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Article

Corn straw return effectively improves the stability and increases the carbon and nitrogen contents of water-stable aggregates in northeastern China black soil

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ABSTRACT: In view of the current situation of black soil degradation, straw return as an important conservation tillage measure has been extensively promoted. Based on ^{15}N tracing technology, this paper carried out experiments of different straw returning modes, including CK (conventional fertilizing tillage with straw-free returning), straw mulching (*i.e.*, M), straw mixed with topsoil (*i.e.*, T), and straw deep incorporation (*i.e.*, D), to explore the influence of straw returning on the distribution and stability, and the carbon and nitrogen content of water-stable aggregates in black soil, and to analyze the distribution and stability of aggregates on the carbon and nitrogen content of aggregates. The results showed that the macroaggregate content, mean weight diameter (MWD) and geometric mean diameter (GMD) of the returned soil layers were 16.53-84.65%, 16.73-128.73% and 23.47-97.14% higher than those in CK, respectively. The contents of organic carbon, total nitrogen and ^{15}N accumulation of aggregates in the straw-returning soil layer were 6.38-23.55%, 8.65-31.19% and 13.52-150.19% higher than those in CK, respectively. Pearson correlation analysis and redundancy analysis showed that the content of macroaggregates and stability of aggregates were positively correlated with the carbon and nitrogen contents. In conclusion, straw return significantly improved soil structure characteristics and carbon and nitrogen content. The results of this study provided a theoretical basis and technical guidance for farmland soil improvement in black soil areas, and selected an appropriate straw returning mode according to local soil conditions to maximize the effect of straw returning.

Key words: returning modes, ^{15}N, redundancy analysis, C/N.

INTRODUCTION

Aggregate is the basic unit of soil structure and nutrient storage, and its stability is one of the main indexes used to evaluate soil antierodibility and soil fertility (Mikha and Rice 2004). Natural and human factors affect the formation and stability of aggregates, and the transformation process of aggregates is closely related to soil carbon sequestration, which affects the sustainability, productivity, and crop growth of soil (Meng et al. 2019).

The northeast black soil region is an important industrial and commercial grain base in China, which produces approximately 35 billion kg of commodity grain every year. Due to the limitations of natural conditions, although the area of black land in China is relatively large, the grain output is not as high as that in the United States of America. The advantages of China's black soil are in the Northeast region, low population density, and mechanized production, which provide an important guarantee for national food security. The black soil area is mainly composed of black soil and chernozem. The soil aggregate structure is good, the salt content is low, and the humus layer is thick, but the soil layer is thin.

Black soil areas with abundant organic matter have relatively high soil erodibility factors, poor corrosion resistance, and high potential risk. Land use has made the black land degradation more serious (Li et al. 2006). At present, improper irrigation (Zhao et al. 2021), freeze-thaw cycles (Sun et al. 2021), overgrazing (Pei et al. 2021), disturbance of soil in cultivation and the use of agricultural machinery can compact soil and destroy the structure of aggregates. The destruction of soil aggregate structure not only reduces soil porosity, aeration, and permeability, but also the capacity of water and fertilizer conservation and water supply and fertilizer supply.

At present, straw return is an essential means of soil improvement (Du et al. 2013) that can improve soil aggregate distribution and stability. China is extremely rich in straw resources, with 718.8 million tons of resources, and the total nutrient resources of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) reached 6.3, 197.9 and 11.6 million tons, respectively (Song et al. 2018). Crop straw is not only a vehicle for matter, energy, and nutrients, but also a key to the physical, chemical and biological cycling of soil in agroecosystems (Turmel et al. 2015). Straw return affects the growth and reproduction of microorganisms and the production of extracellular organic polymers, improving the stability of aggregates (Xu et al. 2020). At the same time, it can increase the amount of organic carbon in macroaggregates, promote the transformation from microaggregates to macroaggregates, and improve soil structure (Zhang et al. 2016). Moreover, crop straw return increased invertase, urease and phosphatase activities and increased soil respiration efficiency (Zhang et al. 2018). Straw return reduces fertilizer input, air pollution, and environmental load (Yin et al. 2018). Overall, straw return can not only promote the development of root morphology, spatial distribution of the plough layer and crop growth, but also promote dry matter accumulation and increase crop yield (Liu et al. 2014).

Straw return can effectively improve soil structure and soil fertility. At present, research on the improvement of soil structure after straw returning is mostly limited to a single method (such as straw deep returning or straw mulching). Comprehensive experiments on the effects of different straw return modes on soil structure and nutrient content are rarely seen in literature.

Based on ^{15}N tracing technology, we studied the distribution of soil water-stable aggregates and the contents of carbon and nitrogen in aggregates under different straw return modes (CK; M; T; D), and explored the influence of aggregate distribution and stability on the carbon and nitrogen contents of aggregates. We assumed that straw return would improve soil structure and soil nutrients, and T treatment would have the best effect. The study has important supporting significance for restoring black soil, reducing fertilizer input, and developing sustainable agriculture.

MATERIALS AND METHODS

Site description

The experiment was conducted at the Black Soil Experimental Base of Jilin Agricultural University, Changchun City, Jilin Province, in Northeast China (N43°48'43.57", E125°23'38.50"). The climate is temperate subhumid with an average annual temperature of 4.8 °C and annual precipitation of 671 mm. The soil is classified as black soil assigned to the semiluvic subclass (31.69% sand, 26.40% silt, and 41.91% clay), which is equivalent to Typic Hapludoll according to the United States Department of Agriculture Soil Taxonomy (Zhu et al. 2015).

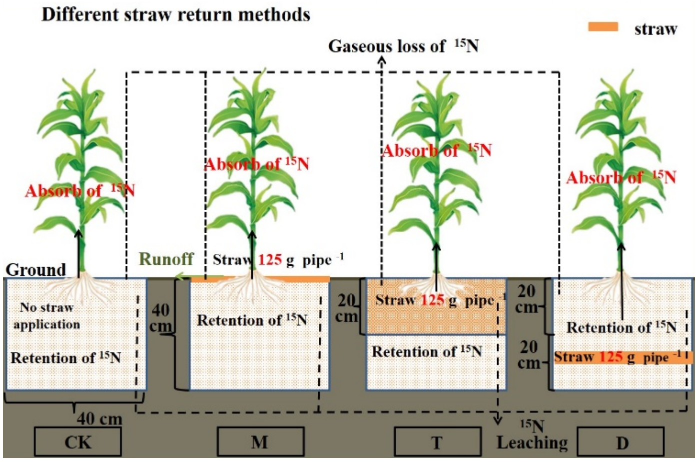
The experimental site is a long-term continuous cropping of corn. The pH (H_2O) of the soil (0-40 cm) was 6.11, and the soil contained 22.28 $g \cdot kg^{-1}$ organic matter, 1.15 $g \cdot kg^{-1}$ total N, 76.08 $mg \cdot kg^{-1}$ hydrolysable N, 20.74 $mg \cdot kg^{-1}$ available phosphorus (P), and 103.85 $mg \cdot kg^{-1}$ available potassium (K). The ^{15}N-labelled urea (containing 5.15% ^{15}N atom abundance) was produced by the Institute of Chemical Engineering (Shanghai, China).

Experimental design

The trial began in May 2017, and *in-situ* cultivation of polyvinyl chloride (PVC) pipe (i.e., 40 cm in length and 40 cm in diameter) was carried out in the field. Soil columns with a vertical diameter slightly larger than 40 cm and depth of 35 cm were dug out with a spade. The PVC pipe was sheathed on the soil column, and the height of the PVC pipe was 5 cm above the ground (to prevent fertilizer loss from surface runoff). The amount of straw returning was 10,000 kg/hm^2, and the equivalent PVC pipe area was 125 g. The straw material was corn straw, which was applied after the PVC pipe set up. There were four treatments, which were replicated three times (Fig. 1):

- CK: conventional fertilizing tillage with straw-free returning;
- Straw mulching (*i.e.*, M), simulated no-tillage straw mulching (Ye et al. 2021): corn straw was evenly spread in a PVC pipe;
- Straw mixed with topsoil (*i.e.*, T), equivalent to straw returning with rotary tilling (Wang et al. 2022): mixed the straw and 0-20 cm soil in the PVC pipe evenly;
- Straw deep incorporation (*i.e.*, D), equivalent to straw deep-buried returning (Dong et al. 2021): removed PVC pipe 30-cm soil layer, spread straw on the subsurface, and put soil back into PVC pipe according to the original soil layer.

Nitrogenous fertilizer (225 kg N·ha^{-1} – ^{15}N-labelled urea), phosphorus fertilizer (90 kg P_2O_5·ha^{-1} – potassium dihydrogen phosphate), and potassium fertilizer (120 kg K_2O·ha^{-1} – potassium sulfate) were applied as basal fertilizers and disposable application. Corn (*Zea mays* L.) was sown after fertilization. All the treatments received the same field management practices and were conducted in the field under natural water temperature conditions.



CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation.

Figure 1. Different straw return modes.

Sample collection and processing

Soil samples were collected on April 30, 2018 (^{15}N-labeled urea was applied for one year). When soil samples were taken (*i.e.*, 0-10, 10-20, 20-30, and 30-40 cm), we paid attention to the depth of the soil layer to prevent soil sample pollution. After soil samples were brought back to the laboratory, the original soil was gently peeled into small blocks of approximately 10 mm along the natural structure of the soil, and the deformation caused by external force was prevented in the peeling process. Finally, the soil sample was air-dry.

Analysis and determination

Regarding aggregate separation, > 2, 2-0.25, 0.25-0.53, and < 0.053 mm aggregates were separated using the wet sieve method (Elliott 1986). After soaking and wetting, the samples were vibrated up and down for 5 minutes, transferred to an aluminum box, and dried at 60 °C to constant weight. The mass of aggregates of each particle size was weighed after drying. The dried aggregates were ground and sieved before determining organic carbon, total nitrogen and 15N abundance. With 0.25 mm as the boundary, the aggregates were divided into macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm) (Zhu et al. 2021).

The abundance of ^{15}N in aggregates was determined by the Isoprime100 Mass Spectrometer (Elementar Analysensysteme GmbH Inc., Germany). Organic carbon and total N were measured with an elementer analyser (vario ISOTOPE select, German).

Calculations

Mean weight diameter (MWD) (Van Bavel 1950) (Eq. 1):

$$MWD = \sum_{i=1}^{n} (Wi * Xi) \,/\, \sum_{i=1}^{n} Wi \tag{1}$$

in which: *Wi*: the mass percent of aggregates in each size fraction (%); *Xi*: the average diameter of each size fraction (mm).

Geometric mean diameter (GMD) (Eqs. 2, 3 and 4):

$$GMD = \exp\left[\sum_{i}^{n} Wi\ln Xi \,/\, \sum_{i=1}^{n} Wi\right] \tag{2}$$

$$Q_i \text{ (organic carbon stock)} = C_i \times \rho i \times D \times Wi \times 10 \tag{3}$$

Q_i: the organic carbon storage of i-th grade aggregates, t/hm^2; C_i: the organic carbon content of i-th grade aggregates, g/kg; ρ_b: the soil bulk density, g/cm^3; *D*: the thickness of the soil layer (this experiment was 0.1 m) (Fan et al. 2021).

$$^{15}\text{N Ratio: } \frac{15N}{\text{Total nitrogen of aggregates}} * 100 \tag{4}$$

The ^{15}N accumulation--N (g·kg^{-1}) of water-stable aggregates was determined by Eq. 5.

$$N = N_0 \times A \tag{5}$$

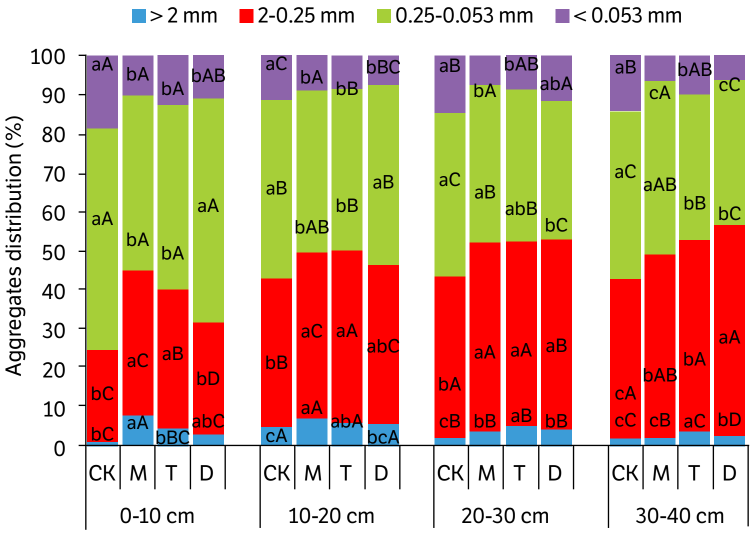
N: the total nitrogen of aggregates comes from ^{15}N fertilizer nitrogen content g·kg^{-1} (calculated value); N_0: total nitrogen content of aggregates (instrumental determination); APC^{15}N: ^{15}N fertilizer atoms in aggregates exceed (calculated value); APC^{15}N = [1-1000/(δ^{15}N + 1003.676)]; A: percentage of aggregate total nitrogen derived from ^{15}N fertilizer(%) (calculated value), A = APC^{15}N/C×100; C: labelled ^{15}N fertilizer abundance of ^{15}N (known) (abundance 5.15%, Shanghai Institute of Chemical Technology); δ^{15}N: instrumental determination.

Excel 2010 was used to process the raw data, and Origin2021, for graphing. Statistical Package for the Social Sciences (SPSS) Statistics 17.0 was used for the analysis of variance (ANOVA) (least significant difference–LSD, P = 0.05) and Pearson correlation analysis. The redundancy analysis (RDA) of the relationship between the distribution and stability and the carbon and nitrogen content of water-stable aggregates was carried out using CANOCO 5.

RESULTS

Distribution characteristics and stability of water-stable aggregates

Soil aggregates are important sites for organic nitrogen transformation and accumulation (Mao et al. 2015). Distribution and stability directly reflect the quality of soil structure. The distribution of water-stable aggregates is shown in Fig. 2. The main aggregates were 2-0.25 mm and 0.25-0.053 mm particles, accounting for 23.30-54.32% and 35.33-57.45%, respectively. The distribution of aggregates in the 0-10, 10-20, 20-30, and 30-40 cm layers was consistent, and the proportion of macroaggregates (> 2 and 2-0.25 mm) increased significantly in all layers in treatments M, T and D in relation to CK. Straw return can improve the distribution characteristics of soil water-stable aggregates.



*Columns represent means (n = 3) and bars represent the standard deviation; means with the same letter within groups are not significantly different at P < 0.05. Different lowercase letters indicate that the difference among treatments of each grain size at each depth reaches a significant level (*P* < 0.05), and different capital letters indicate that the difference among depths of each grain size at each treatment reaches a significant level (*P* < 0.05); CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation.

Figure 2. Distribution of soil water-stable aggregates under different straw return modes*.

The results showed that the stability of aggregates under different modes of straw return was significantly greater than that of CK (Table 1). The macroaggregate content of the soil layer in the returning treatment was significantly higher than that in the CK. Compared with CK, the proportion of macroaggregate in M (0-10 cm), T (10-20 cm), D (20-30 cm) and D (30-40 cm) increased by 84.65, 16.53, 21.93, and 32.33%. The MWD of the straw return treatment showed (Table 1) that, compared with CK, M increased 128.72 and 22.22% at 0-10 and 10-20 cm, respectively. T increased by 34.48% at 20-30 cm, followed by 16.73 and 34.48% at 10-20 and 30-40 cm, respectively. D significantly increased by 32.28% in the 30-40 cm soil layer. From the GMD results (Table 1), the straw return treatment could improve GMD compared with CK, but there were significant differences among soil layers. Among them, M increased significantly at 0-10 and 20-30 cm, by 97.14 and 39.42%, respectively, and T and D increased by 23.47 and 54.78% at 10-20 and 30-40 cm, respectively.

Different straw return modes changed the spatial distribution characteristics of macroaggregates, MWD and GMD in the 0-40 cm soil layer. In CK, T and D, the proportion of macroaggregates in the 10-20-cm soil layer was significantly higher than that in the other soil layers, while in M the proportion in the 0-10 cm soil layer was the highest. According to the spatial variation in MWD, the soil layer of 10-20 cm was the highest in all treatments, while it decreased with increasing depth in the 20-30 and 30-40 cm soil layers. The spatial distribution of GMD was different from that of MWD. CK was the largest in the 10-20 cm soil layer; M had no significant difference among soil layers; T and D were the largest in the 20-30 and 30-40 cm soil layers, respectively.

Table 1. Macroaggregates, mean weighted diameter (MWD) and geometric mean diameter (GMD) of water-stable aggregates under the different returns of corn straw*.

Soil depth (cm)	Treatment	> 0.25 mm (%)	MWD (mm)	GMD (mm)
0-10	CK	24.34 ± 0.60cB	0.42 ± 0.01dD	0.18 ± 0.01cC
	M	44.95 ± 4.19aB	0.95 ± 0.12aAB	0.36 ± 0.04aA
	T	40.13 ± 4.80aB	0.73 ± 0.08bC	0.29 ± 0.04bB
	D	31.52 ± 1.26bD	0.59 ± 0.03cC	0.25 ± 0.01bC

continue...

Table 1. Continuation,,,

Soil depth (cm)	Treatment	> 0.25 mm (%)	MWD (mm)	GMD (mm)
10-20	CK	42.99 ± 0.87bA	0.79 ± 0.02cA	0.32 ± 0.01bA
	M	49.53 ± 2.50aAB	0.97 ± 0.04aA	0.39 ± 0.03aA
	T	50.10 ± 3.13aA	0.92 ± 0.05abA	0.39 ± 0.03aA
	D	46.67 ± 1.32abC	0.87 ± 0.03bA	0.37 ± 0.02aB
20-30	CK	43.49 ± 0.98bA	0.66 ± 0.02cB	0.29 ± 0.02bB
	M	52.38 ± 0.39aA	0.83 ± 0.01bB	0.40 ± 0.02aA
	T	52.21 ± 3.41aA	0.88 ± 0.02aAB	0.40 ± 0.03aA
	D	53.03 ± 2.33aB	0.85 ± 0.01bAB	0.38 ± 0.03aB
30-40	CK	42.78 ± 0.78dA	0.61 ± 0.01cC	0.28 ± 0.00cB
	M	49.09 ± 2.10cAB	0.70 ± 0.03bC	0.37 ± 0.02bA
	T	52.86 ± 1.78bA	0.82 ± 0.02aBC	0.39 ± 0.01bA
	D	56.61 ± 1.77aA	0.81 ± 0.02aB	0.44 ± 0.02aA

CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation; *data are shown as the mean ± standard deviation (SD) (repeated three times). Different lowercase letters indicate that the difference among treatments of each grain size at each depth reaches a significant level ($P < 0.05$), and different capital letters indicate that the difference among depths of each grain size at each treatment reaches a significant level ($P < 0.05$).

Organic carbon content and organic carbon stock of soil and water-stable aggregates

Soil organic carbon (SOC) is an important cementation material that can enhance the aggregation between soil particles and promote the formation of aggregates (Wander and Bollero 1999, Eynard et al. 2005). Therefore, soil aggregates and soil organic carbon are inseparable, and their content directly affects the formation of aggregates. Straw return had a significant effect on the soil organic carbon content and organic carbon stock (Table 2). The soil organic carbon content of straw return was significantly higher than that of the control treatment, with M, T, D, and D increasing 26.57, 19.90, 30.44, and 31.46% of soil organic carbon in the 0-10, 10-20, 20-30, and 30-40 cm soil layers, respectively, compared with CK. The effect of straw return on soil organic carbon storage was different from that on soil organic carbon, and its content was related to soil organic carbon and soil bulk density. In this study, the return treatment was higher than CK in the 0-10- and 30-40-cm soil layers, and soil organic carbon storage was higher in T and D than in CK and M in the 10-20-cm soil layer. There was no significant difference among treatments in the 20-30-cm soil layer.

Table 2. Soil organic carbon and stocks with different straw return modes*.

Treatment	Soil organic carbon ($g·kg^{-1}$)				Soil organic carbon stock ($t·hm^{-2}$)			
	0-10 cm	10-20 cm	20-30 cm	30-40 cm	0-10 cm	10-20 cm	20-30 cm	30-40 cm
CK	13.13 ± 0.06dB	13.51 ± 0.25cA	12.27 ± 0.22cC	11.44 ± 0.2cD	15.08 ± 0.3bB	15.51 ± 0.46bAB	16.12 ± 0.37aA	15.03 ± 0.41bB
M	16.62 ± 0.22aA	15.24 ± 0.22abB	13.44 ± 0.17bC	13.04 ± 0.23bC	16.08 ± 0.12aA	14.44 ± 0.65bB	16.53 ± 0.58aA	16.04 ± 0.16aA
T	15.38 ± 0.49bA	16.2 ± 1.06aA	13.72 ± 0.14bB	13.3 ± 0.15bB	16.01 ± 0.51aA	16.85 ± 0.91aA	16.33 ± 0.71aA	15.82 ± 0.44abA
D	14.25 ± 0.28cB	14.82 ± 0.11bB	16.01 ± 0.92aA	15.04 ± 0.49aAB	16.16 ± 0.29aA	16.8 ± 0.02aA	16.35 ± 1.88aA	15.31 ± 0.65abA

CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation; *data are shown as the mean ± standard deviation (SD) (repeated three times). Different lowercase letters indicate that the difference among treatments of each grain size at each depth reaches a significant level ($P < 0.05$), and different capital letters indicate that the difference among depths of each grain size at each treatment reaches a significant level ($P < 0.05$).

The organic carbon and organic carbon storage of soil water stable aggregates in different straw returning modes is shown in Table 3. The content and storage of organic carbon in soil aggregates decreased with soil depth. The content of organic carbon in soil aggregates was higher than that in CK in the straw-returning soil layer. The organic carbon storage of macroaggregates was significantly higher than that of CK, while the organic carbon storage of microaggregates was lower than that of CK in the straw-returning soil layer. The content of organic carbon in the soil aggregates of the straw-returning soil layer was 10.20-39.72% higher than that in the CK. The organic carbon storage of macroaggregates in the soil layer with straw return was 0.91-587.60% higher than that in the CK. The contribution rate of the aggregate organic carbon stock to the soil organic carbon stock was obtained from the ratio of the aggregate organic carbon stock to the soil organic carbon stock at each grain level. The contribution rate of aggregate organic carbon stocks was mainly from 2-0.25-mm aggregates and 0.25-0.053-mm aggregates, with the total contribution rate of 70.72-93.35%. The organic carbon stock contribution rate of aggregates was the same as that of the organic carbon stock among the different treatments.

Table 3. Organic carbon, organic carbon stock and organic carbon stock contribution rate to soil of water-stable aggregates with different straw return modes*.

Soil depth (cm)	Treatment	Organic carbon (g·kg^{-1})					Organic carbon stock (t·hm^{-2})			Organic carbon stock contribution rate to soil (%)			
		> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm	> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm	> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm
0-10	CK	13.19 ± 0.29bA	14.38 ± 0.39bA	12.32 ± 0.21cA	12.10 ± 0.29bA	0.16 ± 0.03cD	3.85 ± 0.21bB	8.07 ± 0.39aA	2.58 ± 0.30aC	1.04	25.52	53.52	17.13
	M	14.70 ± 0.61bB	16.88 ± 0.59aA	12.97 ± 0.32bA	14.67 ± 0.94aA	1.08 ± 0.37aB	5.95 ± 0.53aA	5.55 ± 0.63cA	1.39 ± 0.29bB	6.74	37.00	34.52	8.67
	T	18.43 ± 0.91aA	15.86 ± 0.36abA	13.58 ± 0.33aA	13.43 ± 0.39abA	0.81 ± 0.14abB	5.95 ± 0.95aA	6.65 ± 0.35bA	1.78 ± 0.51bB	5.06	37.15	41.57	11.12
	D	17.53 ± 2.61aA	16.70 ± 1.97aA	13.17 ± 0.24abA	13.47 ± 1.10abA	0.57 ± 0.03bD	5.42 ± 0.76aB	8.57 ± 0.43aA	1.69 ± 0.34bC	3.53	33.56	53.06	10.43
10-20	CK	13.08 ± 0.31cA	13.53 ± 0.15cB	11.79 ± 0.18bB	11.71 ± 0.06cAB	0.72 ± 0.07bC	5.94 ± 0.22cA	6.21 ± 0.21abA	1.50 ± 0.04aB	4.65	38.28	40.01	9.70
	M	16.09 ± 0.47aA	15.05 ± 0.46bB	12.98 ± 0.87aA	14.21 ± 0.38aA	1.08 ± 0.20aC	6.06 ± 0.30cA	5.12 ± 0.57cB	1.20 ± 0.23bC	7.46	41.93	35.48	8.31
	T	14.33 ± 1.00bB	16.66 ± 1.20aA	12.92 ± 0.06aB	12.46 ± 0.41bB	0.89 ± 0.07abC	7.62 ± 0.29aA	5.58 ± 0.69bcB	1.11 ± 0.09bC	5.31	45.25	33.13	6.57
	D	13.86 ± 0.20bcB	14.67 ± 0.51bcB	12.87 ± 0.14aAB	12.41 ± 0.32bA	0.89 ± 0.07abB	6.82 ± 0.46bA	6.66 ± 0.20aA	1.08 ± 0.19bB	5.31	40.61	39.64	6.42
20-30	CK	12.75 ± 0.27dA	12.64 ± 0.19bC	11.71 ± 0.31cB	12.00 ± 0.21cA	0.35 ± 0.03cC	6.88 ± 0.10bA	6.42 ± 0.37aA	2.33 ± 0.31aB	2.14	42.68	39.82	14.45
	M	13.53 ± 0.06cC	13.36 ± 0.29abC	12.43 ± 0.21bA	12.60 ± 0.17bcB	0.61 ± 0.05bC	8.01 ± 0.41aA	6.13 ± 0.41aB	1.17 ± 0.50bC	3.70	48.46	37.09	7.06
	T	14.62 ± 0.09bB	14.13 ± 1.00aB	13.07 ± 0.19aB	13.23 ± 0.20abA	0.84 ± 0.10aC	7.94 ± 0.29aA	6.08 ± 0.70aB	1.38 ± 0.28bC	5.14	48.61	37.24	8.45
	D	15.69 ± 0.30aAB	13.93 ± 0.49aB	12.82 ± 0.31abAB	13.55 ± 0.65aA	0.65 ± 0.05bD	6.94 ± 0.37bA	4.62 ± 0.38bB	1.62 ± 0.42abC	3.95	42.46	28.26	9.91
30-40	CK	13.05 ± 0.07bA	12.58 ± 0.70bC	10.10 ± 0.20bC	10.97 ± 0.76bB	0.21 ± 0.01cD	6.87 ± 0.49bA	5.70 ± 0.09bB	2.05 ± 0.23aC	1.40	45.73	37.93	13.67
	M	14.82 ± 0.76abB	14.38 ± 0.43aB	12.01 ± 0.11aA	11.78 ± 0.57abB	0.30 ± 0.05bcD	8.39 ± 0.43aA	6.58 ± 0.16aB	0.92 ± 0.15cC	1.87	52.30	41.05	5.72
	T	15.56 ± 2.62abB	14.07 ± 0.58aB	12.28 ± 0.33aC	12.04 ± 0.21abB	0.63 ± 0.12aD	8.29 ± 0.80aA	5.40 ± 0.12bB	1.46 ± 0.19bC	3.98	52.43	34.13	9.21
	D	15.84 ± 0.56aAB	14.45 ± 0.09aB	12.47 ± 0.32aB	12.83 ± 0.85aA	0.37 ± 0.02bC	8.00 ± 0.43aA	4.73 ± 0.31cB	0.80 ± 0.24cC	2.42	52.23	30.88	5.25

CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation; *data are shown as the mean ± standard deviation (SD) (repeated three times); different lowercase letters indicate that the difference among treatments of each grain size at each depth reaches a significant level ($P < 0.05$), and different capital letters indicate that the difference among depths of each grain size at each treatment reaches a significant level ($P < 0.05$).

Total nitrogen and ^{15}N content of water-stable aggregates

The results showed that the total nitrogen and ^{15}N accumulation of soil aggregates in different straw return modes decreased with depth (Table 4). Compared with CK, the total nitrogen and 15N accumulation of macroaggregates in the straw-returning soil layer were increased. In the 0-10 cm soil layer, in the 2-0.25 mm aggregates the total nitrogen and ^{15}N accumulation of T were higher, increasing by 14.16 and 1,077.36% respectively; in the > 2 mm aggregates, the total nitrogen of M and the ^{15}N accumulation of D were higher, increasing by 20.36 and 123.22%, respectively. The total nitrogen of > 2 mm aggregates in the 20-30 cm soil layer treated with M increased by 7.19%, and T was higher in the 2-0.25 mm aggregates of the 10-20 cm soil layer, increasing by 31.19%. The total nitrogen of macroaggregates (> 2 and 2-0.25 mm) in D increased in the 10-40 cm soil layer, with an average increase of 13.48%. The ^{15}N accumulation of macroaggregates (> 2 and 2-0.25 mm) in soil layers of 10-20, 20-30 and 30-40 cm was the highest in T, which was 88.87 and 150.19%, 156.70 and 99.62%, 163.27 and 82.81% higher than CK, respectively.

The percentage of ^{15}N accumulation/total nitrogen in water-stable aggregates was higher than that of CK in different modes of straw return (Table 4). At 0-10 and 10-20 cm, except for 0-10 cm aggregates of > 2 mm, the 15N/total nitrogen of aggregates was the highest for T. In the 20-30- and 30-40-cm soil layers, the proportion of ^{15}N in each particle size aggregate was the highest in D, except in the 30-40-cm soil layer, in which 0.25-0.053 mm aggregates T was the highest, *i.e.*, T and D significantly increased the proportion of ^{15}N in total nitrogen in the 10-20-, 20-30- and 30-40-cm soil layers, respectively. Regarding ^{15}N accumulation of aggregates in the 0-40-cm soil layer, T and D was better than that in M.

Table 4. Total nitrogen content and ^{15}N accumulation of soil water-stable aggregates and proportion in different straw return modes*.

Soil depth (cm)	Treatment	Total N (g·kg^{-1})				Accumulation of ^{15}N(g·kg^{-1})				^{15}N/total N (%)			
		> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm	> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm	> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm
0-10	CK	1.56 ± 0.09bA	1.20 ± 0.04bA	1.13 ± 0.03cA	1.10 ± 0.03cA	0.023 ± 0.002cB	0.022 ± 0.003cA	0.012 ± 0.004bB	0.011 ± 0.001bC	1.50	1.75	0.89	0.86
	M	1.88 ± 0.16aA	1.36 ± 0.00aA	1.27 ± 0.04aA	1.26 ± 0.03aA	0.041 ± 0.002abA	0.033 ± 0.003bA	0.028 ± 0.001aB	0.026 ± 0.006aC	2.16	2.41	1.90	1.66
	T	1.83 ± 0.20abA	1.36 ± 0.02aA	1.24 ± 0.02abA	1.21 ± 0.02abB	0.040 ± 0.010bB	0.042 ± 0.004aA	0.031 ± 0.007aB	0.030 ± 0.011aB	2.23	3.00	2.13	1.86
	D	1.75 ± 0.09abA	1.35 ± 0.12aA	1.18 ± 0.05bcA	1.19 ± 0.03bB	0.052 ± 0.006aA	0.034 ± 0.003bA	0.014 ± 0.001bA	0.025 ± 0.003aA	2.97	2.37	0.93	1.59
10-20	CK	1.27 ± 0.03bB	1.10 ± 0.02cB	1.10 ± 0.07cA	1.05 ± 0.03bB	0.032 ± 0.002bB	0.026 ± 0.002cA	0.021 ± 0.002dB	0.024 ± 0.003bC	2.71	2.39	1.84	2.39
	M	1.37 ± 0.01aB	1.25 ± 0.01bB	1.21 ± 0.03abA	1.28 ± 0.21aA	0.039 ± 0.001bA	0.036 ± 0.002bcA	0.025 ± 0.001cB	0.032 ± 0.001bC	2.88	2.86	2.14	2.78
	T	1.39 ± 0.05aB	1.44 ± 0.12aA	1.28 ± 0.04aA	1.28 ± 0.05aA	0.067 ± 0.026aA	0.066 ± 0.014aA	0.042 ± 0.000aB	0.045 ± 0.010aC	4.95	4.53	3.38	3.69
	D	1.43 ± 0.04aC	1.13 ± 0.03bcB	1.17 ± 0.01bcA	1.13 ± 0.03abB	0.050 ± 0.008abB	0.041 ± 0.001bA	0.029 ± 0.002bC	0.031 ± 0.002bC	3.71	3.68	2.29	2.53
20-30	CK	1.35 ± 0.04bB	1.14 ± 0.04cAB	0.97 ± 0.01cB	1.04 ± 0.03cB	0.023 ± 0.002bA	0.019 ± 0.003bA	0.011 ± 0.001cBC	0.014 ± 0.002dC	2.06	1.75	1.10	1.68
	M	1.45 ± 0.03aB	1.19 ± 0.01bC	1.01 ± 0.01bB	1.19 ± 0.06bA	0.029 ± 0.001abB	0.024 ± 0.001aB	0.017 ± 0.000bC	0.019 ± 0.001cD	2.26	1.96	1.70	1.97
	T	1.46 ± 0.08aB	1.24 ± 0.03aB	1.16 ± 0.01aB	1.32 ± 0.02aA	0.033 ± 0.003abA	0.024 ± 0.002aA	0.019 ± 0.001abC	0.022 ± 0.001bC	2.68	1.88	1.59	2.03
	D	1.47 ± 0.03aC	1.25 ± 0.02aAB	1.14 ± 0.03aA	1.29 ± 0.05aA	0.045 ± 0.021aA	0.024 ± 0.002aA	0.021 ± 0.003aB	0.033 ± 0.001aC	3.75	2.03	1.84	3.13
30-40	CK	1.32 ± 0.05bB	1.03 ± 0.04cC	0.86 ± 0.06cC	0.96 ± 0.02cC	0.010 ± 0.003bA	0.009 ± 0.002bA	0.006 ± 0.002bB	0.008 ± 0.003bC	0.95	0.85	0.61	0.80
	M	1.56 ± 0.16aB	1.15 ± 0.02bD	0.98 ± 0.07bB	1.09 ± 0.02bA	0.021 ± 0.002abA	0.017 ± 0.002aA	0.009 ± 0.000abC	0.017 ± 0.001aC	1.64	1.32	0.77	1.57
	T	1.61 ± 0.07aB	1.21 ± 0.02aB	1.09 ± 0.06aC	1.07 ± 0.02bC	0.022 ± 0.001abA	0.018 ± 0.001aA	0.013 ± 0.003aB	0.019 ± 0.002aB	1.78	1.38	0.97	1.78
	D	1.59 ± 0.06aB	1.22 ± 0.04aB	1.07 ± 0.02abB	1.17 ± 0.05aB	0.032 ± 0.011aA	0.018 ± 0.001aA	0.011 ± 0.002aA	0.017 ± 0.002aC	2.71	1.63	0.84	1.48

CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation; *data are shown as the mean ± standard deviation (SD) (repeat three times), different lowercase letters indicate that the difference among treatments of the each grain size at the each depth reaches a significant level ($P < 0.05$), and different capital letters indicate that the difference among depths of the each grain size at the each treatment reaches a significant level ($P < 0.05$).

C/N in water-stable aggregates

Soil C/N is an index used to evaluate the degree of decomposition of organic matter. The lower ratio can indicate the soil organic matter decomposition status and its stability; the higher ratio indicates a fresh input of soil organic matter (Schipper and Sparling 2011).

The C/N of each size aggregate of different straw returning modes is shown in Table 5. The C/N of the 2-0.25- and 0.25-0.053-mm aggregates was higher, reaching 11.08-12.54 and 10.11-12.28, respectively, and that of the > 2 and < 0.053 mm aggregates was lower, reaching 7.85-11.73 and 9.75-11.66, respectively. The C/N of aggregates in distinct soil layers and particle sizes was different, but the C/N of straw-returning soil was higher than that of CK. In 0-10 cm, > 2 mm and 0.25-0.053 mm were higher in T and D, respectively, 19.67 and 2.75% higher than CK. In 10-20 cm, the C/N of > 2 mm aggregates was higher for M, while the C/N of aggregates in 2-0.25 and 0.25-0.053 mm aggregates were higher for D, which were 13.47, 5.59, and 2.58% higher than CK, respectively. At 20-30 cm, the C/N of aggregates in > 2 and 0.25-0.053 mm were D and M, respectively, 13.27 and 2.31% higher than that of CK. At 30-40 cm, the 2-0.25 mm of M was higher than that of CK by 2.69%. The results showed that the water stable aggregate C/N of the > 2, 2-0.25, and 0.25-0.053 mm fractions was mainly increased by straw return.

Table 5. Water-stable aggregate C/N under different straw return modes*.

Soil depth (cm)	Treatment	C/N			
		> 2 mm	2-0.25 mm	0.25-0.053 mm	< 0.053 mm
0-10	CK	8.46 ± 0.68abC	12.04 ± 0.67aA	10.88 ± 0.13aB	10.97 ± 0.13aB
	M	7.85 ± 0.84bC	12.45 ± 0.44aA	10.19 ± 0.04bB	11.66 ± 1.04aA
	T	10.12 ± 0.62aB	11.63 ± 0.37aA	10.93 ± 0.27aA	11.09 ± 0.22aA
	D	10.09 ± 1.86aB	12.37 ± 0.39aA	11.18 ± 0.65aAB	11.29 ± 0.98aAB
10-20	CK	10.33 ± 0.22bC	12.32 ± 0.28abA	10.75 ± 0.48abBC	11.19 ± 0.29aB
	M	11.73 ± 0.31aA	12.08 ± 0.40abA	10.72 ± 0.48abA	11.33 ± 1.87aA
	T	10.32 ± 0.94bAB	11.59 ± 0.96bA	10.11 ± 0.33bB	9.75 ± 0.08aB
	D	9.71 ± 0.27bC	13.00 ± 0.14aA	11.03 ± 0.24aB	10.94 ± 0.39aB
20-30	CK	9.43 ± 0.10bC	11.08 ± 0.24aB	12.01 ± 0.37aA	11.59 ± 0.40aAB
	M	9.33 ± 0.16bC	11.24 ± 0.35aB	12.29 ± 0.26aA	10.61 ± 0.60bB
	T	10.07 ± 0.57aB	11.40 ± 1.02aA	11.22 ± 0.20bA	10.04 ± 0.22bB
	D	10.68 ± 0.27aA	11.18 ± 0.26aA	11.28 ± 0.60bA	10.53 ± 0.49bA
30-40	CK	9.87 ± 0.36aB	12.22 ± 0.26abA	11.75 ± 0.91aA	11.41 ± 0.85aA
	M	9.58 ± 0.96aC	12.54 ± 0.44aA	12.24 ± 0.87aAB	10.86 ± 0.69aBC
	T	9.70 ± 2.04aA	11.62 ± 0.38bA	11.24 ± 0.30aA	11.22 ± 0.26aA
	D	9.98 ± 0.63aB	11.87 ± 0.44abA	11.66 ± 0.48aA	11.00 ± 0.62aAB

CK: conventional fertilization and cultivation without straw return; M: corn straw mulching; T: corn straw mixed with topsoil; D: corn straw deep incorporation; *data are shown as the mean ± standard deviation (SD) (repeat three times), different lowercase letters indicate that the difference among treatments of each grain size at each depth reaches a significant level ($P < 0.05$), and different capital letters indicate that the difference among depths of each grain size at each treatment reaches a significant level ($P < 0.05$).

Pearson correlation analysis and redundancy analysis of soil aggregate distribution and stability with aggregate organic carbon content, organic carbon storage, nitrogen content, and ^{15}N accumulation

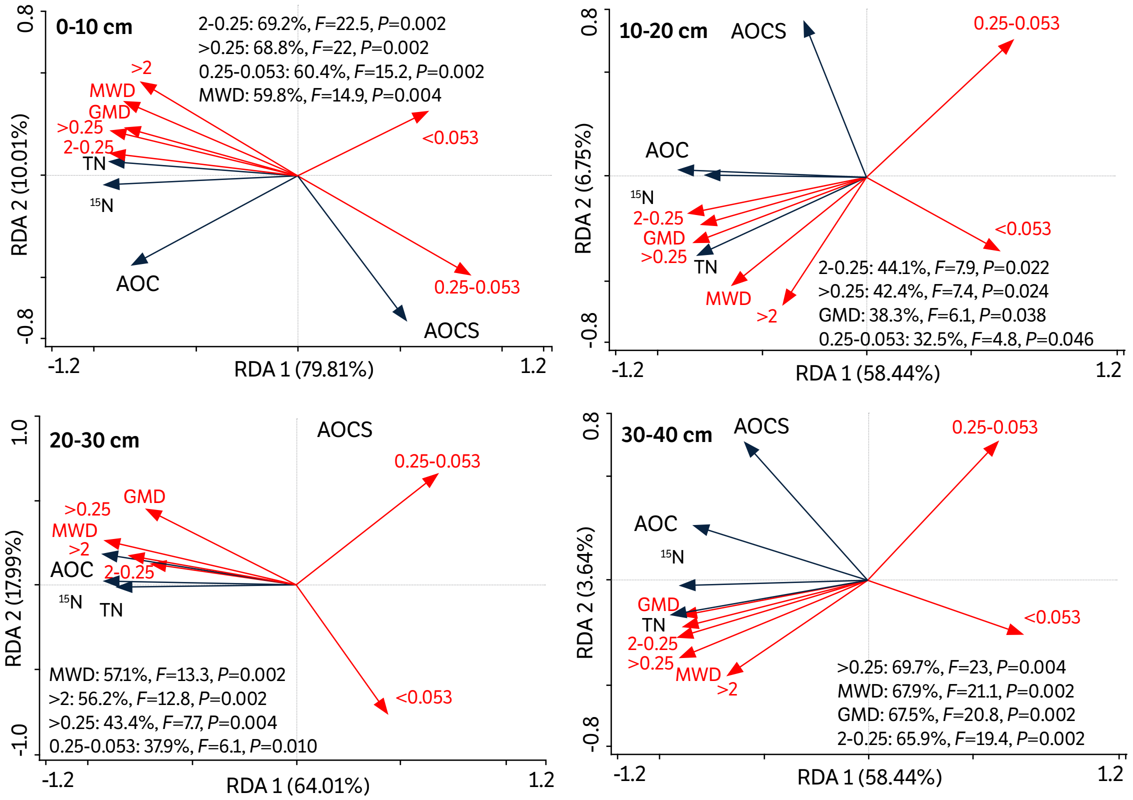
Correlation analysis results between the distribution and stability of aggregates in different soil layers under different straw return methods and soil aggregate organic carbon content, organic carbon stock, total nitrogen content and ^{15}N accumulation are shown in Table 6. The contents of organic carbon, total nitrogen and ^{15}N in aggregates were positively correlated with the contents of macroaggregates (> 2, 2-0.25, > 0.25 mm), MWD and GMD, and negatively correlated with the contents of microaggregates (0.25-0.053 and < 0.053 mm). However, the correlation between aggregate organic carbon stock and aggregate distribution and stability was not consistent, which may be the result of joint calculation of organic carbon stock, aggregate content, and other elements. In general, the increase in macroaggregates and stability of aggregates is conducive to the increase in the carbon and nitrogen contents of aggregates.

Table 6. Pearson correlation analysis of soil water-stable aggregate distribution and stability with aggregate organic carbon content, organic carbon stock, nitrogen content, and ^{15}N accumulation.

Soil layer (cm)	Indexes	Aggregate size (mm)					MWD (mm)	GMD (mm)
		> 2	2-0.25	0.25-0.053	< 0.053	> 0.25		
0-10	AOC	0.449	0.696*	-0.459	-0.677*	0.652*	0.550	0.594*
	AOCS	-0.721**	-0.564	0.816**	0.085	-0.639*	-0.698*	-0.607*
	TN	0.848**	0.904**	-0.809**	-0.720**	0.929**	0.906**	0.904**
	15N	0.677*	0.887**	-0.814**	-0.569	0.863**	0.771**	0.784**
10-20	AOC	0.485	0.727*	-0.581*	-0.637*	0.748**	0.659*	0.747**
	AOCS	-0.316	0.128	0.281	-0.481	0.020	-0.177	0.083
	TN	0.576*	0.761**	-0.832*	-0.357	0.802**	0.733**	0.732**
	15N	0.276	0.674*	-0.573	-0.436	0.645*	0.475	0.599*
20-30	AOC	0.942**	0.634*	-0.513	-0.512	0.760**	0.918**	0.726**
	AOCS	0.112	0.039	0.620*	-0.600*	0.060	0.121	0.301
	TN	0.881**	0.666*	-0.685*	-0.382	0.772**	0.883**	0.690*
	15N	0.838**	0.631*	-0.628*	-0.381	0.733**	0.840**	0.641*
30-40	AOC	0.573	0.642*	-0.258	-0.760**	0.673*	0.709**	0.726**
	AOCS	0.062	0.371	0.087	-0.618*	0.345	0.263	0.411
	TN	0.761**	0.889**	-0.733**	-0.653*	0.927**	0.943**	0.890**
	15N	0.667*	0.865**	-0.665*	-0.667*	0.890**	0.877**	0.862**

MWD: mean weight diameter; GMD: geometric mean diameter; AOC: aggregate organic carbon; AOCS: aggregate organic carbon stock; TN: total nitrogen content of aggregates; ^{15}N: ^{15}N accumulation of aggregates; *P < 0.05; **P < 0.01.

The dominant factors affecting the carbon and nitrogen content of soil aggregates were explored through RDA (Fig. 3). In the 0-10-cm soil layer, two ordination axes explained 89.82% of the total variation, which indicated that the two ordination axes could reflect most of the information about the impact of soil aggregate distribution and stability on soil carbon and nitrogen content. Among them, the vector weights of 2-0.25-mm aggregates (69.2%), > 0.25-mm aggregates (68.8%), 0.25-0.053-mm aggregates (60.4%) and MWD (59.8%) were larger, which was the dominant factor affecting the change in aggregate carbon and nitrogen content. In the 10-20-cm soil layer, the two ranking axes explained 65.19% of the total variation, in which the vector weights of 2-0.25-mm aggregates (44.1%), > 0.25-mm aggregates (42.4%), GMD (38.3%) and 0.25-0.053-mm aggregates (32.5%) were larger. In the 20-30-cm soil layer, the two ranking axes explained 82% of the total variation, among which MWD (57.1%), > 2-mm aggregates (56.2%), > 0.25-mm aggregates (43.4%) and 0.25-0.053-mm aggregates (37.9%) had higher vector weights. In the 30-40-cm soil layer, the two ranking axes explained 84.28% of the total variation, and the vector weights of > 0.25-mm aggregates (69.7%), MWD (67.9%), GMD (67.5%) and 0-0.25-mm aggregates (65.9%) were larger. According to Pearson correlation analysis, the carbon and nitrogen contents of aggregates were positively correlated with the contents of macroaggregates, MWD and GMD, and negatively correlated with the contents of microaggregates. The improvement of soil physical characteristics can be achieved by straw return to promote the aggregation of microaggregates to macroaggregates and increase the carbon and nitrogen contents of aggregates.



RDA: redundancy analysis; *> 2: > 2 mm aggregate content; 2-0.25: 2-0.25-mm aggregate content; 0.25-0.053: 0.25-0.053-mm aggregate content; < 0.053: < 0.053-mm aggregate content; > 0.25: > 0.25-mm aggregate content; MWD: mean weight diameter; GMD: geometric mean diameter; AOC: aggregate organic carbon; AOCS: aggregate organic carbon stock; TN: total nitrogen content of aggregates; 15N: 15N accumulation of aggregates.

Figure 3. Redundancy analysis of soil water-stable aggregate distribution and stability with aggregate organic carbon content, organic carbon stock, nitrogen content, and 15N accumulation.

DISCUSSION

Improving the composition and stability of soil macroaggregates by straw return

Macroaggregates are formed from small aggregates cemented with unstable cementitious agents with high carbon content (*i.e.*, fungal mycelia, roots, microbial, and plant-derived polysaccharides) (Song et al. 2021). This paper showed that straw return could significantly improve the composition and stability of soil aggregates, mainly by increasing the proportion of soil aggregates, MWD and GMD. Many studies have noticed that straw return provides the soil with exogenous organic matter; on the other hand, fresh organic matter as a cementing material formed by aggregates also promotes the formation of soil aggregates and the stability of aggregates (Sodhi et al. 2009).

Notably, straw is not completely exposed to air, less organic carbon is lost in the process of straw decomposition, and greater moist microaggregates of cemented materials are formed and connected with colloidal minerals, thus improving the content and stability of soil macroaggregates in the returning soil layer (Zhang et al. 2021). The results in this paper showed that the proportion of water-stable aggregates in the 20-40-cm soil layer significantly increased by 15.4% under T and D. However, straw mulching treatment was applied to the soil surface, and a large amount of organic N was imported into the soil surface, combined with microbial activities, thus improving the aggregation of the soil layer from aggregate to macroaggregate. Therefore, microbial activities also effectively promote the formation of soil aggregates.

Increasing the content of carbon and nitrogen in soil water-stable aggregates by straw return

Soil organic carbon plays a key role in the soil material cycle and it is an important part of the soil carbon pool. Its content can be used to effectively evaluate soil quality. Its composition and structure changes are closely related to soil properties and fertility (Dong et al. 2017). In addition, soil organic carbon is an important cementation material that can promote the aggregation of soil to form aggregate structures. The aggregates are coated with most of the soil organic carbon to prevent it from being decomposed by microorganisms, thus improving the stability of the soil structure, which is also more stable due to the presence of organic carbon (Meng et al. 2019, Fan et al. 2021). Research shows that nearly 90% of soil organic carbon in the topsoil is located in aggregates (Liu et al. 2011).

The application of organic materials provides an important source for the accumulation of soil organic carbon and total nitrogen (Huang et al. 2022). The enhancement of microbial activity will significantly improve the activity of soil-related enzymes, which can accelerate the microbial decomposition of straw, release carbon and nitrogen in straw to increase soil nutrients, and promote microbial activity (Zhou et al. 2022). Carbon and nitrogen in aggregates benefit from the adsorption and protection of aggregates, and the amount of carbon and nitrogen decomposed by soil microorganisms is greatly reduced, improving soil organic matter resilience (Six et al. 1998, Zhang et al. 2020).

In this study, M can promote the accumulation of SOC by reducing soil disturbance and increasing the input of exogenous carbon (Lu and Liao 2017). The straw of T was fully in contact with the soil, which accelerated the decomposition of straw by microorganisms and the accumulation of surface organic carbon (Henriksen and Breland 2002). Compared with M and T, D returns straw to the soil subsurface, forming a straw layer in the deep soil layer, improving microbial metabolic activity, facilitating the formation of subsurface soil humus and soil carbon fixation, effectively avoiding runoff and volatilization of nutrient elements (Muhammad et al. 2006, Zhu et al. 2016).

Nitrogen is a key nutrient in the soil and it is the largest element absorbed biomass by plants from the soil. It plays a major role in maintaining the composition and function of terrestrial ecosystems (Feng et al. 2015), and its dynamic changes are often consistent with those of organic carbon (Chen et al. 2013). The results of this study showed that total N and ^{15}N accumulation of straw mulching tillage in the 0-10-cm soil layer were significantly higher than other treatments, with contribution rates of 51.4 and 55.1%, respectively. Many studies have reported that the input of organic materials provides an essential source for the accumulation of soil organic carbon and total nitrogen and enhances microbial activity (Huang et al. 2022).

Fungi, bacteria, and other microorganisms, through the decomposition of organic matter, preferentially distribute into macroaggregates, and microbial activities will significantly improve soil-related enzyme activities (Lv et al. 2013). Some studies have shown that an increase in enzyme activity accelerates the decomposition of straw by microorganisms and releases the carbon and nitrogen in straw. Thus, soil nutrients are increased, and microbial activities are promoted (Zhou et al. 2022). However, compared with different soil layers, 0.25-0.053 and < 0.053 mm had greater accumulation of nitrogen, which is related to the modes of straw return. Carbon and nitrogen entering the aggregates benefit from the adsorption protection of the aggregates, resulting in a significant reduction in the amount of decomposition by soil microorganisms and a reduction in leaching losses, thereby increasing soil fertility (Six et al. 1998, Xiafeng et al. 2017). Many studies have demonstrated that there is an important relationship between soil carbon and nitrogen content; available nitrogen in soil decreases rapidly when organic materials such as straw are applied, and available nitrogen reduction is supplemented by microbial decomposition of organic matter (Shahbaz et al. 2018). In addition, the higher the C/N ratio applied to the organic material, the stronger the microbial decomposition of organic matter, and the immobilization of inorganic nitrogen by microorganisms (Wild et al. 2019).

The results of this study also showed that the C/N of soil water-stable aggregates of the straw-returning soil layer increased, and a higher C/N indicated that there was more organic matter available for microorganisms in the soil, which was more conducive to microbial activities, promoting soil material and the energy cycle, improving soil structure, and enhancing soil fertility. Therefore, further in-depth analysis will be conducted in conjunction with microorganisms.

Effects of straw return on urea ^{15}N absorption by improving soil structure

As the source of ^{15}N is urea, its absorption is influenced by soil structure and other factors. On one hand, the absorption and immobilization of nitrogen fertilizer by soil is high (Gu et al. 2021); on the other hand, the N element in aggregates is a dynamic change process, including fixation in straw and mineralization and decomposition of organic nitrogen in aggregates (Li et al. 2020). The proportion is relatively high in this study, indicating that, when the aggregate total nitrogen increment is small, soil with straw return has a strong ability to immobilize or retain nitrogen fertilizer.

Zhang et al. (2022) indicated that long-term straw return affects the adsorption and fixation of NH_4^+ by improving the soil organic carbon content, which can improve the effectiveness of crop nitrogen absorption and reduce nitrogen loss in rice–wheat cropping systems. In this study, T (straw mixed with topsoil) and D (straw deep incorporation) shifted the aggregate structure and the fixed amount of nitrogen in farmland soil, which will help to improve the content of urea source 15N in aggregates and effectively solve the problem of soil fertilizer utilization.

Straw return can improve soil structure, promote soil aggregate stability, and increase soil nutrient content. The results of this study focused on soil structure and nutrients and found that straw mixed with topsoil was the most effective in improving soil structure and increasing nutrient levels. Considering soil improvement and economic benefits (Jiao et al. 2021), it is found that straw deep incorporation may be suitable for regional agricultural promotion.

CONCLUSION

Straw return significantly improved the content of macroaggregates and the stability of water-stable aggregates in straw returning soil layers. The organic carbon content, total nitrogen content and ^{15}N accumulation of soil water-stable aggregates in straw returning soil layers were significantly higher than those in CK. The organic carbon stock of macroaggregates in returning soil layers was higher than that in CK, and straw returning increased aggregate C/N and ^{15}N/N and increased the input of organic matter and the retention capacity of external source nitrogen. The ^{15}N accumulation of aggregates in T and D was better than that in M. Pearson correlation analysis and RDA showed that the carbon and nitrogen contents of aggregates were positively related to the content of macroaggregates and the stability of aggregates.

Therefore, straw return can improve the stability of soil water-stable aggregates, optimize soil structure, and improve soil nutrient content and nutrient retention capacity. Straw return not only optimizes the physical and chemical properties of black soil, but also provides a method for straw recycling and fertilization.

AUTHORS' CONTRIBUTION

Conceptualization: Xie, S. and Dou, S.; **Methodology:** Xie, S., Dou, S. and Ma, R.; **Investigation:** Xie, S. and Ma, R.; **Writing – Original Draft:** Xie, S. and Fu, J.; **Writing – Review and Editing:** Xie, S. and Fu, J.; **Funding Acquisition:** Dou, S.; **Supervision:** Xie, S., Dou, S., Fu, J. and Ma, R.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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