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Soil Aggregates and Water Infiltration Performance of Different Water and Soil Conservation Measures on Phaeozems Sloping Farmland in Northeast China

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Abstract: The enhancement of soil erosion resistance via soil and water conservation practices is a necessary venture in the modern agricultural industry. Soil infiltration performance, as a necessary indicator of erosion resistance, is closely related to soil aggregates. However, the relationship between the C/N ratio of soil aggregates and soil infiltration and the overall performance under conservation tillage practices is unclear. Experiments were conducted in 2022 and 2023 to observe the relationship between the soil carbon and nitrogen distribution patterns and soil infiltration of sloping cultivated land under different tillage practices. In this study, ridge tillage and pitting field + subsoiling tillage (RF-S) and contour tillage + subsoiling tillage (TP-S) have been used in a plot experiment, with down-slope cultivation (CK) as the control. The results showed that the stability of soil aggregates, the organic carbon and the total nitrogen contents of soil aggregates of different particle-sizes, and the overall soil infiltration performance were greatly increased under the RF-S and TP-S treatments (up-slope, mid-slope, and down-slope). Compared with CK, RF-S and TP-S significantly improved the stability of soil aggregates at different slope positions (on, in, and under the slope) and the C/N ratio and soil infiltration performance of aggregates with particle sizes of >2 mm and 2–0.25 mm. However, TP-S more effectively reduced the deposition of soil macroaggregates down the slope and can comprehensively improve the stability of soil aggregates and the infiltration performance. The mean weight diameter (MWD) and mean geometric mean diameter (GMD) of soil aggregates can reflect the distribution and stability of soil aggregates and also indicate the stability of soil structure. Compared with CK, the MWD of TP-S soil aggregates increased by 6% to 17.7%, the GMD increased by 9.7% to 27.2%, the average soil infiltration rate increased by 41.8% to 78.3%, the initial infiltration rate increased by 19.1% to 46.6%, and the stable infiltration rate increased by 109.2% to 165.9%. Soil infiltration performance is positively correlated with the C/N ratio of aggregates with particle sizes of >2 mm and 2–0.25 mm and negatively correlated with the C/N ratio of aggregates with particle sizes of <0.25 mm. The results of this study show that reasonable tillage measures are helpful in improving soil water and soil conservation and anti-erosion ability and illustrate the influence mechanism of soil aggregates on soil infiltration performance.

Keywords: sloping farmland; soil erosion; tillage measures; agglomerate carbon to nitrogen ratio; infiltration properties

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Citation: Yang, T.; Zhang, Z.; Yu, P.; Yin, Z.; Li, A.; Zhou, X.; Qi, Z.; Wang, B. Soil Aggregates and Water Infiltration Performance of Different Water and Soil Conservation Measures on Phaeozems Sloping Farmland in Northeast China. *Agronomy* **2024**, *14*, 2410. https://doi.org/10.3390/agronomy14102410

Received: 28 September 2024
Revised: 13 October 2024
Accepted: 16 October 2024
Published: 17 October 2024

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1. Introduction

The Northeast Phaeozems region is a necessary commodity grain base in China and consequently holds an irreplaceable role in guaranteeing countrywide food security. Soil

erosion in the Northeast Phaeozems region has been worsening due to inefficient manufacturing and operation activities, and the productivity of arable land has declined significantly. According to applicable statistics, at present, soil erosion in the black soil region of the northeast covers an area of 2.141 × 105 km^2, accounting for 19.69% of the entire area of the region [1]. Sloping arable land is the primary type of land in northeastern China. The total area of sloping arable land in northeastern China is 195,000 km^2, accounting for 58.7% of the total arable land in that area and 14.4% of the entire arable land in the whole country [2]. The experimental site is located in Hailun City, in the Northeast Phaeozems region of China. There are many areas of slope farmland, and the long-term blind reclamation of land, heavy development and light management, and heavy utilization and light fertilization have destroyed natural resources, resulting in the serious erosion of black soil, a sharp declines in soil fertility, greatly reduced land productivity, and a deteriorating agricultural ecological environment, which is a major threat to food security [3]. It is therefore pressing to explore appropriate soil and water conservation measures to mitigate soil erosion in the Phaeozems region of northeastern China.

Soil aggregates are the basic units of soil structure and are one of the most important factors affecting soil quality and health [4]. The structural traits and composition of aggregates are necessary indicators of the soil's structural steadiness and resistance to erosion. At the same time, soil aggregates are principal storage places for organic carbon and nitrogen [5]. The stability of soil aggregates is influenced by the combined effects of carbon and nitrogen and responds significantly to the soil carbon to nitrogen ratio [6]. The soil C/N ratio is an important index for the evaluation of soil quality and has a significant impact on soil carbon and nitrogen cycling [7]. Different tillage measures will affect soil aggregates and their organic carbon and total nitrogen contents. Ying Shen et al. [8] reported that subsoiling increased carbon and nitrogen sequestration in aggregates. Yang Jie et al. [9] demonstrated that cross-slope tillage reduced the loss of organic carbon and total nitrogen from soil. The organic carbon and total nitrogen contents can enhance the cementation of materials, therefore promoting the formation of soil macroaggregates [10]. This can enhance the soil porosity and permeability and improve the soil structure [11]. It can be seen that the study of soil aggregates and their organic carbon and total nitrogen contents under different tillage measures is helpful in reducing the risk of soil erosion and to protect soil health [12].

Soil infiltration performance also reflects soil erosion resistance to a large extent [13]. In general, the stronger the soil infiltration, the easier it is for surface runoff to be transported via infiltration to deeper soil layers, and the lower the threat of flooding and erosion [14]. Soil infiltration, as a bridge between above- and below-ground water, is an essential prerequisite for water uptake via plant roots [15]. In addition, infiltration is a necessary link in the water cycle of farmland, and it can reflect the soil and water conservation ability of farmland to a certain extent. Infiltration performs a pivotal function in the transformation between rainfall, surface water on the ground, soil water, and groundwater [16,17]. J. A Gómez et al. [18] found that subsoiling could improve the soil structure and enhance the soil infiltration performance. The slope accelerates the formation of slope runoff by increasing its component force along the slope direction, thus affecting its infiltration process. Previous studies have shown that cross-slope tillage and ridge tillage can effectively intercept surface runoff and prevent decreases in the soil infiltration performance [19]. Therefore, studying the soil infiltration performance under different tillage measures is of great significance for protecting farmland soil from soil erosion and for the sustainable development of agriculture.

It has been demonstrated that soil aggregates are inextricably linked to soil infiltration. This is because soil infiltration performance is sensitive to soil porosity [20]. The influence of soil porosity on soil infiltration is primarily controlled by the volume, size, and connectivity of soil pores. Talita et al. [21,22] showed that changes in the proportion of soil aggregates will lead to changes in soil porosity, which will affect the soil infiltration performance. Moreover, Nkanyiso et al. [23,24] demonstrated that the stability of soil aggregates rose

with the increase of organic carbon in soil aggregates, thus improving the soil structure and enhancing the volume and size of soil pores. The C/N ratio is an important indicator of the carbon and nitrogen balance and the degree of organic matter decomposition. This ratio can also indicate the trend of organic carbon accumulation [25]. It can be seen that the organic carbon and total nitrogen content of soil aggregates and the C/N ratio affect the infiltration performance of the soil.

Soil and water conservation measures are an important methods used to control the erosion of sloping arable land. Soil and water conservation tillage practices can significantly reduce runoff, thereby enhancing soil and crop yields [26–28]. Soil aggregates and soil infiltration performance are the main influencing factors of soil erosion resistance. Therefore, it is very important to study and analyze soil aggregates and soil infiltration performance under different tillage measures for the prevention and control of soil erosion. However, most previous studies on the relationship between soil aggregates and soil infiltration performance mainly focus on the influence of the physical properties of soil aggregates on soil infiltration performance, while few studies have examined the correlation between the carbon–nitrogen ratio of soil aggregates and the soil infiltration performance. Therefore, the objectives of the current study were to (1) explore soil and water conservation tillage measures that are more suitable for sloping farmland in the Northeast Phaeozems region and (2) the examine the correlation between the C/N ratio of soil aggregates and soil infiltration performance. These results can provide a theoretical basis for improving soil and water conservation and erosion resistance.

2. Materials and Methods

2.1. Study Location and Environmental Conditions

The test site was located in Guangrong Village, Qianjin Township, southwestern Hailun City, northern Songnen Plain, Heilongjiang Province (47°22′38″ N, 126°51′4″ E). The site is in a typical diffuse river and hillock erosion area, with an average elevation of 210 m, a slope gradient of 0.5–7°, and a slope length of 200–1000 m. The test site has a temperate continental monsoon climate. Winters are cold and dry, summers are hot and rainy. The average annual temperature is 1.5 °C, the average annual precipitation is 500 mm, the average annual evaporation is 2300 mm, and the frost-free period is 135 days. The soil of the experimental site is a typical black soil, with clear soil stratification. The soil has a total nitrogen (N) of 2.27 g/kg, alkaline dissolved nitrogen (N) of 154.4 mg/kg, total phosphorus (P_2O_5) of 0.88 g/kg, effective phosphorus (P_2O_5) of 40.1 mg/kg, effective potassium (K_2O) of 376.8 mg/kg, organic matter of 42.1 g/kg, and a pH value of 7.27. These data were obtained from the China Meteorological Administration. The changes in rainfall and temperature during the observation period of the experimental area are shown in Figure 1.

2.2. Experimental Design

A maize-soybean rotation system was used for testing. Maize was used as the test crop in 2022, and soybean was used as the test crop in 2023. The procedures used for planting, seedling care, and transplanting were the same for both crops. The experiment was conducted with two treatments: ridge tillage and pitting field + subsoiling tillage (RF-S) and contour tillage + subsoiling tillage (TP-S), with down-slope cultivation (CK) as the control treatment. The different treatments were sampled and analyzed at the top, middle, and bottom of the slope for comparison. The sampling point on the slope was 3 m from the upper boundary of the plot, the sampling point at the bottom of the slope was 3 m from the lower boundary of the plot, and the sampling point in the middle of the slope was located in the center of the plot. The experiment included three replicates. The size of each plot was 5 × 20 m, the inclination angle of each plot was 5°, and the slope was 8.7%. Steel plates were inserted around each plot for zoning. The steel plates were 1.5 m high, 1 m deep, and 50 cm above the surface of the ground. Sampling and analysis were conducted after crop harvest. In 2022, the fertilizer applied to each treatment was

250 kg/hm^2 of nitrogen fertilizer, 90 kg/hm^2 of phosphorus fertilizer, and 120 kg/hm^2 of potash fertilizer. In 2023, the fertilizer applied to each treatment was 35 kg/hm^2 of nitrogen fertilizer, 60 kg/hm^2 of phosphorus fertilizer, and 30 kg/hm^2 of potash fertilizer [29]. The location and layout of the test area are shown schematically in Figure 2.

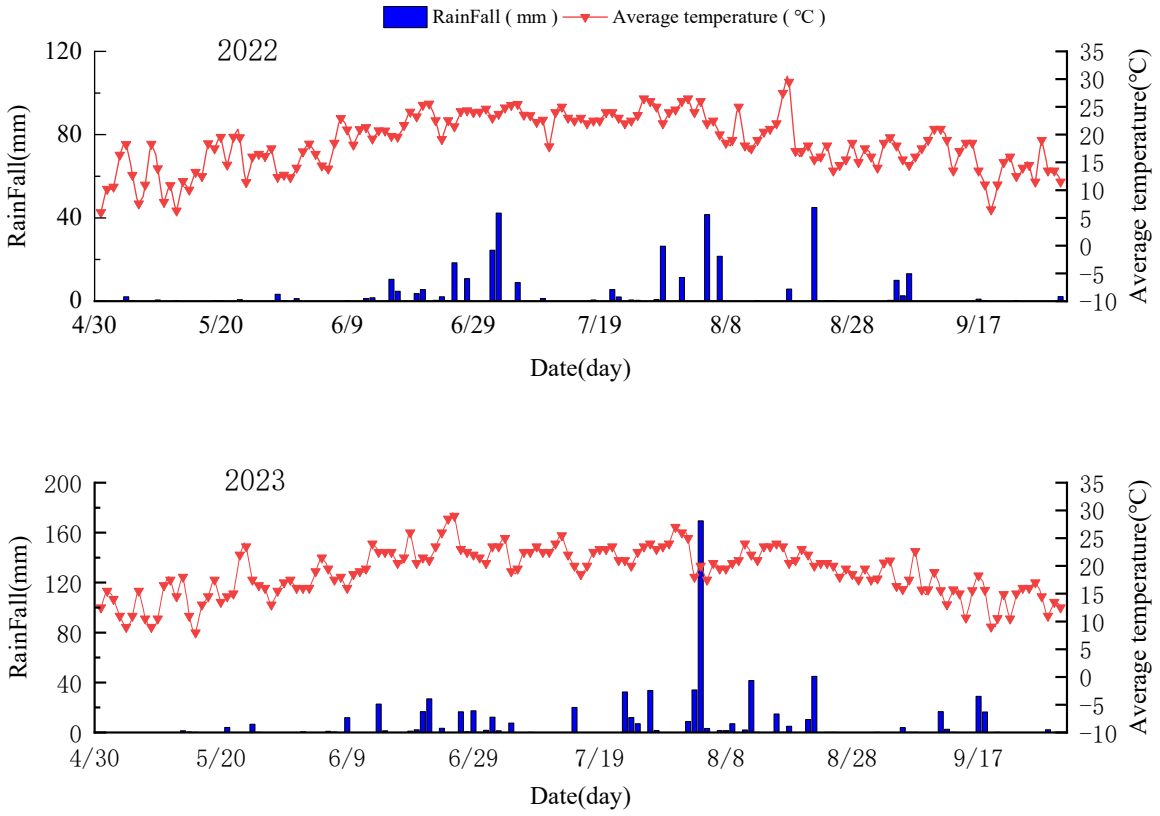


Figure 1. Changes in rainfall and temperature during the observation period.

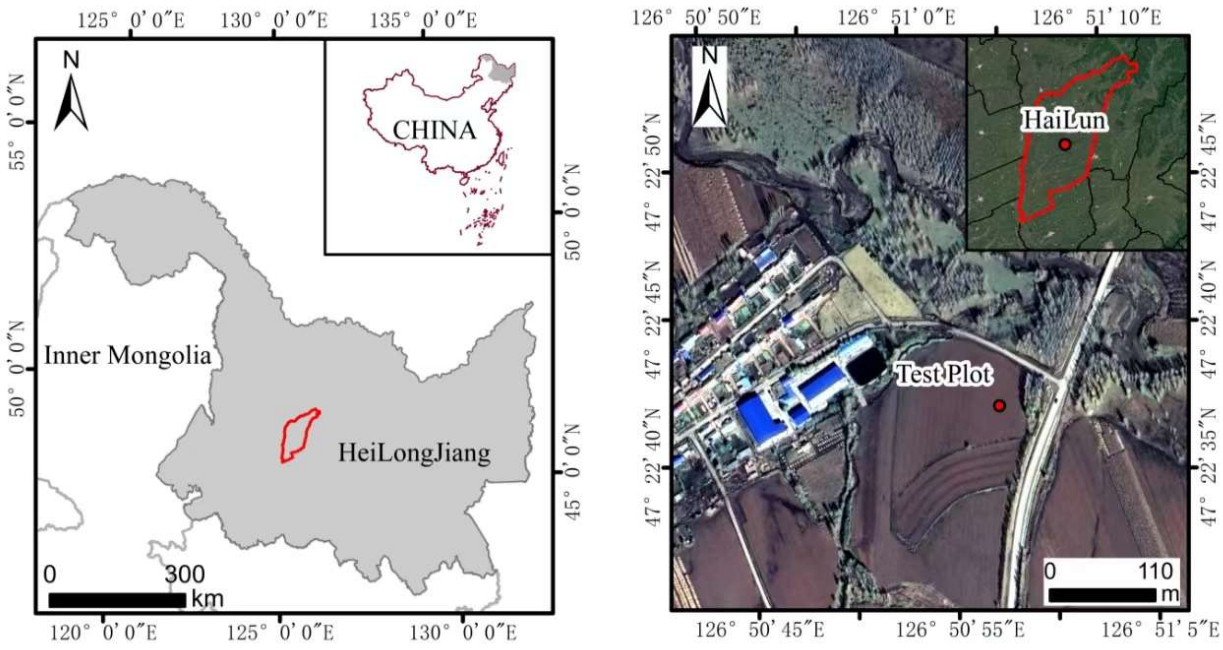


Figure 2. Schematic diagram of the location and layout of the test area.

2.3. Methods of Measurement and Calculation of Relevant Indicators

2.3.1. Soil Sample Collection

In situ soil samples were collected from the 0–20 cm, 20–40 cm, and 40–60 cm soil layers. The collected soil samples were gently broken into small pieces along the natural structure and sieved through an 8 mm sieve to remove large plant residues and stones. These soil samples were dry sieved into soil aggregates of different particle sizes and subsequently analyzed for aggregate stability and aggregate carbon and nitrogen content. The soil samples were taken from the soil layers using a ring knife. The inner side of the ring knife was coated with petroleum jelly to prevent water leakage at the edge of the infiltration process. This also prevented the soil samples from slipping and was used to analyze the infiltration properties of the soil.

2.3.2. Determination of Agglomerate Stability

After the soil samples were air-dried at room temperature, the proportion of mechanical agglomerates at each grain level was determined by the dry sieve method. The mean weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregates are important indicators of the stability of aggregates, and higher values of *MWD* and *GMD* indicate that the aggregates are more stable.

The average weight diameter of agglomerates was calculated as follows:

$$MWD = \sum_{i=1}^{5} \overline{x} \times W_i \quad (1)$$

The geometric mean diameter of the agglomerate was calculated as follows:

$$GMD = E_{XP}\left(\frac{\sum_{i=1}^{5} W_i \ln \overline{x}}{\sum_{i=1}^{5} W_i}\right) \quad (2)$$

where $\overline{x}$ is the average diameter of agglomerates of grain size i (mm) and W_i is the mass percentage of agglomerates of particle size i (%).

2.3.3. Determination of Organic Carbon and Total Nitrogen in Agglomerates

Soil aggregate organic carbon was determined using an elemental analyzer (Vario TOC, Elementar, Berlin, Germany,). Total nitrogen content in the aggregates was determined using a continuous flow injection analyzer (Seal Analytical GmbH, Berlin, Germany, sensitivity 0.001 AUFS), and the carbon to nitrogen ratio (C/N) refers to the ratio of soil organic carbon to the total nitrogen content [30].

2.3.4. Determination of Soil Infiltration Rate

After retrieving the ring knife containing undisturbed soil, an empty ring knife of the same size was connected to the original ring knife from above. The two ring cutters were sealed with a transparent adhesive to prevent water from leaking through the joints, and a ring cutter cap was placed on one end to prevent the soil from shedding. The ring cutter was fixed horizontally at a certain height, and a funnel and a beaker of known mass were placed underneath to collect the water. The beaker was then placed on an electronic balance to measure the weight of the water. Then, water was added to the mouth of the empty ring cutter and a syringe was used to continuously add water to maintain a volume of 5 cm of water in the ring cutter. Timing began when the first drop of water appeared below the funnel. For the first 30 min, the volume was recorded every minute; after 30 min this was recorded every 2 min, and after 60 min every 5 min for a total of 2 h [31]. The initial infiltration rate was defined as the quantity of water in the beaker during the first 1 min, when the infiltration water moved under the action of gravity. The infiltration rate decreased with the increase of infiltration duration and eventually reached stability; this was considered the stable infiltration rate.

The infiltration rate was calculated using the following formula:

$$f_s = \Delta m/2 \times (0.7 + 0.03T) \quad (3)$$

where f_s is the rate of soil infiltration at the standard water temperature of 10 °C (mm), Δm is the increment of water received by the balance at a certain time ΔT (g), ΔT is a period (min), and T is the water temperature (°C).

2.4. Data Analysis

In this experiment, WPS Office was used for data processing, Origin Pro 2021 software was used for graphing, and SPSS 27.0 was used for statistical analysis. Duncan's method was used for the significance analysis of the differences between samples of multiple groups, and Pearson's method was used for the correlation analysis between the infiltration performance of the soil and various other indicators.

3. Results

3.1. Influence of Different Tillage Practices on Soil Aggregates in Agricultural Fields of Phaeozems Sloping Farmland

3.1.1. Distribution of Different Grain Sizes of Soil Aggregates in Different Soil Layers from 0 to 60 cm

The percentages of aggregates of each grain size in each soil layer in different slopes under different treatments are shown in Figure 3. RF-S, TP-S, and CK have the highest proportion of aggregates larger than 2 mm in size. In the same soil layer at the same slope position, the proportion of aggregates larger than 2 mm in the TP-S and RF-S soils was significantly higher than that in CK ($p < 0.01$). Compared with CK, the proportion of aggregates larger than 2 mm in RF-S increased by 12% to 44.4%, and the proportion of aggregates larger than 2 mm in TP-S increased by 8.5% to 48.6%. In the same soil layer on the upper slope, the proportion of aggregates with a particle size greater than 2 mm in RF-S soil was significantly higher than in TP-S compared with CK, and it is significantly larger than that in TP-S soil with a particle size of more than 2 mm. In the same soil layer in the middle slope, the proportion of aggregates with a particle size greater than 2 mm in TP-S soil was significantly higher than that of RF-S compared with CK, and it was significantly greater than that in RF-S soil.

During the two-year experiment, in the same soil layer under the same treatment, the proportion of aggregates larger than 2 mm in CK and RF-S soil was the least in the slope and the most in the lower slope, and the proportion of aggregates larger than 2 mm in the upper slope and the middle slope ($p < 0.01$). The proportions of aggregates smaller than 0.25 mm in CK and RF-S soils were the least in the downslope position and the highest in the mid-slope position. The proportion of aggregates of all grain sizes in TP-S soils was the least in the downslope position and the highest in the mid-slope position. Each slope position was similar in proportion, with no clear pattern. The proportion of aggregates smaller than 0.25 mm was significantly less than the proportion of aggregates of other grain sizes in the soil layers of each treatment on each slope. On the same slope in the same treatment, as the soil layer deepened, there were more agglomerates larger than 2 mm and fewer agglomerates smaller than 0.25 mm. In 2023, all aggregates larger than 2 mm were increased compared to 2022.

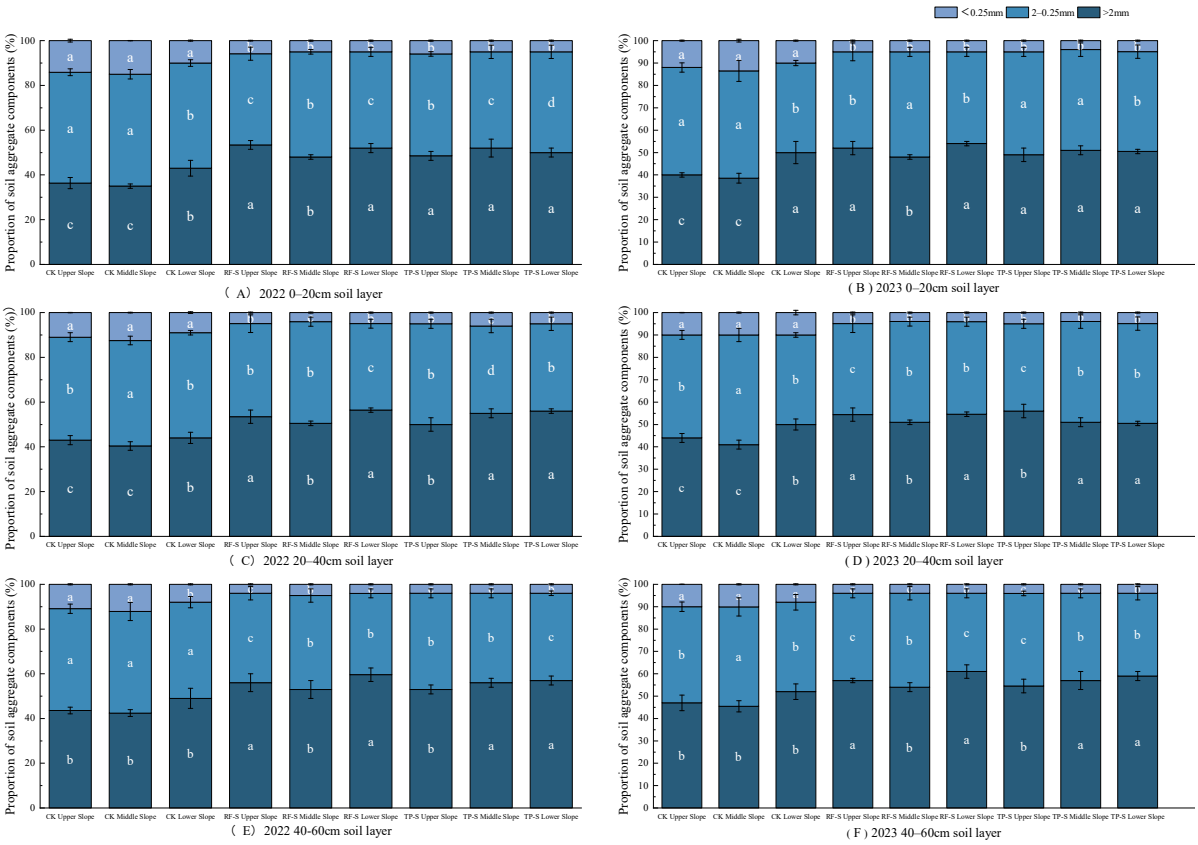


Figure 3. Aggregate particle size distribution. Note: The significance of the difference between different treatments at different slopes in the same soil layer is marked with lowercase letters ($p < 0.01$). CK: downslope cultivation, RF-S: ridge tillage and pitting field + subsoiling tillage, TP-S: contour tillage + subsoiling tillage.

3.1.2. Mean Weight Diameter and Geometric Mean Diameter of Soil Aggregates

The characteristics of MWD and GMD of soil aggregates in various soil horizons according to slope and treatments are shown in Figure 4. In the same soil horizons on the same slopes, the MWD and GMD of both TP-S and RF-S were significantly increased compared with CK ($p < 0.01$). The 2023 results showed a small increase in the overall soil MWD and GMD relative to 2022. From the perspective of 2022 and 2023, compared to CK, the MWD of RF-S soil aggregates increased between 7.5% and 15.9% and the GMD increased between 11.2% and 24.5%, while the MWD of TP-S soil aggregates increased between 6% and 17.7% and the GMD increased between 9.7% and 27.2%. In the upper and lower soil layers of the slope, the increase of RF-S and soil MWD and GMD compared with CK was significantly greater than that of TP-S. In the same soil layer in the middle slope, the increase of the soil MWD and GMD in TP-S and compared with CK was significantly greater than that in RF-S.

During the two years of the experiment, the effect of the change of slope position on the soil MWD and GMD was also significant ($p < 0.01$). In all soil horizons of CK and RF-S, the pattern of soil MWD and GMD on slope position was below slope > above slope > mid-slope; compared to CK, this pattern was less significant in RF-S on slope position, and in all soil horizons of TP-S the pattern of soil MWD and GMD on slope position was roughly below slope > mid-slope > upper slope. Soil MWD and GMD both increased with deeper soil horizons on the same slopes in the same treatments.

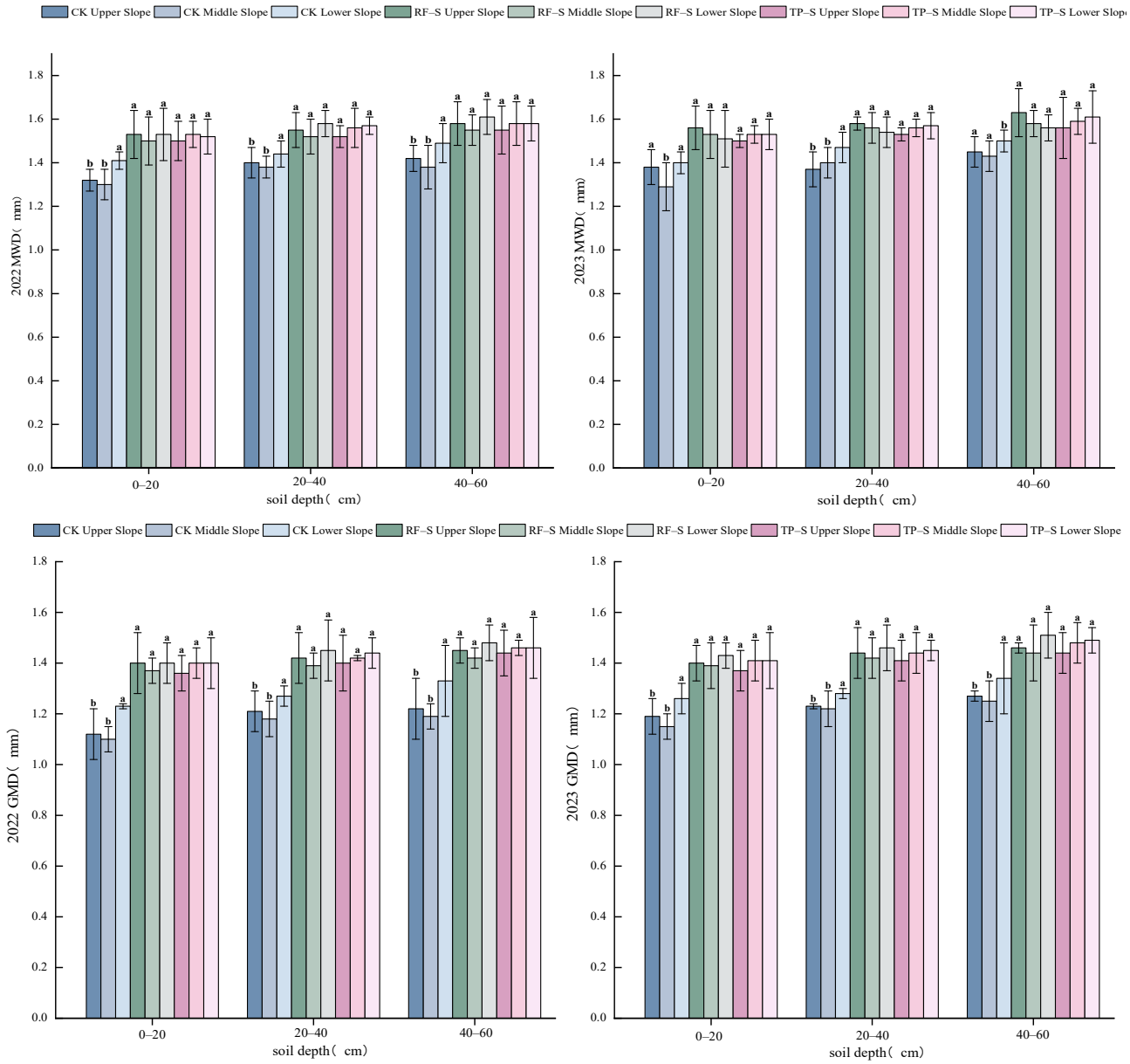


Figure 4. Soil aggregate mean weight diameter and geometric mean diameter. Note: The significance of the difference between different treatments at different slopes in the same soil layer is marked with lowercase letters ($p < 0.01$). CK: downslope cultivation, RF-S: ridge tillage and pitting field + subsoiling tillage, TP-S: contour tillage + subsoiling tillage.

3.1.3. Organic Carbon Content of Soil Aggregates of Different Grain Sizes

As shown in Figure 5, there were significant differences between the treatments on the organic carbon content of agglomerates at all grain levels ($p < 0.01$). Compared with CK, TP-S and RF-S significantly increased the organic carbon content of aggregates at all grain sizes. Compared with CK, TP-S and RF-S exhibited significant increases in the organic carbon content of aggregates in all grain sizes. The results from 2023 showed an overall increase in the organic carbon content of each grain-size aggregate compared with 2022. From the perspective of 2022 and 2023, compared with CK, the organic carbon content of RF-S agglomerates in grain sizes > 2 mm increased by 15.2% to 28%, that of agglomerates in grain sizes 2–0.25 mm increased by 16.8% to 30.3%, and that of agglomerates in grain sizes < 0.25 mm increased by 16.8% to 28.3%. Compared with CK, TP-S increased the organic carbon content of agglomerates > 2 mm by 18.1% to 47.8%, those of 2–0.25 mm by 6.5% to 44%, and those of < 0.25 mm by 16.7% to 32%. Compared with CK, RF-S significantly

increased the organic carbon content of aggregates in each size fraction at the upper slope position compared to TP-S. In the same soil layer in the middle slope, the increase of the organic carbon content of aggregates in TP-S was significantly greater than that in RF-S. At the lower slope position, RF-S increased the organic carbon content of soil aggregates of each particle size more than TP-S.

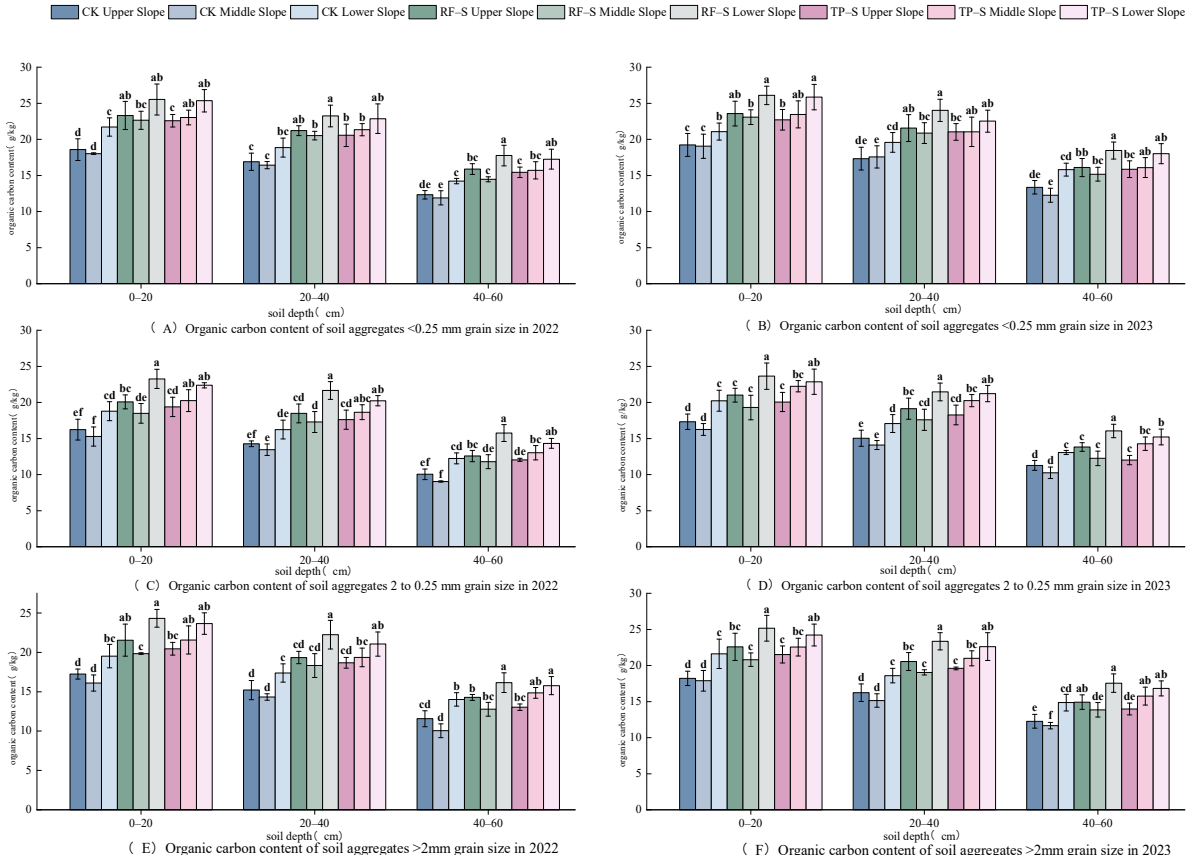


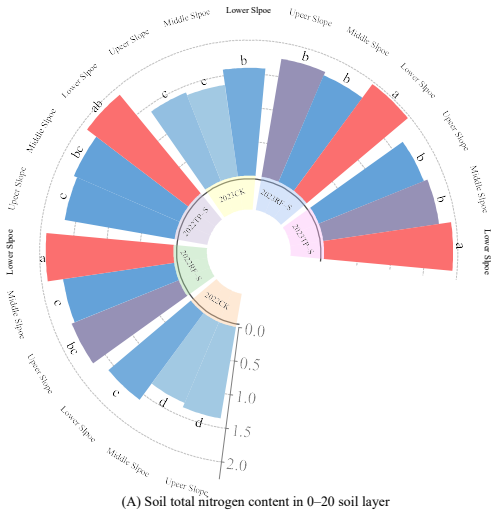
Figure 5. The content of organic carbon in soil aggregates of different particle sizes. Note: The significance of the difference between different treatments at different slopes in the same soil layer is marked with lowercase letters ($p < 0.01$). CK: downslope cultivation, RF-S: ridge tillage and pitting field + subsoiling tillage, TP-S: contour tillage + subsoiling tillage.

There were significant differences between different slope positions in terms of the organic carbon content of aggregates of each grain size during the two-year period of the experiment ($p < 0.01$). Among the soil layers of CK and RF-S, the downslope position had the highest organic carbon content of each grain-size aggregate. The pattern of organic carbon content of the aggregates of each grain level with the slope position was downslope > upslope > mid-slope. In the TP-S soil layers, the organic carbon content of the aggregates at the downslope position was the highest, but the pattern for the organic carbon content of the aggregates at each grain level with the slope position was downslope > mid-slope > up-slope. The organic carbon content of each grain-size aggregate decreased as the soil layer deepened in the same treatment and on the same slope position.

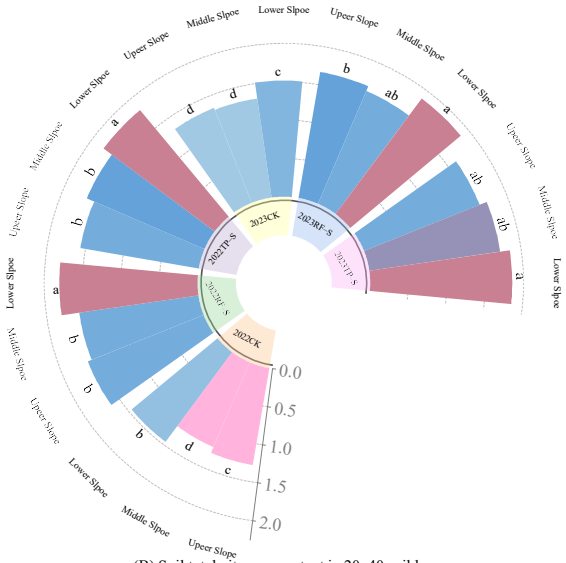
3.1.4. Content of Total Nitrogen in Soil Aggregates of Different Grain Sizes

As shown in Figure 6, there was a significant difference between the different treatments in the total nitrogen content of aggregates at all grain levels ($p < 0.01$). Compared with CK, TP-S and RF-S significantly increased the nitrogen content of aggregates at all grain sizes, and the most significant increase was observed in aggregates smaller than 0.25 mm. The total nitrogen content of aggregates in RF-S was 19.2 to 34.1% higher than

that in CK for grain sizes of <0.25 mm. The total nitrogen content of aggregates in TP-S was 18.1 to 42.7% higher than that in CK less than 0.25 mm. During the two years of the experiment, compared with CK, RF-S significantly increased the total nitrogen content of aggregates in the upper slope to a greater degree than TP-S. TP-S significantly increased the total nitrogen content of aggregates in the mid-slope to a greater degree than RF-S, and RF-S increased the total nitrogen content of aggregates in the lower slope more than TP-S.



(A) Soil total nitrogen content in 0–20 soil layer



(B) Soil total nitrogen content in 20–40 soil layer

Figure 6. *Cont*.

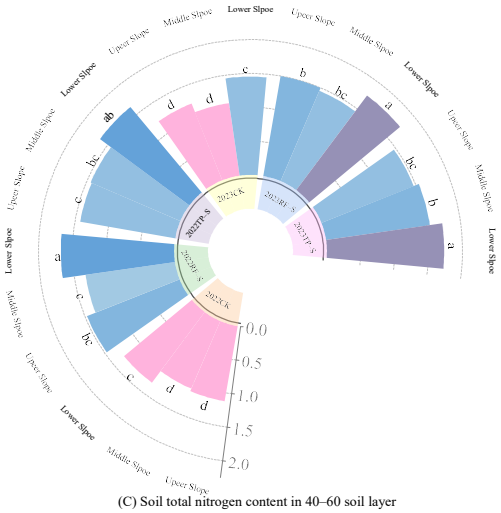


Figure 6. Total nitrogen content of soil aggregates at different grain sizes. Note: The significance of the difference between different treatments at different slopes in the same soil layer is marked with lowercase letters ($p < 0.01$). CK: downslope cultivation, RF-S: ridge tillage and pitting field + subsoiling tillage, TP-S: contour tillage + subsoiling tillage.

During the two years of the experiment, there were also significant differences in the total nitrogen content of each particle size aggregate at different slope positions ($p < 0.01$), and the total nitrogen content of each particle size aggregate was similar in the slope position. Among the soil layers of CK and RF-S, the total nitrogen content of each grain-level aggregate was the highest in the down-slope position. The pattern of total nitrogen content of aggregates of each grain level with slope position was downslope > upslope > mid-slope. In each soil layer of TP-S, the downslope position had the highest nitrogen content of aggregates at each grain level, and the pattern of the nitrogen content of aggregates at each grain level with the slope position was downslope > middle of slope > upslope. On the same slope location of the same treatment, the total nitrogen content of each grain-level aggregate became less as the soil layer depth increased. The total nitrogen content of each grain-level aggregate increased overall in 2023 compared with 2022.

3.1.5. Carbon and Nitrogen Ratios of Soil Aggregates of Different Grain Sizes

The carbon to nitrogen ratios of larger than 2 mm and 2–0.25 mm grain-size aggregates were significantly different for the corresponding different treatments ($p < 0.01$), while the carbon to nitrogen ratios of smaller than 0.25 mm grain-size aggregates were not significantly different between treatments (Figure 7). Compared to CK, the TP-S and RF-S treatments significantly enhanced the C/N ratio of agglomerates larger than 2 mm grain size. Compared with 2022, the carbon–nitrogen ratio of each aggregate in 2023 has increased slightly. The C/N ratio of RF-S was 2.3 to 11.7% higher than that of CK > 2 mm aggregates, and the C/N ratio of 2–0.25 mm aggregates was increased by 2.5% to 11.9%. The C/N ratio of TP-S was 0.1 to 21.4% higher than that of CK > 2 mm aggregates, and the C/N ratio of 2–0.25 mm aggregates was increased by 0.06% to 16.4%. According to the two-year experiment, the carbon–nitrogen ratio of RF-S to aggregates > 2 mm and 2–0.25 mm in the upper slope was significantly higher than that of TP-S. The carbon–nitrogen ratio of TP-S to aggregates > 2 mm and 2–0.25 mm in the middle slope was significantly higher than that of RF-S. The carbon–nitrogen ratio of RF-S to aggregates larger than 2 mm and 2–0.25 mm in the lower slope was higher than that of TP-S.

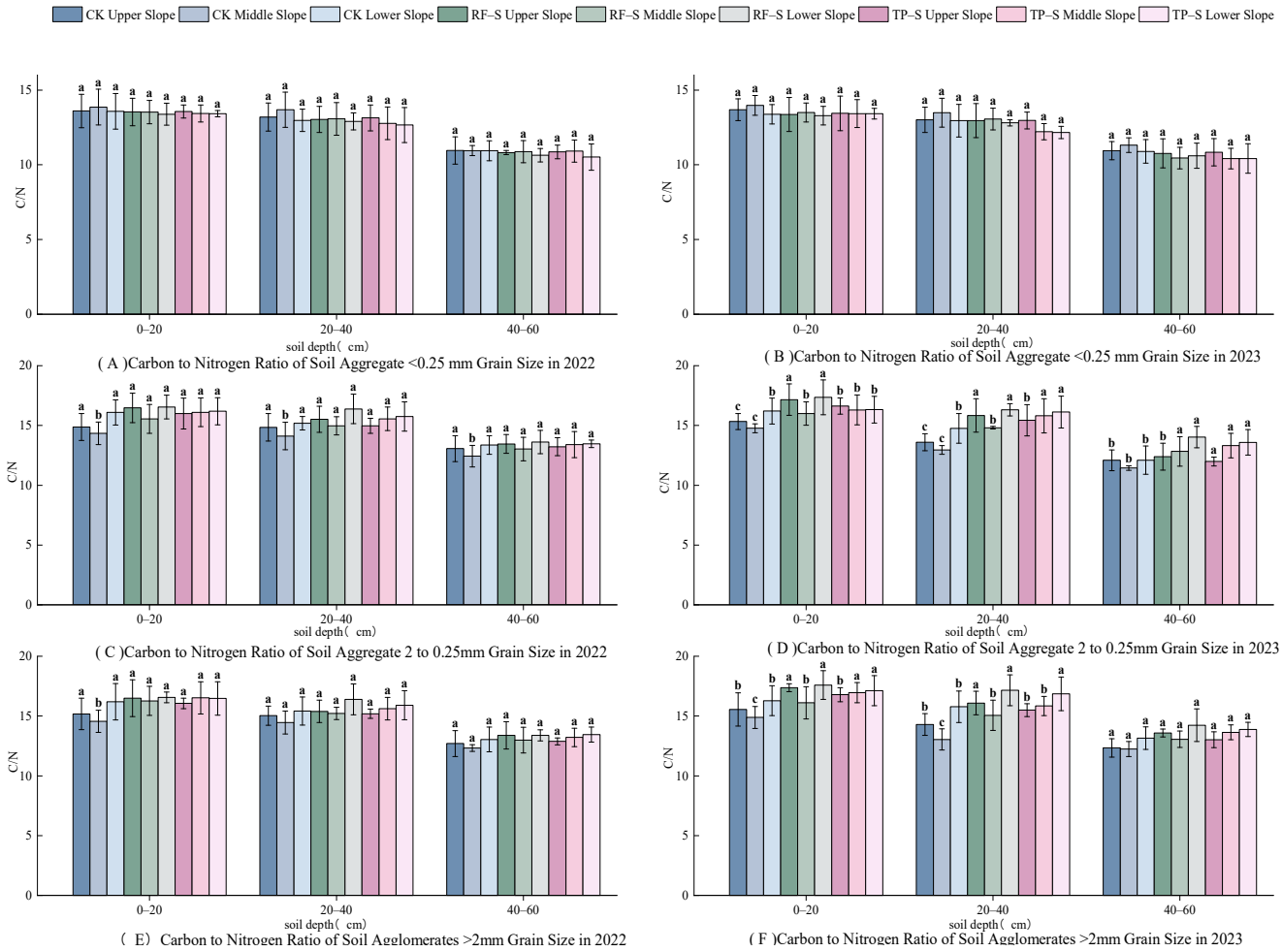


Figure 7. C/N ratio of soil aggregates with different particle sizes. Note: The significance of the difference between different treatments at different slopes in the same soil layer is marked with lowercase letters ($p < 0.01$). CK: downslope cultivation, RF-S: ridge tillage and pitting field + subsoiling tillage, TP-S: contour tillage + subsoiling tillage.

In the two-year experiment, the C/N ratios of aggregates > 2 mm and 2–0.25 mm were also significantly different from the slope position ($p < 0.01$). In CK and RF-S, the C/N ratios of > 2 mm and 2–0.25 mm grain-size agglomerates were highest in the downslope position, and the pattern was downslope > upslope > mid-slope. In TP-S, the carbon to nitrogen ratio was highest for sub-slope locations and greater than 2 mm and 2–0.25 mm grain-level aggregates, and the pattern was sub-slope > mid-slope > up-slope. Slope position had no significant effect on the C/N ratio of agglomerates smaller than 0.25 mm grain size. In the same treatment with the same slope position, the C/N ratios of individual grain-size aggregates showed a consistent pattern in response to soil depth.

3.2. Influence of Different Plowing Practices on the Infiltration Performance of Soil Moisture in Phaeozems Sloping Farmland

Significant differences in the mean, initial, and steady infiltration rates were observed between the different tillage practices ($p < 0.01$) (Figure 8). The mean, initial, and steady infiltration rates were significantly higher in RF-S and TP-S soils than in CK. In 2022, compared with CK, the average infiltration rate of RF-S soil increased by 48% to 63.5%, the initial infiltration rate increased by 24.6% to 38.2%, and the stable infiltration rate increased by 126.7% to 156.8%. The average infiltration rate of TP-S soil increased by 41.8% to 78.3%, the initial infiltration rate increased by 18.7% to 46.6%, and the stable infiltration rate increased by 116.6% to 165.9%. In 2023, compared with CK, the average infiltration rate

of RF-S soil increased by 49.6% to 66.3%, the initial infiltration rate increased by 24.8% to 38.6%, and the stable infiltration rate increased by 110.7% to 133.3%. The average infiltration rate of TP-S soil increased by 44.4% to 79.0%, the initial infiltration rate increased by 19.1% to 45.1%, and the stable infiltration rate increased by 109.2% to 144.6%. At the uphill and downhill locations, RF-S improved the average infiltration rate, initial infiltration rate, and stable infiltration rate of the soil. In the mid-slope position, TP-S had a greater enhancement of the average soil infiltration rate, initial infiltration rate, and stable infiltration rate.

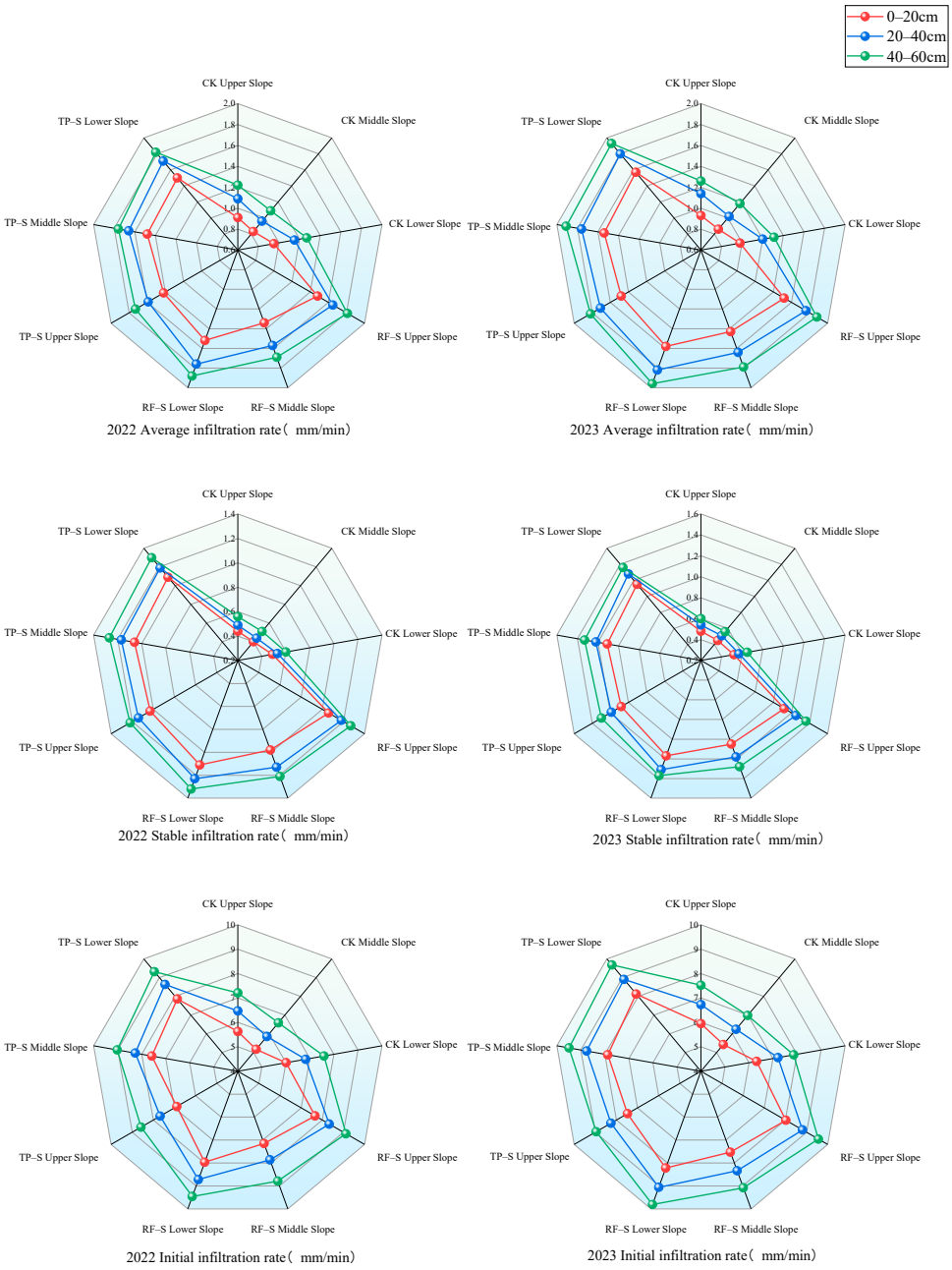


Figure 8. Soil average infiltration rate, initial infiltration rate, and stable infiltration rate.

There were significant differences regarding the influence of slope position on the average soil infiltration rate, the initial infiltration rate, and the stable infiltration rate ($p < 0.01$). The responses of the mean soil infiltration rate, the initial infiltration rate, and the stable infiltration rate to slope position also showed a consistent pattern. In all treatments, the highest average, initial, and stable soil infiltration rates were found at the downslope location, and the response of average, initial, and stable soil infiltration rates to the slope

location in the CK and RF-S treatments was downslope > upslope > mid-slope. In the TP-S treatment, the mean soil infiltration rate, the initial infiltration rate, and the stable infiltration rate responded to slope position in the order downslope > mid-slope > upslope. The average soil infiltration rate, the initial infiltration rate, and the stable infiltration rate increased with the depth of the soil layer on the same slope in the same treatment. The average soil infiltration rate, the initial infiltration rate, and the stable infiltration rate were increased in 2023 compared to 2022.

3.3. Factors Affecting the Soil Infiltration Performance

The correlations between soil infiltration characteristics and various factors are shown in Figure 9A,C,E. In 2022, the proportion of >2 mm aggregates in each soil layer; the soil MWD, GMD, organic carbon content, and total nitrogen content of <2 mm aggregates; the organic carbon and total nitrogen contents of 2–0.25 mm aggregates; the organic carbon and total nitrogen contents of <0.25 mm aggregates; the carbon and nitrogen ratio of >2 mm aggregates; and the carbon and nitrogen ratio of 2–0.25 mm aggregates were significantly positively correlated with the soil average infiltration rate, the initial infiltration rate, and the stable infiltration rate. The content of 2–0.25 aggregates, the proportion of aggregates smaller than 0.25 mm, and the carbon–nitrogen ratio of aggregates smaller than 0.25 mm were significantly negatively correlated with the average infiltration rate, the initial infiltration rate, and the stable infiltration rate in each soil layer.

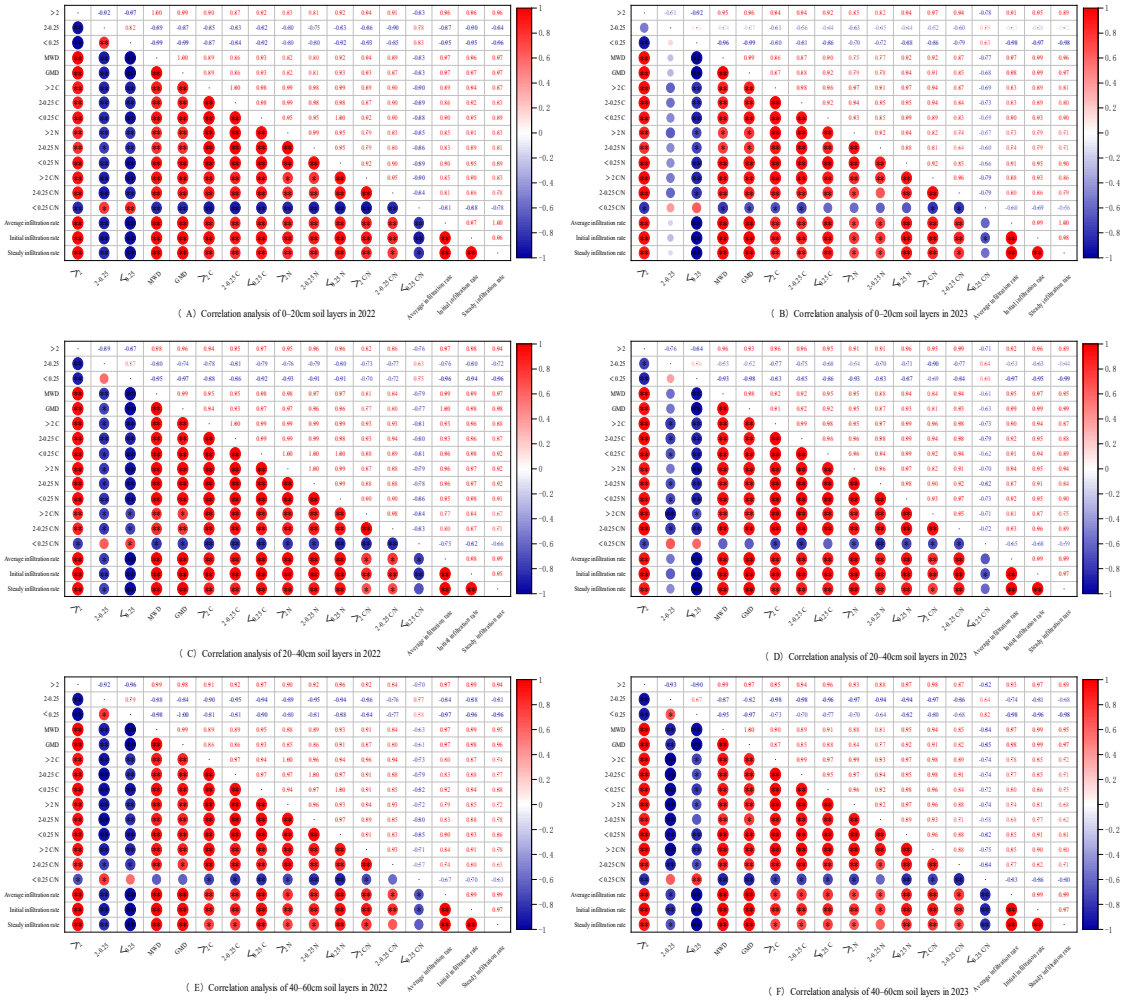


Figure 9. Correlation analysis of the soil infiltration rate and various factors. Note: * $p < 0.05$.** $p < 0.01$.

The correlations between soil infiltration characteristics and various factors are shown in Figure 9B,D,F. In 2023, only the correlation between the proportion of 2–0.25 mm aggregates and soil average infiltration rate, initial infiltration rate, and stable infiltration rate was different from that in 2022. Unlike 2022, in the 0–20 cm soil layer, the proportion of 2–0.25 mm aggregates exhibited a very small negative correlation with the average soil infiltration rate, the initial infiltration rate, and the stable infiltration rate. As the soil deepened, the negative correlation between the proportion of 2–0.25 mm aggregates and the average soil infiltration rate, the initial infiltration rate, and the stable infiltration rate became increasingly stronger.

4. Discussion

4.1. Effects of Different Tillage Measures in Agricultural Fields in the Phaeozems Zone

The MWD and GMD of aggregates, as important indexes for evaluating the stability of soil aggregates, can reflect the universal distribution of combination particle dimension [32–35]. In this study, we confirmed that TP-S and RF-S generally will see an increase in the share of soil macroaggregates and the soil aggregate stability. No significant difference was observed between the two treatments in soil depth, and each treatment resulted in greater soil macroaggregate proportions and larger soil combination steadiness with soil depth. This is consistent with previous studies. Compared with traditional tillage TP-S and RF-S, they maintain the integrity of the soil tillage layer, increase the thickness of the plough layer, and result in less soil disturbance, which helps to improve the stability of soil aggregates [36].

The adsorption and agglomeration of soil particles can promote the sequestration of soil organic carbon and total nitrogen [37]. In this study, TP-S and RF-S improved the organic carbon and total nitrogen contents of aggregates of all grain sizes. Among these, micro agglomerates less than 0.25 mm in size contained the highest total nitrogen content and showed the greatest enhancement. This finding indicates that the accumulation of nitrogen was more dependent on microaggregates in the RF-S and TP-S treatments, which was consistent with the results of previous studies. Six et al. [38] pointed out that particulate organic carbon in 0.25–2 mm fine aggregates was the most sensitive to tillage. However, in this study, the response of organic carbon to RF-S and TP-S treatments in microaggregates less than 0.25 mm in size and in fine macroaggregates of 0.25–2 mm was similar. This may be due to the fact that RF-S and TP-S enhance soil aeration and increase the activity of carbon-related enzymes in microaggregates, which promotes the decomposition and transformation of organic carbon in aggregates [39].

The soil C/N ratio performs a vital role in soil carbon and nitrogen cycling. In addition, the C/N ratio is an indicator of the degree of decomposition of organic matter; the higher the ratio, the lower the degree of decomposition, and organic carbon tends to accumulate [40,41]. In this study, TP-S and RF-S significantly increased the C/N ratios of coarse macroaggregates larger than 2 mm and fine macroaggregates between 0.25 and 2 mm, while reducing the C/N ratio of microaggregates smaller than 0.25 mm to a certain extent. This may have been because the carbon within the micro agglomerates largely comes from the metabolites produced by microbial activity, and the organic carbon is stabilized to a higher degree. The total nitrogen content of micro-aggregates was most sensitive to TP-S and RF-S, resulting in a decrease in the C/N ratio of micro-aggregates [42].

The slope position has an impact on slope role on soil aggregate stability and carbon and nitrogen distribution [43,44]. In this study, TP-S soil combination steadiness and its organic carbon and total nitrogen content material increased from the top to the bottom of the slope. RF-S and CK soil aggregate stability and the organic carbon and total nitrogen content material had been highest at the bottom of the slope and lowest at the mid-slope position. This pattern was less pronounced for RF-S compared to CK on the slope. This suggests that both cross-slope plowing and ridge-orientated fields can intercept surface floor runoff and control runoff scour to a certain extent, leading to the prevention of soil erosion and the accumulation of aggregates and their organic carbon and total nitrogen contents in the downslope position. However, the effect of TP-S was better [45,46]. This

is in accordance with previous reports that advantageous tillage measures can effectively limit the slope impact. However, cross-slope plowing was more effective in decreasing the slope impact than ridge-oriented district fields. This finding may be due to the fact that cross-ridges under cross slope-tillage are stronger than the soil ridges of ridge fields [47].

The stability of soil aggregates and their organic carbon and total nitrogen contents in 2023 were typically elevated compared to 2022. This was consistent with the findings of previous research that rotating maize with legume vegetation can considerably enhanced the organic carbon and total nitrogen contents of soil aggregates. Ligia F.T. Souza et al. [48]. have shown that soybean roots are longer than maize, and longer crop roots can effectively protect the sequestration of organic carbon and total nitrogen in soil aggregates. In addition, some studies have shown that soybean rhizosphere microbial biomass is higher, so it can increase the number of macroaggregates compared with non-legume plants. This may also be due to the fact that soil aggregate stability and its organic carbon and total nitrogen content also respond strongly to tillage intensity [49].

4.2. Influence of Different Tillage Practices on the Infiltration Performance of Agricultural Soils in the Phaeozems Zone

In this study, TP-S and RF-S were able to increase the initial infiltration rate, the stable infiltration rate, and the average infiltration rate of the soil, thereby enhancing soil infiltration performance. This was consistent with the results of previous studies that deep pine reduced the soil bulk mass and increased the soil porosity, significantly improving soil water infiltration [50–52]. In this study, the infiltration performance of the soil became stronger with the soil layer depth. This was consistent with the results of previous studies showing there was a significant difference in the infiltration performance of different soil layers in agricultural soils with soil depth [53,54].

Soil infiltration performance was strongly responsive to different slope positions. The pattern of infiltration intensity with slope position for the CK and RF-S treatments was downslope > upslope > downslope. The infiltration intensity of the TP-S treatment gradually increased with the upward slope position. This was because, under rainfall washout, all particle-size aggregates are transported and accumulated with runoff to the downslope position. Smaller aggregates are more likely to infiltrate vertically with rainfall and fill the existing cracks and large voids, resulting in better soil porosity at the downslope location, and thus a stronger soil infiltration performance [55–57]. Cross-slope plowing, in contrast, can effectively intercept surface runoff, thereby reducing the effect of slope on infiltration. Ridge-facing fields also intercept surface runoff to some extent, but not as effectively as cross-slope plowing.

The overall soil infiltration rate increased in 2023 compared to 2022. This is consistent with a previous study by Alexander, K et al. [58]. Crop rotation can play an important role in maintaining and improving soil quality, thereby improving soil infiltration performance.

4.3. Relationship between Soil Infiltration Properties and Soil Aggregates and Their C/N Ratio

There was a significant positive correlation between the soil infiltration rate and the share of soil aggregates larger than 2 mm in size, and a significant negative correlation with the percentage of aggregates smaller than 0.25 mm in size. This was consistent with previous research finding showing that the soil water infiltration rate is chiefly affected by the soil pore space. An increase in the share of large soil aggregates improves the porosity, thereby improving the overall performance of the soil infiltration. Smaller aggregates are more likely to consolidate; this reduces porosity and increases the bulk density [59,60]. Also, during infiltration, small aggregates tend to fill the cracks [14], thereby reducing soil moisture infiltration. The 2–0.25 mm particle size agglomerates were negatively correlated with the soil infiltration rate in all treatments in all soil layers in 2022. However, in 2023, the negative correlation between 2–0.25 mm particle size aggregates and soil infiltration rate was stronger in the deeper soil layers. This may have been due to the difference in the rainfall year pattern. The year 2023 had abundant precipitation, and the excessive rainfall

increased the head of vertical soil infiltration. The 2–0.25 mm particle size aggregates were transported deeper into the soil layers under excessive head pressure.

The process of formation and transformation of soil aggregates is accompanied by the uptake and mineralization of carbon and nitrogen within the soil aggregates. The soil C/N ratio impacts soil aggregate stability to a great extent. The more stable the soil aggregates, the higher the percentage of soil macro aggregates and the better the soil pore conditions, leading to superior overall soil infiltration performance. The soil infiltration rate was significantly positively correlated with the carbon and nitrogen ratios of soil aggregates with particle sizes larger than 2 mm and 2–0.25 mm and negatively correlated with the carbon and nitrogen ratios of aggregates with particle sizes smaller than 0.25 mm [61,62]. The reason for the difference in correlation between the carbon and nitrogen ratios of different particle sizes on soil infiltration performance may be that large aggregates have better porosity and aeration conditions, and the stability of carbon and nitrogen balance within the larger aggregates is different from that of small aggregates [63,64].

5. Conclusions and Outlook

5.1. Conclusions

Compared with conventional tillage, RF-S and TP-S significantly improved the stability of soil aggregates, the content of organic carbon and total nitrogen in all particle size aggregates, and the soil infiltration performance. To a certain extent, RF-S and TP-S can increase the C/N ratio of >2 mm and 2–0.25 mm aggregates in soil. However, TP-S is more effective than RF-S in blocking surface runoff, reducing the accumulation of organic carbon and total nitrogen content in soil macroaggregates and aggregates of different particle sizes at the lower slope position, and in reducing the slope effect. Therefore, TP-S is more suitable for sloping farmland in the Northeast Phaeozems region. Soil infiltration performance and the carbon and nitrogen ratio of aggregates larger than 2 mm and 2–0.25 mm particle size showed a significant positive correlation, and the carbon and nitrogen ratio of aggregates smaller than 0.25 mm particle size showed a significant negative correlation.

5.2. Outlook and Shortcomings

Compared with CK, the TP-S and RF-S treatments in this experiment significantly improved the stability of soil aggregates and the soil infiltration performance, effectively enhanced the soil texture, and exhibited better soil erosion resistance. During the test, climate factors also had an influence on the test results. Increased rainfall leads to greater soil aggregate stability and improved infiltration performance, while excessive rainfall intensity destroys the formation of soil macro-aggregates, leading to the decrease of the infiltration capacity. The stability of soil aggregates and the soil infiltration performance also have different responses to microbial activities. Microbial biomass and extracellular enzymes can promote the formation of large soil aggregates, thus enhancing the stability of soil aggregates and the soil infiltration performance. The stability of soil aggregates and the soil infiltration performance are affected by various factors, making it difficult to fully develop them in a single experimental demonstration. In addition, long-term crop rotation will also enhance the soil erosion resistance, soil aggregate stability, and soil infiltration performance. This experiment was only conducted for two years, and there were limitations in studying the effects of long-term crop rotation on soil aggregate and infiltration performance. Therefore, the stability of soil aggregates and the soil infiltration performance under different tillage measures should be investigated in long-term studies under the same and other influencing factors.

Author Contributions: Methodology, P.Y. and Z.Y.; Validation, A.L. and X.Z.; Formal analysis, Z.Q. and B.W.; Writing—review and editing, Z.Z.; Writing—original draft, T.Y.; Project administration, B.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the China National Key Research and Development Program (2021YFD1500802) an National Natural Science Foundation of China (52079050d).

Data Availability Statement: Data will be made available upon reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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