossRef]
28. Yang, J.; Zheng, H.J.; Chen, X.A. Effects of Tillage Practices on Nutrient Loss and Soybean Growth in Red-Soil Slope Farmland. *Int. Soil Water Conserv. Res.* **2013**, *1*, 49–55. [CrossRef]
29. Chen, X.; Liang, Z.; Zhang, Z.; Zhang, L. Effects of Soil and Water Conservation Measures on Runoff and Sediment Yield in Red Soil Slope Farmland under Natural Rainfall. *Sustainability* **2020**, *12*, 3417. [CrossRef]
30. Wang, B. LinHo Rainy Season of the Asian-Pacific Summer Monsoon. *J. Clim.* **2002**, *15*, 386–398. [CrossRef]
31. R Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria. *Computing* **2009**, *14*, 12–21. [CrossRef]
32. Nu, F.F.; Shi, Z.H.; Li, L.; Guo, Z.L.; Liu, Q.J.; Ai, L. The Effects of Rainfall Regimes and Land Use Changes on Runoff and Soil Loss in a Small Mountainous Watershed. *Catena* **2012**, *99*, 1–8. [CrossRef]
33. Ma, J.Y.; Ma, B.; Wang, Y.X.; Wang, C.G.; Li, C.D.; Xiao, J.B. Combined Effects of the Wheat Straw Length and Incorporation Rate on Reducing Runoff and Sediment Yields. *Catena* **2022**, *215*, 106310. [CrossRef]
34. Ma, X.; Zheng, J.K.; Wang, W.W.; Chen, X.; Qin, W.; Shan, Z.J.; Lang, D.X.; Liao, F. Characteristics of the Runoff and Sediment Yield of Sloping Farmland in the Purple Soil Area Under Different Rainfall Patterns. *J. Soil Water Conserv.* **2017**, *31*, 17–21, (In Chinese with English Abstract). [CrossRef]
35. Zhang, X.Y.; Shi, X.Z.; Yu, D.S.; Wang, H.J.; Liu, Z.B.; Zhang, W.T. Effects of antecedent soil moistrue on hill slope runoff-generation and soil erosion over red soil-mantled landscapes. *Adv. Water Sci.* **2010**, *21*, 23–29, (In Chinese with English Abstract). [CrossRef]
36. Giménez, R.; Govers, G. Effects of Freshly Incorporated Straw Residue on Rill Erosion and Hydraulics. *Catena* **2008**, *72*, 214–223. [CrossRef]

37. Knapen, A.; Poesen, J.; Govers, G.; De Baets, S. The Effect of Conservation Tillage on Runoff Erosivity and Soil Erodibility during Concentrated Flow. *Hydrol. Process.* **2008**, *22*, 1497–1508. [CrossRef]
38. Duan, J.; Yang, J.; Tang, C.; Chen, L.; Liu, Y.; Wang, L. Effects of Rainfall Patterns and Land Cover on the Subsurface Flow Generation of Sloping Ferralsols in Southern China. *PLoS ONE* **2017**, *12*, e0182706. [CrossRef]
39. Chen, X.A.; Yang, J.; Tang, C.J.; Zheng, T.H.; Li, L.F. Effects of rainfall intensity and slope on surface and subsurface runoff in red soil slope farmland. Trans. *Chin. Soc. Agric. Eng.* **2017**, *33*, 141–146, (In Chinese with English Abstract). [CrossRef]
40. Nanda, A.; Sen, S.; Mcnamara, J.P. How Spatiotemporal Variation of Soil Moisture Can Explain Hydrological Connectivity of Infiltration-Excess Dominated Hillslope: Observations from Lesser Himalayan Landscape. *J. Hydrol.* **2019**, *579*, 124146. [CrossRef]
41. Fiori, A.; Russo, D. Numerical Analyses of Subsurface Flow in a Steep Hillslope under Rainfall: The Role of the Spatial Heterogeneity of the Formation Hydraulic Properties. *Water Resour. Res.* **2007**, *43*, W07445. [CrossRef]
42. Shi, D.M.; Jiang, G.Y.; Jiang, P.; Lou, Y.B.; Ding, W.B.; Jin, H.F. Effects of soil erosion factors on cultivated-layer quality of slope farmland in purple hilly area. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 270–279, (In Chinese with English Abstract). [CrossRef]
43. Parhizkar, M.; Shabanpour, M.; Lucas-Borja, M.E.; Zema, D.A.; Li, S.; Tanaka, N.; Cerdà, A. Effects of Length and Application Rate of Rice Straw Mulch on Surface Runoff and Soil Loss under Laboratory Simulated Rainfall. *Int. J. Sediment Res.* **2021**, *36*, 468–478. [CrossRef]
44. Wang, C.G.; Ma, J.Y.; Wang, Y.X.; Li, Z.B.; Ma, B. The Influence of Wheat Straw Mulching and Straw Length on Infiltration, Runoff and Soil Loss. *Hydrol. Process.* **2022**, *36*, e14561. [CrossRef]
45. Won, C.H.; Choi, Y.H.; Shin, M.H.; Lim, K.J.; Choi, J.D. Effects of Rice Straw Mats on Runoff and Sediment Discharge in a Laboratory Rainfall Simulation. *Geoderma* **2012**, *189*, 164–169. [CrossRef]
46. Gao, Z.C.; Xu, Q.X.; Si, Q.; Zhang, S.P.; Fu, Z.Y.; Chen, H.S. Effects of Different Straw Mulch Rates on the Runoff and Sediment Yield of Young Citrus Orchards with Lime Soil and Red Soil under Simulated Rainfall Conditions in Southwest China. *Water* **2022**, *14*, 1119. [CrossRef]
47. Liu, L.; Zhang, L.; Liu, J.; Fu, Q.; Xu, Q. Idimesheva Soil Water and Temperature Characteristics under Different Straw Mulching and Tillage Measures in the Black Soil Region of China. *J. Soil Water Conserv.* **2021**, *76*, 256–262. [CrossRef]
48. Ram, H.; Dadhwal, V.; Vashist, K.K.; Kaur, H. Grain Yield and Water Use Efficiency of Wheat (*Triticum Aestivum* L.) in Relation to Irrigation Levels and Rice Straw Mulching in North West India. *Agric. Water Manag.* **2013**, *128*, 92–101. [CrossRef]
49. Sun, J.N.; Yang, R.Y.; Zhu, J.J.; Zhou, C.X.; Yang, M.; Pan, Y.H.; Zhang, Z.H. Contrasting Effects of Corn Straw Biochar on Soil Water Infiltration and Retention at Tilled and Compacted Bulk Densities in the Yellow River Delta. *Can. J. Soil Sci.* **2019**, *99*, 357–366. [CrossRef]
50. Glab, T.; Kulig, B. Effect of Mulch and Tillage System on Soil Porosity under Wheat (*Triticum Aestivum*). *Soil Tillage Res.* **2008**, *99*, 169–178. [CrossRef]