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Effects of Different Straw Return Methods on the Soil Structure, Organic Carbon Content and Maize Yield of Black Soil Farmland

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Abstract: Straw return is an effective measure to increase soil sustainability. However, few studies have examined the effects of different straw return methods on soil structure, soil organic carbon content and maize yield or the potential relationships between those variables. Therefore, we developed a field orientation experiment to study the effects of different straw return methods on soil porosity, soil aggregate stability, the soil organic carbon content and maize yield. Four treatments were established: flat no-tillage with full straw mulching (FM), ridge no-tillage with full straw mulching (LM), rotary tillage with full straw incorporation (LX), and conventional tillage without straw (CK) as the control treatment. Compared with those of the CK treatment, the soil porosities (*f*) in the FM, LM and LX treatments significantly increased by 6.7%, 8.8% and 7.9%, respectively; the soil aggregate destruction rates (PAD) decreased by 17.3%, 34.3% and 16.9%, respectively. In addition, the FM, LM and LX treatments effectively increased the mean mass diameters (MWDs) of the soil aggregates and the soil organic carbon content. Compared with those in the CK treatment, the three-year average yields in the FM, LM and LX treatments significantly increased by 5.2%, 7.2% and 4.1%, respectively. Moreover, the f, MWD, soil organic carbon content and corn yield were positively correlated. Our study indicates that the LM treatment was most effective in improving soil structure and increasing soil organic carbon content with corn yield.

Keywords: straw return; soil porosity; soil aggregates; organic carbon; corn yield

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1. Introduction

The Northeast China black soil region is one of the four major black soil regions in the world, with fertile soil and a total area of up to 1,090,000 km^2, making it an important grain production area in China, with its grain output accounting for approximately one-fifth of the country's total grain output [1,2]. However, the degradation of black soil's structure and the decline in organic carbon content caused by long-term highly intensive cultivation are becoming increasingly prominent, posing a potential risk to the sustained food production capacity in the northeastern black soil region [3,4]. Therefore, the adoption of rational agricultural management practices is important for improving soil quality and grain yield in black soils. Straw-returning measures are potential candidates for achieving these goals [5], but most studies have focused only on the effects of straw-returning measures on soil quality or grain yield while neglecting the potential relationship between them.

Soil quality is crucial for sustainable agricultural development [6]. Soil aggregates, as the basic structural units of soils, play an important role in soil structure through their composition [7]. Currently, soil aggregate stability is an important feature for measuring

the stability of a soil structure, which is important for improving soil fertility and increasing soil porosity [8,9]. The average mass diameter (MWD) of soil aggregates is an important index for evaluating the stability of soil aggregates, and the larger the MWD value, the more stable the aggregates are [10]. Moreover, soil aggregates are the main storage site for soil organic carbon, and aggregates can effectively reduce the mineralization and decomposition of soil organic carbon by microorganisms, thus protecting soil organic carbon [11]. The soil organic carbon can be used as a charged colloid to promote the formation of soil aggregates through the effects of cementation and organic matter filling [12]. Therefore, soil aggregates and soil organic carbon are closely related. In addition, soil organic carbon is an important indicator of soil fertility [13], and the dynamic changes in soil organic carbon are largely affected by soil microbial activity, and microorganisms play a key role in the decomposition, transformation and fixation of soil organic matter; as such, changes in soil microbial biomass carbon content have an important impact on soil organic carbon fixation [14,15]. Therefore, exploring the changes in soil microbial biomass carbon content plays an important role in understanding the microbial processes of soil organic carbon accumulation and promoting soil fertility.

Straw return to a field is a way to fully utilize abundant straw resources and is an important measure supporting sustainable agricultural management [16]. Some studies have shown that returning straw to the soil can promote the formation of soil aggregates and increase soil porosity, thereby improving the soil structure [17]. In addition, the decomposition of straw as exogenous organic matter entering the soil, promotes microbial growth and reproduction, which in turn affects changes in soil microbial biomass carbon, regulates soil organic carbon fixation and contributes to crop yields [18]. Gao et al. reported that the average yield of wheat grown with straw return measures increased by 5.1% to 5.6% compared with when the straw was removed from the field [19]. However, some studies also noted that there was no significant change or even a negative effect of straw return on the increase in grain yield [20,21]. These uncertainties hinder our understanding of the relationships between soil structure, microbial biomass carbon, organic carbon content and grain yield under different straw return methods.

The different methods used for straw return have different effects on the soil structure, organic carbon content and grain yield [22]. For example, traditional rotary plowing of straw can provide sufficient nutrients and energy to soil microorganisms, promote the conversion of exogenous carbon from straw, and increase the soil organic carbon content [23]. Kan et al. reported that no-tillage straw mulching and return to the field can minimize the degree of disturbance to the surface soil and reduce the mineralization and decomposition of soil organic carbon by enhancing the physical protection of soil aggregates, and thus increase the soil organic carbon content [24]. However, it is not clear whether no-tillage straw mulching is more effective at increasing crop yields in the current crop or long term than conventional rotary straw mulching. In recent years, the protection and utilization of black soil zones has been highly emphasized, and returning straw to farmland has gradually replaced the traditional farming method. Although the area of straw returned to farmland has been increasing annually, owing to the differences in the concept of production, the method of farmland management and the efficacy of the popularization of the technology, the widely adopted ways of returning straw to farmland are not currently consistent. To the best of our knowledge, there is a lack of research on the soil structure, organic carbon content and maize yield under different straw return methods in maize cropping systems in the black soil zone of Northeast China.

This study was based on a 3-year straw return field positioning experiment at the Heilongjiang Provincial Experimental Research Center of Water Resources Science and Technology. By studying the soil porosity, soil aggregate composition, aggregate stability, organic carbon content and corn yield in the 0~20 cm and 20~40 cm soil layers under different straw-returning methods, we compared and analyzed the relationships among the soil structure, organic carbon content, and corn yield under different straw-returning

methods. This study provides a theoretical basis for the selection of suitable straw return methods in the black soil area of Northeast China.

2. Materials and Methods

2.1. Study Site

Our study site was located at the Water Conservancy Technology Research Station of the Heilongjiang Province Hydraulic Research Institute (126°36′ E, 45°43′ N) in Harbin city, Heilongjiang Province, Northeast China. The test site has a temperate continental monsoon climate, with rain and heat in the same season and concentrated precipitation, and it is prone to spring drought. The average temperature at this experimental station has been −4~5 °C for many years, the frost-free period is 130~140 d, the average annual precipitation is between 400 and 650 mm, the rainfall from July to September accounts for 70% of the annual precipitation and the average evaporation has been 796 mm for many years. The test site is dry land, and local farmers manage the land without irrigation. The test area is located in a typical black soil belt in the northeast, the test soil was classified as Phaeozems according to the WRB (2022) standard and the soil texture was a sandy loam; the basic physical and chemical properties of the soil are shown in Table 1.

Table 1. Soil properties in different soil layers.

Soil Depth/ (cm)	pH	Available Nitrogen/ ($mg \cdot kg^{-1}$)	Available Phosphorus/ ($mg \cdot kg^{-1}$)	Available Potassium/ ($mg \cdot kg^{-1}$)	Organic Matter/ ($g \cdot kg^{-1}$)
0~20	7.3	154	40.2	377	25.3
20~40	7.2	150	37.1	357	23.0

2.2. Experimental Design

A total of four treatments were set up in the experiment: flat no-tillage with full straw mulching (FM), ridge no-tillage with full straw mulching (LM), rotary tillage with full straw incorporation (LX), and conventional tillage without straw (CK). FM and LM: maize straw was cut into approximately 20 cm pieces and evenly distributed on the soil surface after harvest, and all the straw was piled in interrow spacing before spring sowing in the second year so as not to affect the seedlings. Rotary tillage with full straw incorporation was adopted for LX, and after the maize harvest, deep plowing (depth 25–30 cm) was first carried out, followed by mixing crushed straw (<10 cm) into the soil tillage layer with a rotary tiller. The straw returning rate for each year was 0.6 t/ha. Large-ridge double-row planting was adopted for CK, and all residue was removed from the field after fall harvest and rotary tillage was used before spring sowing in the second year.

Each treatment had three replications for a total of 12 experimental plots, which were randomly arranged, with each plot measuring 100 m^2 (10 m × 10 m). The local maize variety "Dalong 568" was selected as the test crop and was planted in rows spaced 23 cm apart. Combined with the local maize planting experience, 250 kg/ha of N fertilizer (urea, containing 46% N mass fraction) was applied with 40% of the basal fertilizer, 30% at the pulling stage and 30% at the filling stage, while P_2O_5 and K_2O were applied as basal fertilizers. The application rate was 90 kg/ha for both.

2.3. Sampling and Measurement

2.3.1. Soil Sample Collection

Soil samples were collected after the corn harvest in 2023, and 2 soil layers, 0–20 cm and 20–40 cm, were collected from each experimental plot using the five-point sampling method, and soil samples of the same soil depth were evenly mixed and divided into two parts. One portion of fresh soil was stored at low temperature for the determination of soil microbial biomass carbon, and the other portion was air-dried indoors to remove coarse roots, small stones and plant roots, and the large soil sample was divided into 1 cm^3 small soil blocks according to the natural fissures. In addition, a ring knife with a volume

of 100 cm^3 was used to collect original soil samples from the 0~20 cm and 20~40 cm soil layers in each test plot for the determination of the soil bulk density.

2.3.2. Assessment of the Soil Samples

(1) The soil bulk density was determined via the ring knife method [25], and the soil porosity was calculated.

(2) Soil force stability aggregates were determined via dry sieving [26]. Air-dried soil samples were placed on top of the sieve set with apertures of 5 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm in descending order. After shaking for 2 min (200 times/min) using the vibratory mechanical sieve apparatus, the soil samples were collected in a graded manner and weighed to calculate the percentage of aggregates.

(3) Soil water stability aggregates were determined via the wet sieve method [26,27], 50 g air-dried soil samples were prepared according to the mass ratio of aggregates at all levels of the dry sieve, and after settling, the saturated soil samples were transferred to the top of the set of sieves (apertures of 5 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm) filled with bucket of deionized water. The whole set of sieves was slowly lifted and lowered into the water for 5 min, and aggregates at all levels of sieves were washed with deionized water into an aluminum box and dried at 60 °C for 48 h to a constant mass type. Thus, six levels of soil aggregates >5, 2~5, 1~2, 0.5~1, 0.25~0.5 and <0.25 mm, were obtained and retained for the determination of the organic carbon in the aggregates.

(4) The soil microbial biomass carbon content was determined by the chloroform fumigation–K_2SO_4 extraction method [28]. The soil organic carbon content and aggregate organic carbon content were determined via a total organic carbon analyzer (Elementar Vario TOC, Germany), which requires pretreatment with 0.5 mol/L HCl to remove inorganic carbon carbonate from the soil samples before determination [29].

2.3.3. Maize Yield Determination

The middle 3 rows of each plot were taken at maturity from 2021 to 2023 for yield measurements. The ears of corn were then air-dried until the mass was constant. Threshing, weighing and conversion to a corn kernel yield with a kernel moisture content of 14% were subsequently performed.

2.4. Data Calculation and Analysis

2.4.1. Formulas for the Previous Methods

Below we present a series of equations that were used in the methods presented in the previous section.

Soil porosity [30]:

$$f = \left(1 - \frac{\rho_b}{\rho_d}\right) \times 100\% \quad (1)$$

where f is the soil porosity (%), ρ_b is the soil bulk density ($g \cdot cm^{-3}$) and ρ_d is the soil particle density, which is approximately 2.65 $g \cdot cm^{-3}$.

Mass fractions of aggregates of different particle sizes and aggregate destruction rates [31]

$$W_i = \frac{m_i}{m} \times 100\% \quad (2)$$

where W_i is the mass fraction (%) corresponding to grade i aggregates, m_i is the mass of Grade i aggregates (g) and m is the total mass of the aggregates (g).

$$PAD = \frac{DR_{0.25} - WR_{0.25}}{DR_{0.25}} \times 100\% \quad (3)$$

where PAD is the aggregate destruction rate (%), $DR_{0.25}$ is the mass fraction of >0.25 mm force-stabilized aggregates (%) and $WR_{0.25}$ is the mass fraction of >0.25 mm water-stabilized aggregates (%).

Average Mass Diameter of Aggregates [31]:

$$X_i = \frac{N_{max} + N_{min}}{2} \quad (4)$$

$$MWD = \sum_{i=1}^{n} X_i W_i \quad (5)$$

where MWD is the average mass diameter of aggregates (mm), X_i is the average diameter of soil aggregates of grade i (mm), N_{max} is the upper limit of a certain grain size, N_{min} is the lower limit of a certain grain size and W_i is the mass fraction (%) corresponding to grade i aggregates.

Carbon Preservation Capacity of Soil Aggregate [32]:

$$CPC_i = SSAC_i \times W_i \quad (6)$$

where CPC_i is the carbon preservation capacity of soil aggregate at level i ($g \cdot kg^{-1}$), $SSAC_i$ is the soil organic carbon content in aggregates at level i ($g \cdot kg^{-1}$) and W_i is the mass fraction (%) corresponding to Grade i aggregates.

2.4.2. Data Analysis

The statistical analysis was performed using SPSS 27.0 (SPSS Inc., Chicago, IL, USA), and the figures were created using Origin 2021. The effects of different straw return methods on ρ_b, f, W_i, PAD, MWD, CPC_i, soil microbial biomass carbon, soil organic carbon and yield were evaluated using one-way analysis of variance (ANOVA). When the F-values were significant, the differences between the means for treatments were compared using a least significant difference (LSD) test at the 0.05 probability level. Pearson correlation analysis was used to examine the relationships between different indicators.

3. Results

3.1. Soil Bulk Density and Porosity

The soil bulk density and porosity under different treatments are shown in Figure 1. In the 0–20 cm soil layer, the soil bulk density significantly decreased by 7.1%, 9.5% and 8.7% in the FM, LM and LX treatments compared with the CK treatment, respectively, and the soil porosity significantly increased by 6.8%, 9.1% and 8.3% in the FM, LM and LX treatments, respectively, compared with the CK treatment ($p < 0.05$). In the 20~40 cm soil layer, the soil bulk density significantly decreased by 6.5%,8.3% and 7.3% in the FM, LM and LX treatments compared with the CK treatment, respectively, and the soil porosity significantly increased by 6.6%, 8.4% and 7.5% in the FM, LM and LX treatments, respectively, compared with the CK treatment ($p < 0.05$).

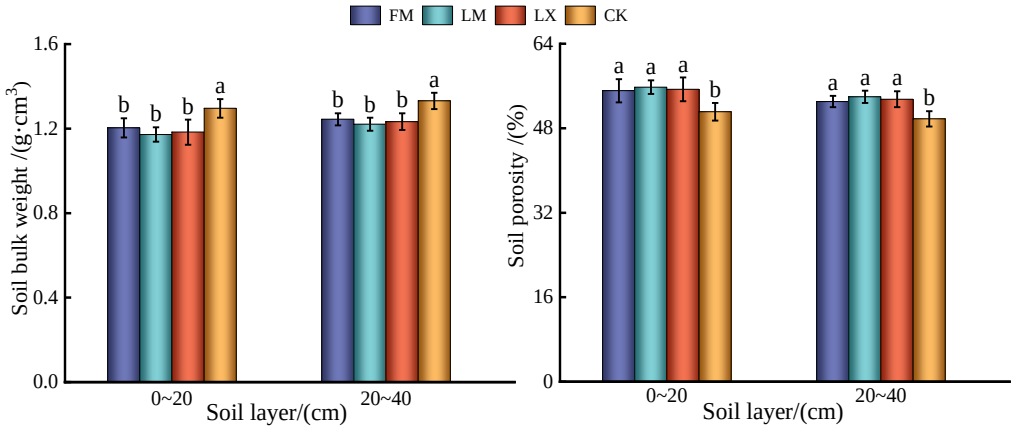

Figure 1. Soil bulk density and porosity under different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level.

3.2. Soil Aggregate Content

3.2.1. Soil Force-Stabilized Aggregate Content

The soil force-stabilized aggregate fractions under the different treatments are shown in Figure 2. In the 0–20 cm soil layer, the content of >5 mm aggregates significantly increased by 35.9%, 39.1% and 18.7% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment ($p < 0.05$), and the content of >5 mm aggregates significantly increased by 17.2% and 14.5% ($p < 0.05$) in the FM and LM treatments, respectively, compared with that in the LX treatment among the three straw return methods. In the 20~40 cm soil layer, the content of >5 mm aggregates significantly increased by 14.7%, 31.5% and 24.9% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment ($p < 0.05$).

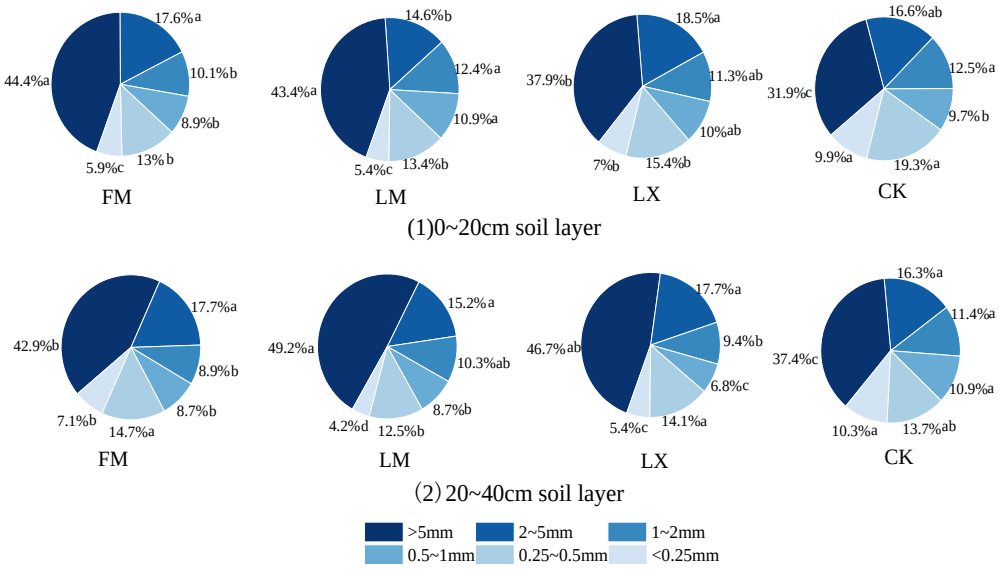

Figure 2. Soil force-stabilized aggregate content under the different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level.

In the 0–20 cm soil layer, the content of the <0.25 mm aggregates in the FM, LM and LX treatments significantly decreased by 40.2%, 45.8% and 29.3% ($p < 0.05$) compared with the CK treatment. Among the three straw-returning methods, the content of the <0.25 mm aggregates significantly increased by 18.2% and 30.4% ($p < 0.05$) in the LX treatment compared with those in the FM and LM treatments. In the 20~40 cm soil layer, the content of <0.25 mm aggregates significantly decreased by 30.4%, 59.7% and 47.8% in the FM, LM and LX treatments compared with the CK treatment, respectively ($p < 0.05$).

3.2.2. Soil Water-Stable Aggregate Content

The soil water-stable aggregate fractions under the different treatments are shown in Figure 3. In the 0–20 cm soil layer, the content of >5 mm aggregates significantly increased by 75.2%, 104.8% and 33.2% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment ($p < 0.05$), and the content of >5 mm aggregates significantly increased by 16.9% and 53.8%, respectively, in the LM treatment compared with the FM and LX treatments in the three straw-returning methods ($p < 0.05$). In the 20~40 cm soil layer, the content of >5 mm aggregates significantly increased by 49.9%, 99.6% and 67.2% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment ($p < 0.05$).

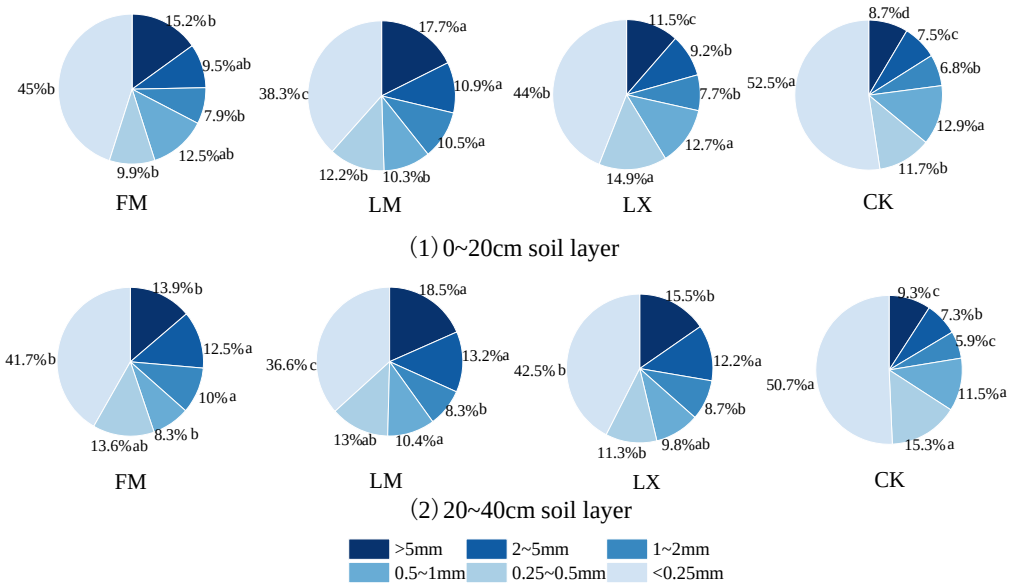

Figure 3. Soil water-stable aggregate fractions under the different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level.

In the 0~20 cm and 20~40 cm soil layers, the FM, LM, LX and CK treatments presented the greatest percentage of <0.25 mm water-stable aggregates at each grain size. In the 0–20 cm soil layer, the content of <0.25 mm aggregates significantly decreased by 14.1%, 26.9% and 16.2% in the FM, LM and LX treatments compared with those in the CK treatment ($p < 0.05$). Among the three straw return methods, the content of <0.25 mm aggregates significantly increased by 17.5% and 14.7% in the FM and LX treatments compared with those in the LM treatment ($p < 0.05$). In the 20~40 cm soil layer, the content of <0.25 mm aggregates significantly decreased by 17.8%, 27.8% and 16.3% in the FM, LM and LX treatments compared with those in the CK treatment ($p < 0.05$).

3.3. Soil Aggregate Stability

3.3.1. Soil Aggregate Destruction Rate

The soil aggregate destruction rates (PADs) under different treatments are shown in Figure 4. Compared with that in the CK treatment, the PAD in the 0–20 cm soil layer significantly decreased by 13.6%, 35.6% and 18.8% in the FM, LM and LX treatments, respectively. The PAD in the LM treatment was significantly lower by 19.4% ($p < 0.05$) than that in the FM treatment among the three straw-returning methods. In the 20~40 cm soil layer, the PADs of the FM, LM and LX treatments were significantly lower (21.0%, 33.0% and 14.9%, respectively) than those of the CK treatment. Among the three straw return methods, the PAD of the LM treatment significantly decreased by 15.7% compared with that of the LX treatment ($p < 0.05$).

3.3.2. Average Mass Diameter of Soil Aggregates

The mean mass diameter (MWD) of the soil aggregates under the different treatments is shown in Figure 5. In the 0–20 cm soil layer, the force-stabilized aggregate MWDs in the FM, LM and LX treatments were significantly higher by 23.0%, 18.8% and 12.7%, respectively, than that in the CK treatment. Among the three straw return methods, the MWD significantly increased by 9.11% in the FM treatment group compared with that in the LX treatment ($p < 0.05$). In the 20~40 cm soil layer, the MWD of the force-stabilized aggregates in the FM, LM and LX treatments significantly increased by 9.6%, 17.9% and 15.9%, respectively, compared with that in the CK treatment ($p < 0.05$).

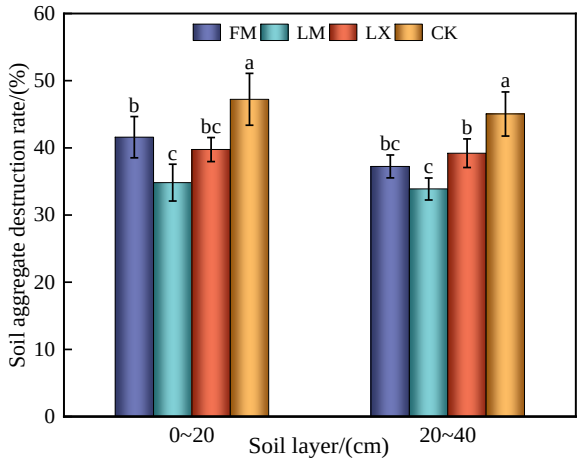

Figure 4. Soil aggregate destruction rate under different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level.

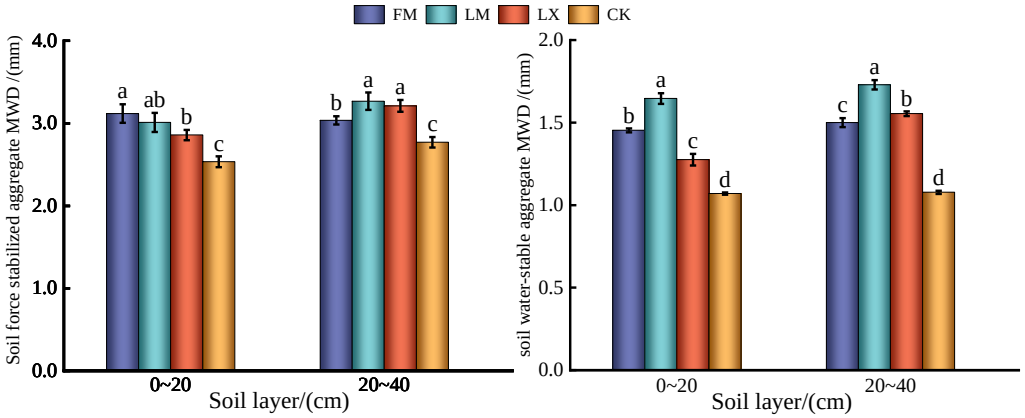

Figure 5. Mean mass diameter (MWD) of the soil aggregates under different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level.

In the 0–20 cm soil layer, the MWD of the water-stable aggregates significantly increased by 35.8%, 53.8% and 19.2% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment. In the three straw-returning methods, the MWD of the LM treatment significantly increased by 13.3% and 29.1%, respectively, compared with those of the FM and LX treatments, and the MWD of the FM treatment significantly increased by 13.9%, respectively, compared with that in the LX treatment ($p< 0.05$). In the 20~40 cm soil layer, the MWD of the water-stable aggregates significantly increased by 39.1%, 60.4% and 44.2% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment.

3.4. Organic Carbon Content and Carbon Preservation Capacity of Soil Aggregates

3.4.1. Organic Carbon Content of the Soil Aggregates

The organic carbon contents of the soil aggregates from the different treatments for each grain size are shown in Table 2. In the 0~20 cm and 20~40 cm soil layers, the peak organic carbon content of the aggregates in each treatment was located within the 2–5 mm or 1–2 mm grain sizes. In the 0–20 cm soil layer, the organic carbon contents of the >5 mm aggregates in the FM, LM and LX treatments significantly increased by 10.3%, 13.2% and 8.6%, respectively, compared with the CK treatment ($p < 0.05$). The organic carbon contents of the 1–2 mm, 0.5–1 mm, 0.25–0.5 mm and <0.25 mm aggregates in the LM treatment were significantly greater than those in the CK treatment ($p < 0.05$). The organic carbon contents of the 2–5 mm, 0.5–1 mm, 0.25–0.5 mm and <0.25 mm aggregates in the LM treatment

were significantly greater than those in the LX treatment in the three straw return methods ($p < 0.05$).

Table 2. Organic carbon content in aggregates of different grain sizes.

Soil Layer/(cm)	Treatment	Organic Carbon Content under Different Grain Sizes /(g·kg^{-1})					
		>5 mm	2~5 mm	1~2 mm	0.5~1 mm	0.25~0.5 mm	<0.25 mm
0~20	FM	12.12 ^{a}	12.76 ^{ab}	12.14 ^{bc}	11.50 ^{a}	10.42 ^{ab}	9.51 ^{b}
	LM	12.44 ^{a}	13.26 ^{a}	12.60 ^{ab}	11.80 ^{a}	11.00 ^{a}	10.55 ^{a}
	LX	11.94 ^{a}	11.92 ^{b}	13.03 ^{a}	10.86 ^{b}	10.17 ^{b}	9.55 ^{b}
	CK	10.99 ^{b}	10.81 ^{c}	11.44 ^{c}	10.66 ^{b}	10.03 ^{b}	8.94 ^{b}
20~40	FM	11.78 ^{b}	12.23 ^{b}	12.35 ^{b}	12.12 ^{b}	10.27 ^{a}	8.37 ^{c}
	LM	12.21 ^{ab}	13.05 ^{a}	13.96 ^{a}	12.86 ^{a}	10.17 ^{a}	8.92 ^{b}
	LX	12.53 ^{a}	13.15 ^{a}	13.93 ^{a}	12.58 ^{ab}	10.45 ^{a}	9.89 ^{a}
	CK	10.79 ^{c}	11.97 ^{b}	11.22 ^{c}	10.36 ^{c}	9.95 ^{a}	8.00 ^{c}

Note: Treatments with the same letter do not differ at the $p < 0.05$ level.

In the 20~40 cm soil layer, the organic carbon content of the >5 mm aggregates in the FM, LM, and LX treatments significantly increased by 9.2%, 13.2% and 16.1% ($p < 0.05$), respectively, compared with that in the CK treatment. The organic carbon contents of the 1–2 mm and 0.5–1 mm aggregate in the FM, LM and LX treatments significantly increased compared with those in the CK treatment ($p < 0.05$). Compared with that in the FM treatment, the organic carbon contents of the >5 mm, 2~5 mm and 1~2 mm aggregates in the LX treatment were significantly greater, and the organic carbon content of the <0.25 mm aggregates in the LX treatment was significantly increased by 10.9% compared with that in the LM treatment ($p < 0.05$).

3.4.2. Carbon Preservation Capacity of Soil Aggregates

The carbon preservation capacity of the soil aggregates under the different treatments is shown in Table 3. In the 0~20 cm and 20~40 cm soil layers, the carbon preservation capacity of aggregates in each treatment was greater for the >5 mm and <0.25 mm particle sizes. In the 0–20 cm soil layer, the carbon preservation capacity of the >5 mm grain size aggregates significantly increased by 93.7%, 132.6% and 45.3% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment. Compared with those in the FM and LX treatments, the carbon preservation capacity of the >5 mm particle size aggregates in the LM treatment significantly increased by 20.1% and 60.1%, respectively ($p < 0.05$).

Table 3. Carbon preservation capacity of the soil aggregates under the different treatments.

Soil Layer/(cm)	Treatment	Carbon Preservation Capacity of the Soil Aggregates under Different Grain Sizes /(g·kg^{-1})					
		>5 mm	2~5 mm	1~2 mm	0.5~1 mm	0.25~0.5 m	<0.25 mm
0~20	FM	1.84 ^{b}	1.22 ^{ab}	0.95 ^{b}	1.43 ^{a}	1.04 ^{c}	4.29 ^{ab}
	LM	2.21 ^{a}	1.45 ^{a}	1.33 ^{a}	1.21 ^{b}	1.34 ^{ab}	4.05 ^{b}
	LX	1.38 ^{c}	1.10 ^{b}	1.01 ^{b}	1.38 ^{ab}	1.51 ^{a}	4.20 ^{ab}
	CK	0.95 ^{d}	0.81 ^{c}	0.78 ^{c}	1.37 ^{ab}	1.17 ^{bc}	4.68 ^{a}
20~40	FM	1.64 ^{b}	1.53 ^{a}	1.24 ^{a}	1.01 ^{b}	1.39 ^{ab}	3.49 ^{b}
	LM	2.26 ^{a}	1.72 ^{a}	1.16 ^{a}	1.34 ^{a}	1.32 ^{ab}	3.26 ^{b}
	LX	1.94 ^{ab}	1.60 ^{a}	1.22 ^{a}	1.23 ^{a}	1.18 ^{b}	4.20 ^{a}
	CK	1.00 ^{c}	0.87 ^{b}	0.67 ^{b}	1.20 ^{ab}	1.52 ^{a}	4.05 ^{a}

Note: Treatments with the same letter do not differ at the $p < 0.05$ level.

In the 20~40 cm soil layer, the carbon preservation capacity of the >5 mm particle size aggregates significantly increased by 64.0%, 126.0% and 94.0% in the FM, LM and

LX treatments, respectively, compared with that in the CK treatment. Compared with that in the CK treatment, the carbon preservation capacity of the <0.25 mm particle size aggregates significantly decreased by 19.5%and 13.8%, respectively ($p < 0.05$), in the LM and FM treatments. The carbon preservation capacity of <0.25 mm particle size aggregates in the LX treatment was significantly increased by 20.3% and 28.8% compared with that in the FM and LM treatments ($p < 0.05$).

3.5. Soil Organic Carbon and Microbial Biomass Carbon Content

3.5.1. Soil Organic Carbon Content

The soil organic carbon content under the different treatments is shown in Figure 6. In the 0–20 cm soil layer, the soil organic carbon content significantly increased by 14.8%, 21.4% and 11.9% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment, and the soil organic carbon content in the LM treatment significantly increased by 8.6% ($p < 0.05$) compared with that in the LX treatment among all three of the straw return methods. In the 20~40 cm soil layer, the soil organic carbon contents of the FM, LM and LX treatments significantly increased by 13.2%, 19.6% and 33.1%, respectively, ($p < 0.05$) compared with the CK treatment, and the soil organic carbon contents of the LX treatment significantly increased by 11.3% and 17.6%, respectively, ($p < 0.05$) compared with those of the LM and FM treatments among the three straw-returning methods.

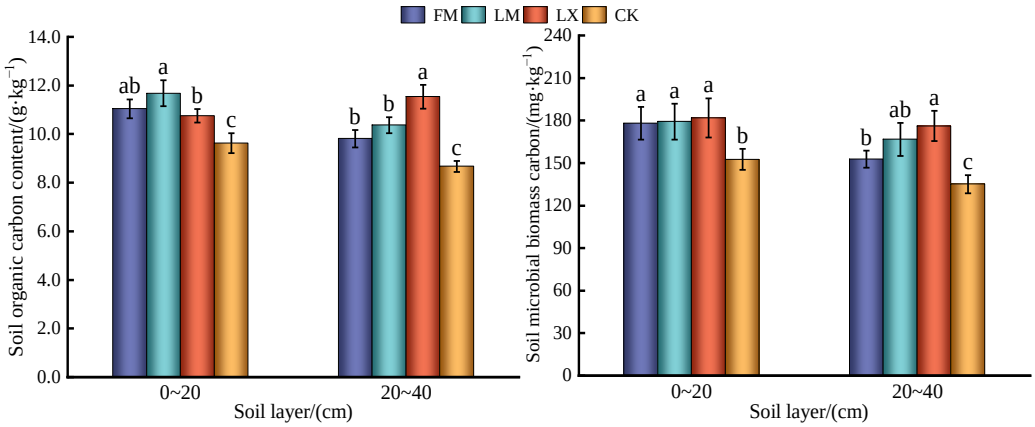

Figure 6. Soil organic carbon and microbial biomass carbon content under different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level.

3.5.2. Soil Microbial Biomass Carbon Content

The soil microbial biomass carbon content under the different treatments is shown in Figure 6. In the 0–20 cm soil layer, the soil microbial biomass carbon content significantly increased by 16.7%, 17.5% and 19.2% in the FM, LM and LX treatments, respectively, compared with that in the CK treatment. In the 20~40 cm soil layer, the soil microbial biomass carbon contents in the FM, LM and LX treatments significantly increased by 13.0%, 23.4% and 30.4%, respectively, ($p < 0.05$) compared with the CK treatment, and the soil microbial biomass carbon contents in the LX treatment significantly increased by 15.4%, respectively, ($p < 0.05$) compared with the FM treatment among the three straw-returning methods.

3.6. Corn Production

The corn yield under the different treatments is shown in Figure 7. In each growing year from 2021 to 2023, corn yields were highest for the LM treatments, ranging from 13.1 to 13.5 t/ha, and lowest for the CK treatments, ranging from 12.2 to 12.7 t/ha. Compared with those in the CK treatment, the three-year average corn yields in the FM, LM and LX treatments significantly increased by 5.2%, 7.2% and 4.1%, respectively ($p < 0.05$). Among the three straw return methods, the 3-year average corn yield under the LM treatment was 1.9% and 3.0% greater than those under the FM and LX treatments, respectively, and

the 3-year average corn yield under the FM treatment was 1.2% greater than that of the LX treatment.

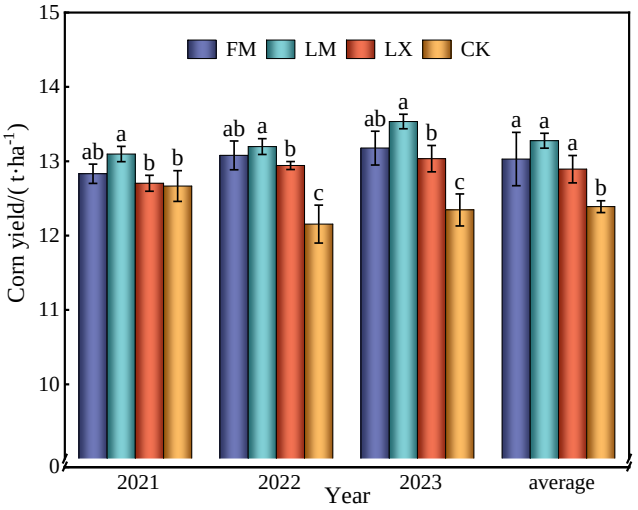

Figure 7. Corn yields under the different treatments. Treatments with the same letter do not differ at the $p < 0.05$ level. average: average corn yield, 2021–2023.

3.7. Relationships between Soil Indicators and Maize Yield

The correlations between the soil indicators and corn yield are shown in Figure 8. The Pearson correlation analysis revealed that the soil porosity, soil aggregate MWD, >5 mm aggregate carbon preservation capacity, 2–5 mm aggregate carbon preservation capacity, 1–2 mm aggregate carbon preservation capacity, soil microbial biomass carbon content and soil organic carbon content were positively correlated with corn yield. The aggregate destruction rate was negatively correlated with corn yield, and the carbon preservation capacity of the 0.5–1 mm aggregates, 0.25–0.5 mm aggregates and <0.25 mm aggregates was weakly correlated with corn yield.

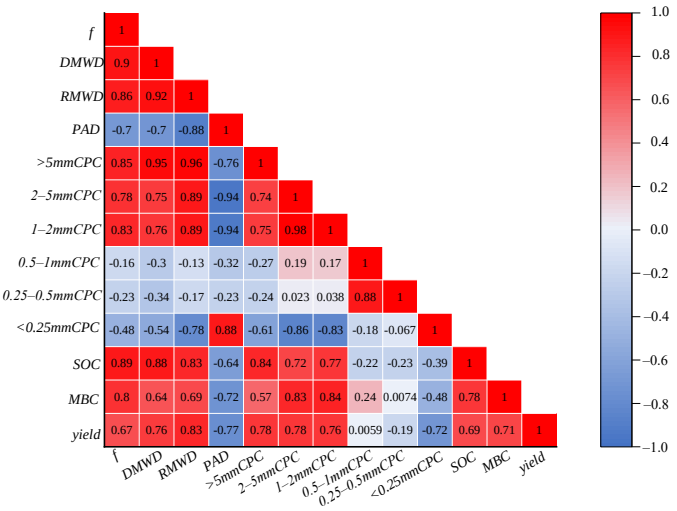

Figure 8. Correlations between the soil indicators and corn yield. f: soil porosity; DMWD: soil force stabilized aggregate MWD; WMWD: soil water-stable aggregate MWD; PAD: soil aggregate destruction rate; >5 mm CPC: >5 mm aggregate carbon preservation capacity; 2–5 mm CPC: 2–5 mm aggregate carbon preservation capacity; 1–2 mm CPC: 1–2 mm aggregate carbon preservation capacity; 0.5–1 mm CPC: 0.5–1 mm aggregate carbon preservation capacity; 0.25–0.5 mm CPC: 0.25–0.5 mm aggregate carbon preservation capacity; <0.25 mm CPC: <0.25 mm aggregate carbon preservation capacity; SOC: soil organic carbon; MBC: soil microbial biomass carbon; yield: corn production.

4. Discussion

4.1. Effects of Different Straw Return Methods on Soil Porosity

Soil porosity is an important parameter for measuring soil structure [33,34]. The results of this study revealed that three consecutive years of straw return to the field significantly decreased the soil bulk density and increased the soil porosity in the 0~20 cm and 20~40 cm soil layers. The reason for this result is that straw produces a large amount of decomposed matter, which forms a stable granular structure with the soil particles [35], thus reducing the soil bulk density and increasing the soil porosity. Many studies have confirmed that returning straw to the field is an effective measure for improving soil structure, with the effects of reducing soil bulk density and increasing porosity [36,37]. In addition, Leskiw et al. showed that rotary tillage of straw was effective in reducing soil bulk density and increasing soil porosity [38]. However, there were no significant differences in the soil bulk density or porosity of the LM, FM, and LX treatments, which may be due to the shorter and weaker effects of rotary tillage on soil loosening, and the overload pressure caused by field operations will recompact the soil and restore the soil density, which in turn will have a smaller effect on the soil bulk density and porosity.

4.2. Effects of Different Straw-Returning Methods on Soil Aggregate Fractions and Their Stability

As an important component of soil, soil aggregates store and transport soil nutrients, which are important factors in improving crop yields [39]. There are obvious differences in the distributions of soil aggregates obtained via dry sieving and wet sieving methods; for example, force-stable aggregates are dominated by >5 mm particle size aggregates, whereas water-stable aggregates are dominated by <0.25 mm particle size aggregates. In addition, the role of cementing substances is crucial in the formation of soil particles [40]. Among other things, calcium ions promotes the coalescence of negatively charged colloids (such as humus and clay particles) in the soil and thus has the ability to cement soil particles [11]. Previous studies have shown that straw could increase the amount of cementing substances in the soil [40], which promote the formation of macroaggregates by bonding the microaggregates to each other, thus increasing the content of the soil macroaggregates, which is consistent with the results of this study. However, exogenous organic matter may cause changes in exchange complexes, leading to the decomposition of some macroaggregates [41], which may be the reason why the number of >5 mm water-stable aggregates decreased after the straw was returned to the field. In addition, this study revealed that the content of soil macroaggregates in the 0–20 cm soil layer was significantly greater in the LM and FM treatments than in the LX treatment, possibly because no-tillage measures were used in the LM and FM treatments, which could minimize damage to the soil structure [42,43], and straw mulching reduces the impact of rainfall on the soil surface [44].

The soil aggregate destruction rate (PAD) is calculated from the force stability and water stability of aggregates >0.25 mm and can better reflect the soil aggregate stability; the smaller the PAD is, the greater the aggregate stability [45]. The PADs of the soil aggregates decreased significantly after straw return, indicating an increase in the stability of the aggregates. In addition, the mean mass diameter (MWD) of soil aggregates, which is used to assess aggregate stability by measuring the diameter of soil aggregates, is positively correlated with aggregate stability [46]. In this study, returning the straw to the field increased the MWD of the soil aggregates, which was attributed to the fact that the added straw promoted the formation of soil macroaggregates, and the higher the content of macroaggregates was, the greater the value of the MWD, which increased the stability of the aggregates. Moreover, the soil macroaggregate content was the highest in the LM treatment, and the MWD was the largest. This may be because the crops in the LM treated plots are planted in ridged fields, which can reduce water run-off and also increase the soil's water holding capacity, which is conducive to the retention of soil moisture [47,48], enhances soil aggregation and improves the stability of aggregates.

4.3. Effects of Different Straw-Returning Methods on Aggregate Organic Carbon and Soil Organic Carbon

It has been found that, as the particle size of the aggregates increases, so does the organic carbon content [49,50]. However, the results of this study revealed that most of the peak organic carbon content of the aggregates in each treatment was located in the 2–5 mm and 1–2 mm grain sizes, which indicated that the size of the organic carbon content of the aggregates was related to their range of grain size division. In addition, returning straw to the field can effectively increase the organic carbon content of aggregates, and this is probably because the increase in organic carbon content after straw application can compensate for the loss caused by the priming effect, thus increasing the organic carbon content of soil aggregates [51,52]. Previous studies have shown that large aggregates have a high carbon preservation capacity [53]. However, the results of this study revealed that the highest carbon preservation capacity of the aggregates in all the treatments was associated with the <0.25 mm aggregates, possibly because <0.25 mm water-stable aggregates have the highest mass content in each particle size, which can completely offset the effect of the low organic carbon content of <0.25 mm aggregates [54], thus increasing the carbon preservation capacity of the <0.25 mm aggregates.

In this study, the soil organic carbon content of the LM, FM and LX treatments was significantly greater than that of the CK treatment, which was mainly because the fact that added straw promotes microbial activity and increases soil microbial biomass carbon content [55,56], and this led to the accumulation of organic carbon in the soil. Yang et al. reported that the addition of straw increased the soil organic carbon content [57], which is consistent with the results of this study. In this study, the soil organic carbon content in the 0–20 cm soil layer following the LM and FM treatments was greater than that following the LX treatment, possibly because straw mulching effectively decreased the amount of soil water evaporation and accelerated the decomposition of straw [58], which resulted in an increase in the input to the soil in terms of organic carbon. In addition, with increasing soil depth, the soil organic carbon content in the 20~40 cm soil layer in the LM and FM treatments was significantly lower than that in the LX treatment because the rotary tillage operation used in the LX treatment put the straw in close contact with the soil, which promoted microbial activity, accelerated the decomposition of straw, and effectively improved the accumulation of soil organic carbon in the 20~40 cm soil layer [59].

4.4. Effects of Different Straw Return Methods on the Corn Yield

The results of the 3-year maize yield measurement revealed that, compared with the removal of the straw from the field, returning straw to the field effectively increased the maize yield, which might be related to changes in the soil structure and fertility. First, the LM, FM and LX treatments were able to reduce the soil bulk density and increase the soil porosity, providing a more suitable soil structure for the root penetration [60], which in turn increased crop yields. Second, the MWD of the soil aggregates increased significantly after the straw was returned to the field [61], which promoted the stability of the aggregates and improved the crop yield. This phenomenon was also consistent with the positive correlation between the aggregate MWD and maize yield in the correlation analysis. Third, returning straw to the field can effectively increase the soil organic carbon content and indirectly affect the CEC, which contributes to high crop yields [62]. In addition, the LM treatment significantly improved the stability of the aggregates and effectively increased the soil organic carbon content compared with the FM and LX treatments, which had a greater effect on increasing the crop yield.

5. Conclusions

Tillage practices and straw returning effectively decreased the soil bulk density, increased the soil porosity and improved the stability of the aggregates by promoting the formation of large soil aggregates >0.25 mm, with the ridge no-tillage with full straw mulching (LM) treatment having the greatest beneficial effect. In addition, the LM treat-

ment substantially increased the content of soil organic carbon in the 0~20 cm soil layer, whereas the LX treatment had a more prominent effect on the accumulation of soil organic carbon in the 20~40 cm soil layer. The maize yield data revealed that, compared with conventional planting (CK), the tillage practices and straw returning significantly increased the maize yield, and the LM treatment had the greatest yield increase effect. Moreover, this study revealed that soil porosity, average mass diameter of aggregates and soil organic carbon content were positively correlated with maize yield, which deserves further in-depth study. In summary, ridge no-tillage with full straw mulch (LM) had the greatest effect on improving the soil structure, soil organic carbon content and corn yield, and the results of this study provide both a theoretical and experimental bases for safeguarding the soil quality of black soil farmland and increasing crop yield.

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