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ORIGINAL PAPER

Changes in carbon fractions with corn straw incorporation and comparison of carbon sequestration efficiency in Phaeozem derived from two parent materials in China

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Abstract

Returning corn straw to soil improves soil carbon sequestration in the Phaeozem regions of Northeast China. This research was to investigate the changes in soil carbon fractions of Phaeozem derived from loess and laterite PM with corn straw incorporation and quantify the influence of the key factors on soil carbon accumulation in order to improve the soil carbon stabilization efficiency. A simulative laboratory incubation experiment was conducted over 12 months using Phaeozem derived from loess and laterite PM and eight corn straw doses. Results showed that the clay mineral of Phaeozem was dominated by a mixed-mineral illite-smectite layer, illite, vermiculite, kaolinite, and smaller amounts of montmorillonite. Clay mineral species of topsoil were identical with its PM. The LOC and HOC of six soils increase with increase in straw incorporation level. The promoting effectiveness of straw incorporation on C accumulation declined when the C inputs reached a certain level. At 15% straw incorporation levels, the LOC and HOC of six soil increased by 1.86–3.01 g kg^{-1} and 1.33–2.22 g kg^{-1} than CK, respectively. The increment of LOC and HOC of six soils followed the trend of LHAp > LLAp > RHAp > RLAp > LC > RC. At 15% straw incorporation levels, the RLOC of RC (419%) and LC (296%) was greater than topsoil (103–254%) and the RHOC of RC (90%) and LC (61%) was much greater than topsoil (9–26%). Further analysis suggested that C input, TSOC, and clay content were the most influential variables on carbon sequestration efficiency. They accounted for about 73% of the variations of RLOC and RHOC. The relative contributions of 2:1 clay to RLOC and RHOC were about 10% and 15%, respectively and that of 1:1 clay were about 4.4% and 3.5%, respectively. In conclusion, both the topsoil and PM of Phaeozem have considerable C-stabilizing capacity and the C sequestration efficiency of topsoil and PM derived from loess was greater than those for topsoil and PM derived from laterite.

Keywords Phaeozem · Parent materials · Corn straw incorporation · Heavy fraction · Light fraction · Carbon sequestration efficiency

Introduction

Soil is the world's largest terrestrial organic carbon (OC) pool. It stores approximately 2344 Gt of OC which is ≥3× greater than the sum of that in the atmosphere and vegetation (Schmidt et al. 2011; Stockmann et al. 2013). Obviously, soil plays an important role in the C cycle and nutrient storage globally (Jobbágy and Jackson 2000). Soil carbon sequestration stabilizes atmospheric CO$_2$, enhances soil fertility, and improves soil quality and structure (Wiesmeier et al. 2014). In terms of improving terrestrial ecosystem health, mitigating climate change and ensuring global food security, increasing soil carbon storage has been of key concern worldwide (Wang et al. 2018).

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Returning straw to soil is an environmentally friendly and effective method for improving soil carbon sequestration capacity and sustaining soil productivity (Cui et al. 2017). Decomposition of crop straw by soil microbial biomass will cause the residual mineralization of OC to CO2. Synchronously, microbial products become stable by adsorbing to mineral surfaces or chelating soil aggregates and forming humus (Ramnarine et al. 2018). During continuous process of decomposition as above, two main pools of SOM can be identified, which were recovered by density fractionation usually. Firstly, there is a light fraction (LF) pool as a transitory intermediate pool composed of plant fragments and microbial residues in various decomposition states. Secondly, a heavy fraction (HF) pool consisting of more processed materials (i.e., low-molecular weight organic compounds and high-molecular weight humified organic matter) is generally more stable (Christensen 1992). Density separation may help distinguish SOM dynamics based on turnover time. The heavy fraction (HF) constitutes 91–98% of the SOC in Chinese Mollisols (Li et al. 2007).

Several researches showed that soil carbon accumulation was significantly correlated with the amount of returning straw (Lu et al. 2009; Wang et al. 2015; Li et al. 2016; Zhao et al. 2016). However, researches on long-term field experiments demonstrated that as the increase in SOM is concerned, the incorporation of straw is usually not very effective, indicating that soil C content has reached saturation relative to the C input in the equilibrium state (Six et al. 2002; Stewart et al. 2009). Soil carbon sequestration efficiency (i.e., SOM increase per unit of input) is subjected to many factors including climate, type and amount of C input, and inherent soil properties (nutrients, texture, and mineralogy) (Shahbaz et al. 2017; Liu et al. 2019; Cai et al. 2021). It is necessary to quantify the influence of the key factors on soil carbon accumulation in order to improve the soil carbon stabilization efficiency.

Phaeozem is the typical soil in Northeast China. It distributes in Songliao Plain, concentrated in Heilongjiang and Jilin Provinces, and is one of three zonal Phaeozem areas worldly (Guo et al. 2013). Phaeozem stores ~12.6 Pg C and accounts for 28.3% of the soil C stocks of China (44.5 Pg C) (Pan 1999), which is an important terrestrial C store with great significance in the global C cycle. The parent material (PM) of Phaeozem in Northeast China is mainly Quaternary sediment (Q3), which was deposited in the late Pleistocene era. Certain Phaeozems were derived from Triassic sandstone (Shen et al. 2013). The Phaeozem of Northeast China has a high organic matter content and is continuously distributed over wide tracts of farmland. Therefore, it is a major crop production region and provides about one-third of the nation's grain. A large quantity of crop straw is produced every year in this area but it is not fully utilized. Instead of being returned to the soil, it is used as livestock feed or heating fuel (Wang et al. 2018). Some farmers burn it to facilitate sowing. However, long-term intensive cultivation and improper management of this area have reduced SOC by 50% after 60 years of tillage (Yu et al. 2006). The annual rate of SOC loss there is 0.5% (Liu et al. 2010). Some of the Phaeozem is eroded to the extent that the PM is either near the surface or fully exposed. This situation has raised concerns about future food security (You et al. 2014). Degradation of the Phaeozem as a result of the loss of SOC and nutrients is a major challenge for sustainable agriculture in Northeast China (Liu et al. 2010).

Few studies on the comparison of carbon sequestration efficiency of Phaeozem derived from different PMs have been conducted in the China Corn Belt of the Phaeozem region. From the perspective of both promoting OC storage and alternative uses of crop straw, it is crucial to investigate the changes in carbon fractions and quantify the influence of the key factors on soil carbon accumulation in order to improve the soil carbon stabilization efficiency. A simulative laboratory incubation experiment was conducted over 12 months using Phaeozem derived from loess and laterite PM and eight corn straw doses. The objectives of this study were to (1) explore the difference of mineral composition between Phaeozems derived from loess PM and laterite PM, (2) investigate the changes in carbon fractions of topsoil and PM in Phaeozems with corn straw incorporation, (3) compare the C sequestration efficiency of Phaeozems derived from two different PMs, and (4) quantify the contribution of various factors (edaphic variables and farmland management) to variations of the OC increase rate in light and heavy fraction.

Materials and methods

Experimental materials and analysis

The experimental material used was Phaeozem topsoil and PM (loess and laterite). Loess PM was Quaternary sediment (Q3) deposited in the late Pleistocene. The laterite PM was derived from Triassic sandstone. In the autumn of 2015, soils were sampled from six sites located in the cultivated Phaeozem region of Northeast China (Table 1). The topsoil samples were randomly collected from several points in the field. At each of the sites, the samples were cleaned of macroscopic straw and other organic residues then bulked together into a composite. At 20–25°C, all samples were air-dried, ground, homogenized, and stored for analysis and incubation through a 2-mm sieve. Soil pH for a 1:5 soil-to-distilled water suspension was measured, adopting ammonium acetate exchange method to detect the cation exchange capacity (Lu 2000). SOC was evaluated by dry combustion with a Multi N/C2100 total organic carbon (TOC) analyzer (Analytik Jena AG, Jena, Germany). Lu (2000) measures the total soil nitrogen by the semi-micro Kjeldahl method. Particle size was

Table 1 Description of soils used in present research

Sampling site	Location coordinates	Parent material	Sample depth (cm)	Munsell color	Land use
Site 1 (LC)	Jilin Changchun 125°24′41″E/43°48′3″N	Loess	150–200	10YR 7/6 (bright yellowish brown)	
Site 2 (LLAp)	Jilin Changchun 125°24′41″E/43°48′3″N	Loess	0–20	10YR 4/3 (dull yellowish brown)	Continuous corn cropping
Site 3 (LHAp)	Heilongjiang Hailun 125°01′48″/47°32′11″N	Loess	0–20	10YR 3/1 (brownish black)	Continuous corn cropping
Site 4 (RC)	Jilin Siping 125°10′31″E/43°44′38″N	Laterite	150–200	10R 5/8 (red)	
Site 5 (RLAp)	Jilin Siping 125°47′16″E/44°03′54″N	Laterite	0–20	10YR 5/8 (yellowish brown)	Continuous corn cropping
Site 6 (RHAp)	Jilin Siping 124°36′23″E/43°18′40″N	Laterite	0–20	10YR 4/4 (brown)	Continuous corn cropping

analyzed by the pipette method (Gee and Bauder 1986). Except for particle size, all extractions and analyses of the individual bulk soil samples were performed in triplicate. Mineral compositions of the clay fraction were analyzed by X-ray diffraction (XRD) as described by Yeasmin et al. (2017). According to Stokes' law, the clay fractions (<2 μm) were collected by sedimentation. The clay samples were processed by the sodium dithionate-sodium citrate-sodium bicarbonate method (DCB method), immersed with magnesium-glycerol (Mg-gly) and potassium (K) and analyzed with an X-ray diffractometer (AA-7000; Shimadzu Corporation, Kyoto, Japan) fitted with CuKα radiation and a nickel filter. The operating settings were 40.0 kV, 30.0 mA, and a 0.02° step size. The identification of clay minerals was based on definitions reported by Środoń (2006). The estimations of semi-quantitative proportions of clay minerals were performed by comparing reflection areas (Ohtsubo et al. 1995; Sridharan et al. 2002).

Corn straw was derived from corn stalks. It was air-dried in the fields, heated in a stove at 30 °C, passed through a 2-mm sieve, and set aside for analysis and experimental use. Its organic C content, total nitrogen (N), and C/N were 486.15 g kg^{-1}, 5.29 g kg^{-1}, and 91.9, respectively.

Experimental design and methods

The incubation experiment consisted of eight treatments with the following corn straw doses: 0%, 0.5%, 1%, 2%, 3%, 5%, 10%, and 15% of the soil dry mass. Each treatment was repeated in triplicate. Rectangular plastic boxes (15.6 cm ×11 cm × 7 cm; 1,200 mL) fitted with perforated lids were used in the incubation experiment. Corn straw powder was homogenized with soil (500 g per treatment) on polyethylene film. The quantity of corn straw powder used varied with the treatment. Based on the average field capacity of Phaeozem, distilled water was added to adjust the soil water content to 15%. The 144 mixed samples (6 soil samples × 8 treatments × 3 replicates) were placed in the boxes and maintained at 25 °C in a constant-temperature incubator. Appropriate volumes of distilled water were added every 7 days to maintain a constant water content. The soil was removed from the boxes after 12-month incubation, air-dried at 20–25 °C, and subjected to density fractionation and determination of organic C concentrations.

Bulk soil samples were separated into light fraction (LF: <1.8 g cm^{-3}) and heavy fraction (HF: >1.8 g cm^{-3}) according to the method described by Ramnarine et al. (2018). Briefly, 30 g of air-dried soil was passed through a 250-μm sieve and transferred to a 250-mL centrifuge bottle containing 100 mL of sodium iodide (NaI) solution (density = 1.8 g cm^{-3}). The bottles were shaken for 2 h in a horizontal shaker (300 rpm), then gently tilted to remove heavy particles from the upper wall of the bottles. After overnight standing at room temperature, the suspension was centrifuged for 60 min at 1250×*g* at 25 °C. The supernatant was filtered into a millipore vacuum unit through a membrane filter (0.45 μm). The fraction recovered on the filter (LF) was washed with 50-mL 0.01 M calcium chloride ($CaCl_2$) solution and 100 mL distilled water, then transferred to a pre-weighed 50-mL beaker and dried in a water bath at 50°C to constant weight for future use. Meanwhile, the residual soil in the centrifuge bottles was washed in 100 mL of 0.05M $CaCl_2$ in order to flocculate mineral particles, shaking for 1 h, followed by further washing with deionized water three times. Finally, the residue (HF) was dried in an oven at 50°C to a constant weight and grounded <250 μm for C determination. Both of the two soil fractions were analyzed by the dry combustion method with a Multi N/C2100 TOC analyzer (Analytik Jena AG, Jena, Germany).

Data management and statistical analysis

The experimental data were analyzed in Microsoft Excel 2013. The figures were plotted with OriginPro v. 8.0 (OriginLab Corporation, Northampton, MA, USA). The XRD analysis was run in Jade v. 5.0 (Materials Data, Inc., Livermore, CA, USA). ANOVA was performed to identify significant differences in soil parameters with different treatments. The threshold was $P < 0.05$. Statistical analyses were conducted in IBM SPSS v. 20.0 (IBM Corp., Armonk, NY, USA). In order to compare the contributions of key regulating factors on the variation of the OC increase rate in light fraction (RLOC) and heavy fraction (RHOC), management practices (e.g., carbon input) and edaphic factors (e.g., SOC, soil texture, pH, and mineralogical composition of clays) were taken into account. We screened the indicators and then estimate their relative contributions by using boosted regression tree (BRT) analysis with the following recommended parameters: learning rate of 0.01, bag fraction of 0.75, and tree complexity of 5 (Elith et al. 2008; Cai et al. 2021). BRT analyses were performed in the gbm package of R, version 3.3.3 (https://www.r project.org/).

Results

Physical and chemical properties of bulk soils and mineralogical composition of clays

All soil was acidic (pH 5.02–6.93) except for RHAp (pH = 7.85) (Table 2). LHAp contained the highest clay content (50%) followed by LLAp (34%), LC (31%), RLAp (30%), RHAp (28%), and RC (24%). The CEC of all topsoil was relatively high (28.01–61.00 cmol kg^{-1}). LHAp had the highest CEC followed by LLAp, LC, RLAp, RHAp, and RC. The CEC was significantly positively correlated with soil clay content ($r = 0.984$; $P < 0.01$). The total soil organic carbon concentration (TSOC) and total N concentration (TN) of PMs were significantly lower than that of topsoil. TSOC of the LC and RC was 3.08 g kg^{-1} and 2.24 g kg^{-1}, respectively. TN of the LC and RC was 0.37 g kg^{-1} and 0.27 g kg^{-1}, respectively. TSOC in the topsoil ranged from 9.35 to 29.4 g kg^{-1} and TN was in the range of 0.88–2.43 g kg^{-1}. TSOC and TN in topsoil followed the trend of LHAp > RHAp > LLAp > RLAp.

The XRD patterns of clay fractions from PM and topsoil showed that plagioclase (3.19 Å), K-feldspars (3.23 Å), and quartz (4.25 Å) as non-clay minerals were present in trace in LC, LLAp, LHAp, RLAp, and RHAp (Fig. 1). In RC, quartz was detected in trace amounts, but K-feldspars and plagioclase were absent. The XRD patterns of clay fractions have similar for four topsoil. For all XRD patterns of the clay fractions of Phaeozem, the peaks at 7.1 Å and 3.57 Å (3.56 Å) in samples saturated with Mg and Mg-gly are attributed to kaolinite, which collapsed when K-saturated samples were heated at 550 °C. The proportions of kaolinite in soil samples followed the trend of LHAp (16.47%) > LLAp (15.14%) > RHAp (14.85%) > RLAp (12.57%) > LC (10.57%) > RC (7.80%) (Table 2). The reflections at 10.1, 4.97 (4.99), and 3.33 (3.34) Å were also identified on the Mg and Mg-gly XRD patterns. After heating K-saturated samples at 550 °C, these reflection peaks remain unchanged, showing the presence of illite. The reflection of illite was asymmetric on all XRD patterns and it was highlighted and broad in the clay fractions of four topsoil and LC. The proportions of illite in LLAp (40.05%), LHAp (44.43%), RLAp (50.39%), RHAp (36.93%), and LC (40.71%) were significantly higher than RC (15.46%). Among all XRD patterns, the high background level at small (2θ) angles and the swelling behavior in Mg-gly saturated samples, showing the existence of illite-smectite mixed layers (I/S) and montmorillonite. The proportions of illite-smectite mixed layers and montmorillonite in soil samples were in the range of 19.48–48.08% and 1.17–3.94%, respectively. The proportions of illite-smectite-mixed layers and montmorillonite in RC were both highest compared with other soils. The presence of vermiculite was identified when the peaks at 14.15 Å on all Mg-saturated XRD patterns were absent after K saturation, the proportions of vermiculite in PMs and topsoil range from 9.5 to 24.72%. LC and RHAp were 9.51% and 10.34%, respectively, which were relatively lower than other

Table 2 General characteristics of the six bulk soils used in this study

Sites	pH	CEC (cmol kg^{-1})	Particle size (%)		TSOC (g kg^{-1})	TN (g kg^{-1})	Semi-quantitative analysis of clay compositions (%)						IC (°Δ2θ)
			Silt	Clay			I	I/S	Ver	Kao	M	Chl	
LC	6.93 ± 0.01	31.32 ± 0.24c	19	31	3.08 ± 0.06e	0.37 ± 0.06e	40.71	36.04	9.51	10.57	2.74	0.44	0.44
LLAp	5.32 ± 0.01	37.66 ± 0.33b	26	34	13.3 ± 0.53c	1.12 ± 0.10c	44.05	19.48	19.10	15.14	1.45	0.78	0.48
LHAp	5.83 ± 0.00	61.00 ± 1.22a	26	50	29.4 ± 0.61a	2.43 ± 0.19a	44.43	21.61	14.89	16.47	2.11	0.49	0.89
RC	6.46 ± 0.02	28.01 ± 0.50e	16	24	1.96 ± 0.03f	0.27 ± 0.04e	15.46	48.08	24.72	7.80	3.94	0.00	0.55
RLAp	5.02 ± 0.01	30.96 ± 0.21c	20	30	9.39± 0.06d	0.88 ± 0.07d	50.39	19.70	16.17	12.57	1.17	0.00	0.43
RHAp	7.85 ± 0.00	29.61 ± 0.29d	20	28	14.4 ± 0.4b	1.35 ± 0.15b	36.93	35.33	10.34	14.85	2.56	0.00	0.82

Note: *CEC*, cation exchange capacity; *TSOC*, total soil organic carbon; *TN*, total nitrogen; *I*: illite; *I/S*: illite-smectite mixed layer mineral; *Ver*: vermiculite; *Kao*: kaolinite; *M*: montmorillonite; *Chl*: chlorite; *IC*: illite crystallinity

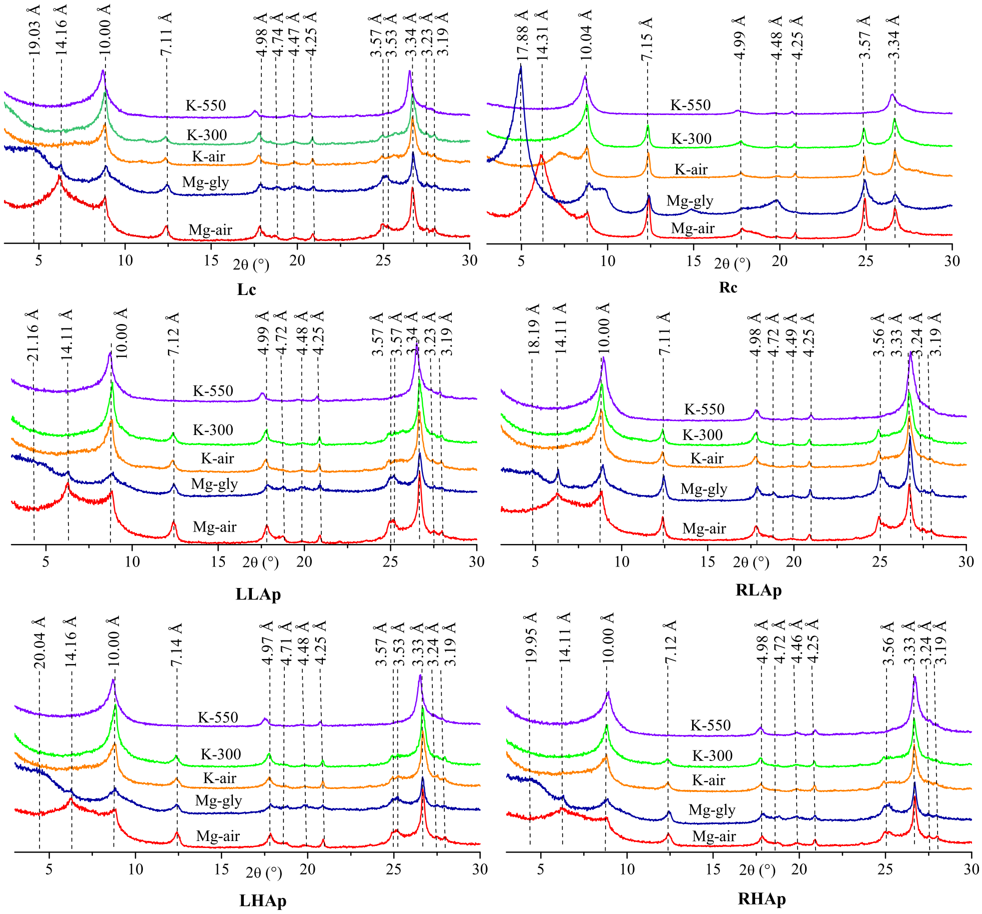

Fig. 1 XRD patterns of the clay fractions (< 2 μm) in Phaeozem determined on an oriented specimen. Mg-air: magnesium-saturated and naturally air-dried; Mg-gly: magnesium-saturated and glycerol-treated; K-air: potassium-saturated and naturally air-dried; K-550: potassium-saturated and dried at 550 °C; K-300: potassium-saturated and dried at 300 °C

soils. In the XRD patterns of LC, LLAp, and LHAp, the weak reflections at 3.53 Å remain unchanged after the sample was heated at 550 °C, indicating the detection of trace amount of chlorite in LC, LLAp, and LHAp.

Changes of organic carbon concentration in light fraction and heavy fraction

Figure 2 shows the LOC and HOC of PMs and topsoil at different straw incorporation levels after 12-month incubation. The HF occupied the largest portion of TSOC (55.0–89.6%). The LOC and HOC of six soils increase with increase in straw incorporation level. Compared with 0% straw incorporation levels (CK), the LOC and HOC of PM showed significant increase at ≥1 % and ≥2% straw incorporation level respectively, and the LOC and HOC of topsoil showed significant increase at ≥0.5 % and ≥1% straw incorporation level respectively. It is shown that LF is more sensitive to changes in soil management practices than HF. The input OC preferentially accumulated in LF, and with organic materials inputs increase, the C was subsequently stabilized and sequestered in HF. The C sequestration efficiency of PM was lower than topsoil at low straw incorporation levels (0.5%, 1%, 2%, and 3%). At 15% straw incorporation levels, the LOC and HOC of six soil increased by 1.86–3.01 g kg^{-1} and 1.33–2.22 g kg^{-1} than that at 0% straw incorporation levels (CK), respectively. The increment of LOC and HOC of six soils was in the following order: LHAp > LLAp > RHAp > RLAp > LC > RC. It showed that the C sequestration efficiency of topsoil and PM derived from loess was greater than those for topsoil and PM derived from laterite.

Changes of organic carbon increase rate in light fraction and heavy fraction

Statistical data regarding the OC increase rate in light fraction (RLOC) and heavy fraction (RHOC) at different straw incorporation levels are presented in Fig. 3. All the curves of RLOC and RHOC appeared an inflection point. Before the inflection point, the RLOC and RHOC showed a process of rapid increasing then showed a slow increasing trend after the inflection point. Thus, it could be seen that the promoting effectiveness of straw incorporation on C accumulation declined when the C inputs reached a certain level. At 15% straw incorporation levels, the RLOC of RC (419%) and LC (296%) was greater than topsoil (103–254%) and the RHOC of RC (90%) and LC (61%) was much greater than topsoil (9–26%). The RLOC and RHOC were negatively correlated to

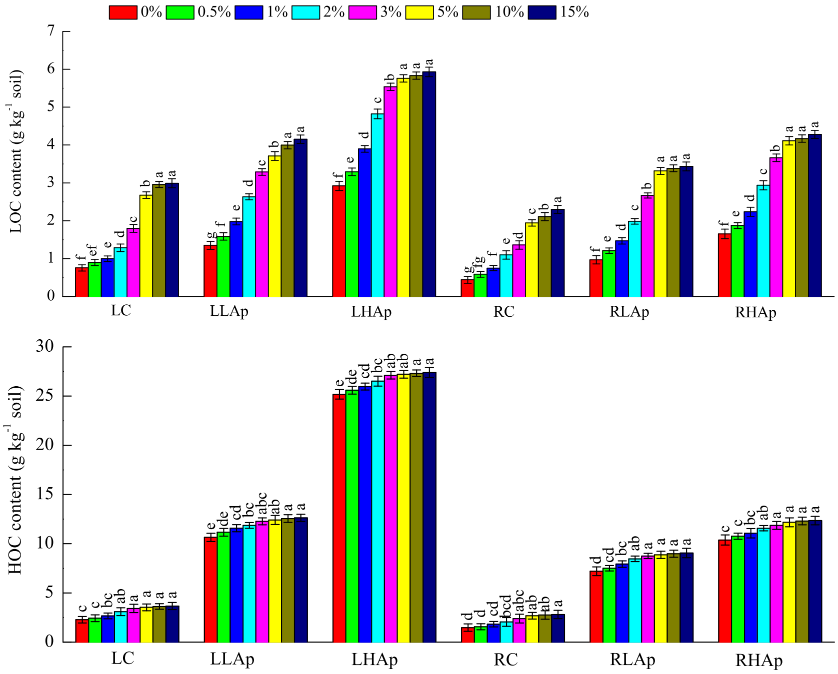

Fig. 2 Changes of organic carbon concentration in light fraction (LOC) and heavy fraction (HOC) with different straw incorporation levels (0%, 0.5%, 1%, 2%, 3%, 5%, 10%, and 15% of soil dry mass). Lowercase letters indicate significant differences ($p < 0.05$) among different straw incorporation levels in the same soil sample

the initial organic C concentration of soil, suggesting the promoting effectiveness of straw incorporation on C stock was better in the soil with lower organic C concentration.

Relative contributions of key factors to the variation of carbon increase rate in light fraction and heavy light fraction

Correlation matrices were calculated to identify parameters related to RLOC and RHOC (Table 3). Significant correlations ($P \leq 0.05$) were found in RLOC and RHOC with C input, TSOC, silt, clay, I, I/S, 2:1 clay, and 1:1 clay. BRT analysis indicated that out of the 12 studied variables, C input was the variable that most strongly influenced RLOC (Fig. 4 a), accounting for about 44% of the overall effects of all assessed variables on RLOC. C input, TSOC, and clay content most strongly influenced RHOC (each factor> 20%) and they together accounted for about 73% of the overall influence of all assessed variables on RHOC (Fig. 4 c). Some variables had little contributions and were dropped from BRT model. The relative contributions of TSOC to RLOC and RHOC were 15 % and 25 %, respectively. Silt explained about 8–12 % of the variations. The relative contributions of clay content to RLOC and RHOC were 15 % and 27 %, respectively. 2:1 clay made greater relative contributions than 1:1 clay to the variations of RLOC and RHOC. The relative contributions of 2:1 clay to RLOC and RHOC were about 10 % and 15 %, separately. Generally, BRT model was driven by its variables (see Fig. 4), which explained the variance in the observed RLOC and RHOC was 85 % and 89 % respectively (Fig. 4 b, d).

Discussion

Phaeozem topsoil has higher TSOC, TN, CEC, and clay content than PM, which is in one accord with former researches reported by Poirier et al. (2014) and You et al. (2014). The results show that the clay mineral species of

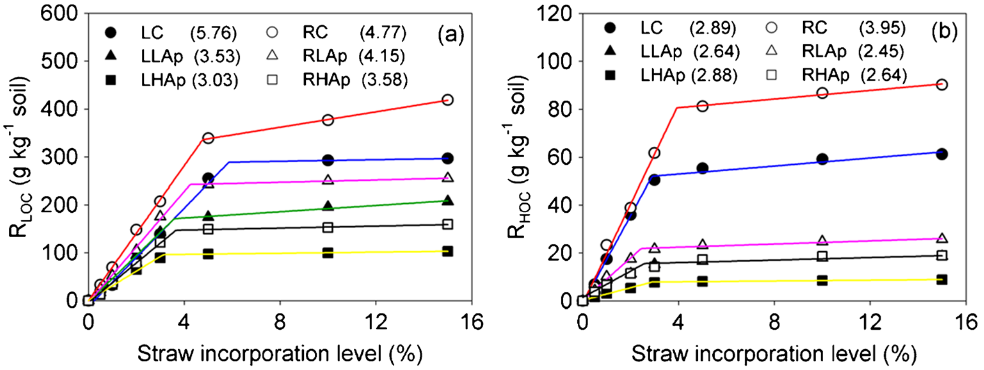

Fig. 3 Changes of organic carbon increase rate in light fraction (R_{LOC}, a) and heavy fraction (R_{HOC}, b). The numbers in the legend represent the inflection point of regression equations

Table 3 Correlation coefficients (Spearman's R^2) among carbon input, soil properties, mineralogical characteristics, and carbon increase rate in light and heavy fraction. Significant correlation under *P* value below 0.05 is in bold

	C input	TSOC	pH	Silt	Clay	I	I/S	Ver	M	Chl	2:1clay	1:1clay
TSOC	0.00	1.00										
pH	0.00	0.16	1.00									
Silt	0.00	**0.82**	0.20	1.00								
Clay	0.00	**0.67**	0.11	**0.66**	1.00							
I	0.00	0.46	0.22	**0.55**	**0.72**	1.00						
I/S	0.00	**0.62**	0.31	0.42	0.09	0.39	1.00					
Ver	0.00	0.21	0.26	0.27	0.24	0.01	0.01	1.00				
M	0.00	0.26	0.17	0.23	0.37	0.33	0.06	0.04	1.00			
Chl	0.00	0.24	0.18	0.47	0.05	0.05	0.26	0.13	0.01	1.00		
2:1clay	0.00	**0.54**	0.23	**0.52**	**0.68**	**0.81**	**0.53**	0.39	0.41	0.25	1.00	
1:1clay	0.00	**0.83**	0.05	**0.79**	**0.62**	**0.66**	0.30	0.17	**0.54**	0.08	1.00	1.00
R_{LOC}	**0.47**	**0.17**	0.00	**0.14**	**0.13**	**0.11**	**0.17**	0.01	0.06	0.01	**0.22**	**0.19**
R_{HOC}	**0.16**	**0.53**	0.03	**0.23**	**0.37**	**0.24**	**0.21**	0.06	0.08	0.06	**0.30**	**0.25**

Note: *C input*, organic carbon input; R_{LOC}, carbon increase rate in light fraction; R_{HOC}, carbon increase rate in heavy fraction; *TSOC*, total soil organic carbon concentration; *I*: illite; *I/S*: illite-smectite mixed layer mineral; *Ver*: vermiculite; *M*: montmorillonite; *Chl*: chlorite; *2:1 clay*, 2:1 layer phyllosilicate;*1:1 clay*, 1:1 layer phyllosilicate

topsoil were identical with its PM, which proved the inheritance relationship between topsoil and PM. As for the origins of soil phyllosilicates, Barré et al. (2014) believed that it could be inherited from PM or transformed from other minerals in water-rock interaction or new synthesis. The clay fractions of Phaeozem were dominated by a mixed-mineral illite-smectite layer, illite, vermiculite, kaolinite, and smaller amounts of montmorillonite. It seems that illite-smectite mixed layer minerals are the most common, especially in temperate climate soils (Velde 2001). The relative content of phyllosilicate of topsoil followed the trend of I > I/S > Kao or Ver > M > Chl. Zheng et al. (2010) achieved the same results. Similar climatic and agricultural conditions may have led to the co-evolution of the clay minerals of Phaeozem with different PMs.

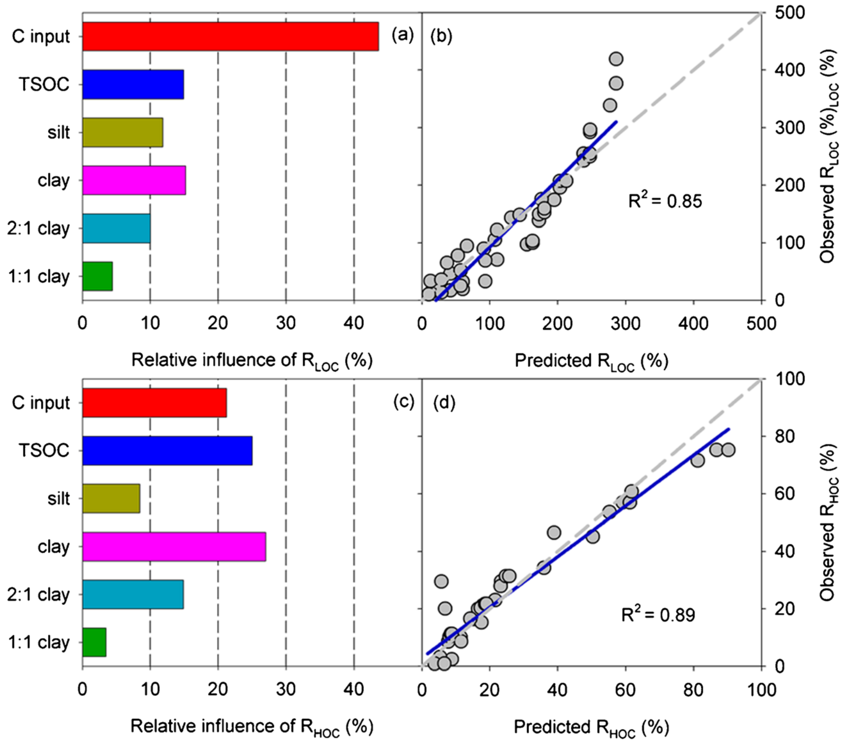

Fig. 4 Relative influence (%) of predictor variables to organic carbon increase rate in light fraction (R_{LOC}, a) and heavy light fraction (R_{HOC}, c) by using BRT model. Observed and predicted R_{LOC} and R_{HOC} are based on BRT model using the predictors shown in Fig. 4 (b) and (d). The dashed lines are 1:1 line. Note: *C input*, organic carbon input; *TSOC*, total soil organic carbon concentration; *2:1 clay*, 2:1 layer phyllosilicate; *1:1 clay*, 1:1 layer phyllosilicate

After the corn straw is incorporated into the soil, some are mineralized by soil microorganisms to CO_2. The rest accumulates in the soil by occlusion and adsorption (Mancinelli et al. 2013). As predicted, straw incorporation increased LOC and HOC in the present study. At 15% straw incorporation levels, the LOC and HOC of six soil increased by 1.86–3.01 g kg^{-1} and 1.33–2.22 g kg^{-1} than that at 0% straw incorporation levels (CK), respectively. Straw returning seems to be effective in improving soil carbon sequestration capacity and restoring soil fertility. The promoting effectiveness of straw incorporation on C accumulation declined when the C inputs reached a certain level and it was better in the soil with lower organic C concentration. Returning maize straw to the subsoil layers with lower organic C concentration is more conducive to the accumulation of SOC and the OC in the subsoil can be renewed (Cui et al. 2017). In long-term agricultural experiments, high carbon input levels and/or high soil carbon levels have been observed to reduce SOC sequestration efficiency (Six et al. 2002; Stewart et al. 2007; Gulde et al. 2008). There is a limit to the accumulation of increased C in soil. The efficiency of agricultural management practices to store SOC depends on C input level and how far a soil is from its saturation level (i.e., saturation deficit); the larger the saturation deficit is, the greater the SOC storage potential will be (Stewart et al. 2008).

Long-term C sequestration is critically dependent on the quantity of stable SOM fraction. LF is more sensitive to changes in soil management practices than HF. The input OC preferentially accumulated in LF, and when organic material inputs increase, the C was subsequently stabilized and sequestered in HF. The HF accounted for the largest share of total SOC (55.0–89.6%) in Phaeozem. You et al. (2014) found that HF C pool accounted for a larger proportion of TSOC (78–89%) than both the free and occluded LF pools of Chinese Mollisols. The HF is more stable and consists of recalcitrant C associated with soil minerals, with turnover times of several decades to centuries (McLauchlana and Hobbie 2004).

The increment of LOC and HOC of six soils followed the pattern LHAp > LLAp > RHAp > RLAp > LC > RC. It showed that the C sequestration efficiency of topsoil and PM derived from loess was greater than those for topsoil and PM derived from laterite. Relative differences in carbon sequestration potential were found between the loess and laterite PMs of Chernozem (Gao et al. 2017). In addition to C input and TSOC, clay content was the variable that most strongly influenced the OC increase rate in Phaeozem. Phaeozem derived from loess PM has a higher clay content than that derived from laterite PM. Martin et al. (2010) measured 2200 SOC stock levels in France and found that clay content was one of the best predictors of SOC stocks. Some authors reported that the fine mineral particle content was the crucial factor for the "protective capacity" of a soil and, by extension, the amount of C which can be accumulated in it (Stewart et al. 2009; Feng et al. 2013). Furthermore, it is believed that clay type is of great importance as different clay types (i.e., 1:1 and 2:1 clays) have significant differences in CEC and specific surface (Greenland 1965) and, therefore, have different capacities to adsorb organic materials. 2:1 clays have greater relative contributions on the OC increase rate in Phaeozem compared to 1:1 clay. In contrast to the 1:1 minerals, 2:1 clay layers have higher CEC values, which attributed to the presence of interlayer sites and permanent negative charge because of isomorphic cation substitutions. These negative charges promote the adsorption of organic compounds onto the phyllosilicate surfaces by cation bridging, hydrogen bonding, van der Waals interactions, and ligand exchange interaction. Based on the phyllosilicate/OM interaction mechanisms and the surface properties of soil clay fractions, the 2:1 minerals have a relatively greater ability to protect C and among the 2:1 minerals, the "protective capacity" of clay minerals followed the trend of allophane > smectite > illite > kaolinite (Bruun et al. 2010; Barré et al. 2014). Bothe the two PMs have a higher proportion of I/S and M than topsoil of Phaeozem, which may lead to a greater C sequestration efficiency in PMs.

The total amount of straw returned to the field was the principle parameter used in the improvement of soil fertility in the Phaeozem region of Northeast China. Based on the annual straw production in this area, we assumed that the total quantity of straw returned to soil (bulk density = 1.2 g cm^{-3}) in the 0–20-cm layer was 10 t ha^{-1} (Cui et al. 2017). A 0.5% straw addition is approximately equivalent to the full amount of straw returned to the field. The inflection points of the curves of RLOC and RHOC in Phaeozem were 3.03–5.76 and 2.45–3.95 (straw incorporation level, %), respectively. Before the inflection point, the RLOC and RHOC appeared a process of rapid increasing with the straw incorporation. These results suggest that implementation of the aforementioned straw management in the coming years will not reduce soil C sequestration capacity by C saturation. It will also not exacerbate C emissions from straw return. Corn straw return may be effective at improving the fertility of Phaeozem and transforming infertile PM into a productive agricultural soil within a relatively short time.

Conclusions

Returning corn straw to Phaeozem promotes OC preferentially accumulating in LF, and with organic material input increase, the C was subsequently stabilized and sequestered in HF. The promoting effectiveness of straw incorporation on C accumulation declined when the C inputs reached a certain level and it was better in the soil with lower OC concentration. C input, initial OC concentration, and clay content were the most influential variables on carbon sequestration efficiency, which accounted for about 73% of the variations of RLOC and RHOC. Both the topsoil and PM of Phaeozem have considerable C-stabilizing capacity and the C sequestration efficiency of topsoil and PM derived from loess was greater than those for topsoil and PM derived from laterite. The total amount of straw returned to the field will not reduce soil C sequestration capacity by C saturation in the Phaeozem region of Northeast China. Corn straw return may be effective at improving the fertility of Phaeozem and transforming infertile PM into a productive agricultural soil within a relatively short time.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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