

Article

Effects of Furrow Corn Straw Mulch on Soil Erosion and Organic Carbon Loss in Sloping Farmland in the Black Soil Region

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Abstract: Black soil with high fertility is a valuable soil resource, which plays an important role in guaranteeing regional food security and ecological security. Straw return is also a widely recognized way of straw resource utilization. However, it is still not clear which corn straw return method is more suitable for the Chinese black soil region with cold characteristics. The objectives of this study were to classify rainfall patterns (I—light rain with long duration, II—heavy rain with short duration, III—moderate rain with moderate duration; T1 and T2—special rains) and reveal the effects of furrow corn straw mulch—a new straw return—on soil erosion and organic carbon loss. Natural runoff plots (a planned size of 100 m² and dimensions of 20 m × 5 m for each one) with or without the furrow corn straw mulch, which had slope gradients of 3°, 6° and 9°, were applied for natural rainfalls. Runoff and sediment samples were collected after each erosive rainfall to measure runoff, sediment, and organic carbon concentration. The results showed that when comparing treatments with the furrow corn straw mulch to control treatments, runoff coefficients, sediment concentration, and mean ratios of organic carbon loss in sediment to total carbon loss decreased by 48.0–97.7%, 45.6–99.7%, and 4.7–12.9%, respectively. Furthermore, the ratios of <0.053 mm sediment increased but the ratios of >0.25 mm sediment generally decreased. The mean organic carbon concentration both in runoff and sediment decreased in the following order: II > III > I > T1 > T2. Rainfall pattern II induced greater ratios of organic carbon loss. Therefore, the furrow corn straw mulch measure, which effectively decreased soil erosion and regulated organic carbon loss from the black soil, is suitable for the farmlands in the black soil regions.



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Keywords: natural rainfall; runoff; straw return; sediment size distribution; field runoff plot; black soil region

1. Introduction

Soil erosion causes 25–40 billion tons of topsoil loss every year worldwide [1], equal to 33.7 million tons of grain yield reduction and about 8 billion US dollars of economic loss [2]. Soil erosion has become one of the most serious global ecological challenges [3]. The black soil accounts for 29% agricultural land with high organic matter and is considered as one of the highest fertile soils on a worldwide scale [4,5]. Severe black soil loss accompanies decline in the yield of corn, soybean and other grains [6]. The black soil plays an important role in maintaining food security in the world [7]. However, there has been extensive degradation for the past 200 years because of intensely cultivated agriculture, which results in soil erosion and nutrient loss in the black soil regions [5]. Most black soils have lost at least half of their carbon storage and have undergone moderate to severe almost irreversible

erosion processes [8]. Thus, soil erosion and soil organic carbon loss have been identified as the most urgent challenges in the black soil regions.

The black soil region in Northeast China is one of the four major black soil regions [9]. It has serious soil erosion due to its high-intensity cultivation and improper management, although the cultivation period is not as long as in other black soil regions, and over 60% of farmland areas suffer from severe soil erosion [5,10]. Corn yield was reduced by 9–22% caused by soil erosion based on the report [11]. The thinner black soil layer and loss of soil organic carbon are also key soil degradation issues in the black soil region of China [4]. Agricultural practice is an important factor in preventing land degradation and ensuring the sustainability of agriculture [12,13]. Straw returning is a highly recommended agricultural practice because its ability to efficiently control runoff, boost soil infiltration, and increase crop yield in Northeast China [14]. However, which straw mulching method is more suitable for this region to decrease soil erosion and soil organic carbon loss needs further study.

Straw returning is frequently used in Northeast China and includes two major styles: one is the straw mulching with different kinds of straw lengths, and the other is the straw incorporation into different depth of soil layers with different crushing degrees [15–18]. Straw mulching increases the infiltration and conserves soil and water, but decreases the soil temperature and makes tillage inconvenient and unsuited to root penetration with complete coverage [14,15,19,20]. Straw strip mulching and mulching only on furrows improve water-use efficiency and crop production [20,21]. Meanwhile, the effect of straw mulching on increasing soil organic carbon is weaker and has a slower decomposition rate when compared with straw deep incorporation [18]. The effect of straw mulching on increasing soil organic carbon is not as good as that of straw burying. The other method needs a machine for crushing or burying, which increases fuel consumption and costs. However, shallow burial causes slow decomposition of straw and hinders crop growth [17]. The deep burial of straw refers to burying straw below the soil surface layer about 20–40 cm [22]. Deep straw burial has little impact on crop growth and has a good effect on promoting aggregate formation and increasing crop yields simultaneously [16]. Therefore, straw strip mulch and deep burial are more suitable in Northeast China to meet the requirements of increasing ground temperature and straw decomposition.

This study adopted a novel straw returning method with furrow corn straw mulch in the sloping farmland in the Chinese black soil region, which combined strip mulching and deep straw burial. It was hypothesized that the furrow corn straw mulch would bring about specific variations in soil erosion and organic carbon loss. Thus, the monitoring study was conducted under natural erosive rainfall events. The objectives of this study are to investigate the rainfall pattern classification, to reveal characteristics of runoff coefficient, sediment concentration, and organic carbon loss in runoff and sediment, and to further analyze sediment sizes and their organic carbon loss.

2. Materials and Methods

2.1. Study Area

Natural runoff plots are located at the Changchun Qinggou Small Watershed (125°24′55″ E, 43°48′34″ N), which is the national soil and water conservation observation station in Jilin Agricultural University, Changchun City, Jilin Province, the black soil region of Northeast China (Figure 1). The topography is slightly undulating, with an altitude between 226 and 236 m, rising high in the south and falling low in the north. There are four different seasons in the study area's moderate continental monsoon climate. Spring is dry and windy, summer is hot and rainy, autumn is cool and sunny, and winter is cold and lengthy. The mean annual temperature is 4.6 °C, and the lowest value is −30.5 °C. The

mean annual precipitation from 1996 to 2020 was 553.3 mm, and more than 60% of this occurred in summer. The typical black soil (Chinese Soil Taxonomy) is widely distributed, with a high quantity of soil organic matter but a high soil erodibility [23]. Soil erosion has grown worse since the 1950s due to both natural factors and human activities [24]. The mean annual runoff depth is about 50 mm. The soil erosion intensity ranges from 100 to 5000 t km⁻² yr⁻¹.

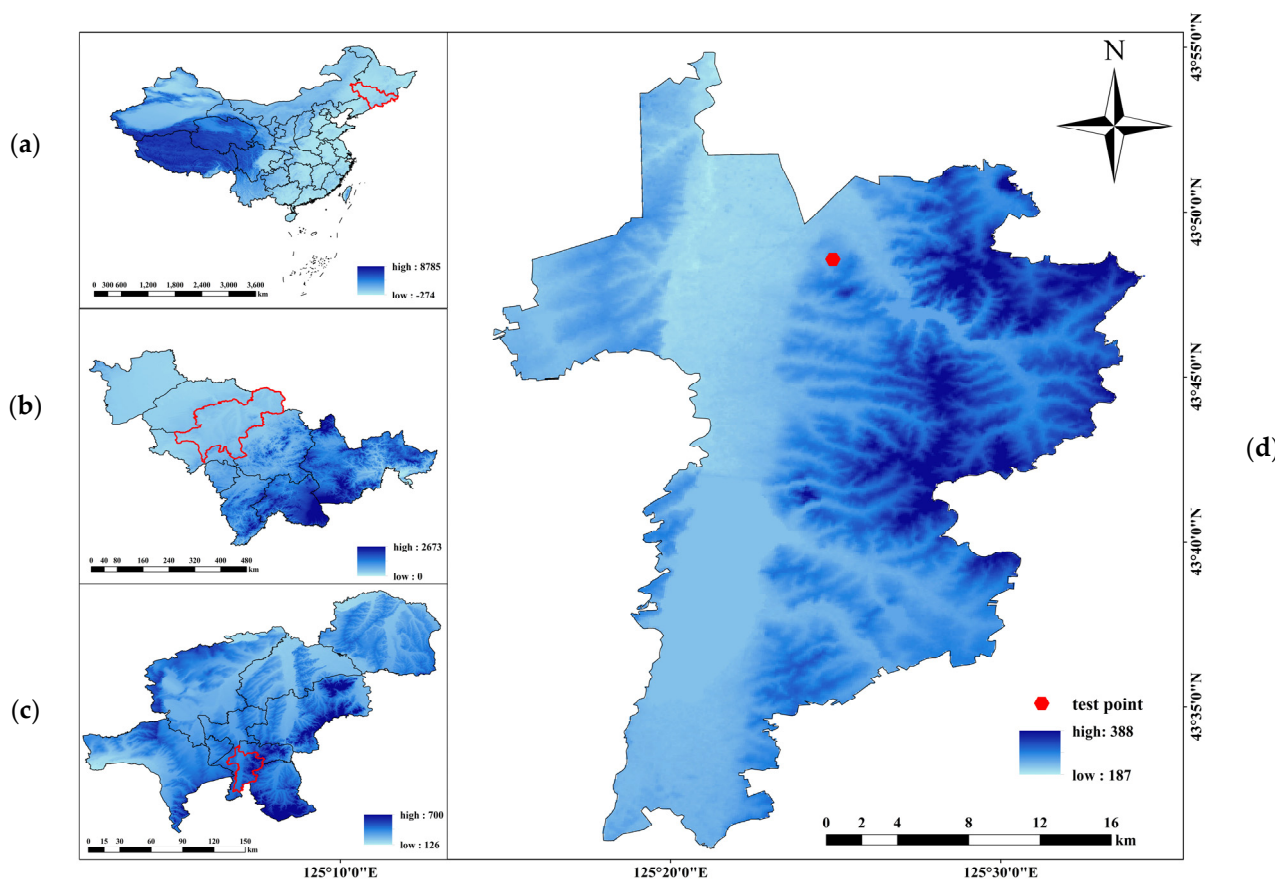


Figure 1. The study area. (a) Jilin Province of China; (b) Changchun City; (c) Jilin Agricultural University; (d) Qinggou Small Watershed. This figure will be reproduced in color on the Web and in black-and-white in print. The same as below.

2.2. Experimental Design and Procedures

It is difficult for crop straw to be decomposed in the Chinese black soil region due to the region's low mean annual temperature and lengthy winters. This has an impact on the following year's planting and mechanization processes. Moreover, ridge tillage is a conventional method to drain water and improve soil temperature; therefore, up- and downslope tillage is a common form of ridge tillage in this region [25]. Thus, the furrow corn (*Zea mays* L.) straw mulch was adopted in this study since it is appropriate for the straw decomposition in cold and cool climates and does not interfere with regular mechanized operations.

In natural runoff plots, which were established in 2008, conventional up- and downslope tillage was used. From 2011 till the present, half of them used the furrow corn straw mulch technology; the other half used control treatments devoid of furrow corn straw mulch. To address the issues of straw decomposition, soil temperature and achieving low costs in the cold region of Northeast China, this study explored a new straw returning mode (Figure 2). Regarding the furrow corn straw mulch technology, the corn straw was harvested and positioned on one side of the plots. The first year, standard ridge platform

sowing was carried out, followed by the placement of corn straw in the ridge furrow for increasing the infiltration and conserves of soil and water. The second year's spring plowing involved transformed position of furrow and ridge for the convenience of the furrow straw burial. The furrow straw with a year's mechanical rolling and subjected to rain and snow was more easily decomposed and was turned 20 cm underground, and the previous year's corn straw was positioned in the ridge furrow, as was the third year's. The third year's position of furrow and ridge was the same as the first year's. Out of the 7500 kg ha⁻¹ yearly corn straw yield in this region's farmland, 100% of the corn straw was returned to the field. The purpose of switching the ridge platform and ridge furrow every other year was to guarantee that the corn straw was returned to the field evenly. The typical black soil had 24.7% sand (>50 µm), 71.9% silt (50–2 µm), 3.3% clay content (<2 µm), 6.3 pH, 18.6 g kg⁻¹ soil organic matter content, 105.4 mg kg⁻¹ available nitrogen, 20.8 mg kg⁻¹ available phosphorus, and 116.7 mg kg⁻¹ rapidly available potassium.

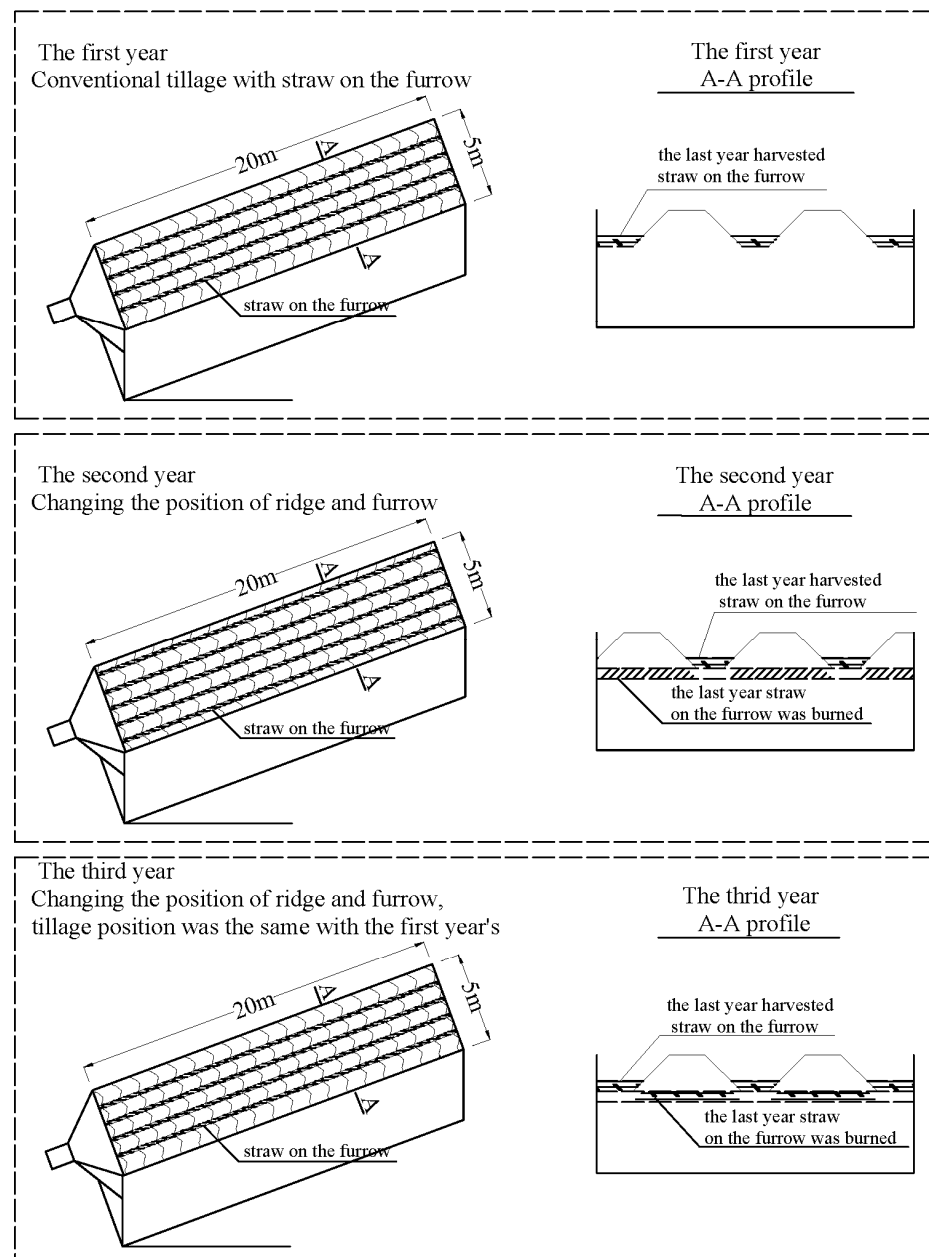


Figure 2. Layout form of the furrow corn straw mulch and the A-A profile.

Three representative slope gradients of 3° , 6° and 9° were designed because they are very common in the Chinese black soil region [25]. The ' 3° ', ' 6° ', ' 9° ' were displayed for the control treatments without furrow corn straw mulch under different slope gradients, while ' 3°S ', ' 6°S ', ' 9°S ' were displayed for the treatments with furrow corn straw mulch under various slope gradients. Each runoff plot had a planned size of 100 m^2 and dimensions of $20\text{ m} \times 5\text{ m}$ with a slope direction of 30° north to east. Following the technical code of practice on water and soil conservation monitoring in the water conservancy industry standard of the People's Republic of China (SL 277–2002), stone slabs were inserted underground to a depth of around 0.3 m and left on the surface to a depth of 0.2 m to create the surrounding hydrological border of each plot. The equipment for monitoring runoff and sediment during an erosive rainfall process from each plot was a cylindrical shunt bucket and a runoff collecting bucket made of stainless-steel material. The shunt mode was a first-level mode with a nine-hole shunt. The cylindrical shunt bucket had a diameter of 0.57 m and a shunt hole that was 0.45 m from the bucket's bottom. The runoff collecting bucket measured 0.47 m in diameter and 0.45 m in height. The TRM-ZS2 (Sunshine weather, Jinzhou, China) was a standard weather station and produced according to the meteorological observation standard of World Meteorological Organization, which was programmed to automatically gather rainfall data every 2 mm of precipitation, recorded the rainfall. Manual sampling was used to determine the amounts of runoff and sediment in cylindrical shunt and runoff collecting buckets following each erosive rainfall.

2.3. Rainfall Characteristics

The black soil region experienced the same season of heat and precipitation, with the peak temperature and most rainfall falling over the same period. For the Changchun Qinggou Small Watershed, the total precipitation (e.g., rain, snow, hail) was 890.1 mm in 2022 (Figure 3a). Here, the annual rainfall was 794.2 mm , accounting for 89.2% of the total precipitation. The majority of the rainfall fell in three months: June, July, and August combined for 674.4 mm , or 75.8% of the total. In addition, the months of June through August had the greatest air temperatures, with monthly mean values ranging from 20.4 to 24.1°C .

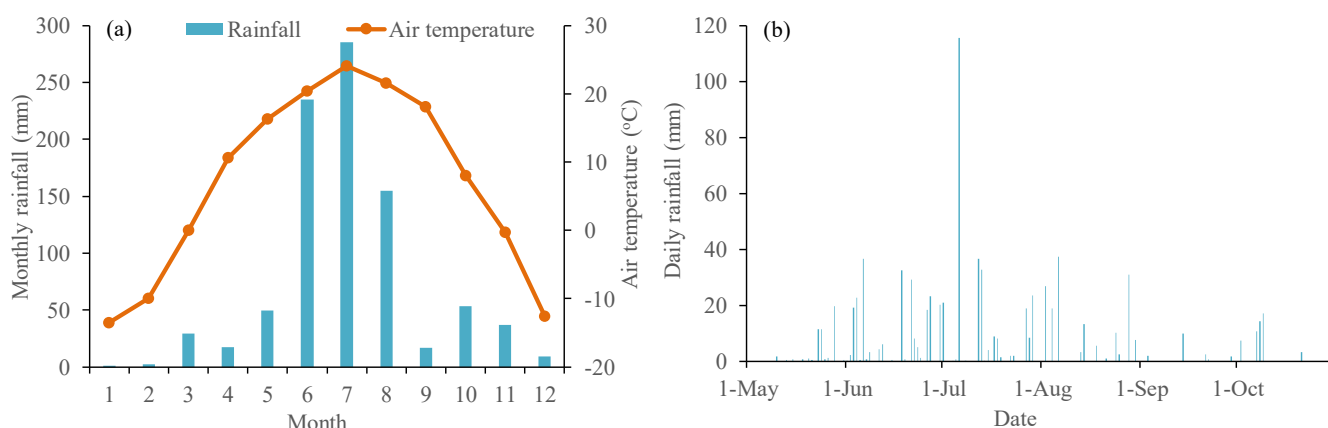


Figure 3. Rainfall and air temperature at the Changchun Qinggou Small Watershed in 2022. (a) Monthly rainfall and air temperature; (b) daily rainfall.

Rainfall was recorded from 1 May to 31 October 2022 (Figure 3b). The number of observed rainfall days was 70. And the daily rainfall ranged from 0.2 to 115.6 mm with the 1.46 coefficient of variation. The maximum daily rainfall occurred on 6 July with a 115.6 mm total rainfall. According to the rainfall classification criteria of the Central Meteorological Observatory of China Meteorological Administration, the rainfall on 6 July reached the

standard of heavy rain, accounting for 14.6% and 40.1% of the total rainfall in 2022 and in July, respectively. The number of days with daily rainfall ranging from 10 to 40 mm was 26, accounting for 71% of the total annual rainfall.

2.4. Sample Collection and Determination

The straw, grass and other contaminants were taken out of the buckets following the conclusion of runoff production in the runoff plots. After that, runoff heights were measured and runoff samples were gathered. The runoff and sediment in each bucket were thoroughly mixed and agitated to create a sample that was separated into upper, middle and lower layers. Three runoff samples and three sediment samples were collected from each plot.

The runoff samples were brought back to the laboratory via 0.45 µm filter membrane so that the total organic carbon analyzer (Shimadzu TOC-VCPH, Shimadzu Corporation, Handu, Germany) could measure the amount of organic carbon concentration in the runoff. In the event that a determination could not be made in a timely manner, it was promptly made and refrigerated at 4 °C.

The sediment samples were divided into three parts. The first part was utilized to calculate the amount of sediment using oven-drying at 105 °C. The second part was utilized to determine the sediment size distribution. Elliott's [26] wet sieving method was applied for classification. The sediment sample was placed on the soil sieve (first 0.25 mm, then 53 µm), oscillating for 2 min at an amplitude of 40 mm and up and down at a speed of 30 r/min. Not only should water not pass through the upper sieve, but it also should not pass through the lowest sieve's soil. Following a 4 h precipitation, the top layer of water was poured, and the sediment on the sieve was then shaken, weighed, and labeled before being moved to the metal boxes. The metal boxes were oven-dried at 60 °C. The third part involved grinding the dried sediment, putting it through a 100-mesh sieve, and using a total organic carbon analyzer to calculate the organic carbon concentration in each sediment size level.

2.5. Data Analysis

Indicators of erosive rainfall, runoff coefficient, sediment concentration, sediment size distribution, and organic carbon loss in runoff and in sediment were obtained based on the sample collection and determination described above. These indicators were used to analyze the effects of furrow corn straw mulch on soil erosion and organic carbon loss. The statistical software SPSS 19.0 software (SPSS Inc., Chicago, IL, USA) was used for the analysis. Before formal statistical analysis, the data were first verified for compliance with the normal distribution. The K-means clustering analysis method was adopted to classify all erosive rainfall events. One-way ANOVA were used to determine whether variables, such as runoff coefficients, sediment concentration, organic carbon concentration in runoff, proportions of organic carbon in sediment, ratios of organic carbon loss in sediment to total carbon loss, and organic carbon enrichment indexes in sediment have significant differences. The Pearson correlation analysis was used to determine the correlation between erosive rainfall and organic carbon loss characteristics. Significant correction coefficients were tested at $p < 0.05$, and $p < 0.01$, $p < 0.001$.

The rainfall erosivity [27] was calculated as follows:

$$R = EI_{30} \quad (1)$$

where R is the rainfall erosivity ($\text{MJ mm hm}^{-2} \text{ h}^{-1}$); E is the rainfall kinetic energy (MJ hm^{-2}); I_{30} is the maximum 30 min rainfall intensity (mm h^{-1}).

The organic carbon enrichment index in sediment [28] was calculated as follows:

$$ER_{OC} = OC_{sediment} / OC_{soil} \quad (2)$$

where ER_{OC} is the organic carbon enrichment index, which has no dimension; $OC_{sediment}$ is the amount of organic carbon in sediment (g kg^{-1}); OC_{soil} is the amount of organic carbon in original soil (g kg^{-1}).

3. Results and Discussion

3.1. Rainfall Pattern Classification

The rainfall beyond or equal to the minimum amount of rainfall intensity that causes soil loss is known as erosive rainfall [29]. Soil loss can generally result from any rainfall that creates surface runoff. Thus, the critical rainfall generates surface runoff is basically defined as erosive rainfall. We defined erosive rainfall in this study as rainfall that runoff generated in the runoff plots. Based on statistical data, rainfall with a rainfall interval of less than 6 h or a rainfall of less than 1.2 mm for 6 consecutive hours was considered an individual rainfall process; if not, it was considered the following rainfall [30]. A total of 16 distinct erosive rainfall processes were observed in 2022 (Table 1). The total amount of erosive rainfall was 626.6 mm or 78.9% of the annual rainfall. Its total rainfall erosivity was strong enough to significantly induce soil erosion, at $3285.1 \text{ MJ mm hm}^{-2} \text{ h}^{-1}$.

Table 1. Indicators of erosive rainfall in 2012.

Sequence Number	Date	Rainfall (mm)	Duration (min)	Mean Rainfall Intensity (mm h^{-1})	Maximum 30 min Rainfall Intensity (mm h^{-1})	Rainfall Erosivity ($\text{MJ mm hm}^{-2} \text{ h}^{-1}$)	Rainfall Pattern [†]
1	24-May	23.0	904	1.5	6.8	21.9	I
2	28-May	19.6	474	2.9	12.4	41.7	I
3	04-Jun	34.0	1456	0.9	7.2	35.3	I
4	07-Jun	36.4	488	2.8	60.0	557.9	III
5	19-Jun	32.6	444	3.1	41.6	336.9	III
6	22-Jun	37.4	1136	1.2	16.4	97.6	I
7	27-Jun	41.6	1012	1.4	15.2	104.4	I
8	01-Jul	41.2	890	1.6	9.7	37.7	I
9	06-Jul	116.4	1212	1.1	26.8	671.2	T1
10	13-Jul	69.4	2946	0.5	25.6	325.5	T2
11	29-Jul	50.8	928	1.5	31.6	218.2	I
12	02-Aug	27.0	536	2.6	28.6	183.7	I
13	04-Aug	18.8	198	7.0	32.6	155.8	II
14	07-Aug	37.4	224	6.2	46.4	306.6	III
15	28-Aug	31.0	145	9.5	52.6	108.2	II
16	14-Sep	10.0	42	32.9	43.2	82.6	II
Total or mean		626.6	13,035	4.8	28.5	3285.1	-

[†] The rainfall pattern I represents light rain with long duration, the rainfall pattern II represents heavy rain with short duration, and the rainfall pattern III represents moderate rain with moderate duration based on the K-means clustering method; the rainfall patterns T1 and T2 represent special rains.

In this study, all of the erosive rainfall events were classified using the K-means clustering analysis method [31] in order to better assess the impact of different rainfall patterns on regional soil erosion. It was difficult to combine the two exceptional rainfall events—on 6 July, when the rainfall total was 116.4 mm, and on 13 July, when the duration total was 2946 min—into the same rainfall pattern as the other rainfall events in the clustering study. And thus, the two unique rainfall events were recorded as a single rainfall pattern and given the labels T1 and T2, respectively. For the remaining erosive rainfall events, clustering analysis was carried out based on rainfall indices, such as rainfall amount (mm), rainfall duration (min), mean rainfall intensity (mm h^{-1}), maximum 30 min rainfall intensity (mm h^{-1}) and rainfall erosivity ($\text{MJ mm hm}^{-2} \text{ h}^{-1}$) (Table 1). Prior to performing

the clustering analysis, the data were standardized. With a significance level of $p < 0.001$, the clustering variables significantly impacted the clustering process, suggesting a superior clustering effect.

Rainfall pattern I was distinguished by a lengthy duration of 917 min with low rainfall intensity (1.7 mm h^{-1}), as well as low rainfall erosivity ($92.6 \text{ MJ mm hm}^{-2} \text{ h}^{-1}$) and a maximum 30 min rainfall intensity (16.0 mm h^{-1}) (Table 1). Rainfall pattern I was the most frequent, occurring 8 times overall and accounting for 50% of all erosive rainfall events. Rainfall pattern II was characterized by short rainfall duration (128 min) with high rainfall intensity (16.5 mm h^{-1}), coupled with high maximum 30 minute rainfall intensity (42.8 mm h^{-1}) and rainfall erosivity ($115.5 \text{ MJ mm hm}^{-2} \text{ h}^{-1}$). Three occurrences of the rainfall pattern II accounted for 18.8% of the total number of erosive rainfall events. Rainfall pattern III was designated by a medium rainfall duration (385 min), accompanied by a medium rainfall intensity (4.0 mm h^{-1}), a high maximum 30 minute rainfall intensity (49.3 mm h^{-1}), and rainfall erosivity ($400.5 \text{ MJ mm hm}^{-2} \text{ h}^{-1}$). Rainfall pattern III also occurred 3 times and accounted for 18.8% of the total number of erosive rainfall events.

3.2. Characteristics of Runoff Coefficient and Sediment Concentration

Runoff coefficients for treatments with the furrow corn straw mulch were generally lower than those for control treatments without the furrow corn straw mulch with the exception for treatments experiencing the rainfall pattern T1 under 6° and 9° slope gradients (Figure 4a). Compared to control treatments without the furrow corn straw mulch, runoff coefficients for treatments with the furrow corn straw mulch decreased by 97.7%, 48.0%, and 52.3% under 3° , 6° , and 9° , respectively, when suffering from the rainfall pattern I. They reduced by 82.7%, 79.2%, and 66.1% when suffering from the rainfall pattern II; 92.5%, 49.4%, and 48.3% when suffering from the rainfall pattern III; 83.8%, 50.6%, and 49.7% when suffering from the rainfall pattern T2. The values reduced by 84.1% under 3° , but increased by 2.6% and 1.2% under 6° and 9° when suffering from the rainfall pattern T1. The mean runoff coefficients decreased in an order as follows: rainfall pattern III (0.099) > rainfall pattern T2 (0.091) > rainfall pattern II (0.069) > rainfall pattern I (0.064) > rainfall pattern T1 (0.058).

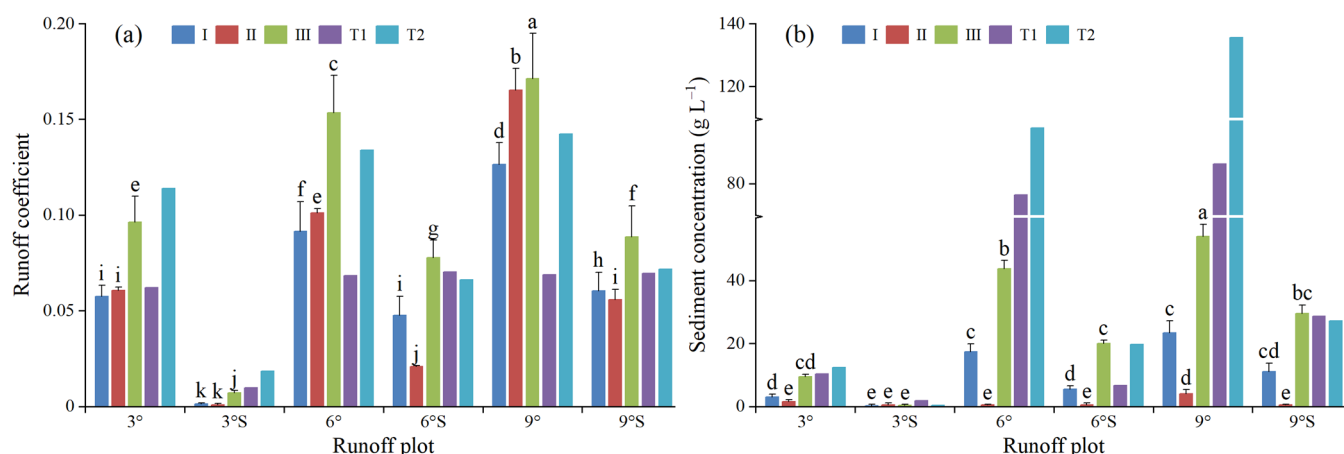


Figure 4. Runoff coefficients (a) and sediment concentration (b) of natural runoff plots under different rainfall patterns. Different small letters indicate significant differences ($p < 0.05$) among the values of runoff coefficients or sediment concentration. The T1 and T2 only occurred once, and thus, no significant difference analysis and error bar.

The findings, which were consistent with earlier research [32], revealed that runoff coefficients for treatments with the furrow corn straw mulch dropped by 48.0–97.7% when compared with control treatments (Figure 4a). The corn straw's ability to efficiently control

runoff in the furrow and boost soil infiltration was the cause [20]. With regard to general rainfall patterns, rainfall pattern III, i.e., the medium rainfall duration with medium rainfall intensity, produced the highest runoff, and rainfall pattern I, i.e., the long rainfall duration with low rainfall intensity, produced the lowest runoff in this study. This result was different from the other pertinent results [33], which stated that rainfall pattern II—the short rainfall duration with large rainfall intensity—produced the greater runoff due to the greater peak flow velocity [34] and poorer soil infiltration [35]. The observed variation may have resulted from variations in soil properties, including but not limited to soil water content, soil texture, and vegetation coverage, total rainfall [4,14]. With regard to special rainfall patterns, the rainfall pattern T2 generated a lot more runoff than the rainfall pattern T1 since it persisted longer, allowed more time for soil infiltration, drained surplus runoff discharge, and happened after the T1. Moreover, runoff coefficients for control treatments without the furrow corn straw mulch increased by 0.5–66.3% as the slope gradient increased because of the increasing runoff velocity and erosive power along the hillslope [36]. In contrast to steep slope gradients, runoff coefficients under 6° were 2.0–35.6 times higher than those under 3° , and under 9° were 1.0–2.7 times higher than those under 6° . Nevertheless, runoff coefficients for treatments with the furrow corn straw mulch were incredibly low under gentle slope gradients. Therefore, in the black soil region, farmlands with gentle slope gradients were a good fit for the furrow corn straw mulch.

Sediment concentration for treatments with the furrow corn straw mulch was significantly lower than that for control treatments without the furrow corn straw mulch (Figure 4b). Sediment concentration for treatments with the furrow corn straw mulch decreased relative to control treatments without the mulch by 99.7%, 63.1%, and 52.4% under 3° , 6° , and 9° , respectively, when suffering from the rainfall pattern I; they reduced by 97.5%, 54.8%, and 45.6% when suffering from the rainfall pattern III, 81.6%, 91.2%, and 49.4% when suffering from the rainfall pattern T1, and 96.5%, 79.8%, and 76.3% when suffering from the rainfall pattern T2. With regard to the treatments suffering from the rainfall pattern II, it had the lowest sediment concentration or virtually no sediment due to the late occurrence date of this rainfall pattern with a higher vegetation coverage, and due to the lower overall rainfall. The following is the order in which the mean sediment concentration decreased: rainfall pattern T2 (48.84 g L^{-1}) > rainfall pattern T1 (35.05 g L^{-1}) > rainfall pattern III (26.22 g L^{-1}) > rainfall pattern I (8.42 g L^{-1}) > rainfall pattern II (0.89 g L^{-1}).

When comparing treatments with the furrow corn straw mulch to control treatments, the sediment concentration decreased by 45.6–99.7% (Figure 4b). This fluctuation trend differed from that of the runoff coefficients, and the reduction ratio was higher than that of runoff [37]. This was because, even with some water passing through the straw, the corn straw reduced soil particle separation and increased sediment deposition [37]. The special rainfall patterns T2 and T1 created the highest sediment concentration due to their significant total rainfall and extended duration. These patterns were followed by the rainfall pattern III, rainfall pattern I, and rainfall pattern II. The rainfall pattern III, the medium rainfall duration with medium rainfall intensity, produced the higher sediment as similar to the runoff. Thus, the rainfall pattern III was a key pattern needing to find the optimum measures to reduce the hillslope erosion. This was also caused by variations in different soil properties, vegetation coverage [38] and rainfall intensity and persistent time [33]. Furthermore, as a rise in the slope gradient, the values of sediment concentration for control treatments without the furrow corn straw mulch for the latter were 1.4–7.9 times greater than that of the former. However, when compared to steep slope gradients, the values of sediment concentration for treatments with the furrow corn straw mulch were incredibly low under gentle slope gradients. For example, under 6° , the values of sediment concentration were 3.5–390.4 times greater than that under 3° ; and under 9° ,

they were 1.3–4.3 times greater than that under 6°. Therefore, for farmlands with gentle slope gradients, the furrow corn straw mulch could greatly reduce the sediment; however, this effect would progressively weaken as the slope gradient grew.

As previously indicated, even though the furrow corn straw mulch had a shifting tendency for different rainfall patterns, it was still effective at controlling runoff and avoiding sediment loss. In general, the highest levels of soil erosion were created by the rainfall pattern III in general rainfall patterns and the rainfall pattern T2 in special rainfall patterns. Additionally, the slope gradient had a significant role in determining the runoff and sediment concentration at sloping farmlands.

3.3. Characteristics of Organic Carbon Loss in Runoff and Sediment

3.3.1. The Organic Carbon Concentration in Runoff and Sediment

The organic carbon concentration in runoff for treatments with the furrow corn straw mulch increased by 2.0–20.9% when compared to control treatments without the furrow corn straw mulch (Figure 5a). The organic carbon concentration in runoff increased by 14.7%, 13.7%, and 10.3% under 3°, 6°, and 9° for the rainfall pattern I; 8.2%, 6.6%, and 10.6% under 3°, 6°, and 9° for the rainfall pattern II; 2.0%, 11.0%, and 8.5% for the rainfall pattern III; 3.2%, 3.8%, and 18.1% for the rainfall pattern T1; 23.9%, 4.3%, and 20.5% for the rainfall pattern T2. The lowest organic carbon concentration in runoff occurred under the rainfall pattern III, and the highest value occurred under the rainfall pattern T2. For different rainfall patterns, the mean organic carbon concentration in runoff decreased in the following order: II (19.5 mg L⁻¹) > III (17.4 mg L⁻¹) > I (12.8 mg L⁻¹) > T1 (10.8 mg L⁻¹) > T2 (9.5 mg L⁻¹). The mean organic carbon concentration in runoff decreased as the slope gradient increased. For example, when the slope gradient increased from 3° to 6° and from 6° to 9° for control treatments, the mean organic carbon concentration in runoff decreased by 3.9–24.5% and 7.3–18.2%, respectively; the ratios were 3.1–25.9% and 3.4–20.6% for treatments with the furrow corn straw mulch.

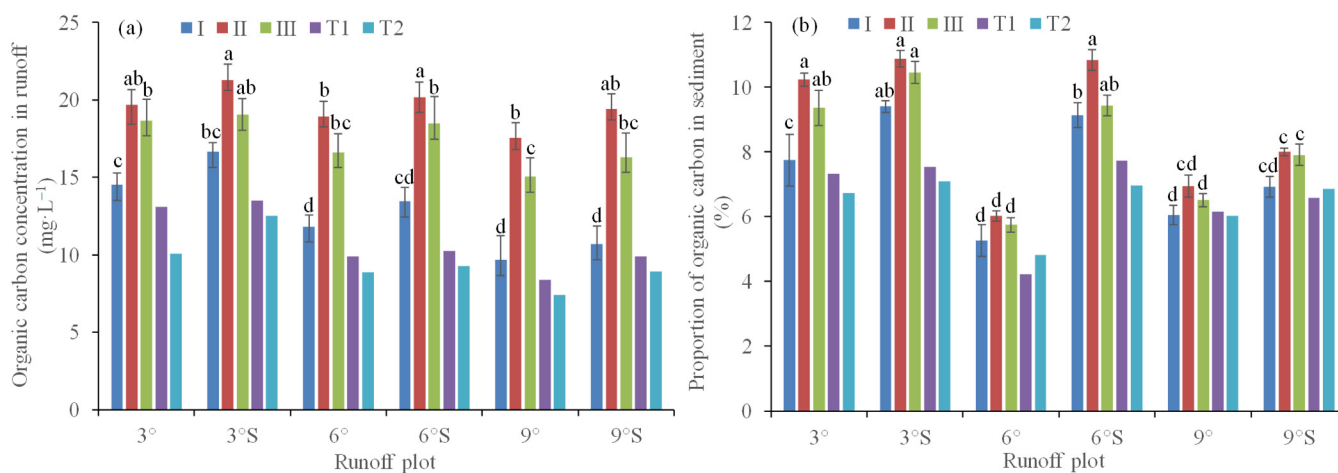


Figure 5. Concentration and proportion of organic carbon in runoff (a) and in sediment (b) under different rainfall patterns for treatments with or without furrow straw mulch. Different small letters indicate significant differences ($p < 0.05$) among the values of runoff coefficients or sediment concentration.

The proportions of organic carbon in sediment for treatments with the furrow corn straw mulch increased by 2.9–82.7% when compared to control treatments without the furrow corn straw mulch (Figure 5b). The proportions of organic carbon in sediment increased by 21.4%, 73.5%, and 14.5% under 3°, 6°, and 9° for the rainfall pattern I; 6.4%, 80.0%, and 15.3% for the rainfall pattern II; 1.6%, 64.2%, and 21.4% for the rainfall pattern

III; 2.9%, 82.7%, and 6.8% for the rainfall pattern T1; 5.5%, 44.7%, and 13.6% for the rainfall pattern T2. Both the lowest and highest proportions of organic carbon in sediment occurred under the rainfall pattern T1. The mean proportions of organic carbon in sediment for different rainfall patterns also decreased in the same sequence as that of the mean organic carbon concentration in runoff: II (8.8%) > III (8.2%) > I (7.4%) > T1 (6.6%) > T2 (6.4%).

The aforementioned findings demonstrated a substantial correlation between erosive rainfall and organic carbon loss characteristics. The correlation analysis of organic carbon concentration in runoff or in sediment and key rainfall indicators for different treatments with or without furrow straw mulch was carried out (Table 2). The organic carbon concentration in runoff and rainfall intensity exhibited a highly substantial positive association (Pearson linear correlation coefficients: 0.756–0.869). This happened as a result of the stronger disruption effect that heavier rainfall intensity had on organic carbon-rich soil surface particles, which raised the amount of organic carbon concentration in runoff [39]. When the slope gradients were gentle, only heavier rainfall amount and longer rainfall duration could cause runoff; however, this could also induce the organic carbon concentration in runoff. When the slope gradients were steep, greater rainfall generated runoff, which, in turn, reduced the organic carbon concentration in runoff. Therefore, there was a substantial negative association between the organic carbon concentration in runoff and rainfall amount or rainfall duration; this trend either decreased or disappeared as the slope gradient increased. The effect of rainfall intensity on the soil surface was lessened by the corn straw. Then, compared to that of the control treatments, the correlation coefficients between the organic carbon concentration in runoff and rainfall intensity decreased, while the correlation coefficients between the organic carbon concentration in runoff and rainfall amount increased for treatments with the furrow corn straw mulch.

Table 2. Correlation analysis of organic carbon concentration in runoff or in sediment and major rainfall indicators for different treatments with or without furrow straw mulch.

Treatment	Organic Carbon Concentration in Runoff (mg L ^{−1})			Organic Carbon Concentration in Sediment (%)		
	Rainfall Amount (mm)	Rainfall Intensity (mm h ^{−1})	Duration (min)	Rainfall (mm)	Rainfall Intensity (mm h ^{−1})	Duration (min)
3°	−0.676 *†	0.869 **	−0.886 *	−0.719 *	0.901 **	−0.669 *
3°S	−0.805 *	0.782 **	−0.862 *	−0.907 *	0.889 *	−0.971 **
6°	−0.668 *	0.819 **	−0.820 *	−0.817 **	0.745 *	−
6°S	−0.723 *	0.733 *	−0.821 *	−0.810 **	0.701 *	−
9°	−	0.758 **	−0.807 *	−	0.795 *	−
9°S	−	0.756 **	−0.789 *	−	0.740 *	−

† The ‘*’ indicates a significant correlation at the $p < 0.05$ level; the ‘**’ indicates a significant correlation at the $p < 0.01$ level. The ‘3°’ is the control treatment without furrow corn straw mulch under the 3° slope gradient, and the ‘3°S’ is the treatment with furrow corn straw mulch under the 3° slope gradient; the same as ‘6°’, ‘6°S’, ‘9°’, ‘9°S’.

As an increase in the slope gradient, the mean proportions of organic carbon in sediment showed an initially decreasing and then increasing trend for control treatments, which decreased by 28.5–42.3% when the slope gradient increased from 3° to 6°, but increased by 13.3–45.6% from 6° to 9°; the mean proportions of organic carbon in sediment generally showed a decreasing trend for treatments with the furrow corn straw mulch, which decreased by 0.5–9.7% and 1.6–26.1% when the slope gradient increased from 3° to 6° and from 6° to 9° (Figure 5b). The explanation for this was that the bigger particle size sediment was more difficult to move when the slope gradient was gentle, as it was in this study (3°), and the fine particle size sediment rich in organic carbon accounted for a larger proportion of the migrating sediment [28]. The corn straw mulch in the furrow could intercept some larger size particles and thus induced greater proportions of organic

carbon in sediment. When the slope gradient increased from 3° to 6° , the soil erosion power increased dramatically (Figure 4) and some bigger size particles drained with the runoff, resulting in a drop in the proportions of organic carbon in sediment. When the slope gradient further increased from 6° to 9° , the soil erosion power also significantly increased and some larger size particles drained with the runoff, but these runoff and sediments might not be discharged in time, resulting in velocity decreasing. Then, partial larger size particles were deposited [40] at the bottom of the natural runoff plots, making the values of proportions of organic carbon in sediment slightly greater than that under 6° , though there was no significant difference between the values of the two slope gradients.

There were significant relationships between the organic carbon concentration in sediment and rainfall amount, rainfall intensity, and rainfall duration under 3° , rainfall amount and rainfall intensity under 6° , and only rainfall intensity under 9° (Table 2). As there was an increase in the slope gradient, erosive rainfall effects on the organic carbon concentration in sediment decreased or disappeared. Although the function of rainfall intensity on the organic carbon concentration in sediment was affected by the slope gradient, this function always existed. The slope and rainfall indicators are essential factors for loss of organic carbon concentration of soil [41]. However, the similar functions of rainfall amount and rainfall duration decreased as the slope gradient increased. The Pearson linear correlation coefficients showed that there was a significant positive correlation between the organic carbon concentration in sediment and rainfall intensity, which was 0.701–0.901, but there was a significant negative correlation between the organic carbon concentration in sediment and rainfall amount or rainfall duration, which were from -0.719 to -0.907 and from -0.669 to -0.971 , respectively. Furthermore, the correlation coefficients for treatments with the furrow straw mulch were lower than that of control treatments. This occurred because the corn straw reduced rainfall kinetic energy and the disturbance of rainfall to surface soil particles [37]. Therefore, the organic carbon concentration in sediment showed similar changes in the organic carbon concentration in runoff, except for rainfall duration which had only a certain function under gentle slope gradients.

3.3.2. The Ratios of Organic Carbon Loss in Sediment to Total Values

The mean ratios of organic carbon loss in sediment to total carbon loss for treatments with the furrow corn straw mulch were 77.0–93.7%, which were lower than 88.4–98.3% for control treatments without the furrow corn straw mulch (Figure 6). With regard to different rainfall patterns, the rainfall pattern II effectively decreased the mean ratios of organic carbon loss in sediment to total carbon loss, which was followed by rainfall pattern I, III, T1, and T2. As the slope gradient was increased from 3° to 6° and from 6° to 9° , the mean ratios of organic carbon loss in the sediment to total carbon loss decreased by 7.0–21.3% and 0.3–1.2% for treatments with the furrow corn straw mulch, and by 2.2%–5.0% and 0.1–0.4% for control treatments, except for the rainfall pattern II.

The organic carbon enrichment indexes in sediment under different rainfall patterns for treatments with the furrow corn straw mulch were 3.2–4.9%, which were slightly greater than 3.0–4.7% for control treatments (Figure 6). The organic carbon enrichment indexes for the rainfall pattern II were largest, and followed by the rainfall pattern III, and I; the indexes for the rainfall pattern T1 and T2 were similar and lower. As the slope gradient was increased from 3° to 6° and from 6° to 9° , the mean organic carbon enrichment indexes in sediment decreased by 22.4–32.0% and 2.9–18.1% for treatments with the furrow corn straw mulch, and by 20.9–30.9% and 3.9–15.8% for control treatments.

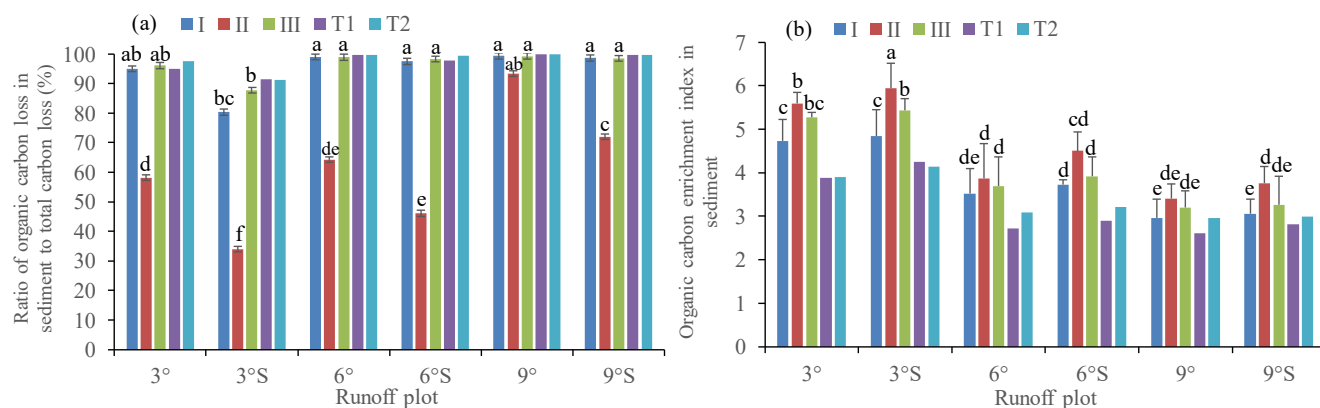


Figure 6. Ratios of organic carbon loss in sediment to total carbon loss (a) and organic carbon enrichment indexes in sediment (b) under different rainfall patterns for treatments with or without furrow straw mulch. Different small letters indicate significant differences ($p < 0.05$) among the values of runoff coefficients or sediment concentration.

The above results occurred because selective transportation of finer particles is one of the many reasons for the sediment's organic carbon enrichment [28]; the corn straw returning back to the farmland increased the selective transportation degrees, and but this effect weakens due to the increase in slope gradient. Rainfall pattern II, short rainfall duration with large rainfall intensity, had greater rainfall kinetic energy and runoff velocity and resulted in greater ratios of organic carbon loss in sediment to total carbon loss and organic carbon enrichment indexes in sediment. Thus, the general rainfall patterns produced greater effects on organic carbon loss than the special rainfall patterns.

3.4. Sediment Sizes and Their Organic Carbon Loss

The mean ratios of <0.053 mm sediment increased from 45.7% to 59.1% under 3° , from 28.8% to 39.4% under 6° , and from 35.3% to 43.1% under 9° for treatments with the furrow corn straw mulch when compared to control treatments without the furrow corn straw mulch (Figure 7). On the other hand, the mean ratios of >0.25 mm sediment decreased from 36.1% to 23.9% under 3° , from 53.6% to 43.3% under 6° , and increased from 46.5% to 49.2% under 9° . Moreover, the primary forms of sediment loss were the <0.053 mm and >0.25 mm soil particles and aggregates [42,43]. The mean ratios of 0.053–0.25 mm sediment did not change much. The decrease in the ratios of >0.25 mm sediment for relatively gentle slope gradients like 6° and 9° was caused by corn straw's ability to assist in trapping larger soil particles or aggregates [42]. On larger soil particles or aggregates, however, the trap effect of corn straw would be less than that of slope gradient and slope stability. Therefore, while using the furrow corn straw mulch treatments, the ratios of <0.053 mm sediment increased but the ratios of >0.25 mm sediment generally decreased.

The ratios of <0.053 mm sediment increased most for the rainfall patterns I and III under 3° , and for the rainfall patterns II and I under 6° or 9° for treatments with the furrow corn straw mulch when compared to control treatments without the furrow corn straw mulch (Figure 7). However, the ratios of >0.25 mm sediment decreased most for the rainfall patterns T1 and I under 3° , for the rainfall patterns I and II under 6° , and for the rainfall patterns II and I under 9° . This occurred because rainfall characteristics were the vital factors for the soil erosion [44], and in this study, the rainfall amount had a greater influence on the transportation of soil particles or aggregates for gentle slope gradients like the 3° in this study; however, both the rainfall intensity and rainfall amount obviously had an impact as well for 6° and 9° slope gradients.

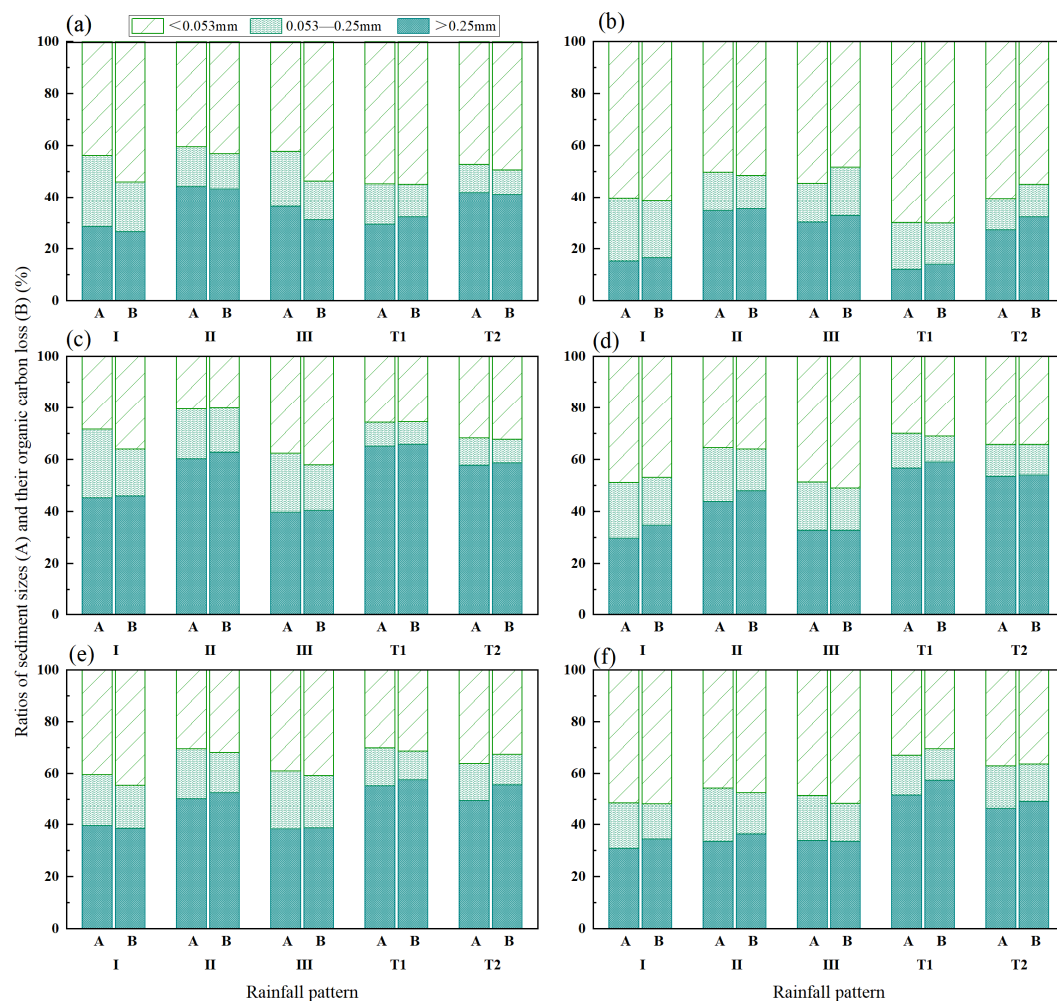


Figure 7. Ratios of sediment sizes (A) and their organic carbon loss (B) under different rainfall patterns. (a) the control treatment without furrow corn straw mulch under the 3° slope gradient; (b) the treatment with furrow corn straw mulch under the 3° slope gradient; (c) the treatment with furrow corn straw mulch under the 6° slope gradient; (d) the treatment with furrow corn straw mulch under the 6° slope gradient; (e) the treatment with furrow corn straw mulch under the 9° slope gradient; (f) the treatment with furrow corn straw mulch under the 9° slope gradient.

The rainfall intensity, rainfall erosivity, and runoff carrying capacity of the rainfall pattern II were all greater than those of the rainfall pattern I. The result was basically consistent with the finding that the ratios of larger soil particles in eroded sediments increased with the increase in rainfall intensity [45]. Therefore, sediment sizes were significantly affected by the rainfall pattern II and followed by the rainfall pattern I, and the furrow corn straw mulch measure could successfully mitigate their effects.

The sediments with a <0.053 mm sediment had the highest ratios of organic carbon loss, followed by those with a >0.25 mm sediment and a 0.053–0.25 mm sediment (Figure 7). The mean ratios of organic carbon loss in <0.053 mm sediment increased from 50.1% to 57.8% under 3°, from 31.2% to 39.8% under 6°, and from 36.3% to 43.9% under 9° for treatments with the furrow corn straw mulch when compared to control treatments without the furrow corn straw mulch. However, the mean ratios of organic carbon loss in >0.25 mm sediment decreased from 35.5% to 26.1% under 3°, from 54.7% to 45.6% under 6°, and from 48.5% to 42.1% under 9°. Greater organic carbon loss was seen in <0.053 mm sediment due to the higher organic carbon content of the fine soil particles or aggregates [46]. Furthermore, a gentle slope gradient prevented large soil particles or aggregates from migrating out of the runoff plot and reduced the component force of runoff down the hillslope. The selective

migration of organic carbon decreased as the slope gradient increased. This was consistent with the findings of Liu et al. [41]. As a result, the changes in organic carbon loss across a range of sediment sizes mirrored those in sediment loss.

The ratios of organic carbon loss in <0.053 mm sediment increased most for the rainfall patterns T1 and II under 3°, for the rainfall patterns II and I under 6°, and for the rainfall patterns II and III under 9° for treatments with the furrow corn straw mulch when compared to control treatments without the furrow corn straw mulch (Figure 7). However, the ratios of organic carbon loss in >0.25 mm sediment decreased most for the rainfall patterns T1 and I under 3°, for the rainfall patterns I and II under 6°, and for the rainfall patterns II and III under 9°. This occurred because greater rainfall intensity and rainfall amount fragmented soil macro- and microaggregates into finer soil particles [47]. The rainfall amount played a much bigger role in the transportation of soil particles or aggregates for gentle slope gradients like 3° in this study, but both the rainfall intensity and rainfall amount obviously affected the transportation of soil particles or aggregates for 6° and 9° slope gradients. Therefore, the rainfall patterns II and I had a considerable impact on the sediment sizes, and the furrow corn straw mulch measure could successfully mitigate their effects.

4. Conclusions

The study focusing on furrow corn straw mulch measure at the sloping farmland in the black soil region was conducted to evaluate its effects on soil erosion and organic carbon loss under natural erosive rainfall events. The results showed that when comparing treatments with the furrow corn straw mulch to control treatments, runoff coefficients and sediment concentration decreased by 48.0–97.7% and 45.6–99.7%, organic carbon concentration in runoff and sediment increased by 2.0–20.9% and 2.9–82.7%, the ratios of <0.053 mm sediment increased but the ratios of >0.25 mm sediment generally decreased. The mean ratios of organic carbon loss in sediment to total carbon loss for treatments with the furrow corn straw mulch were 77.0–93.7%, which were lower than 88.4–98.3% for control treatments. The mean organic carbon concentration both in runoff and sediment decreased in the following order: II > III > I > T1 > T2. Rainfall pattern II with greater rainfall kinetic energy and runoff velocity resulted in greater ratios of organic carbon loss in sediment to total carbon loss and organic carbon enrichment indexes in sediment. In conclusion, the common rainfall patterns produced greater effects on soil erosion and organic carbon loss than the special rainfall patterns, and the furrow corn straw mulch measure could successfully mitigate their effects, especially for farmlands with gentle slope gradients. Therefore, it is suggested that farmers and policy makers may consider applying the furrow corn straw mulch measure in production practices.

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