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Effects of Straw Returning on Soil Aggregates and Its Organic Carbon and Nitrogen Retention under Different Mechanized Tillage Modes in Typical Hilly Regions of Southwest China

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Abstract: Tillage modes and straw returning influence soil aggregate stability and the distribution of organic carbon (C) and nitrogen (N) in aggregates of different particle sizes. In the typical hilly regions of southwest China, the predominant soil type is purple soil, characterized by heavy texture and high stickiness, with relatively lower soil fertility compared to other soil types. The improper use of fertilizers and field management practices further exacerbates soil compaction. However, abundant straw resources in the region provide an opportunity for comprehensive straw utilization. The effective utilization of straw resources is of significant importance for stabilizing agricultural ecological balance, improving resource utilization efficiency, and alleviating ecological pressure. Previously, most studies have focused on the impact of different mechanized tillage systems on the physical and chemical properties of soil in hilly areas, while research on the preservation of water-stable aggregates' organic C and N content remains limited. In this study, the soil properties of fields under a winter pea–summer corn rotation for two years were studied with regards to the effects of straw returning on its water-stable aggregate distribution, macroaggregate content ($R_{0.25}$), mean weight diameter (MWD), geometric mean diameter (GMD), and the organic C and N content in soil aggregates of different particle sizes and at different depths. The effects of five different tillage modes were assessed, namely rotary tillage with straw mixed retention (RTM), conventional tillage with straw burial retention (CTB), no-tillage with straw covered retention (NTC), subsoiling with straw covered retention (STC), and no-tillage without straw retention (NT). Based on the study results, under different tillage modes, straw returning effectively enhanced the soil organic carbon (SOC) and total nitrogen (TN) reserves at the plow layer (0–30 cm), SOC increased by 17.2% to 88%, and TN increased by 8.6% to 85.9%. At the same time, the content of 0.25–2 mm aggregates increased under the straw-return treatments under different tillage patterns. The NT treatment had the lowest $R_{0.25}$ and MWD and GMD values for soil aggregates at different depths, which were significantly different ($p < 0.05$) from the other treatment modes. The correlation coefficients between SOC and soil aggregate stability indices ranged from 0.68 to 0.90, with most of them showing highly significant positive correlations ($p < 0.01$). In conclusion, straw returning under different tillage systems has improved soil aggregate stability and promoted soil structure stability. Specifically, the STC treatment has shown more pronounced effects on soil improvement in the upper soil layer of the hilly regions in southwest China, while the RTM treatment is beneficial for improving the lower soil layer. Therefore, the comprehensive experimental results indicate that the combination of STC and RTM treatments represents the most promising mechanized tillage and straw returning practices for the hilly regions in southwest China.

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1. Introduction

Soil aggregates are the key determinants of nutrient exchange in soil and the basic constituent unit of soil structure [1,2]. The stability of soil aggregates and soil organic matter are important characteristics influencing soil quality, environmental sustainability, and crop yield in agricultural systems [3,4]. At the same time, soil aggregate stability is a viable and effective factor in understanding the complex interactions between soil physicochemical properties and soil structure [5]. Numerous studies have demonstrated that the soil aggregate properties and size distribution are closely associated with organic matter. On the one hand, stable aggregates contribute to the physical protection of soil organic matter and can improve the soil structure and reduce soil erosion. On the other hand, soil organic matter can promote the assemblage of soil minerals into aggregates, promote biological activities in soil, and enhance aggregate stability, and at the same time, affect the soil texture and soil fertility, which plays an important role in the soil structure, crop growth and development, the global C cycle, and sustainable development of agriculture; moreover, the soil with a high content of organic matter can play a role in retaining water and moisture and preventing soil erosion [6].

Organic C and N turnover and mineralization rates are significantly different in soil aggregates of different particle sizes [7]. It was shown that C and N sequestration in soils was related to the size of aggregates and was mainly influenced by larger aggregates, and the improvement of soil structure was associated with an increase in SOC and TN, which were positively correlated with $R_{0.25}$ and MWD [8,9]. Moreover, SOC is more stable in aggregates of <2000 μm in diameter than in those of 2000–6300 μm, while N is more stable in aggregates of 2000–6300 μm than in those of <2000 μm [10]. Based on the above, the mineralization velocity of organic carbon in 53–250 μm aggregates is lower than that in 250–2000 μm aggregates, resulting in a more stable retention of organic C [11]. Thus, no consensus has been reached on the influence of aggregates of different particle sizes on organic carbon and the underlying mechanisms. The complexity of the soil environment may result in variations in the interaction between organic C and aggregates under different conditions.

The disturbance produced by tillage will cause organic matter oxidation and, at the same time, reduce soil aggregate stability [12]. Frequent cultivation, such as continuous deep plowing, significantly disturbs soil structure and causes a loss of organic carbon [13]. Moreover, long-term mechanical shallow plowing (conventional tillage or rotary tillage) was shown to cause increasing soil degradation in areas of multiple cropping [14,15]. Some researchers have proposed protective tillage mode schemes, such as minimal tillage, no-tillage, and straw returning. Protective tillage can increase the macroaggregate content in soil and promote SOC stability [16]. However, in straw returning under conventional tillage, aggregates of various particle sizes have a higher priming effect compared to the protective tillage mode [11,17]. Compared with conventional tillage modes, protective tillage modes (no-tillage and straw returning) were shown to increase the large water-stable aggregates (>2 mm) in surface soil by 35.18%, increase the small aggregates (2–0.25 mm) by 33.52%, and increase the microaggregates (<0.25 mm) by 25.10%. The same trend was also observed in the subsoil, along with a significant increase in the organic C content in aggregates [18]. Some studies have demonstrated that conventional tillage modes influence specific constituents of the N pool and the discharge of N_2O. In contrast, protective tillage modes can reduce the soil's C, N, and phosphorus loss and increase the macroaggregate content [19].

It is imperative to study the effects of combining mechanical tillage and straw return on soil aggregate structure and C and nitrogen in southwest China. This study selected the most important grain production region in southwest China, Renshou County in Sichuan Province, as the area of study. In the Sichuan Basin, this region is typically hilly with low water availability, and slope cropland is the major agricultural landscape. The land reclamation rate is high in the region, and the forest coverage rate is low, making it vulnerable to soil erosion. Currently, China's agricultural machinery and equipment are advancing towards being lighter weight and implementing smart farming features, and mechanized tillage and straw returning are being tested and applied in the low hilly lands of Western China. In this study, the effects of mechanized tillage modes such as rotary tillage, plow tillage, subsoiling, and no-tillage combined with straw returning on organic C, total N, and the distribution and stability of water-stable aggregates in the area's soil were evaluated through field experiments. The study aimed to identify environmentally sustainable and low-carbon emitting mechanized tillage modes for the typical hilly areas of southwest China. The results provide the scientific basis and data support for maintaining the stable farmland soil structure and optimizing the soil C pool and nitrogen pool management.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted in Community 2, Tashui Village, Zhujia Town, Renshou County, Sichuan Province (29°51′15.58″ N, 104°12′41.56″ E). Located in the south of Chengdu Plain, it is the most typical hilly area of southwest China. The experimental site has a subtropical monsoon humid climate. The average annual air temperature is 17.4 °C, the average annual sunshine duration is 1196.6 h, and the average annual precipitation is 1009.4 mm. The rainfall is unevenly seasonally distributed throughout the year and is mainly concentrated from June to August. The agricultural soil type in the experimental area is purple soil with weathered shale as its parent material, and its texture is sticky and heavy. In the World Reference Base for Soil Resources system classified as Cambisols. The basic physical and chemical properties of the soil at the experiment initiation are shown in Table 1.

Table 1. The background value of test soil at the start of the positioning test.

Density	pH	SOC	TN	AN	AP	AK
1.37 g/cm^3	6.8–8.1	11.12 g/kg	0.91 g/kg	27.78 mg/kg	3.16 mg/kg	112.39 mg/kg

Note: SOC: soil organic carbon, TN: total nitrogen, AN: alkali-hydrolyzed nitrogen, AP: available phosphorus, AK: available potassium.

2.2. Experimental Design and Management

Field experiments were conducted, and the layout of the test site and sampling is shown in Figure 1. This study included five soil treatment modes: rotary tillage with straw mixed retention (RTM), conventional tillage with straw burial retention (CTB), no-tillage with straw covered retention (NTC), subsoiling with straw covered retention (STC) and no-tillage without straw retention (NT). The area of each plot was 36 m^2 (6 m × 6 m). Each treatment mode was repeated three times in randomly arranged experimental plots. In this experiment, the straw returned to the field was maize straw. Adopting the full straw returning mode. Except for the NT treatment, maize straw was shredded into 8–15 cm pieces and used to cover the soil's surface in all other treatment modes. Meanwhile, all pea straws were removed after the winter pea harvest.

The experiment was initiated in 2020, and the planting pattern was traditional winter pea–summer corn rotation and the experiment spanned two years. The winter pea variety planted was "Cheng Wan No. 8", with a 150 kg/hm^2 sowing rate. The summer corn variety, "Chuan Dan 189", was planted with a sowing rate of 93,000 plants/hm^2. The same field management practices were adopted across all different treatment modes: calcium superphosphate was applied in the growing period of winter pea, with a fertilizer amount of 300 kg/hm^2; slow and controlled release fertilizer was applied as the base fertilizer before summer corn was planted, with a fertilizer amount of 375 kg/hm^2; compound fertilizer was applied during the growth period of corn, with a fertilizer amount of 300 kg/hm^2. The same amount of fertilizer was applied in the different experimental plots. Moreover, other management procedures, including the quantity of seeds and irrigation water, were the same under various treatment modes.

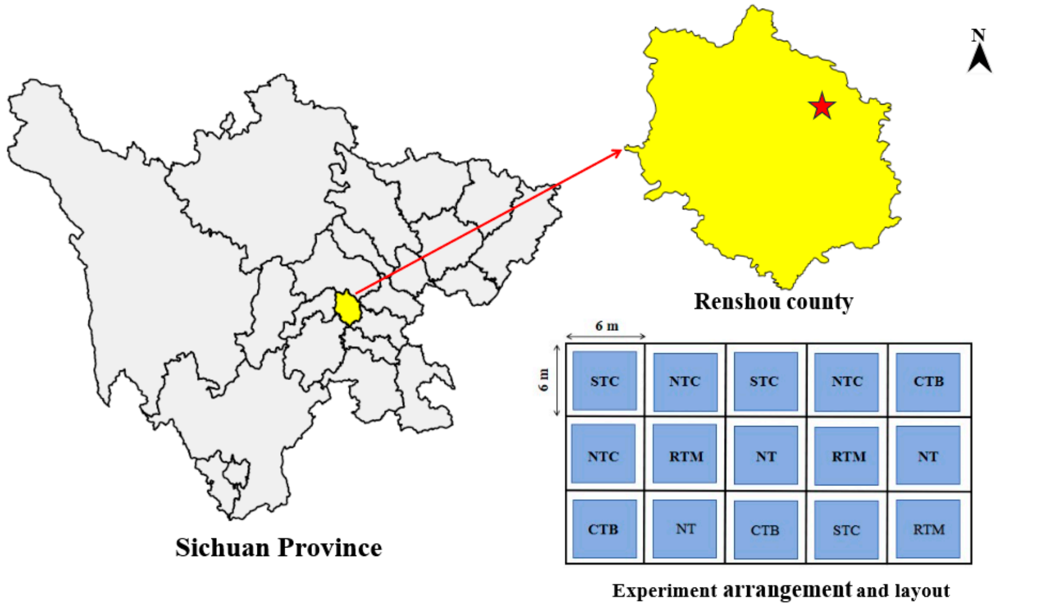

Figure 1. Layout of study sites and sampling plots.

2.3. Soil Sampling and Analysis

The soil samples were collected from three layers using the plum sampling method immediately after the corn was harvested. The sampling depths were 0–10 cm, 10–20 cm, and 20–30 cm, and the sampled soil was extracted from the middle part of the different soil depths. The soil samples collected were placed in plastic valve bags and were brought to the laboratory. After removing the plant remains and rocks, they were placed in cool and dark conditions for drying. Then, the soil samples were divided into two parts. One part was ground, passed through a 0.15 mm sieve, and then used to analyze the SOC and TN. The other part was ground and passed through a 10 mm sieve. The improved Eillot wet sieving method was adopted [20]; 50 g of soil was weighed, placed into the sieve screen, and immersed for 5 min. The aggregate particle analyzer TTF-100 (Liaoning Sayas Technology Co., Ltd., Tieling, China) was used to extract aggregates of four particle sizes, including >2 mm, 2–0.25 mm, 0.25–0.053 mm, and <0.053 mm, with an amplitude of 30 times/min and a time period of 3 min. Afterward, the end of the sieve group of aggregates was carefully washed into a beaker, dried in the oven at 60 °C, and weighed separately to calculate the content of water-stable aggregates of different particle sizes. The dried and weighed aggregates were then ground and passed through a 0.25 mm stainless steel sieve for measurement. The organic C content of aggregates of different particle sizes was determined by external heating method with potassium dichromate, and the total N of aggregates of different particle sizes was determined by Kjeldahl method [21].

2.4. Assessment of Aggregate Stability Indices

The analyses included the content of aggregates of different particle sizes and aggregates' stability:

$$\text{content of aggregates} = (M_i/M_T)100\%$$

In the above formula, M_i denotes the weight of a size class (i) to the total weight; M_T denotes the aggregate total weight.

The aggregate stability was evaluated with three indexes, including $R_{0.25}$, MWD, and [22].

The specific calculation method is as follows:

$$\text{Macro aggregate content } R_{0.25} = M_{r>0.25}/M_T$$

In the above formula, $M_{r>0.25}$ corresponds to the weight of over 0.25 mm aggregates; M_T corresponds to the total weight of the aggregates.

$$\text{Standardized mean equivalent diameter } NMWD = MWD/(X_{\max} - X_{\min})$$

In the above formula, $MWD = \sum(M_i/M_T)X_i$, in which M_i corresponds to the mass of aggregates of a certain particle size; X_i corresponds to the average diameter of aggregates of this particle size; $X_{\max}$ corresponds to the stainless steel sieve aperture of the top layer; $X_{\min}$ corresponds to the stainless steel sieve aperture of the bottom layer.

$$\text{Geometric mean diameter } GMD = \exp\left\{\sum(M_i/M_T)\ln X_i\right\}$$

2.5. Statistical Analysis

One-way analysis of variance (ANOVA) was performed using the SPSS18.0 software package, and pairwise statistically significant differences were assessed with the LSD test. The graphs were prepared with Origin 2022. Different lowercase letters were used to represent significant differences among various treatment modes ($p < 0.05$).

3. Results

3.1. Effect of Straw Returning on Soil Organic Carbon and Total Nitrogen under Different Tillage Modes

As shown in Figure 2a, the content of SOC decreases with increasing soil depth, with the NT treatment exhibiting the lowest SOC content across different soil layers, while other treatments all resulted in increased SOC content. In the 0–10 cm and 10–20 cm soil layers, each treatment led to an increase in SOC content ranging from 21.47 to approximately 73.54%. Among these, the STC treatment had the strongest effect on increasing SOC content, with the enhancement observed in the 0–10 cm soil layer surpassing that of the 10–20 cm layer. In the 20–30 cm soil layer, each treatment resulted in an increase in SOC content ranging from 17.16 to approximately 88.00%, with the RTM treatment exhibiting the most significant enhancement in SOC content. In summary, all straw return treatments were able to increase SOC content, with the effectiveness diminishing as soil depth increased.

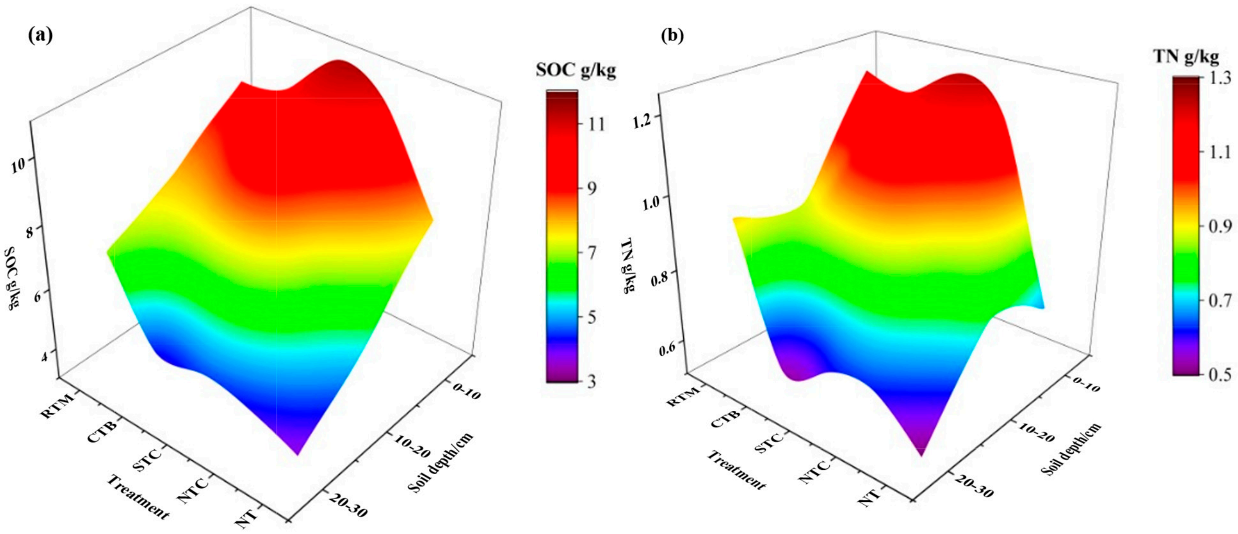

Figure 2. SOC content (**a**) and TN content (**b**) under different tillage modes in the 0–10 cm depth, 10–20 cm depth, and 20–30 cm depth of soil. Note: SOC: soil organic carbon (g/kg); TN: total nitrogen (g/kg).

As shown in Figure 2b, in the 0–10 cm soil layer, the soil TN content was the highest under the STC treatment. However, no significant differences were observed compared to the CTB, RTM, and NTC treatment modes. On the other hand, the NT treatment resulted in a significantly lower soil TN content compared to the other treatment modes. In the 10–20 cm layer, the soil TN content under STC treatment is the highest, followed by CTB, RTM, NTC, and NT, respectively. In the 20–30 cm layer, the soil TN content under the RTM treatment was significantly higher compared to the other four treatment modes, increasing by 49.73% compared to the NT treatment. In addition, soil TN content increased slightly under the CTB, STC, and NTC treatments relative to the NT treatment. However, this increase was not particularly significant.

3.2. Effect of Straw Returning on Soil Aggregate Distribution under Different Tillage Modes

Regarding the distribution of water-stable aggregates, as shown in Figure 3, in the same soil depth, the soil aggregate content in each treatment showed a trend of initially increasing and then decreasing with the decrease in particle size, the 2–0.25 mm aggregates in the soils had the highest content, which accounted for 43.32–59.17%, while <0.053 aggregates had the lowest content, and with the elevation of the depth of the soil layer, the proportion of >2 mm aggregates content in the soils gradually decreased. The proportion of >2 mm aggregate content gradually decreased. At different soil depths, the content of >2 mm aggregates in soil increased by 12.87–85.50% in the straw-returned treatment compared with the NT treatment. The effects of the treatments on the aggregate content in different soil layers were different. In the 0–10 cm and 10–20 cm soil layers, the treatments increased the content of aggregates >2 mm compared to the NT treatment. Among these treatments, CTB and STC showed the most pronounced effect on the content of aggregates >2 mm, while RTM increased the content of aggregates to 0.053–0.25 mm. In the 20–30 cm layer, the treatments resulted in an increase in the content of aggregates >2 mm by 12.87–85.50% compared to the NT treatment. At this depth, there was a slight increase in the content of aggregates 0.25–0.053 mm and <0.053 mm.

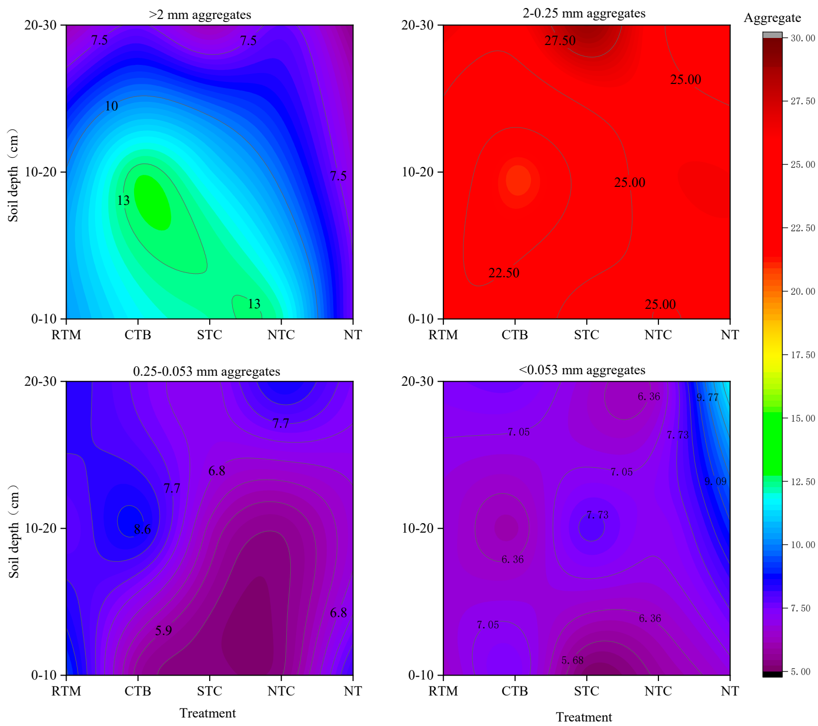

Figure 3. Distribution of water-stable aggregates under different tillage modes in the 0–10 cm depth, 10–20 cm depth and 20–30 cm depth of soil. Note: RTM: rotary tillage with straw mixed retention, CTB: conventional tillage with straw burial retention, NTC: no-tillage with straw-covered retention, STC: subsoiling with straw-covered retention, NT: no-tillage without straw retention.

As shown in Figure 4, the NT treatment had the lowest $R_{0.25}$ values at various depths and was significantly different compared to other treatment modes. Except for the RTM treatment, the $R_{0.25}$ values under the other four treatment modes exhibited a declining trend with the depth increase. In the 0–10 cm layer, the $R_{0.25}$ values under the STC and NTC treatments were significantly higher compared to other treatment modes, increased by 15.40%, 9.13%, 15.69%, 11.75%, 5.68%, and 12.03%, respectively, when compared with the RTM, CTB, and NT treatments. In the 10–20 cm layer, the $R_{0.25}$ values under the NTC and STC treatments were higher compared to the other treatment modes, increased by 4.42%, 5.70%, 8.03%, 3.10%, 4.37%, and 6.66%, respectively, when compared to the RTM, CTB, and NT treatments. In the 20–30 cm layer, the $R_{0.25}$ values were the highest under the STC treatment, increased by 7.58%, 5.28%, 6.41%, and 21.42%, respectively, when compared with the RTM, CTB, NTC, and NT treatments.

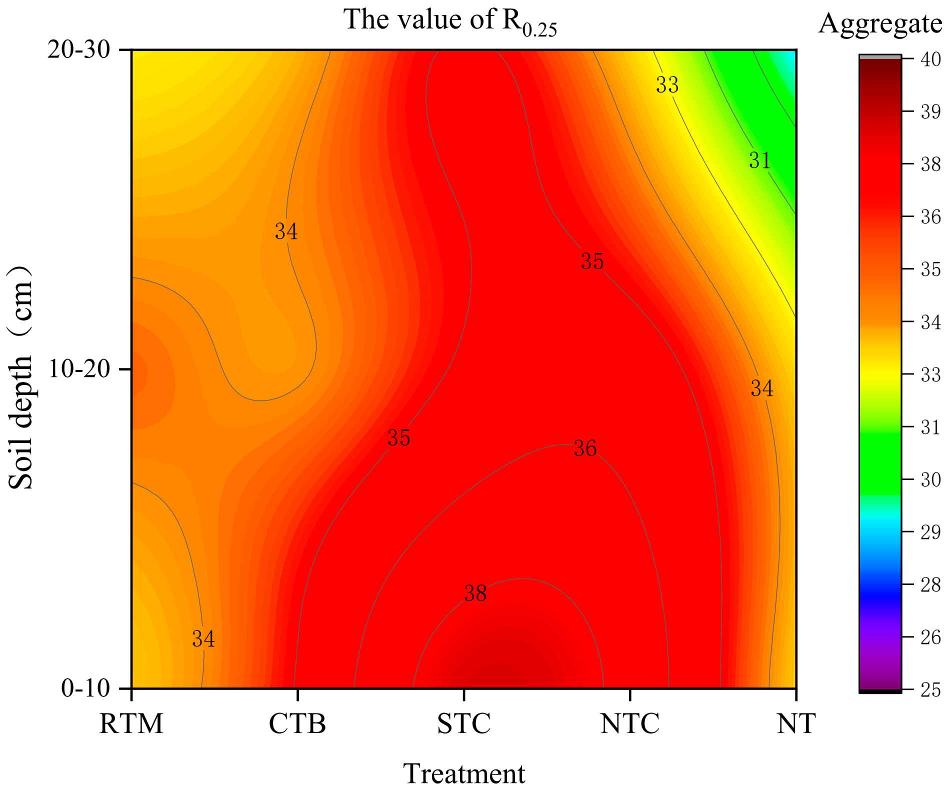

Figure 4. The value of $R_{0.25}$ under different tillage modes in the 0–10 cm depth, 10–20 cm depth, and 20–30 cm depth of soil. Note: RTM: rotary tillage with residue shredding and incorporation, CTB: plow tillage with residue burying and incorporation, NTC: no-tillage with residue covering and incorporation, STC: subsoiling with residue covering and incorporation, NT: no-tillage with residue removal.

3.3. Effects of Straw Returning on MWD and GMD under Different Tillage Modes

As shown in Figure 5a, straw returning significantly increased the MWD under the different tillage modes at various soil depths. In the 0–10 cm layer, the MWD value was relatively higher under the STC and NTC treatments, increasing by 15.76%, 5.16%, 35.67%, 14.67%, 4.17%, and 34.39%, respectively, when compared with the RTM, CTB, and NT treatments. In the 10–20 cm layer, the CTB treatment had the highest MWD value, followed by STC, NTC, RTM, and NT. In the 20–30 cm layer, the MWD value under the CTB treatment was relatively higher and was followed by NTC, STC, RTM, and NT.

As shown in Figure 5b, straw returning significantly increased the GMD under different tillage modes at various soil depths. In the 0–10 cm layer, the GMD values under the STC and NTC treatments were significantly higher than those under other treatment modes, increased by 38.81%, 24.13%, 52.46%, 29.85%, 16.13%, and 42.62%, respectively, when compared with the RTM, CTB, and NT treatments. In the 10–20 cm layer, the CTB treatment had the highest GMD value, followed by NTC, STC, RTM, and NT. In the 20–30 cm layer, the GMD values under the STC and NTC treatments were the same and increased by 12.73%, 4.23%, and 55.00% compared to the RTM, CTB, and NT treatments.

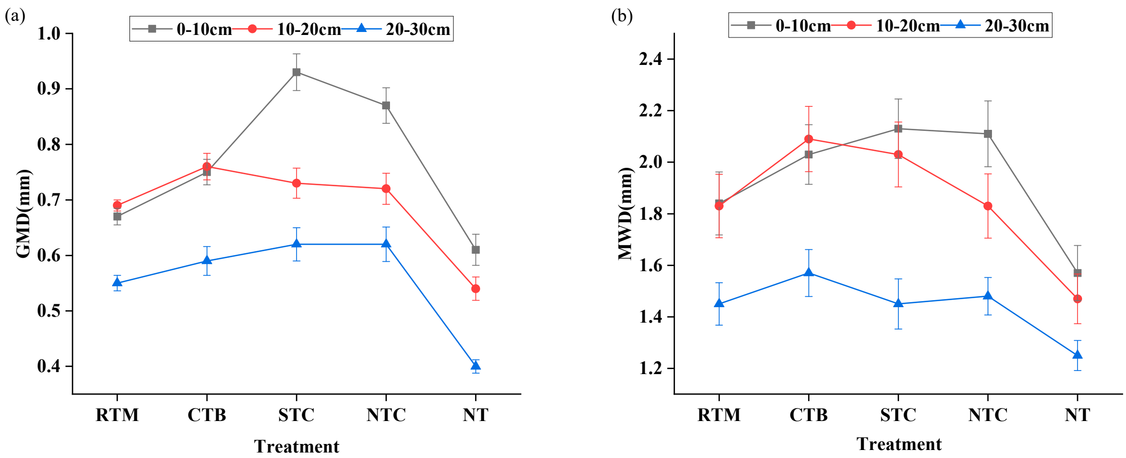

Figure 5. The value of GMD (**a**) and MWD (**b**) under different tillage modes in the 0–10 cm depth, 10–20 cm depth, and 20–30 cm depth of soil. Note: MWD: weight diameter of aggregates; GMD: geometric mean diameter of aggregates.

3.4. Effect of Straw Returning on Aggregate Organic Carbon Content and Total Nitrogen under Different Tillage Modes

As shown in Figure 6a,c,e, compared to the NT treatment, all other treatments led to an increase in organic C content in aggregates of various particle sizes. Across different soil layers, >2 mm and 0.25–2 mm aggregates exhibited relatively high proportions of organic C compared to the organic C content of aggregates, while aggregates sized 0.053–0.25 mm had the lowest proportion. The organic C content of aggregates of different particle sizes decreased with increasing soil depth. Variations were observed in the effects of treatments on the organic C content of aggregates of different particle sizes across different soil layers. In the 0–10 cm and 10–20 cm soil layers, STC exhibited the strongest enhancement effect on organic C content of aggregates of various sizes compared to NT, increasing by 32.56–41.71% and 61.26–74.06%, respectively. In the RTM, CTB, and STC treatments, aggregates sized 0.25–2 mm had the highest proportion of organic C, while 0.053–0.25 mm aggregates had the lowest proportion in all treatments. In the 20–30 mm soil layer, compared to NT, RTM showed the strongest enhancement effect on the organic C content of aggregates of various sizes, ranging from 63.70% to 101.57%. Moreover, 2–0.25 mm aggregates had the highest organic C content. The organic C contents in 2–0.25 mm, 0.25–0.053 mm, and <0.053 mm aggregates were significantly different from those under the other four treatment modes, while there is no significant difference among the remaining four treatment modes.

As shown in Figure 6b,d,f, compared to the NT treatment, all other treatments led to an increase in total N content in aggregates of various particle sizes. Across different soil layers, aggregates sized 0.053–0.25 mm exhibited the lowest proportion of total N among all aggregates. The N content of aggregates of different particle sizes decreased with increasing soil depth, and the effectiveness of treatments in enhancing the total N content of aggregates decreased with soil depth. In the 20–30 cm soil layer, certain treatment groups exhibited a decrease in the total N content of aggregates. Variations were observed in the effects of treatments on the total N content of aggregates of different particle sizes across different soil layers. In the 0–10 cm and 10–20 cm soil layers, STC showed the strongest enhancement effect on the total N content of aggregates of various sizes compared to NT, increasing by 44.32–89.71% and 43.04–79.25%, respectively. In the 20–30 cm soil layer, compared to NT, RTM showed the strongest enhancement effect on the total N content of aggregates of various sizes, ranging from 10.94 to 39.62%. However, other treatments exhibited a reduction in total N content of aggregates sized 0.053–0.25 mm and 0.25–2 mm. Within the RTM treatment, <0.053 mm aggregates had the highest proportion of total N, while in other treatments, aggregates sized 0.25–2 mm and >2 mm had the highest proportion of total N, with aggregates sized 0.053–0.25 mm having the lowest proportion.

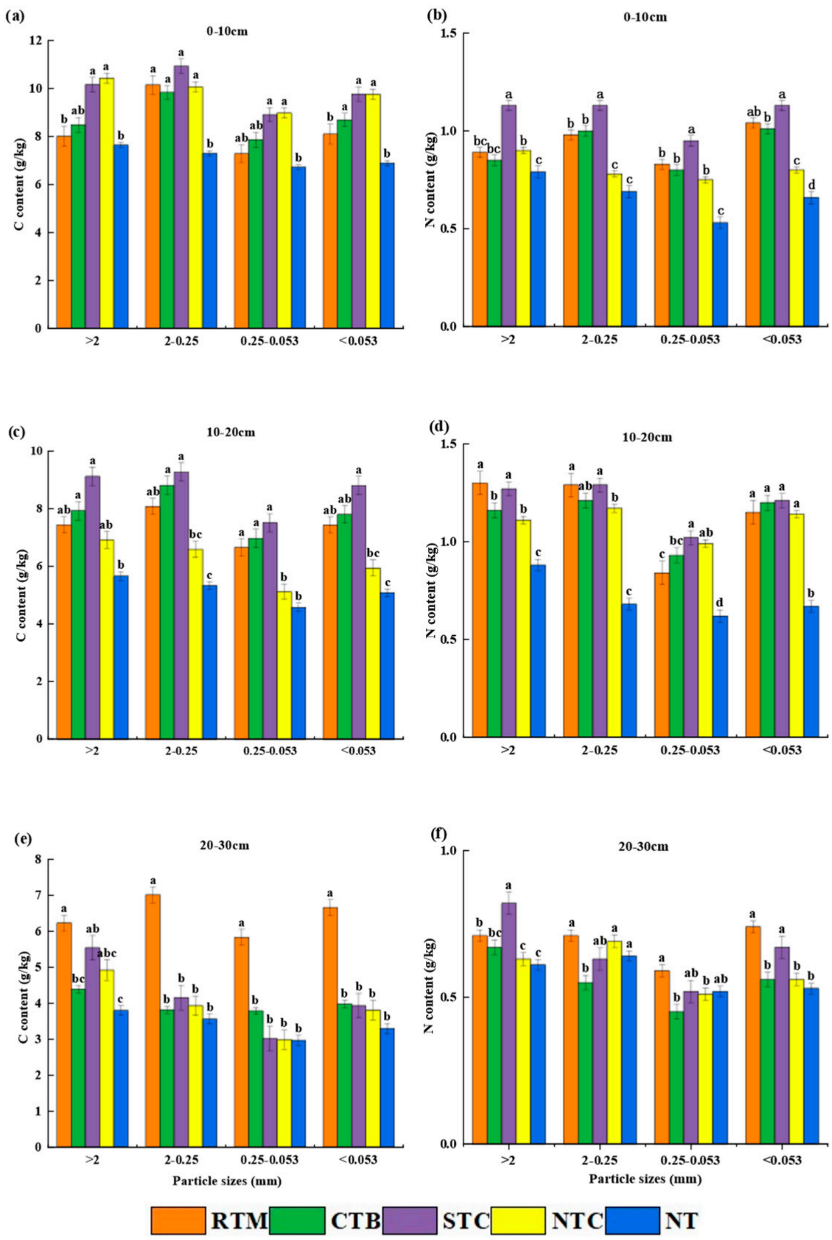

Figure 6. Aggregate organic C content under different tillage modes in the 0–10 cm depth (**a**), 10–20 cm depth (**c**), and 20–30 cm depth (**e**) of soil, aggregate total N content under different tillage modes in the 0–10 cm depth (**b**), 10–20 cm depth (**d**), and 20–30 cm depth (**f**) of soil. Note: C: aggregate organic carbon (g/kg); N: aggregate total nitrogen (g/kg). Different lowercase letters indicate significant difference among various treatment modes ($p < 0.05$).

3.5. Correlation Analysis of Soil Organic Carbon, Total Nitrogen, and Aggregate Stability Index

As shown in Figure 7, the SOC, TN, $R_{0.25}$, MWD, and GMD were pairwise positively correlated. Moreover, except for TN and $R_{0.25}$, which were significantly correlated ($p < 0.05$), all other indexes exhibited highly significant pairwise correlations ($p < 0.01$).

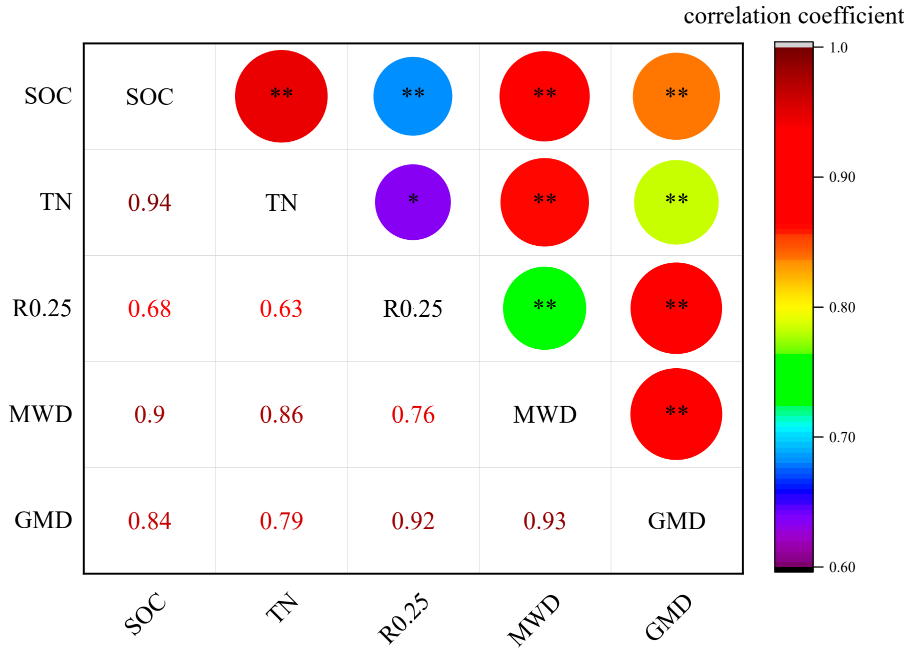

Figure 7. Correlation analysis of SOC, TN, and aggregate stability index. Note: "*" means significant correlation ($p < 0.05$); "**" indicates extremely significant correlation ($p < 0.01$).

4. Discussion

4.1. Effect of Straw Returning on Soil Organic Carbon and Total Nitrogen under Different Tillage Modes

The experimental results indicate significant differences in the effects on SOC and TN among different treatments in various soil layers, with pronounced variations in content. Specifically, the STC treatment significantly increased the SOC and TN in the upper layer (0–20 cm) of the plow layer, with increases of 73.55% and 83.15%, respectively, compared to the NT treatment. Conversely, the RTM treatment notably increased the SOC and TN in the lower layer (20–30 cm) of the plow layer, with increases of 88% and 85.93%, respectively, compared to the NT treatment. After the decomposition of returned straw, the abundant lignin, cellulose, hemicellulose, carbon, nitrogen, phosphorus, potassium, and trace elements enter the soil, effectively increasing the nutrient content in the soil and thereby improving soil quality [23]. Tillage can loosen the soil and enhance air permeability. On the other hand, tillage leads to organic matter oxidation, reducing structural stability. Protective tillage measures centered on reduced tillage, no-tillage, and straw returning reduce soil disturbance intensity and frequency, mitigating the disruption of soil aggregates and contributing to the restoration of soil structural stability to some extent [24]. Under the STC and NTC treatments, the SOC content in the 0–10 cm soil layer is highest and significantly higher than in the 10–30 cm soil layer. This is because deep tillage and no-tillage do not disturb the soil layer, and straw covering the surface soil leads to the significant enrichment of nutrients after decomposition. At soil depths of 0–10 cm and 10–20 cm, the above values under the STC treatment are significantly higher than under other treatment modes, indicating that protective tillage can effectively increase SOC and TN. At a depth of 10–20 cm, the SOC and TN content under the CTB treatment are relatively higher, potentially due to plow tillage bringing straw from the surface soil into the middle and lower soil layers. At a depth of 20–30 cm, the SOC and TN content under the RTM treatment are significantly higher than under other treatment modes, as rotary tillage effectively avoids the enrichment of nutrient elements and organic matter on the soil surface after straw cover decomposition and more effectively transfers straw to the lower soil layer, consistent with previous research findings [25,26].

4.2. Effect of Straw Returning on Distribution and Stability of Water Stable Aggregates under Different Tillage Modes

In this study, the interaction between soil tillage and straw returning significantly affected the distribution and stability of soil aggregates at different particle sizes. Compared to the NT treatment, all other treatments facilitate the formation of larger soil aggregates, with higher values of $R_{0.25}$, MWD, and GMD, indicating that straw returning enhances the stability of soil aggregates. Soil aggregates, as the basic building blocks of a soil structure, are closely linked to soil health, and their distribution and stability are key indicators of the impact of soil management and land use on soil physical properties. Large aggregates are formed by small aggregates bound by high-carbon content unstable aggregates (i.e., fungal hyphae, roots, polysaccharides from microorganisms, and plant sources) [27]. At different soil depths, the treatments showed the most significant increase in the content of >2 mm aggregates, with enhancements ranging from 12.87% to 85.50% compared to the NT treatment. However, this increase was accompanied by a decrease in the content of <0.053 mm aggregates in the soil. These results demonstrate that straw, as organic matter, stimulates biological activities in the soil, promoting the formation of large aggregates and reducing the content of clay. This may be attributed to straw returning, providing exogenous organic matter to the soil, and fresh organic matter serving as the binding material for aggregate formation, thereby promoting the formation and stability of soil aggregates. The impact of straw returning under different tillage modes on aggregates in the 0–20 cm soil layer was most significant, mainly because the depth of different tillage methods varied. Most tillage methods in this study disturbed the soil to a depth of 0–20 cm, with STC showing the strongest promotion effect on >2 mm aggregates, increasing by 67.2% compared to NT. This is because the STC tillage mode allows for better contact between straw and soil, leading to its decomposition into more wet microaggregates that connect with colloidal minerals, thus increasing the content and stability of large soil aggregates in the plow layer. Across the entire plow layer, the $R_{0.25}$, MWD, and GMD values under STC and NTC treatments were relatively higher, especially at a depth of 0–10 cm, compared to other treatment modes. This could be due to frequent mechanical disturbance of the lower part of the plow layer under continuous plowing, which could lead to the rupture of large soil aggregates in the plow layer [28]. Additionally, soil moisture evaporation and organic matter decomposition under plowing treatments decrease the formation of cementing materials for aggregates, while STC and NTC tillage modes can influence soil aggregate composition by altering soil compaction, moisture content, and organic matter content. Therefore, STC and NTC treatments effectively enhance the stability of soil aggregates in the upper part of the plow layer, consistent with results obtained in related experiments in Zambia [29].

4.3. Effect of Straw Returning on Aggregate-Associated Organic Carbon and Nitrogen under Different Tillage Modes

The research findings indicate that compared to NT, the RTM, CTB, NTC, and STC treatment modes all increased the organic C and total N content in soil aggregates of different particle sizes at different depths. Among them, the most significant increases in organic C and N in soil aggregates of 2–0.25 mm size in the upper plow layer were observed, with increases ranging from 34.77% to 49.71% and 72.06% to 89.71%, respectively. SOC and aggregate are closely related [30], and soil aggregates protect C and N from the mineralization effect of microorganisms, enzymes, and soil degradation [31]. It is generally assumed that aggregates of large particle size can better reserve organic C than aggregates of small particle size [32], as the large particle size aggregates consist of smaller particle size aggregates and adhesive materials [33]. The majority of SOC is contained within aggregates, which inhibits its decomposition by microorganisms and enhances soil structure stability. Traditional tillage practices are well-known for their significant soil disturbance, causing interconversion and redistribution among macroaggregates, large aggregates, and microaggregates. This process reduces soil aggregate structure stability and accelerates the loss of soil organic matter and nutrients [34].

This study demonstrates that the STC treatment increased the organic C and N content in soil aggregates at 0–20 cm depth, while the RTM treatment significantly increased at a depth of 20–30 cm. Additionally, soil C and N exhibit strong coupling, with N content and reserves increasing with the increase in organic C content, mainly due to the adsorption and protection role of SOC [35]. The >0.25 mm aggregates were the main contributors to the organic C and N content at various depths among the soil aggregates. This was further enhanced by straw returning, which brought additional organic matter and promoted the formation of macroaggregates [36]. In summary, the combination of straw returning and conservation tillage significantly increases the proportion of macroaggregates in the soil of the southwestern hilly region of China, reduces organic matter mineralization, and increases organic C reserves, leading to better soil improvement.

5. Conclusions

Under different tillage modes, straw returning effectively increased the SOC and TN reserves at various depths in the plow layer (0–30 cm), increased the $R_{0.25}$, MWD, and GMD values in soil aggregates, and promoted soil structure stability. Among them, STC showed the strongest improvement in soil aggregate structure and nutrient indicators in the 0–10 cm and 10–20 cm soil layers, while in the 20–30 cm soil layer, RTM increased the SOC, TN, and different particle size aggregate C and N content. Moreover, the organic C and total N contents in aggregates of various particle sizes were increased to varying degrees. However, organic C and total N content variation in aggregates did not show highly specific trends. Therefore, the comprehensive experimental results indicate that STC and RTM treatments, respectively, have more significant effects on improving the upper and lower parts of the plow layer in the hilly areas of southwestern China. These treatments are more compatible with the mechanized tillage and straw returning techniques in the southwestern hilly region. However, the no-tillage straw mulching and returning model may not be suitable for the southwestern hilly region. Nevertheless, these are preliminary experimental results, and further research is needed to explore and confirm the long-term effects and stability patterns of different tillage methods and straw returning models on soil improvement through longer-term targeted experiments. Additionally, whether other tillage methods (such as rotational tillage or strip tillage) combined with straw returning can achieve better soil improvement effects in the hilly terrain of southwestern China also requires further research and discovery.

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