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Influence of Tillage, Straw-Returning and Mineral Fertilization on the Stability and Associated Organic Content of Soil Aggregates in the North China Plain

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Abstract: Agricultural management, such as tillage and straw-returning, affect soil fertility and nutrient cycling in agroecosystems. With the increasing food demand and challenges imposed by climate change, these effects on soil fertility need to be closely monitored, so that short-term agricultural intensification should not threaten the long-term productivity of the land. Therefore, the main objective of this study was to examine the long-term effects of different management practices on soil aggregate stability and associated organic carbon (OC) and nitrogen (N) over a 33-year period in the croplands of the North China Plain. Bulk soils from the surface and subsurface layers were fractionated using the wet sieving approach. The results showed that the silt + clay (SC) fractions (<0.053 mm) were predominant, accounting for 32–56% of the mass at the 0–20 cm depth, and accounting for 41–55% of the mass at the 20–40 cm depth. Additionally, long-term (33 years) no-tillage management and straw-returning at different application rates increased the mass of large soil macroaggregates (LMA), the LMA- and macroaggregate-associated OC content, but decreased the SC-associated OC content. Mineral N and P fertilizers had a minor effect on the stabilization of soil aggregates. The treatment with straw significantly increased the mean weight diameter (MWD) and geometric mean diameter (GWD), compared with the treatment without straw. Our results indicate that carefully regulated management practices would enhance soil aggregate stability, associated OC and N content in the intensive agroecosystem.

Keywords: soil fertility; agricultural management; long-term experiment; aggregate stability

1. Introduction

Agricultural management practices, such as tillage and straw-returning, affect soil structure and soil organic carbon (SOC) and nitrogen stocks, which are crucial for sustainable agriculture [1,2]. Conventional agricultural practices cause soil disturbance, leading to a loss of approximately 40% of SOC, thereby degrading the soil quality [3,4]. However, in the past two decades, the conservation tillage system (such as no-tillage) has been gradually adopted by farmers due to its economic benefit and its positive effects on soil quality [5]. No-tillage with crop straw management in croplands may be a way to sequester organic carbon (OC) and increase soil fertility [6,7].

As the basic unit of soil structure, soil aggregates are closely related to the degree of SOC stability [8–10]. In addition, soil aggregates are important indicators affecting the physical, chemical,

and biological properties of soils [11]. They are also important storage sites for SOC [12] and exert a positive effect on the accumulation of organic carbon [13–15]. Protecting and enhancing the OC and N content of the soil is vital for driving various processes such as nutrient cycling and microbial activities [16,17], and alleviating land degradation, maintaining soil fertility and quality, and enhancing crop yield [18,19].

Previous studies have proposed mechanisms to explain the degradation of soil quality. Some have suggested that conventional tillage has decreased soil OC and N content by 40% and 32%, respectively, and reduced the mass of large macroaggregates (LMAs) [20–22]. Whereas, some studies have found that macro-aggregates are vulnerable to external pressure, such as from conventional tillage [2,23], enhancing the microbial degradation of the exposed soil organic matter, and thereby decreasing soil OC and N content [1,13]. The stability of soil aggregates also affects its susceptibility to wind or water erosion [8,10]. A decrease in the size of the aggregates increases SOC degradation [24], and decreases the C/N ratio [25,26]. However, the mechanism by which tillage and straw-returning affect the stability of soil aggregates and its organic matter content remains unclear.

The decrease in soil OC content in the croplands [16], could potentially be halted or reversed through improved management practices [27–30]. These include reduced tillage, no-tillage with straw-returning, and the application of N or P fertilizer, which maintain or increase soil organic matter (SOM) and its associated nutrients [31–33].

No-tillage coupled with straw-returning and nitrogen (N) fertilizer application helps to improve soil aggregation [6,28]. It also decreases soil disturbance and reduces the activity of the soil microbial community that results in SOC decomposition, favoring the formation of large macroaggregates (LMA)-associated OC [34,35]. Conventional tillage destroyed LMAs in the soil [10,36]. In contrast, long-term no-tillage drastically reduced the rate of macroaggregate (MA) turnover and resulted in the formation of stable microaggregates (MIs), favoring C stabilization and sequestration [12,37]. The LMAs formed under no-tillage management had higher SOC contents and increased numbers of macropores, resulting in higher water infiltration and better aeration when compared with soils that were richer in MIs [38,39]. LMAs also physically protect the labile soil OC from enzymatic and microbial attack [34,40]. Therefore, the accumulation of soil OC could be achieved by establishing management practices that increase the proportion of soil MAs [8].

The North China Plain is one of the most intensively cropped agroecosystems in China, which produces almost 60–80% of China's wheat and 35–40% of maize annually [41,42], the local farmers have gradually adopted conservation tillage management practices [43]. In recent decades, tillage has been identified as an important factor that influences soil OC content [44,45]. Du et al. [46] concluded that the adoption of no-tillage in the North China Plain increased the soil MA mass and C content of MAs by 6–9% and 73%, respectively. Although several studies have revealed that no-tillage management affects soil aggregation, these studies do not explain the changes in soil quality and food security in the North China Plain. The changes in soil OC and N were remains challenging, so there is still much to learn about the changes in soil OC and N contents and aggregate stability under different tillage fertilizer systems in the North China Plain. We hypothesized that the transition from conventional tillage to the no-tillage and straw-returning pattern would promote MI fraction retention within the LMA, resulting in higher soil OC content in the LMA. The objectives of the present study were to (i) use wet sieving methods to isolate the LMA fraction, and the MA, MI, and silt + clay (SC) fractions and associated OC and N fraction; (ii) analyze the effects of changes in tillage and straw-returning management on the sequestration of OC in different size aggregates and maintain soil structure and quality in the intensive agroecosystem in the North China Plain.

2. Materials and Methods

2.1. Study Sites

A field experiment was conducted in 1985 at the Quzhou Experimental Station of the China Agricultural University (36°51' N, 115°01' E, 36 m above sea level), Hebei Province, China. The study area has a warm-temperate monsoonal climate, a mean annual precipitation (MAP) is 542.8 mm, with a distribution of 65.7% in summer (June–August), 18.1% in autumn (September–November), and 2.8% in winter (December–January). The mean annual temperature (MAT) is 13.0 °C, and the evaporation is 1837 mm. The soil type is saline-alkali soil, the surface layer (0–20 cm) is light loam (10.30% sand, 78.0% silt, and 11.7% clay) [47], and the subsurface layer (20–40 cm) is sandy loam (20% sand, 65% silt, and 15% clay). The basic chemical properties of the soil before the start of the field experiment are shown in Table 1.

Table 1. Basic characteristics of the soil before the experiment in 1985.

Soil Layer (cm)	pH (H ₂ O)	SOC g kg ⁻¹	TN g kg ⁻¹	Alkaline Nitrogen mg kg ⁻¹	Available Phosphorus mg kg ⁻¹	Available Potassium mg kg ⁻¹
0–20	7.80	7.00	0.37	50.60	9.94	92.60
20–40	7.80	4.00	0.22	36.40	3.20	71.30

Note: Soil pH was measured using a glass electrode in a 1:2.5 soil/water (H₂O) suspension. Soil organic carbon (SOC) was determined by a standard potassium dichromate digest method, and TN was measured with the Kjeldahl method. Alkaline-Nitrogen was determined by alkaline-hydrolyzed diffusion method. To determine the available potassium, soil samples were first extracted with HClO₄-H₂SO₄ solution and 0.5-mol L⁻¹ NaHCO₃ (pH 8.5), respectively. Subsequently, the Olsen P method was used. The available K was extracted with an ammonium acetate solution (NH₄OAc, 1 mol L⁻¹) and then determined with a flame photometer.

2.2. Experimental Design and Soil Sampling

The field experiment consisted of 9 treatments on plots with areas of 33 m² (3 m × 11 m) per plot and started in 1985. Each treatment was repeated thrice, resulting in a total of 27 plots. Six treatments consisted of conventional tillage (CT) to 20 cm depth, including CT₁ (straw into the soil) and CT₂ (covered straw on the surface); the other three were no-tillage (NT) treatments. The rates of straw-returning were 0, 2250, 4500 kg ha⁻¹yr⁻¹. The application rates of the N fertilizer were 0, 225, and 375 kg ha⁻¹yr⁻¹, and the application rates of the P fertilizer were 0, 75, and 150 kg ha⁻¹yr⁻¹ (Table 2). Straw was removed from the fields, and the straw from winter wheat was applied early June each year after harvest at one of the rates described above in the treatments with moderate and large straw additions. N fertilizer used urea containing 46% N, and P fertilizer contained heavy superphosphate of 43% P₂O₅. The nitrogen fertilizer was applied winter wheat in 50%, and another 50% was to summer maize. Phosphate fertilizer was applied only once as the base fertilizer before the wheat was planted.

Table 2. Treatments in Quzhou of North China Plain experiment (kg ha⁻¹ yr⁻¹).

Treatment Number	Tillage	Urea-N	P ₂ O ₅	Straw
CT ₁ -N ₀ -P ₀ -Straw ₀	Conventional tillage	0	0	0
CT ₁ -N ₁ -P ₁ -Straw ₁	Conventional tillage	225	75	2250
CT ₁ -N ₂ -P ₂ -Straw ₂	Conventional tillage	375	150	4500
CT ₂ -N ₀ -P ₁ -Straw ₂	Conventional tillage	0	75	4500
CT ₂ -N ₁ -P ₂ -Straw ₀	Conventional tillage	225	150	0
CT ₂ -N ₂ -P ₀ -Straw ₁	Conventional tillage	375	0	2250
NT-N ₀ -P ₂ -Straw ₁	No-tillage	0	150	2250
NT-N ₁ -P ₀ -Straw ₂	No-tillage	225	0	4500
NT-N ₂ -P ₁ -Straw ₀	No-tillage	375	75	0

Note: CT₁, turned the straw into the soil and CT₂, covered straw on the surface.

Depending on rainfall, five or six irrigations (60–80 mm each time) were applied with a sprinkler system. In June 2017, soil samples were obtained from the surface and subsurface layers after the winter wheat harvest. Three soil cores per plot (the locations were determined randomly with “S” type) were collected using a hand auger (4.1 cm diameter) in a 0–20- and 20–40-cm depth, respectively, then pooled to make a composite sample. The soil samples were brought to the laboratory and air-dried at room temperature. Before sieving, large plant residues and stones were removed. After sieving (8 mm sieve), the aggregates were separated into large macroaggregates (LMA; >2 mm), macroaggregates (MA; 0.25–2 mm), microaggregates (MI; 0.053–0.25 mm), and silt and clay fractions (SC; <0.053 mm). At the same time, a portion of the samples was sieved through a 2-mm sieve for the determination of bulk soil OC and total N content.

2.3. Determination of Soil Water-Stable Aggregates

The water-stable aggregates in the soil were separated by a wet sieving approach following the procedure by Cambardella and Elliot [48]. Briefly, a 50-g, air-dried soil sample was spread on the top of a 2-mm sieve submerged in deionized water. The soil samples were left immersed in the water for 5 min and then sieved by moving the sieve 3 cm vertically 30 times per minute. The materials remaining on the three sieves (2, 0.25, and 0.053 mm) were transferred to beakers. The large macroaggregates (LMA; >2 mm), macroaggregates (MA; 2–0.25 mm), microaggregates (MI; 0.25–0.053 mm), and silt and clay fraction (SC; <0.053 mm). All aggregate fractions were air-dried at 60 °C for 48 h and weighed. The OC and N contents of each size aggregate were determined.

Soil organic carbon content in bulk soil and each aggregate were determined using the dichromate oxidation method. The nitrogen content in bulk soil and each aggregate was analyzed using the Kjeldahl method [49].

2.4. Analysis

The mean weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregate were calculated from the aggregate size distribution, according to the following equations [50].

$$MWD = \sum_{i=1}^n d_i \times w_i \quad (1)$$

$$GMD = \exp \left[\frac{\sum_{i=1}^n w_i \times \ln d_i}{\sum_{i=1}^n w_i} \right] \quad (2)$$

where d_i is the mean diameter (mm) of each aggregate fraction and w_i is the weight proportion of each size aggregate.

$$OC (\%soil) = \left(\frac{SOC_i \left(\frac{mg}{g} \text{ aggregate} \right) \times M_i (g)}{Soil\ mass} \right) \times 100\% \quad (3)$$

$$N (\%soil) = \left(\frac{TN_i \left(\frac{mg}{g} \text{ aggregate} \right) \times M_i (g)}{Soil\ mass} \right) \times 100\% \quad (4)$$

OC (%soil) is the aggregate-associated organic carbon in soil; SOC_i is the soil organic carbon content in per aggregate; M_i is the mass (g) of each aggregate; N (%soil) is the aggregate-associated nitrogen in the soil; TN_i is the nitrogen content in per aggregate.

Data were analyzed using analyses of two-way variance (ANOVA) and mean values separated using Turkey tests at 5% level of significance in a DPS program version 7.05, SPSS 25, and SigmaPlot program version 10.0 was used for plotting figures.

3. Results

3.1. Effects of Tillage and Straw on the Mass Distribution of Aggregates

Long-term tillage and straw-returning with different application rates affected the mass distribution of water-stable aggregates (Figure 1). In all the treatments, SC fractions (<0.053 mm) were predominant, accounting for 32–56% of the mass of the 0–20 cm layer (Figure 1). LMAs were the smallest fractions, accounting for 4–12% of the mass of the bulk soil at 0–20-cm depth. The mass of LMAs was not significantly affected by the tillage method, mineral fertilizer, and straw (Figure 1). However, no-tillage increased LMA mass by 55% at 0–20 cm depth, compared with conventional tillage, (Figure 1). The application rates of straw increased the mass of LMA, MA, and MI fractions, and decreased the SC fractions, but had no significant effects on statistically. Additionally, different amounts of N and P fertilization did not significantly influence the mass distribution of MA, MI, and SC fractions (Figure 1).

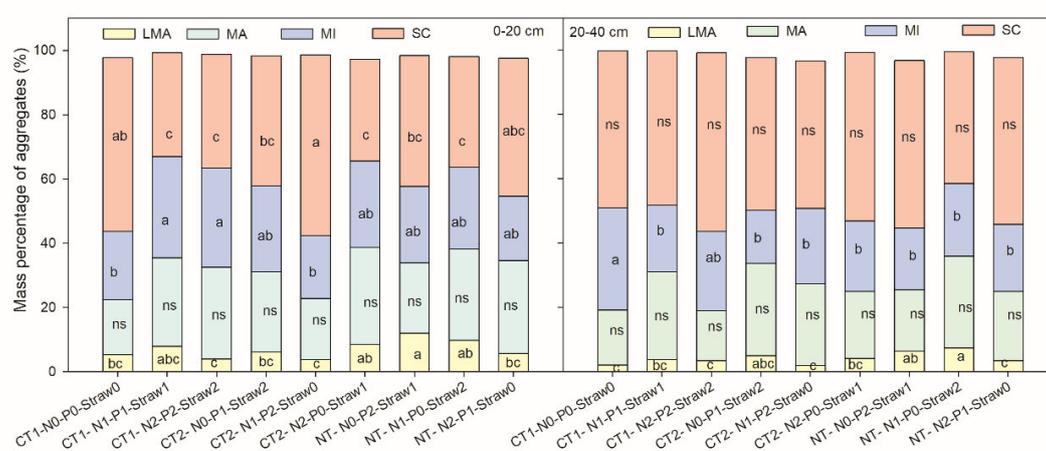


Figure 1. Mass distribution of four different size aggregates (>2, 0.25–2, 0.053–0.25, and <0.053 mm) under tillage and fertilization treatments from 0–20 and 20–40 cm. Similar letters between treatments within a soil layer are not significantly different according to Tukey’s HSD test. CT₁ turned straw into the soil and CT₂ covered straw on the surface.

Similarly, at the 20–40 cm layer, SC fractions were the predominant fractions among all the size aggregates, accounting for 41–55% of the bulk soil. The LMAs were the smallest fraction (Figure 1). No-tillage increased the mass of the LMAs by 71% at the 20–40 cm depth, while the mass of the SC fractions and MIs decreased, compared with the conventional tillage method (Figure 1). The no straw-returning treatments (CT₁-N₀-P₀-Straw₀, CT₂-N₁-P₂-Straw₀, and NT-N₂-P₁-Straw₀) had a lower mass of LMAs and MAs (Figure 1).

3.2. Soil and Water-Stable, Aggregate-Associated Organic Carbon Content

The treatment of CT₁-N₁-P₁-Straw₁ significantly increased the OC content of the bulk soil compared CT₁-N₂-P₂-Straw₂ and other treatments at the 0–20 cm depth (Figure 2). When the treatment without straw (CT₁-N₀-P₀-Straw₀, CT₂-N₁-P₂-Straw₀, and NT-N₂-P₁-Straw₀), soil aggregate-associated OC was highest in the SC fractions than other three aggregate fractions, ranging from 30–50% of bulk soil OC at 0–20 cm depth (Figure 2). Whether conventional tillage or no-tillage method, the treatment with straw-returning increased the aggregate-associated OC content of LMAs, MAs, and MIs. This result showed that straw changed the distribution of OC in the different size aggregates.

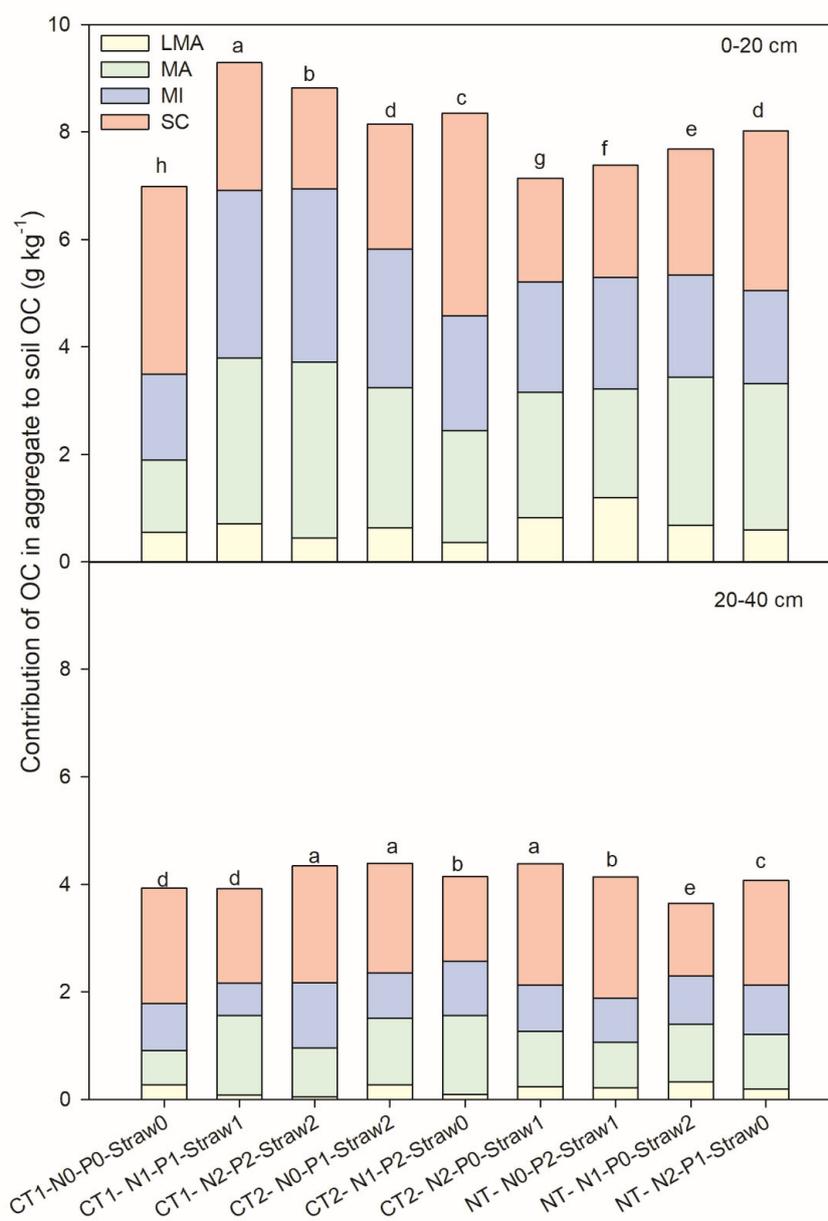


Figure 2. Soil organic carbon (OC) content (g kg^{-1} soil) in four aggregate size fractions (>2 , $0.25\text{--}2$, $0.053\text{--}0.25$, and <0.053 mm) in 0–20 and 20–40 cm. Similar letters between treatments within a soil layer are not significantly different according to Tukey’s HSD test. CT₁ turned straw into the soil and CT₂ covered straw on the surface.

Organic carbon content significantly decreased at the 20–40 cm layer, compared with the 0–20 cm layer (Figure 2). Similar to the surface layer, tillage and straw-returning increased the OC content of bulk soil, without significantly changing their relative proportions in different aggregates. The long-term application of N or P fertilizers also increased soil OC content of the bulk soil at 20–40 cm but did not lead to significant differences in the aggregate-associated OC content.

3.3. Soil and Water-Stable, Aggregate-Associated Nitrogen Content

The treatment of CT₁-N₁-P₁-Straw₁ significantly increased soil N content by 33%, compared with the CT₁-N₀-P₀-Straw₀ treatment at the 0–20 cm depth (Figure 3). Straw-returning at different application rates did not result in significant differences in soil N content but increased the N content

associated with LMAs, MAs, and MIs (Figure 3). The N content of the subsurface layer (20–40 cm) was significantly lower than that of the surface layer (0–20 cm), while there was no significant difference in bulk soil N content between treatments at 20–40 cm depth soil (Figure 3). The increase of soil N content was mainly due to its increase in the MA and SC fractions.

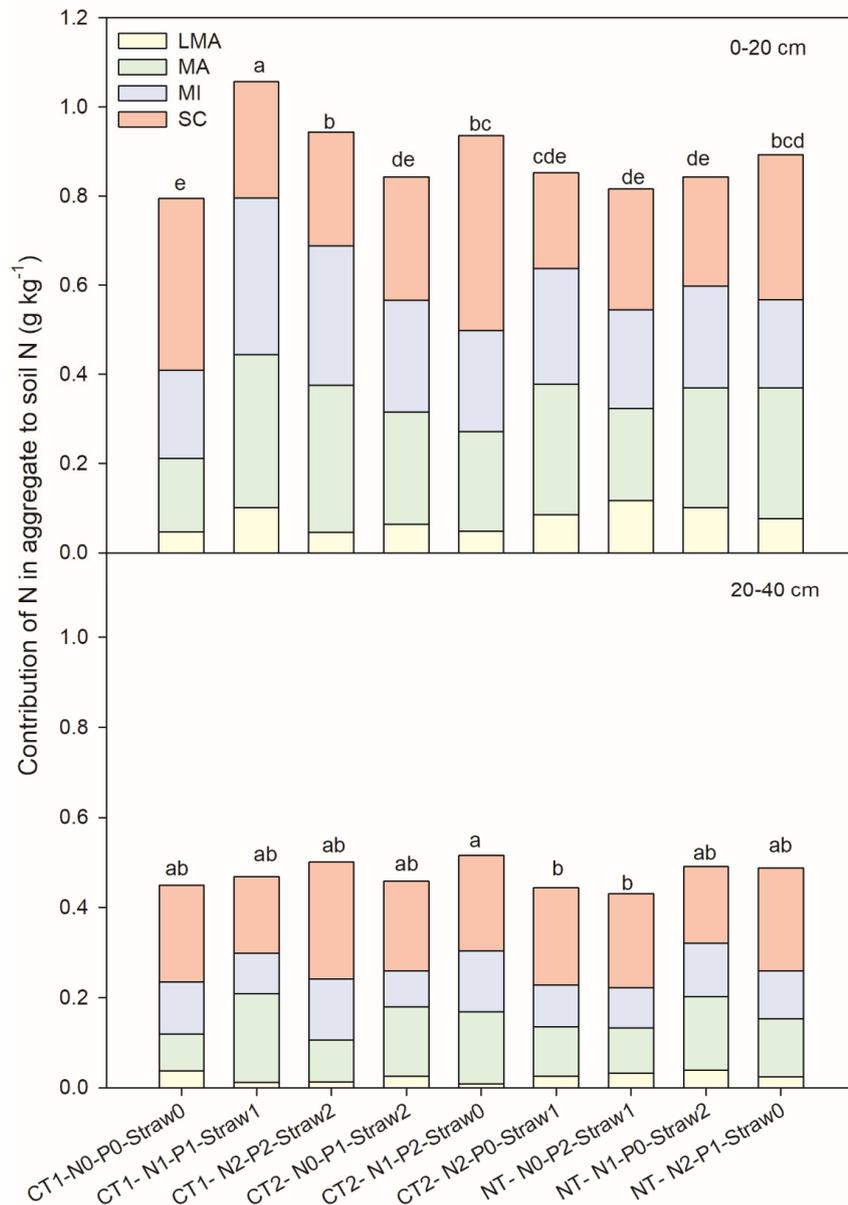


Figure 3. Nitrogen contents (g kg^{-1} soil) in four aggregates size fraction (>2 , $0.25\text{--}2$, $0.053\text{--}0.25$, and <0.053 mm) from 0–20 and 20–40 cm under long-term tillage and fertilization. Similar letters between treatments within a soil layer are not significantly different according to Tukey's HSD test. CT₁ turned straw into the soil and CT₂ covered straw on the surface.

3.4. Effects of Tillage and Fertilization on Aggregate Stability

Long-term tillage, straw, and fertilization management could significantly affect soil aggregate stability in both surface and subsurface layers. Aggregate stability decreased with the depth, as indicated by the mean weight diameter (MWD) and the geometric mean diameter (GWD) (Figures 4 and 5). In the surface layer, the treatment with straw-returning increased the MWD and GWD of soil

aggregates by 16–50% and 14.67–70.88%, respectively, compared with the treatment without straw (CT₁-N₀-P₀-Straw₀, CT₂-N₁-P₂-Straw₀, and NT-N₂-P₁-Straw₀). Long-term applications of N and P fertilizer without straw did not significantly affect soil aggregate stability, as indicated by the similar MWD values in both surface and subsurface layers. However, the GWD of CT₁-N₀-P₀-Straw₀ and CT₂-N₁-P₂-Straw₀ treatments did not decrease at 20–40 cm depth soil (Figure 5).

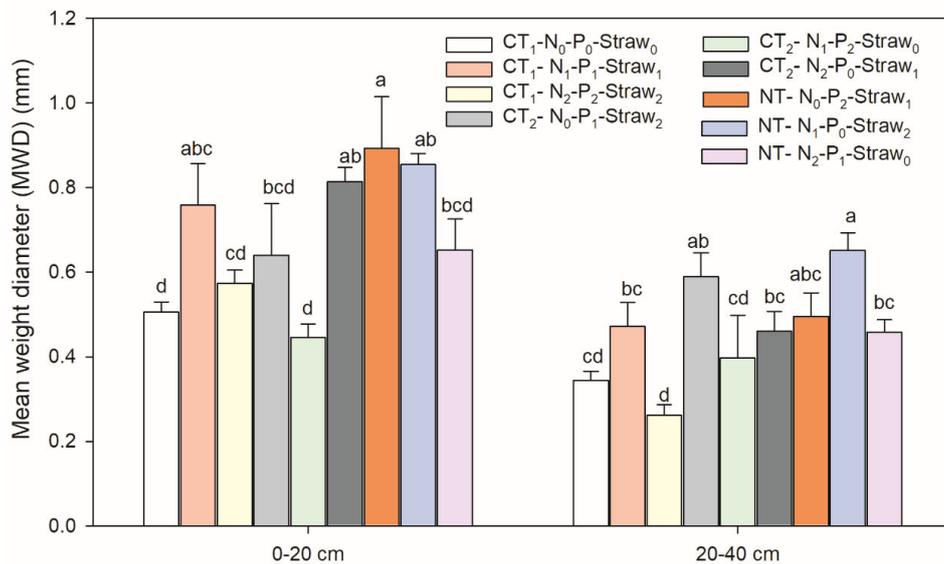


Figure 4. The mean weight diameter (MWD) of different tillage management and fertilization at 0–20 and 20–40 cm. Bars followed by similar letters between treatments within a soil layer are not significantly different according to Tukey’s HSD test. CT₁ turned straw into the soil and CT₂ covered straw on the surface.

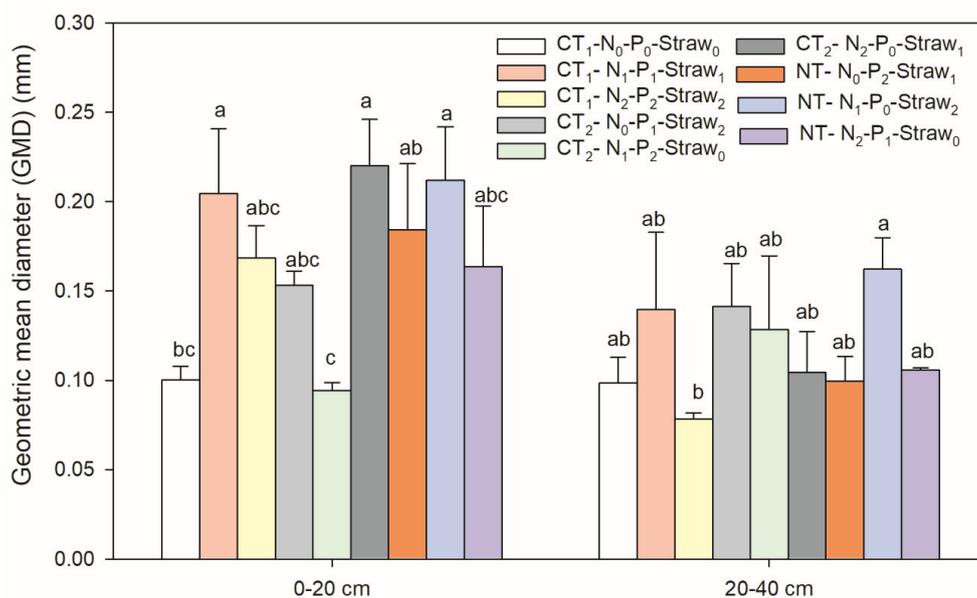


Figure 5. The geometric mean diameter (GMD) of different tillage management and fertilization at 0–20 and 20–40 cm. Bars followed by similar letters between treatments within a soil layer are not significantly different according to Tukey’s HSD test. CT₁ turned straw into the soil and CT₂ covered straw on the surface.

3.5. C/N Ratios in Bulk Soil and Aggregates

There was no significant difference in the C/N ratios in bulk soil and four size aggregates among all treatments at 0–20 cm depth (Table 3). In general, no-tillage treatments decreased the C/N ratios of LMAs, compared with conventional tillage treatments. The straw-returning treatment with the highest application rate (Straw₄₅₀₀) increased the C/N ratios in MAs and MIs. Under the only application N and P fertilization treatment, C/N ratios were not significantly different from the control, except bulk soil and SC fraction, and the N and P fertilization significantly decreased the C/N ratios in LMAs, compared with the control (Table 3).

Table 3. The C/N ratios in bulk soil and different size aggregates at 0–20 cm (Mean \pm standard error (SE)) (n = 3).

Treatments	Bulk Soil	Aggregate			
		>2 mm	0.25–2 mm	0.053–0.25 mm	<0.053 mm
CT ₁ -N ₀ -P ₀ -Straw ₀	8.85 \pm 0.48ab	13.4 \pm 0.59a	9.62 \pm 0.36abc	9.67 \pm 0.14abc	10.5 \pm 0.26a
CT ₁ -N ₁ -P ₁ -Straw ₁	8.79 \pm 0.03ab	7.34 \pm 0.20ef	9.52 \pm 0.13abc	9.43 \pm 0.2bcd	9.60 \pm 0.01c
CT ₁ -N ₂ -P ₂ -Straw ₂	9.43 \pm 0.64a	9.59 \pm 0.08c	9.53 \pm 0.14abc	9.95 \pm 0.28ab	7.19 \pm 0.18d
CT ₂ -N ₀ -P ₁ -Straw ₂	9.67 \pm 0.21a	8.77 \pm 0.42cd	9.25 \pm 0.18bc	9.36 \pm 0.18cd	7.51 \pm 0.13d
CT ₂ -N ₁ -P ₂ -Straw ₀	8.93 \pm 0.18ab	8.16 \pm 0.10de	9.9 \pm 0.18ab	10.13 \pm 0.22a	9.26 \pm 0.14c
CT ₂ -N ₂ -P ₀ -Straw ₁	8.39 \pm 0.23b	10.76 \pm 0.05b	8.97 \pm 0.01cd	8.88 \pm 0.09de	10.02 \pm 0.04e
NT-N ₀ -P ₂ -Straw ₁	9.05 \pm 0.05ab	8.75 \pm 0.17cd	8.36 \pm 0.15d	7.98 \pm 0.12f	6.46 \pm 0.07e
NT-N ₁ -P ₀ -Straw ₂	9.15 \pm 0.36ab	6.71 \pm 0.13f	10.33 \pm 0.52a	8.48 \pm 0.16de	9.53 \pm 0.1c
NT-N ₂ -P ₁ -Straw ₀	9.00 \pm 0.25ab	8.04 \pm 0.21de	9.48 \pm 0.33abc	8.98 \pm 0.06de	9.50 \pm 0.03c

Note: Similar letters between treatments within a soil layer are not significantly different according to Tukey's HSD test. CT₁ turned straw into the soil and CT₂ covered straw on the surface.

4. Discussion

4.1. Effects of Tillage, Straw-Returning, and Mineral Fertilization on OC Content of Soil and Aggregates

The soil OC content decreased with soil depth in all tillage and fertilization treatments (Figure 2). Whereas soil OC content was predominant in the SC fractions, ranging from 30–50% of bulk soil OC at a 0–20-cm depth (Figure 2). Previous reports on agricultural soils show that most of the OC in topsoil is stored in the SC fractions rather than in the other fractions [15,51]. It depends on the texture of the soil, because in this region the SC fractions mass were predominant, accounting for 32–56% (Figure 1), which led to relatively high associated OC of SCs. The treatment with straw increased the OC content in LMAs, and decreased the OC content in the SC fraction (Figure 2). Our results are consistent with those of Guo et al. [52], who found that straw acts as an exogenous C source contributing to OC sequestration, and the increased OC content of LMAs, because the LMAs have higher water infiltration and better aeration, while also having higher stability [38,39]. However, only the application of N and P fertilizers or no fertilizer (CT₁-N₀-P₀-Straw₀, CT₂-N₁-P₂-Straw₀, and NT-N₂-P₁-Straw₀) increased the mass and associated OC content of SC fractions, compared with other straw treatments (Figures 1 and 2). It is also showed that no-tillage method would become meaningless without straw application.

However, some studies have suggested that no-tillage had significantly higher soil OC than conventional tillage in the surface layer [7,53,54]. This contradiction between our findings and the results of other researchers could be attributed to the effect of rainfall and fertilizer application rates. The study area has low rainfall, which takes longer for crop straws to decompose into organic matter completely and release nutrients. Dou et al. [18] and Benbi [55], found that long-term application of N and P fertilizer can increase soil OC content, consequently affecting the dynamics of soil C pools in the agroecosystem. Interestingly, OC content increased by 3–8% for the initial control (in 1985) after 33 years (Table 1 and Figure 2). This finding is consistent with the results reported by [34,35], who showed that the cultivation of wheat and soybean for 30 years in an inceptisol in the Indian

Himalayas without any added organic or inorganic fertilizers increased the OC content by 9%, because the crop root biomass remains in the soil, and eventually increases OC content.

4.2. Effects of Tillage, Straw-Returning, and Mineral Fertilizer on Nitrogen Contents

Aggregate-associated N content was affected by long-term tillage, straw-returning, and mineral fertilizer with different application rates (Figure 3). No-tillage increased the N content of LMAs. The N content of CT₁-N₁-P₁-Straw₁ was higher than CT₁-N₂-P₂-Straw₂ treatment in the bulk soil at 0–20 cm depth and lower at 20–40 cm depth. This is because nitrogen leaching occurs when both N and P fertilizers excessively used [56]. The conventional tillage and straw-returning management increased N contents in surface soil, compared with the treatment of no-tillage and straw-returning (Figure 3). The increased N contents in surface soil under conventional tillage and straw-returning management probably because of two reasons, (i) the straw carried nitrogen into the soil and (ii) conventional tillage breaks down LMAs and MAs to generate greater proportions of MI or SC fractions, enhanced microbial degradation of the exposed soil organic matter, leading to increased nitrogen contents in microbial residues [1,13].

The N content of the surface layer was significantly higher than that of the subsurface layer (Figure 3). These results were in line with previous studies [16,18,31]. At the same time, after more than 30 years, N content without fertilization increased, compared to the amount of N content before the experiment. This result is due to atmospheric nitrogen deposition and precipitation increased soil nitrogen content [57], and the addition of litter could also increase N content in the soil.

4.3. Effects of Tillage, Straw-Returning, and Mineral Fertilizer on Aggregate Stability

Long-term tillage and straw-returning management affected soil aggregate stability in both surface, and subsurface layers and aggregate stability decreased with soil depth (Figures 4 and 5). This results are similar to that of Abid and Lal [36], who showed that MWD decreased with increased soil depth. The NT-N₀-P₂-Straw₁ and NT-N₁-P₀-Straw₂ treatments increased the MWD, but the NT-N₁-P₀-Straw₂ had higher GMD than NT-N₀-P₂-Straw₁. This result is consistent with that of Meng et al. [58], who reported that straw-returning caused lower mineralization of native SOM and thus facilitated increased LMA formation, leading to higher MWD.

In our study, there was no significant difference in MWD and GMD of the CT₁-N₀-P₀-Straw₀ and CT₂-N₁-P₂-Straw₀ treatment, but the NT-N₂-P₁-Straw₀ had higher MWD and GMD (Figures 4 and 5). This result is consistent with previous studies [36,43,46]. This may be attributed to the fact that no-tillage decreased soil disturbance, facilitating the protection of soil organic matter from microbial degradation, which in turn favored the generation of physically stable LMAs and Mas, and increase the soil stability [1]. The N and P fertilizer had no significant effect on MWD in the soil, but when increased the amount of N or P fertilizer, the MWD reduced in both layers (Figure 4). The results were comparable with those of a previous report, where a decrease in the proportion of LMAs was followed by a decrease in the MWD owing to the application of N and P fertilizer [59]. Therefore, our findings suggest that conservation tillage, such as no-tillage and straw-returning, can help improve soil aggregation, as previously described [16].

5. Conclusions

Long-term tillage, straw, and mineral fertilization mainly affect soil organic matter by regulating soil aggregation. Our results showed that long-term (33 years) no-tillage management and straw-returning at different application rates increased soil LMA mass, the LMA, and MA-associated OC content, but decreased the SC-associated OC content. Among them, the SC fractions (<0.053 mm) were predominant, accounting for 32–56% of the mass at the 0–20 cm depth, and accounting for 41–55% of the mass at 20–40 cm depth. No-tillage method decreased the C/N ratios of aggregates by 1–19% compared with conventional tillage and increased the C/N ratios by 1% in the bulk soil. The result indicated that conservation tillage, especially no-tillage with straw-returning, improves soil structure,

and change the size distribution of the aggregates. Mineral N and P fertilizers had a minor effect on the stabilization of soil aggregates. The straw treatment significantly increased the MWD and GWD by 41% and 60%, respectively, compared with the treatment without straw. Overall, straw-returning plays a certain role in improving soil quality and reducing soil erosion in North Plain China.

Furthermore, the results suggest that it needs to optimize the combination of conservation tillage techniques, the application rates of mineral fertilizers and straws to maximize soil fertility and maintain the soil structure in the wheat-maize croplands of the region. Further study is required to determine whether long-term tillage and straw at different application rates affect the abundance and types of soil microbes, which further influence the formation and distribution of aggregates and associated carbon.

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