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Short-Term Effects of Different Straw Returning Methods on the Soil Physicochemical Properties and Quality Index in Dryland Farming in NE China

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Abstract: A field experiment was designed to assess the impacts of various maize straw (stover) returning methods on the basic soil physicochemical properties and soil quality index in Jilin (NE China). The five treatments were no return of straw residues (CK), straw incorporated evenly into the soil using the crashing-ridging technique (EIS), straw mulching (SM), straw plowed into the soil (SP), and straw returned in granulated form (SG). Relative to the no straw return, EIS effectively reduced soil bulk density and penetration resistance, increased soil total organic carbon (TOC), macroaggregate-associated carbon content, and the accumulation of soil humus. Furthermore, EIS improved soil structure and soil aggregate stability and significantly increased the soil quality index. Among the various straw returning treatments, SM and SG significantly promoted soil macroaggregation and increased macroaggregate-associated carbon content by 23.69% and 21.70% at the soil surface, respectively (as compared with the control). Compared to SM, SP, and SG, EIS significantly enhanced the aliphaticity and hydrophobicity of soil organic carbon. These results suggested that EIS was the most efficient straw return mode to increase TOC and improve soil structure and fertility.

Keywords: soil organic carbon; soil compaction; soil aggregate stability; FTIR spectra; straw return; soil quality index

1. Introduction

Due to the depletion of soil organic matter (SOM) and nutrients, the addition of crop residues to agricultural soils has significant agronomical and environmental interest [1]. Crop residues are an important source of nutrients [2], which can impact the biological and physicochemical properties of soil. A few investigations have shown that crop residues incorporated into soil can decrease erosion and prevent nutrient losses by run-off and leaching, as well as increase microbial biomass [3,4].

Crop straw (stover) incorporation may also improve soil aggregation and soil total organic carbon (TOC) stabilization. Choudhury et al. [5] found that straw return could significantly increase soil macroaggregates and TOC levels. Chatterjee et al. [4] found that straw mulching significantly increased the carbon stratification ratio, and the content of water-stable aggregate associated carbon in large macroaggregates and microaggregates compared to no mulch treatment. Wright and Anderson [6] suggested that the possible mechanism behind this phenomenon is that straw addition increases the carbon input and promotes the growth of fungi. Then, the fungal hyphae and their metabolites (e.g., glomalin) might entangle soil microaggregates and create new macroaggregates.

Currently, there are two traditional ways of returning straw. One is to incorporate straw into the soil by plowing, and the other is to cover the straw directly on the soil surface (no plowing). Because conventional farmers do not have large farming machinery, it is difficult to crumble the straw and turn it into the soil. Therefore, crop straw covering on the soil leads to a slow decomposition rate, affecting seedling emergence and crop planting [7]. In order to resolve the problems and improve the utilization of crop straw, two new straw returning methods, even incorporation of straw (EIS) and straw granulated (SG), have been proposed. EIS consists of the following steps: (1) straw is pulverized, 1–2 cm in length, and spread over the field by the combine harvesting the crop; and (2) the straw is plowed evenly to a depth of 0–20 cm using the crashing-ridging technology [8]. The SG treatment involves the granulation of maize straw, which is then added to the soils. To obtain the granulated straw, air-dried straw is removed from the field and crushed to 0.5–1.0 cm followed by the addition of water and then placed into a small granulator under 0.4 MPa steam pressure to convert the crushed straw into the granulated straw with a length of 2–3 cm and a width of 7 mm. Granulated straw has a higher bulk density and small volume, which can greatly improve the distribution of residue material in soil.

So far, little research has been done on the effects of these new straw incorporation methods on the soil structure and TOC content. Therefore, we performed a field experiment to assess the effects of different straw returning methods on TOC content, soil bulk density, penetration resistance, soil organic carbon composition, soil aggregate stability, and aggregate associated carbon. However, through these parameters alone, we cannot accurately judge whether different straw return methods are better at improving the soil. Therefore, in this study, we introduced the soil quality index (SQI) to explore more intuitively and accurately the effects of different straw return methods on the soil. SQI is calculated by the PCA (principal component analysis) method by using different indicators, and the advantage of SQI is that it can visually and accurately evaluate soil quality. Therefore, the objectives of this study were (1) to investigate the effects of different straw returning methods on the soil physicochemical properties and quality index and (2) to explore an optimal straw management practice for improving the soil quality and increasing the local crop production in Northeast China.

2. Materials and Methods

2.1. Experimental Site

The experiments were conducted in Nong' an County (44°26′N 125°21′E), which is located in Jilin Province in Northeast China. The annual average temperature was 5 °C, and the average annual precipitation was 332 mm. The natural vegetation cover types were Aneurolepidium chinensis and Stipa baicalensis. The soil is classified as Calciboroll or Gleyic Chernozem, which developed in loess-derived sediments. The main properties of the sampled soil (0–20 cm depth) were as follows: total organic carbon 12.73 g kg^{-1}, total nitrogen 1.26 g kg^{-1}, alkali-hydrolysable nitrogen 103.53 mg kg^{-1}, available phosphorus 88.1 mg kg^{-1}, available potassium 127.02 mg kg^{-1}, pH (H_2O) 7.75. In addition, the soil contained 41.50% sand, 22.25% silt, and 36.25% clay.

2.2. Experimental Design

The field experiment was conducted in May 2016 and followed a randomized design with five treatments and three replications. The area of each plot was 5 m × 10 m. The five treatments were: no straw return with plowing tillage (CK), straw incorporated evenly into the soil using the crashing-ridging technique (EIS), straw (crushed to 10 cm) that was chopped and plowed into an approximately 0–20 cm soil depth range (SP), return of straw (all stover) as mulch after plowing (SM), and straw that was returned in granulated form using a straw granulating machine and then plowed into approximately 0–20 cm soil (SG). The maize variety was XianYu 335. Each straw return plot had a similar maize straw application rate (9500 kg ha^{-1}) in 2016 and 2017. Each plot was fertilized with inorganic fertilizers (N, P, and K) at applications of 165 kg N ha^{-1}, 82.5 kg P_2O ha^{-1}, and 82.5 kg K_2O ha^{-1}, respectively.

2.3. Soil Sampling and Lab Procedures

Soil samples were collected from three locations in each plot replicate at depths of 0–20 cm, after the maize harvest in October 2017. Then, the samples were air-dried and passed through a 2 mm sieve for determining soil properties and soil fractionation.

Soil bulk density (BD) was determined using the core method, and soil penetration resistance (PR) was measured using an automated soil penetrometer [9]. Soil humus was separated into total alkali-extractable humic fraction (HE), humic acid (HA), and fulvic acid (FA) by successively extracting soil samples with distilled water and 0.1 M NaOH + 0.1 M $Na_4P_2O_7$ solution [10]. Soil aggregates were measured using the wet screening method and classified into 4 groups: > 2000 μm (mega-aggregates (ME)), 250–2000 μm (macroaggregates (MA)), 53–250 μm (microaggregates (MI)), and < 53 μm (silt and clay (SC)) [11]. The carbon contents of total soil, HE (HEC), HA (HAC), and FA (FAC) of the different sizes of soil aggregates were determined through the $K_2Cr_2O_7$ oxidation method [12].

2.4. FTIR Measurements

The organic matter in the samples of bulk soils was analyzed using FTIR and the KBr technique. Spectra were acquired in the 4000–400 cm^{-1} range with 2 cm^{-1} resolution, and 32 scans were performed on each acquisition. The spectral data were processed with Origin software Version 8.0 including baseline corrections and atmospheric correction for H_2O and CO_2.

2.5. Calculations

2.5.1. Mean Weight diameter and Geometric Mean Diameter

The mean weight diameter (MWD) was calculated as follows:

$$\mathrm{MWD} = \sum_{i=1}^{n} (X_i \times W_i) \tag{1}$$

where X_i represents the mean diameter of the aggregates in the i^{th} sieve and W_i represents the weight percentage of the aggregates in the i^{th} sieve.

The geometric mean diameter (GMD) was calculated as follows:

$$\mathrm{GMD} = \exp(\sum W_i \times lnX_i / \sum W_i) \tag{2}$$

where W_i is the weight of the aggregates of each size class (g) and ln X_i is the natural logarithm of the mean diameter of the size classes.

2.5.2. Soil Quality Index

Soil quality index (SQI) was calculated as follows:

$$\mathrm{SQI} = \sum_{i=1}^{n} W_i \times Q(x_i) \tag{3}$$

where W_i is the weight of the soil quality factor (soil property), $Q(x_i)$ is the membership value of each soil quality factor, and n is the number of selected soil quality factors.

The $Q(x_i)$ values were calculated with the ascending and descending functions [13,14]. The ascending and descending functions were:

$$\mathrm{Q}(x_i) = \left(x_{ij} - x_{imin}\right) / (x_{imax} - x_{imin}) \tag{4}$$

$$Q(x_i) = \left(x_{imax} - x_{ij}\right)/\left(x_{imax} - x_{imin}\right) \quad (5)$$

where x_{ij} is the value of the selected physicochemical parameters for the SQI calculation and x_{imax} and x_{imin} are the maximum and minimum values of the soil property i among each treatment.

This study used principal component analysis (PCA) to determine the component capacity score coefficient, and then, the weights of the soil quality factors (W_i) were calculated with the score coefficient, following [15].

$$W_i = \frac{C_i}{\sum_{i=1}^{n}(C_i)} \quad (6)$$

where C_i is the score coefficient of soil quality factor i and n is the number of selected soil quality factors.

2.6. Statistical Analysis

The SPSS 22.0 analytical software package and Excel 2016 were used for the statistical analyses. One-way analysis of variance (ANOVA) with a least significant difference (LSD) test was used to evaluate the differences of dependent variables. The $p < 0.05$ level was considered to be significant. Principal component analysis (PCA) was used for factor extraction, and Excel was used to process the data.

3. Results

3.1. Soil Bulk Density and Penetration Resistance

Compared with CK, EIS and SG significantly decreased the BD at 0–20 soil depths by 14.9% and 12.8%, respectively (Table 1). For soil PR, there was no significant treatment effect in SM, SP, and SG; only EIS was significantly lower than CK at a 0–20 cm soil depth, with a decrease of 30.1%.

Table 1. Soil bulk density (BD) and penetration resistance (PR) under different straw returning methods (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated).

Treatment	BD (g cm^{-3})	PR (MPa)
CK	1.41 ± 0.04a	0.73 ± 0.06a
EIS	1.02 ± 0.04c	0.51 ± 0.09b
SM	1.38 ± 0.06a	0.59 ± 0.05ab
SP	1.33 ± 0.05a	0.65 ± 0.09ab
SG	1.23 ± 0.02b	0.63 ± 0.09ab

Mean values ± standard error of three replicates are presented. Values in a column followed by the same letter are not significantly ($p < 0.05$) different.

3.2. TOC and Humic C

Relative to the control, straw return significantly increased the TOC and humic C, as well as the HAC/FAC ratio in the surface soil (Table 2). In each straw return treatment, EIS and SG had higher TOC, HEC, and HAC contents, while SP had a higher FAC content. Moreover, SM, SG, and EIS had a higher HAC:FAC ratio compared with the SP. However, the Δ log K values in other treatments showed no consistent changes due to straw return treatments.

Table 2. The content of soil total organic carbon (TOC), total alkali-soluble humic fraction (HEC), humic acid fraction content (HAC), and fulvic acid fraction (FAC) under different straw returning methods (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated).

Treatment	TOC	HEC	HAC	FAC	HAC/FAC	Δ Log K (HA)
CK	14.98 ± 0.06d	5.88 ± 0.22d	3.37 ± 0.26d	2.51 ± 0.31b	1.34	0.48
EIS	20.58 ± 0.58a	8.48 ± 0.09a	5.93 ± 0.12a	2.55 ± 0.13a	2.39	0.59
SM	17.97 ± 0.12c	7.45 ± 0.05c	5.23 ± 0.26bc	2.22 ± 0.19b	2.35	0.53
SP	17.98 ± 0.06c	7.92 ± 0.16b	4.90 ± 0.27c	3.02 ± 0.32a	1.62	0.50
SG	19.84 ± 0.13b	7.81 ± 0.14b	5.48 ± 0.10b	2.33 ± 0.09b	2.35	0.43

Mean values ± standard error of three replicates are presented. Values in a column followed by the same letter are not significantly ($p < 0.05$) different.

3.3. Soil Aggregate Stability

In all the treatments, MA and MI were the most abundant size fraction (25.4%–49.4%), whereas ME and SC were the least abundant (6.8%–18.1%) (Figure 1a). Relative to the control, straw return increased the proportions of ME and MA, in the order EIS > SM > SG > SP. Meanwhile, EIS and SM averagely improved MWD and GMD by 19.2% and 35.7%, respectively (Table 3). SG also increased the aggregate stability, but it had less significant effects than EIS and SM. For SP, compared with the control, it had little influence on aggregate stability.

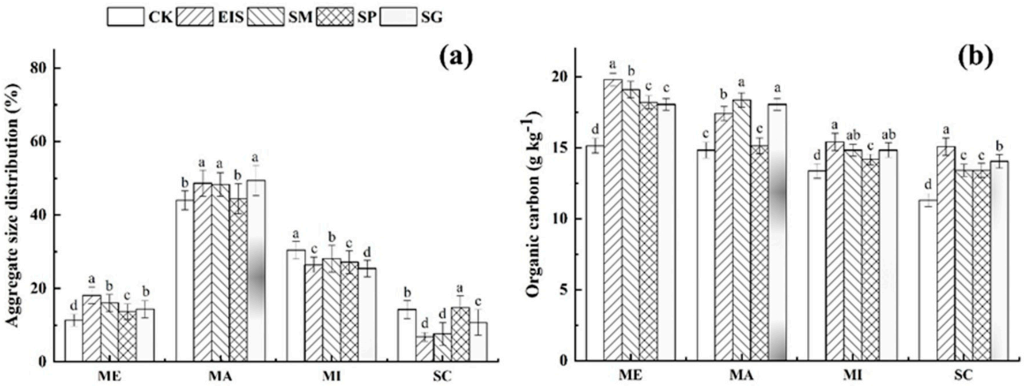

Figure 1. Soil aggregation distribution: (**a**) mega-aggregates (ME), macroaggregates (MA), microaggregates (MI), silt plus clay (SC), and organic C content of aggregates; (**b**) mega-aggregates (ME), macroaggregates (MA), microaggregates (MI), and silt plus clay (SC) under different straw returning methods (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated). Different lowercase letters indicate a significant difference between the different treatments. ($P < 0.05$).

Table 3. Mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates under different straw returning methods under different straw returning modes (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated).

Treatment	MWD (mm)	GMD (mm)
CK	0.78 ± 0.02b	0.42 ± 0.07b
EIS	0.95 ± 0.03a	0.59 ± 0.05a
SM	0.91 ± 0.06a	0.55 ± 0.01a
SP	0.82 ± 0.03b	0.40 ± 0.04b
SG	0.89 ± 0.01a	0.53 ± 0.08a

Mean values ± standard error of three replicates are presented. Values followed by the same letter are not significantly ($p < 0.05$) different.

3.4. Soil Aggregate-Associated Organic C

Mega-aggregate associated organic C (MEC) had the highest content (13.29–20.64 g kg^{-1}) followed by macroaggregates (MAC) (12.9–18.38 g kg^{-1}), microaggregates (MIC) (12.58–16.77 g kg^{-1}), and silt plus clay fractions (SCC) (9.03–16.13 g kg^{-1}) (Figure 1b). Compared with the control, EIS significantly increased the MEC, MAC, and SCC contents by 30.8%, 17.41%, and 24.98%, respectively. For other straw returning treatments, compared with the control treatment, SM, SP, and SG also significantly increased the contents of MEC and SCC, but this effect was smaller than for EIS treatment. However, the content of MAC of SM and SG was higher than for EIS.

3.5. FTIR Spectra of Soil Samples

FTIR spectroscopy can be used to measure the transition between molecular vibrational energy levels and is mainly used to reflect the characteristics of the functional groups of SOM in soil science [10]. Compared with the control, the relative intensities of the C-H bonds were higher after the return of straw (Figure 2), while the changes in vibration of the C = O bonds showed an opposite trend (Table 4). According to the corresponding absorbing peaks, EIS had higher relative intensities of C-H bands than other straw returning treatments, but had lower relative intensities of C = O bonds. Meanwhile, compared with the control, SP had no change of relative intensities of C = O bonds. We used the ratio of the relative intensities of C-H and C = O to calculate the hydrophobicity index (HB). The results showed that relative to the control, the HB value was higher under straw return treatments, especially in the case of EIS.

Table 4. Relative intensity of the main functional groups in the FTIR spectra of soil organic carbon relative to the different treatments (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated).

Treatment	Relative Intensity (%)		Hydrophobicity Index
	C-H	C = O	C-H/C = O
CK	0.828	7.294	0.114
EIS	2.106	4.326	0.487
SM	1.549	5.520	0.281
SP	1.283	7.299	0.176
SG	1.401	5.028	0.279
SG	0.407	7.653	0.053

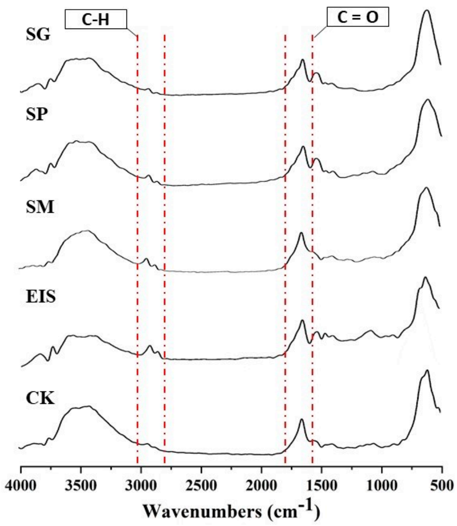

Figure 2. FTIR spectra of soil organic carbon under different straw returning methods (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated).

3.6. Soil Quality Index

To evaluate the effects of different straw returning methods on soil quality, we calculated the SQI through principal component analysis (PCA) and scoring function analysis. In Table 5, the weight of the soil physicochemical properties through PCA for soil quality assessment shows that PC1 explained 81.69% of the total variation, and the loading values also suggested that the value of MI, SC and the relative intensity of C = O bonds indicated soil degeneration, while SOC, HEC, HAC, FAC, and soil aggregate associated organic C meant a higher contribution to soil quality. Then, we computed the weight (Figure 3a) of each parameter by PC1 in the different soil layers and calculated $Q(x_i)$ of each soil quality factor using Eq. (4) and (5). Finally, the SQI was calculated by Eq. (3), and the results are demonstrated in Figure 3b. Compared with SP, the SQI value under SM and SG was much higher.

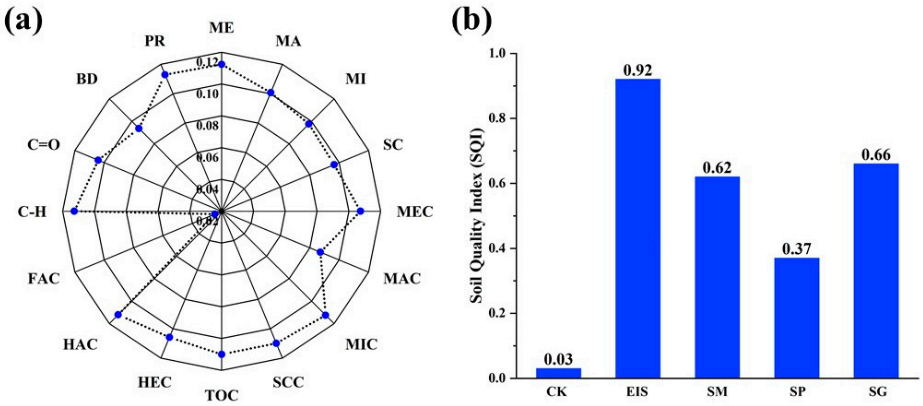

Figure 3. The weight of the soil parameters **(a)** and soil quality index **(b)** under different straw returning methods (CK: no straw return, EIS: even incorporation of straw, SM: straw returned as mulch, SP: straw ploughed down into the soil, and SG: straw returned as granulated).

Table 5. Results of the principal component analysis (PCA) of the soil quality indicators.

Principal components	PC1	PC2
Eigenvalue	13.07	2.41
Percent	81.69%	15.06%
Eigenvectors	Loading values	
Soil bulk density (BD)	–0.229	–0.221
Penetration resistance (PR)	–0.276	0.022
Mega-aggregate content (ME)	0.274	–0.071
Macroaggregate content (MA)	0.246	–0.291
Microaggregate content (MI)	–0.238	–0.267
Silt and clay content (SC)	–0.236	0.321
Mega-aggregate associated organic carbon (MEC)	0.262	0.011
Macroaggregate associated organic carbon (MAC)	0.213	–0.396
Microaggregate associated organic carbon (MIC)	0.275	–0.054
Silt and clay associated organic carbon (SCC)	0.268	0.142
Soil organic carbon (SOC)	0.269	0.145
Humic fraction carbon (HEC)	0.258	0.226
Humic acid carbon (HAC)	0.274	0.081
Fulvic acid carbon (FAC)	0.060	0.627
Relative intensity of C-H bonds (C-H)	0.275	0.018
Relative intensity of C = O bonds (C = O)	–0.254	0.179

4. Discussion

4.1. Effects of Straw Returning on Soil Structural Parameters

Straw return significantly promoted the formation of ME and MA and decreased the SC fraction relative to the control. The possible underlying mechanisms of these observations are: (i) polysaccharides produced from microbial metabolism of glucose, acting as a gluing agent of aggregates, (ii) Ca^{2+}, Al^{3+} and Fe^{2+} from mineral matter acting as an inorganic stabilizing agent, and (iii) metabolites from decomposing residues also acting as a binding agent [16–18]. It was also found that MWD and GMD were significantly higher due to EIS and SM treatments, but there were no significant effects for SP. For EIS, this phenomenon may be due to the capacity of this novel straw returning method to accelerate the combination of straw and soil SC fractions. The reasons for the beneficial effects of EIS were probably related to the crushed straw used. Crushed straw broke the organizational structure and outer cuticle of the original straw, which greatly increased the contact surface of straw cellulose, hemicellulose, and lignin with the soil, thus greatly accelerating straw decomposition and nutrient release, and finally, decreasing the duration of straw decomposition [19,20]. For SM, this result was similar to Akhtar [21], who reported that straw mulching could effectively increase the content of water-stable macroaggregates and the stability of soil aggregates. For SP, Kabir [22] indicated that plowing had a negative effect on the propagules of mycorrhizae and soil microbial activities, and soil microorganisms acted as the binding agent between soil aggregates and played an important role in the formation of soil aggregates.

For soil BD and PR, our results showed that the highest PR and BD values were in CK, whereas the lowest values were in EIS, which might be attributed to the blending of straws with more dense mineral fractions by the crashing-ridging technique and thereby causing a decrease in bulk density. Many studies [23] showed that organic amendments have a dilutive effect, decreasing BD and PR. Meanwhile, BD and PR increased with depth in both straw returning treatments when compared with the 0–20 cm soil depth. Moreover, because of the overburden pressure of the upper depth, higher BD values are normally expected at lower depths of the soil profile [24].

4.2. Effects of Straw Returning on TOC and Humic C

Our results showed higher TOC levels in EIS and SG at 0–20 cm than other treatments. In addition, EIS was more advantageous for the accumulation rate of HEC and HAC compared to SM, SP, and SG. Recent studies showed that soil organic carbon and humic substances were mainly governed by microorganisms. Hao et al. [25] noted that conventional tillage led to a decrease in the microbial community diversity, whereas the maize straw amendment increased the diversity of soil bacterial communities. Furthermore, Santos et al. [26] found that soil microorganisms could greatly reduce the transitional period for organic matter to convert into soil organic carbon and humic substances. This also explained why compared to the control, straw return treatments significantly increased soil humus content for two treatment years. In our study, SP had a higher FAC content than other straw returning treatments. This result was also consistent with Song et al. [27], who reported that the organic matter in maize straw was preferentially converted into HA rather than to FA, and the transformation of FA into HA may have increased the stability of SOC [28]. Therefore, it is suggested that plowing decreased the stability of soil organic carbon.

The HAC/FAC ratio and $\Delta \log K$ value are often used to characterize humic materials [29]. In our research, we found that the HAC/FAC ratios and $\Delta \log K$ values of all straw returning treatments were higher compared with the control, especially EIS. According to the research of Hu et al. [12], the higher HAC/FAC ratio and $\Delta \log K$ value indicated that the soil humus had lower optical density, aromatic condensation, and humification degree. This also shows that the application of crop residues can effectively increase the stability of soil organic carbon. However, SM and SG had the highest HAC/FAC ratio from 0–20 cm. Similar results had been reported by Tao et al. [30], who reported that straw mulching significantly increased the soil water content in the 0–20 cm range.

Furthermore, Chen et al. [31] found that soil moisture exhibited an important influence on the soil microbial community diversity, which promoted the formation of humus. Similar to straw mulching, granulated straw had a strong water retention capacity. Therefore, these results could be attributed to straw mulching, and straw granulated significantly conserved soil moisture and increased the degree of humification.

4.3. Effects of Straw Returning on Soil Aggregate Associated Organic C

Returning straw and tillage practices have an important impact on soil aggregate associated organic C. In our research, return of straw boosted MEC and MAC accumulation, especially for the EIS treatment. This is consistent with the findings by Zhao et al. [16], who reported that the decomposition of fresh straw could effectively increase the SOC content of aggregates and maintain large proportions of macroaggregates. Meanwhile, fresh straw also stimulates the production of fungal and bacterial binding agents that form stable microaggregate cores within macroaggregates [32]. However, different tillage practices and straw return methods lead to a difference in straw decomposing environments and thus decomposition rates, which will also lead to a different distribution of SOC in different particle size aggregates [33]. In the current study, the macroaggregate associated organic C in SM and SG was higher than EIS from 0–20 cm. As mentioned above, this result could be explained by the effect of high soil water content. Straw mulch and granulated straw had strong water absorption and retention capacity, which would improve the bioactivity of the surface soil and accelerate the formation of SOC-containing macroaggregates [30]. Moreover, EIS was found to have high SCC content, and this may be related to the adsorption of clay particles. Zaccone et al. [34] found that most of the labile SOC could be adsorbed on clay surfaces. The low molecular weight compounds produced by the decomposition of fresh straw may be the main source of this labile SOC. This indicated that the new straw returning method promoted the combination of straw and soil clay particles.

4.4. Effects of Straw Returning on SOC Structural Characteristics

As a complex organic amendment, straw return affects the structural characteristics of soil organic carbon. Zhang et al. [35] showed that straw return can significantly increase the aromaticity (probably due to lignin input) and reduce the condensation degree, oxidation degree, and thermal stability of soil organic carbon (due to the input of non-oxidized, thermally labile intact organic detritus). FTIR spectroscopy has shown that the hydrophilic functional group of the C = O bonds determines the adsorption performance of the organic matter, and the hydrophobic functional group of the C-H bonds determines the wettability of the organic matter [36]. The relative content of these functional groups is related to SOC content [37]. In the present study, the relative intensities of the C-H bonds and hydrophobicity (HB) values were higher after the return of straw, but had lower relative intensities of C = O bonds. The C-H bonds were also considered to have a significant correlation with the light organic carbon fraction [36]. This result illustrates that straw return was more effective in increasing soil HB and improved the activation of soil organic matter.

4.5. Effects of Soil Quality Index

Our result suggests that the soils with SG and SM were much better than that of SP. The disparity may be due to the different tillage types, while SG and SM had the same water retention capacity of the soil; therefore, they had a similar SQI value. Meanwhile, the weight coefficient determinations also suggested that soil aggregation was the key factor to improve the soil quality of straw return. In addition, it was found that the SQI of EIS was significantly higher than other treatments, which confirmed our previous research and proved that the EIS straw returning mode had a superior effect on soil quality [8].

5. Conclusions

After two years of field experiments, the returning of straw effectively improved the soil physicochemical properties at different soil depths. Compared with the control, EIS effectively reduced soil bulk density and penetration resistance, increased TOC, macroaggregate associated C content, and the accumulation of soil humus, improved soil structure and soil aggregate stability, and significantly increased the soil quality index. Compared with SM, SP, and SG, EIS also significantly enhanced the aliphaticity and hydrophobicity of soil organic carbon in those different soil depths, which probably reflected the incorporation of aliphatic soil organic carbon from the straw (e.g., fatty acids and lipids rather than the lignocellulose of the straw). For other treatments, SP had no advantage over other straw returning methods, and SM and SG had similar results in soil the physicochemical properties and soil quality index. These results suggested that straw incorporated evenly into the soil using the crashing-ridging technique may be an optimum practice to improve soil structure and soil fertility.

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Conflicts of Interest: The authors declare no conflict of interest.

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