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Effects of amendments on carbon and nitrogen fractions in agricultural soils of Yellow River Delta

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Abstract

Although various measurements (including organic amendments) have been used to ameliorate saline–alkaline soils, soil organic matter (SOM) remains low in most salt-affected agriculture soils. It was hypothesized that lower SOM level was partly attributable to weaker SOM stability (thus greater desorption) in the salt-affected soils. To test this hypothesis, we conducted a 16-week incubation experiment using low- and high-salinity soils to evaluate the effects of soil ameliorants (gypsum, $CaCO_3$, rice straw and biochar) on SOM labile fractions, i.e., water extractable organic carbon (WEOC) and nitrogen (WEON), together with microbial biomass carbon (MBC) and nitrogen (MBN). Our results showed an increase in MBC and MBN under all amendments in both low- and high-salinity soils, reflecting improvements in soil properties. Gypsum amendment led to a decrease in both WEOC (by 15–21%) and WEON (by 14–31%). $CaCO_3$ amendment only caused a decrease in WEON (by 14–27%), with a greater decrease found in the high-salinity soil. There was an increase in WEOC (by 13–66%) but a decrease in WEON (7.6–46%) under biochar and straw amendments in both low- and high-salinity soils. WEOC:SOC ratio (an indicator for SOC desorption) showed a decrease under gypsum and biochar amendments but an increase with $CaCO_3$ and straw treatments. There was a decrease in WEON:TN ratio (an indicator for ON desorption) under all amendments, with the greatest decrease under biochar treatment. Our analyses demonstrated an enhancement in SOC or ON adsorption under all amendments, indicating that SOM stability might be enhanced in association with soil amelioration. Our study also highlights that there is strong decoupling between carbon and nitrogen cycles and further studies are needed to examine the impacts of such decoupling on SOM stability.

Keywords Biochar, Straw, Gypsum, $CaCO_3$, Water extractable organic matter, Saline–alkaline soils

Introduction

Soil organic matter (SOM) is a key index for soil fertility, playing an important role in sustainability of agriculture. Moreover, SOM is also a means for carbon storage and acts as both a source and sink for the atmosphere CO_2 (Lal 2004), having a large influence on the carbon cycle in the terrestrial ecosystem. The strength of the source/sink is largely related to the stability of SOM (Lehmann and Kleber 2015).

SOM stability is regulated by the characteristics of SOM, other soil properties, and environmental conditions (Kan et al. 2022). In general, SOM with high carbon:nitrogen (C:N) ratio has a higher stability because of its complicated chemical composition with more aromatic- and aliphatic-functional groups (Wiesmeier et al. 2019). There is also evidence that high levels of multivalent cations are beneficial for SOM stability due to the formation of organic–mineral complexes (Sowers et al.

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2018; Wuddivira and Camps-Roach 2007). On the other hand, SOM stability is generally weak under high pH and salinity conditions that often lead to poor soil structure (Amini et al. 2015). However, little attention has been paid to SOM stability and its underly mechanisms in saline–alkaline soils.

Numerous studies have reported that application of organic amendment can not only increase SOM level, but also improve SOM quality and other soil physicochemical properties (Diacono and Montemurro 2010). For example, straw incorporation can improve soil structure because of enhanced aggregation by straw-derived organic materials (Jin et al. 2020), and also lead to a more complicated structure through changing chemical composition of SOM (He et al. 2018). Over the past decade, biochar has been increasingly used as a soil amendment to improve soil conditions and enhance carbon sequestration (Hardie et al. 2013). On the one hand, biochar amendment can increase soil adsorption capacity due to its high porosity and large surface area (Amini et al. 2015; Saifullah et al. 2018), leading to more SOM adsorbed in soil. On the other hand, soil aggregation is also enhanced under biochar amendment, because biochar can act as a binding agent between soil minerals and SOM to form mineral–organic complexes (Han et al. 2020; Saffari et al. 2020). Moreover, biochar amendment can decrease exchangeable Na in salt-affected soils due to supply of cation (Rita and Carolina 2018), which leads to improvement of soil structure and thus aggregation. However, our understanding is limited regarding the effects of organic amendments on SOM stability, particularly in salt-affected soils.

Previous studies have reported that inorganic amendments can also improve soil physical and chemical properties and environment conditions (Amini et al. 2015; Inagaki et al. 2016; Luo et al. 2018), with implication for SOM stability. Gypsum, as a common ameliorant, is used to improve soil structure by replacing Na^+ with calcium ions (Ca^{2+}) in saline–alkaline soils (Nan et al. 2016). On the other hand, the existing of extra Ca^{2+} can enhance soil aggregation due to the formation of Ca–SOM complexes (Rowley et al. 2017), and its function of cation bridge between clay and SOM particles (Wuddivira and Camps-Roach 2007). There is also evidence that high level of carbonate ($CaCO_3$) is conducive to aggregate stability due to the formation of SOM–Ca–clay complexes in calcareous soil (Huang et al. 2019; Pihlap et al. 2021). However, little is done to investigate how application of Ca-rich substances in soils affects SOM stability in saline–alkaline soils.

In general, SOM stability can be assessed by SOM's labile fractions (Kalbitz et al. 2000), such as water extractable organic carbon (WEOC) and nitrogen (WEON). For example, Zhang et al. (2020a) analyzed the WEOC content in different salinity soils, and used WEOC:SOC ratio as an indicator for desorption of SOC (or SOC stability), and found greater SOC desorption in higher salinity/pH soils of Yellow River Delta (YRD). Salt-affected soils usually have poor structure, which often lead to low levels of SOM (Mavi and Marschner 2013). Although various amendments have been used to ameliorate the salt-affected soils in YRD, SOM level remain low in most cropland soils. Here, we hypothesized that the low SOM levels were partly attributable to weak SOM stability associated with the poor structure and other charcteristice in the saline–alkaline soils. To test this hypothesis, we conducted an incubation experiment to invesgate how soil salinity and the use of soil amedments affect SOM stability in the YRD's cropland. The main objectives of this study are to: (i) examine the responces of water extractable SOM (an indicator for SOM stability) and microbial biomass to the applications of gypsum, $CaCO_3$, straw and biochar, and (ii) explore the potentials of inorganic and organic amendments to enhance the stability of SOM in salt-affected soils.

Materials and methods

Site description and soil characteristics

The YRD area (34°56′N~37°27′N, 114°36′E~116°27′E) located at the Shandong province of China. The area has a typical temperate monsoon climate zone, with mean annual temperature and precipitation are 11.7–12.6 °C and 530–630 mm, respectively. The soil is a silt loam that was developed on the Yellow River alluvial deposits, and classified as Calcaric Fluvisols (FAO-UNESCO system, 1988). The main cropping system is winter wheat–summer maize rotation in the YRD. We selected two representative sites: low-salinity soil in Huantai county and high-salinity soil in Dongying city. Irrigation is often applied using groundwater and river water from the Yellow River.

Agricultural productivity in Dongying area is constrained by high salinity/alkalinity, due to the shallow groundwater table, salty groundwater and strong evaporation. As shown in Table 1, soil pH was higher in the high-salinity soils at Dongying (8.8–8.9) than in the low-salinity soil at Huantai (8.1–8.2), but SOC and TN contents were significantly higher in the low-salinity soil (6.6–11.7 g kg^{-1} and 0.7–1.2 g kg^{-1}, respectively) than in the high-salinity soil (3.3–6.5 g kg^{-1} and 0.3–0.5 g kg^{-1}, respectively).

Incubation experiment

We collected surface (0–20 cm) and subsurface (20–40 cm) soils in October, 2019. Soil samples were naturally air-dried, well-mixed and then pass a 2-mm sieve.

Table 1 Soil pH and SOM fractions in low-salinity and high-salinity soils

Characteristics	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
pH	8.13 ± 0.24	8.17 ± 0.2	8.80 ± 0.28	8.90 ± 0.28
SOC (g kg^{-1})	11.7 ± 0.22	6.60 ± 0.02	6.46 ± 0.29	3.26 ± 0.26
TN (g kg^{-1})	1.24 ± 0.03	0.74 ± 0.02	0.48 ± 0.01	0.31 ± 0.01
WEOC (mg kg^{-1})	93.8 ± 3.82	70.5 ± 5.4	80.2 ± 6.22	63.7 ± 3.34
WEON (mg kg^{-1})	24.52 ± 0.93	8.23 ± 0.12	12.88 ± 0.77	9.52 ± 0.99

Four types of amendments were used: calcium carbonate (reagent grade), desulfurized gypsum, rice straw (ground to 2 mm) and commercial biochar. Gypsum had a pH of 7.23, and contained 37.6% CaO, 49.5% SO_3 and 2.2% SiO_2. Rice straw contained 40% C, 0.98% N, 0.17% P, and 1.17% K. Biochar was made from corncob under ~ 360 °C for 24 h, and had a pH of 8.2, density of 0.30 g cm^{-3}, 72.0% ash content, 65.7% C, 0.91% N, 0.08% available P (AP) and 1.60% available K (AK).

The incubation experiment consisted of a control (without amendment) and ten amendment treatments with three replicates. All amendments had two application rates: gypsum at 30 g kg^{-1} (G1) and 50 g kg^{-1} (G2), $CaCO_3$ at 40 g kg^{-1} (Ca1) and 80 g kg^{-1} (Ca2), biochar at 15 g kg^{-1} (B1) and 30 g kg^{-1} (B2), and straw at 15 g kg^{-1} (S1) and 30 g kg^{-1} (S2). There were also two combined treatments of straw and gypsum: S1G1 and S2G2. For each treatment, 60 g air-dried soil and amendment were well-mixed, and then put into a 250 ml plastic cup. We added 12 ml distilled water into each cup (~ 60% of the field water capacity), and then incubated at ~ 25℃ in a laboratory for 16 weeks. Water loss due to evaporation was replenished during incubation.

Soil analyses

SOC content was measured using the method of $K_2Cr_2O_7$–H_2SO_4 digestion and followed by $FeSO_4$ titration (Walkley 1935). TN content was determined by the Kjeldahl digestion method. WEOC and WEON contents were measured by following procedure: treating 5.0 g soil (2 mm) with 50 mL 0.5 M K_2SO_4 solution, shaking for 1 h (200 rpm), followed by centrifuging (4500 rpm) for 10 min and filtering (0.45 μm membrane), and then using a TOC analyzer (Liqui TOC II, Elementar, Hanau, Germany).

For soil MBC and MBN measurements, we used the chloroform fumigation incubation method (Vance et al. 1987) for the extraction, followed by measurements of extractable C and N contents. Briefly, 10 g soil samples were fumigated by $CHCl_3$ solution, treated with 40 ml 0.5 M K_2SO_4 and shaken for 30 min, followed by centrifuging and filtering. Microbial biomass C and N contents were calculated from the differences in extractable C and N contents between fumigated samples and control samples (without fumigation) using conversion factors of 0.54 and 0.45, respectively.

Statistical analysis

The effects of various treatments on soil properties were analyzed through a one-way analysis of variance (ANOVA) and the least significant difference (LSD) at $p < 0.05$. All statistical analyses were carried out using SPSS 20.0, and all graphs were generated using origin 9.0.

Results

Effects of soil amendments on WEOC and WEON

There was no significant increase in WEOC after the incubation without amendment (Fig. 1). Soil amendments had various effects on WEOC. Gypsum amendment caused a significant decrease of WEOC content in 0–20 cm layer for both low-salinity (by 20.0–21.3 mg kg^{-1}, or 20–21%) and high-salinity (by 14.8–19.7 mg kg^{-1}, or 17–23%) soils, with no significant difference between G1 and G2 treatments (Fig. 1a, b). For the 20–40 cm soils, G1 treatment led to a significant decrease of WEOC in low-salinity (by 14.8 mg kg^{-1}, or 20%) and high-salinity (by 21.7 mg kg^{-1}, or 34%) soils, and non-significant decrease under G2 treatment (Fig. 1c, d). However, $CaCO_3$ amendment had little effect on WEOC content in all soils. Biochar amendment caused a significant increase (by 18.4–50.6 mg kg^{-1}, or 29–69%) in WEOC content in all soils, except in 0–20 cm layer of low-salinity soil under B1 treatment. Similarly, WEOC content showed a significant increase (by 20.5–32.7 mg kg^{-1}, or 16–44%) under straw amendment. Compared with straw amendment, combined gypsum–straw treatment caused various changes in WEOC, with a significant decrease in low-salinity soils (by 20.6–36.2 mg kg^{-1}, or 20–29%) and high-salinity soils (by 12.8–16.4 mg kg^{-1}, or 15–17%) under S1G1 treatment, and small decrease (by 3.7–16.4 mg kg^{-1}, or 3.6–12%) in all soils under S2G2 treatment.

WEON content showed a significant increase (from 8.23–24.5 mg kg^{-1} to 23.2–58.9 mg kg^{-1}) after 16-week incubation without amendment, with significantly higher values in low-salinity soils than in high-salinity soils (Fig. 2). There was a decrease of WEON in nearly all the treatments. For the low-salinity soils, the greatest decrease of WEON were under B2 treatment in both 0–20 cm soil (by 26.9 mg kg^{-1}, or 46%) and 20–40 cm soil (by 16.4 mg kg^{-1}, or 40%). Similar decreases were also found under gypsum amendment in 20–40 cm soil (by 11.7–12.5 mg kg^{-1}, or 28–31%). The decrease

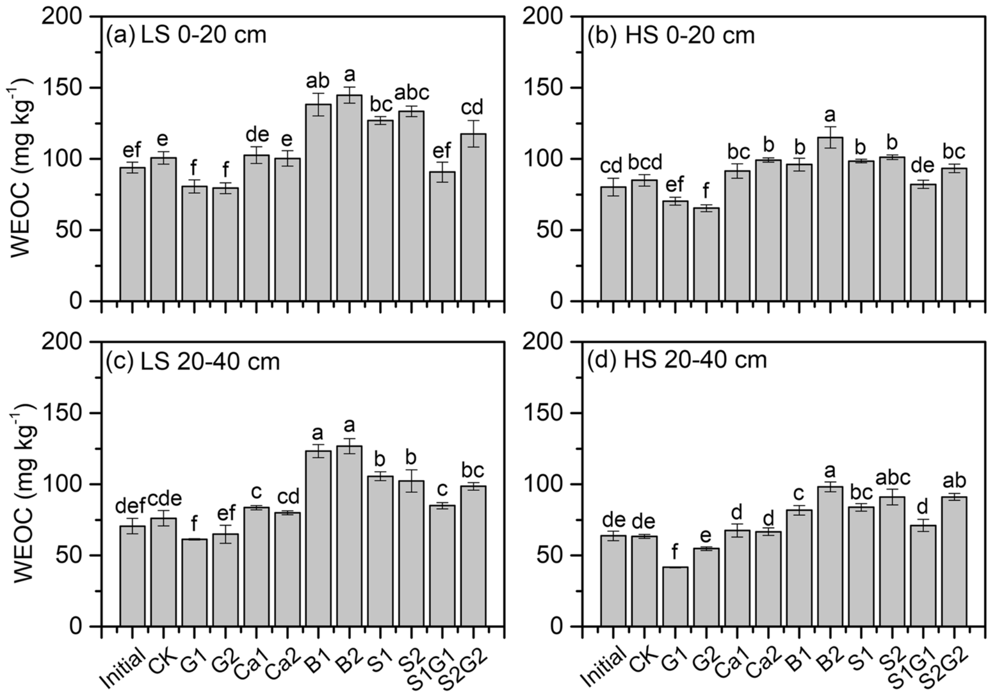

Fig. 1 Means and standard errors (error bars) of water extractable organic carbon (WEOC) in low-salinity (LS) and high-salinity (HS) soils before and after incubation with/without amendment. Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

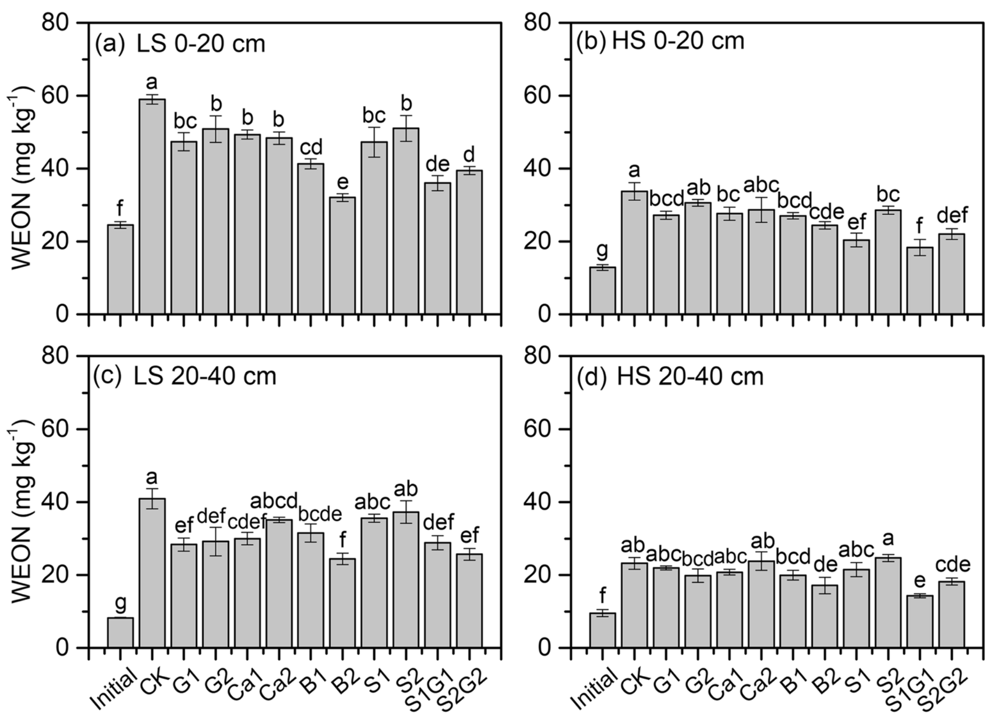

Fig. 2 Means and standard errors (error bars) of water extractable organic nitrogen (WEON) in low-salinity (LS) and high-salinity (HS) soils before and after incubation with/without amendment. Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

of WEON was comparable under combined gypsum–straw amendments (by 19.6–22.9 mg kg^{-1}, or 33–39%) in 0–20 cm soil. $CaCO_3$ (by 9.6–10.6 mg kg^{-1}, or 14–27%) and straw (by 7.95–11.7 mg kg^{-1}, or 8.9–20%) treatments also caused a significant decrease in WEON content in 0–20 cm soil, but a non-significant decrease in 20–40 cm soil (except under higher rate of $CaCO_3$ treatment). For the high-salinity soil, the greatest decrease of WEON was under S1G1 treatment in both 0–20 cm soil (by 15.4 mg kg^{-1}, or 46%) and 20–40 cm soil (by 8.9 mg kg^{-1}, or 38%). Similar decreases were also found under S1 (by 13.4 mg kg^{-1}, or 40%) treatment in 0–20 cm soil, and under S2G2 (5.0 mg kg^{-1}, or 22%) and B2 (6.1 mg kg^{-1}, or 26%) treatments in 20–40 cm soil. There was a significant decrease in WEON content under G1, Ca1 and S2 treatments (5.2–6.6 mg kg^{-1}, or 15–20%) in 0–20 cm soil. Biochar amendments caused a significant decrease (by 6.1–9.3 mg kg^{-1}, or 20–28%) in WEON content, except the B1 for 20–40 cm soil.

Effects of soil amendments on MBC and MBN

MBC and MBN contents were significantly higher (approximately 100%) in low-salinity soils than in high-salinity soils (Figs. 3, 4). There was no increase in MBC after the incubation without amendment in all soils (Fig. 3). Overall, most soil amendments caused an increase in MBC, with the largest increase (by 50.1–147 mg kg^{-1}, or 78–253%) under combined gypsum–straw and the smallest increase (by 7.0–35.1 mg kg^{-1}, or 8.2–47%) in the gypsum and $CaCO_3$ amendments in all soils (except in 20–40 cm layer of high-salinity soil). Biochar and straw amendments both caused a significant increase (by 24.9–89.3 mg kg^{-1}, or 27–140%) in MBC content in all soils.

There was little change in MBN after incubation without amendment, but a significant increase in most treatments with amendments (Fig. 4). The largest increase in MBN content was found under combined gypsum–straw amendments (by 17.6–31.6 mg kg^{-1}, or 142–289%) in all soils, whereas the smallest increase (by 1.7–11.9 mg kg^{-1}, or 8.3–108%) was under gypsum and $CaCO_3$ amendments. MBN content showed an overall significant increase under biochar (by 8.3–15.1 mg kg^{-1}, or 45–155%) and straw (by 9.7–20.5 mg kg^{-1}, or 70–221%) amendments.

Effects of soil amendments on various C:N ratios

There was a significant decrease in WEOC:WEON ratio after incubation without amendment (Table 2). In general, straw and biochar as well as combined straw–gypsum amendments led to a significant increase in WEOC:WEON ratios in all soils. The largest increase was found under B2 treatment in low-salinity (by 2.8–3.3) and high-salinity (by 2.1–3.1) soils. However, there was

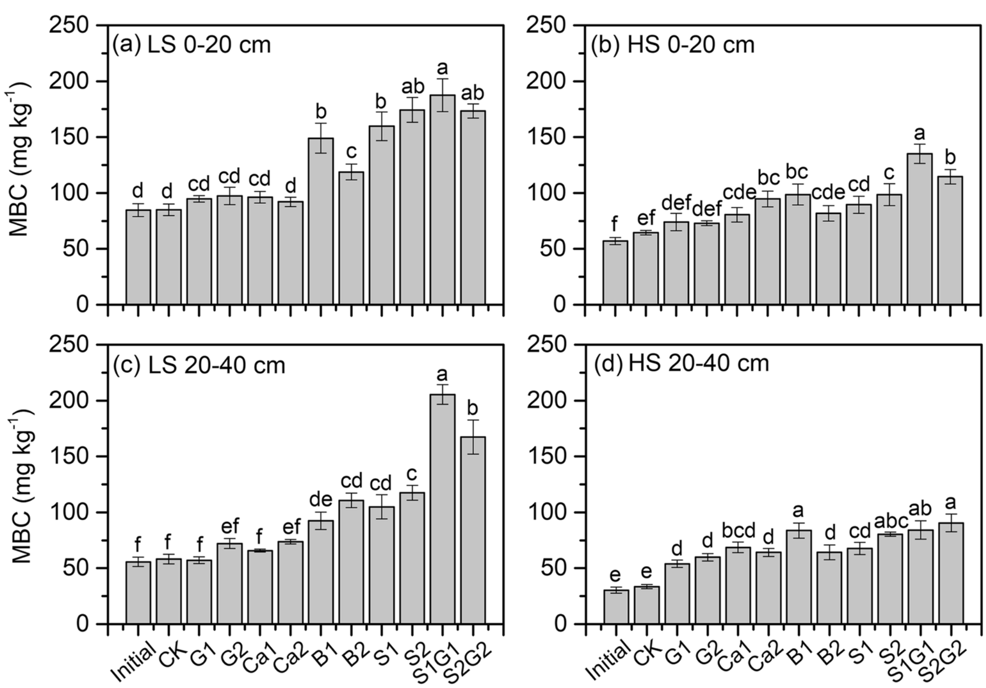

Fig. 3 Means and standard errors (error bars) of microbial biomass carbon (MBC) in low-salinity (LS) and high-salinity (HS) soils before and after incubation with/without amendment. Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

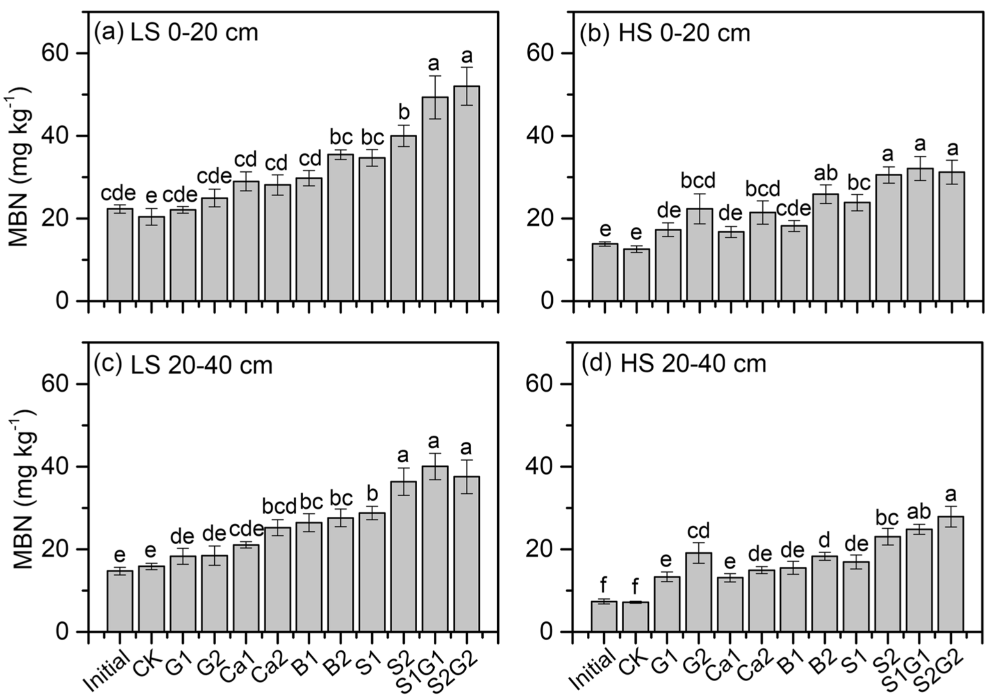

Fig. 4 Means and standard errors (error bars) of microbial biomass nitrogen (MBN) in low-salinity (LS) and high-salinity (HS) soils before and after incubation with/without amendment. Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

Table 2 Effect of soil amendments on WEOC:WEON ratio in low-salinity and high-salinity soils

Treatments	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Initial	3.83 ± 0.01b	8.57 ± 0.37a	6.23 ± 0.08a	6.80 ± 0.75a
CK	1.71 ± 0.11 fg	1.87 ± 0.22f	2.62 ± 0.22ef	2.74 ± 0.17de
G1	1.71 ± 0.15 fg	2.17 ± 0.15ef	2.59 ± 0.20ef	1.90 ± 0.06e
G2	1.56 ± 0.05 g	2.26 ± 0.35ef	2.14 ± 0.12f	2.71 ± 0.29de
Ca1	2.08 ± 0.06ef	2.80 ± 0.19ef	3.32 ± 0.24de	3.25 ± 0.22de
Ca2	2.07 ± 0.06ef	2.28 ± 0.07ef	2.81 ± 0.35def	2.78 ± 0.18de
B1	3.35 ± 0.29bc	3.93 ± 0.38c	3.55 ± 0.24 cd	4.12 ± 0.45 cd
B2	4.53 ± 0.33a	5.21 ± 0.56b	4.76 ± 0.48b	5.83 ± 0.75ab
S1	2.69 ± 0.19d	2.97 ± 0.03de	4.72 ± 0.43b	3.93 ± 0.48 cd
S2	2.62 ± 0.11d	2.76 ± 0.37e	3.47 ± 0.14 cd	3.69 ± 0.29 cd
S1G1	2.52 ± 0.13de	2.96 ± 0.28de	4.62 ± 0.58b	4.97 ± 0.47bc
S2G2	2.98 ± 0.16 cd	3.85 ± 0.31 cd	4.24 ± 0.19bc	5.02 ± 0.38bc

Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

little change in WEOC:WEON ratio under gypsum and $CaCO_3$ amendments in all soils.

MBC:MBN ratio showed small increases after incubation without amendment, from 3.8–4.1 to 4.2–5.6 (Table 3). For low-salinity soils, there was a little change in MBC:MBN ratio after amendments addition in 0–20 cm. The largest increase in MBC:MBN ratio was found under G2 treatment (by 1.0) in 20–40 cm soil, and a significant decrease (by 1.3–2.6) under $CaCO_3$, biochar and straw amendments. For high-salinity soil, the greater increase in MBC:MBN ratio in 0–20 cm and 20–40 cm was found under B1 (by 0.3) and S2G2 (by 2.4) treatments. Similar increase was also found under $CaCO_3$ amendment in 0–20 cm soil. However, there was a significant decrease (by 1.4–1.9) in MBC:MBN ratio under G2, S2G2 treatments and straw amendment in 0–20 cm soil.

Fractions of WEOC/MBC in SOC and WEON/MBN in TN

There was little change in the ratios of WEOC:SOC, MBC:SOC and MBN:TN after incubation without amendments, but a significant increase in WEON:TN ratio (Tables 4–7). All amendments caused an overall increase in MBC:SOC and MBN:TN ratios in all soils (Tables 4, 5), indicating improvement in soil conditions. MBC:SOC and MBN:TN ratios showed the largest increase under combined straw–gypsum amendment, and the smallest increase under gypsum amendment. Straw amendment resulted in a significant increase in MBC:SOC ratio (by 0.2–1.0%) and MBN:TN ratio (by 1.1–3.7%) in all soils, with a general greater increase under S2 treatment than under S1 treatment.

Table 3 Effect of soil amendments on MBC:MBN ratio in low-salinity and high-salinity soils

Treatments	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Initial	3.79 ± 0.16bc	3.78 ± 0.10def	4.12 ± 0.34bcdef	4.15 ± 0.66cde
CK	4.19 ± 0.35abc	5.58 ± 0.10b	5.16 ± 0.38b	4.67 ± 0.28bcd
G1	4.29 ± 0.10ab	5.27 ± 0.11bc	4.32 ± 0.10bcde	4.07 ± 0.47cde
G2	3.94 ± 0.63bc	6.62 ± 0.61a	3.32 ± 0.52ef	3.15 ± 0.28e
Ca1	3.32 ± 0.11c	3.13 ± 0.18ef	4.81 ± 0.35abc	5.26 ± 0.76bc
Ca2	3.28 ± 0.19c	2.94 ± 0.27f	4.43 ± 0.28abcd	4.30 ± 0.28cde
B1	5.07 ± 0.23a	4.31 ± 0.33 cd	5.41 ± 0.39a	5.46 ± 0.40b
B2	3.35 ± 0.09c	4.03 ± 0.43de	4.13 ± 0.22bcdef	3.94 ± 0.35de
S1	4.59 ± 0.11ab	3.67 ± 0.48def	3.76 ± 0.14cdef	4.05 ± 0.20cde
S2	4.36 ± 0.11ab	3.24 ± 0.28ef	3.23 ± 0.39f	3.51 ± 0.40de
S1G1	3.84 ± 0.64bc	5.16 ± 0.60bc	4.24 ± 0.44bcdef	3.41 ± 0.51de
S2G2	3.34 ± 0.19c	4.59 ± 0.06bcd	3.70 ± 0.53def	7.10 ± 0.10a

Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

Table 4 Effect of soil amendments on MBC:SOC ratio (%) in low-salinity and high-salinity soils

Treatments	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Initial	0.72 ± 0.06ef	0.84 ± 0.07e	0.85 ± 0.05ef	0.77 ± 0.06 fg
CK	0.73 ± 0.05def	0.88 ± 0.06de	0.96 ± 0.01de	0.86 ± 0.04 fg
G1	0.81 ± 0.02cde	0.89 ± 0.04de	1.15 ± 0.13 cd	1.37 ± 0.10de
G2	0.73 ± 0.06def	0.89 ± 0.06de	1.12 ± 0.05cde	1.65 ± 0.11bcd
Ca1	0.91 ± 0.08abcd	1.06 ± 0.02de	1.28 ± 0.14c	2.03 ± 0.16a
Ca2	0.82 ± 0.03cde	1.13 ± 0.03d	1.60 ± 0.16ab	1.49 ± 0.19 cd
B1	0.79 ± 0.07cde	0.91 ± 0.06de	0.91 ± 0.1de	1.03 ± 0.06ef
B2	0.56 ± 0.03f	0.84 ± 0.07e	0.57 ± 0.05f	0.64 ± 0.05 g
S1	1.05 ± 0.1ab	1.47 ± 0.13c	1.31 ± 0.09bc	1.60 ± 0.13bcd
S2	0.93 ± 0.06abc	1.50 ± 0.08c	1.41 ± 0.14bc	1.89 ± 0.04ab
S1G1	1.08 ± 0.08a	2.58 ± 0.1a	1.74 ± 0.11a	1.60 ± 0.21bcd
S2G2	0.88 ± 0.03bcde	2.24 ± 0.2b	1.36 ± 0.08bc	1.79 ± 0.17abc

Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

Table 5 Effect of soil amendments on MBN:TN ratio (%) in low-salinity and high-salinity soils

Treatments	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Initial	1.81 ± 0.09de	2.00 ± 0.15e	3.94 ± 0.04f	3.15 ± 0.32 fg
CK	1.65 ± 0.19e	2.15 ± 0.12de	3.57 ± 0.23f	3.06 ± 0.05 g
G1	1.73 ± 0.09e	2.54 ± 0.26cde	4.94 ± 0.53def	5.47 ± 0.60de
G2	1.91 ± 0.16de	2.53 ± 0.34de	6.43 ± 0.86def	8.06 ± 0.96bc
Ca1	2.31 ± 0.24 cd	2.76 ± 0.21cde	4.72 ± 0.37cde	4.31 ± 0.37efg
Ca2	2.30 ± 0.20 cd	3.42 ± 0.27bc	5.86 ± 0.86ef	4.98 ± 0.28defg
B1	2.30 ± 0.16 cd	3.02 ± 0.37bcd	4.22 ± 0.33def	4.98 ± 0.76defg
B2	2.71 ± 0.11bc	3.02 ± 0.23bcd	5.09 ± 0.73 cd	4.25 ± 0.21efg
S1	2.73 ± 0.16bc	3.74 ± 0.17b	6.25 ± 0.71abc	5.02 ± 0.41def
S2	2.98 ± 0.20b	4.65 ± 0.44a	7.29 ± 0.54a	6.36 ± 0.43 cd
S1G1	3.69 ± 0.33a	5.02 ± 0.37a	8.77 ± 0.93a	9.09 ± 0.26ab
S2G2	3.85 ± 0.23a	4.67 ± 0.45a	8.18 ± 0.51ab	10.48 ± 1.60a

Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

Table 6 Effect of soil amendments on WEOC:SOC ratio (%) in low-salinity and high-salinity soils

Treatments	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Initial	0.80 ± 0.03bcd	1.07 ± 0.06de	1.20 ± 0.10bcd	1.62 ± 0.008 cd
CK	0.86 ± 0.03ab	1.15 ± 0.08 cd	1.31 ± 0.10abc	1.61 ± 0.07 cd
G1	0.70 ± 0.06def	0.95 ± 0.006ef	1.10 ± 0.07d	1.06 ± 0.07f
G2	0.60 ± 0.03 fg	0.78 ± 0.07f	1.01 ± 0.05de	1.51 ± 0.08de
Ca1	0.97 ± 0.02a	1.35 ± 0.01ab	1.45 ± 0.09a	2.00 ± 0.11ab
Ca2	0.90 ± 0.05ab	1.23 ± 0.02bcd	1.35 ± 0.09ab	1.50 ± 0.11de
B1	0.74 ± 0.04cde	0.98 ± 0.07ef	0.89 ± 0.01ef	1.01 ± 0.07f
B2	0.68 ± 0.03ef	0.96 ± 0.06ef	0.81 ± 0.05f	0.98 ± 0.07f
S1	0.83 ± 0.04bc	1.48 ± 0.08a	1.42 ± 0.07a	1.98 ± 0.05ab
S2	0.71 ± 0.02de	1.31 ± 0.10bc	1.43 ± 0.04a	2.13 ± 0.14a
S1G1	0.52 ± 0.04 g	1.07 ± 0.03de	1.08 ± 0.06de	1.35 ± 0.08e
S2G2	0.59 ± 0.05 fg	1.32 ± 0.04abc	1.11 ± 0.03 cd	1.80 ± 0.02bc

Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD

WEOC:SOC ratio was lower in low-salinity soils than in high-salinity soils, with the lowest ratio in the 0–20 cm of low-salinity soil and the highest ratio in the 20–40 cm of high-salinity soil (Table 6). In general, WEOC:SOC ratio showed an increase under $CaCO_3$ (by 0.04–0.4%) and straw amendments (by 0.1–0.5%), but a significant decrease under gypsum amendment (by 0.1–0.6%) biochar amendment (by 0.1–0.6%) in all soils. For the low-salinity soils, gypsum amendment resulted in the greatest decrease of WEOC:SOC ratio (by 0.2–0.4%), whereas for the high-salinity soils, the greatest decrease of WEOC:SOC ratio was found under biochar amendment (0.4–0.6%). The decrease of WEOC:SOC ratio was greater under combined straw–gypsum amendment (by ~ 0.3%) than under gypsum (by ~ 0.2%) amendment in the 0–20 cm of low-salinity soil.

All amendments led to a decrease in WEON:TN ratio in all soils (Table 7), with a greater decrease under organic amendments (by 0.8–5.9%) than under inorganic amendments (by 0.9–3.1%), and the largest decrease under B2 treatment (by 2.3–5.9%). Overall, the decrease of WEON:TN ratio was greater under both organic and inorganic amendments in high-salinity soils (by 2.8–5.9% and 0.8–3.1%, respectively) than in low-salinity soils (by 0.8–2.9% and 0.9–1.6%, respectively). The decrease of WEON:TN ratio was greater under biochar treatment (by 1.6–5.9%) than under straw treatment (by 0.8–4.3%) in all soils. For

Table 7 Effect of soil amendments on WEON:TN ratio (%) in low-salinity and high-salinity soils

Treatments	Low-salinity soil		High-salinity soil	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Initial	1.98 ± 0.04f	1.11 ± 0.02e	3.66 ± 0.05f	4.05 ± 0.51f
CK	4.77 ± 0.17a	5.54 ± 0.44a	9.61 ± 0.73a	9.89 ± 0.49a
G1	3.72 ± 0.22bc	3.94 ± 0.31bc	7.76 ± 0.39abcd	8.99 ± 0.18ab
G2	3.89 ± 0.25b	3.98 ± 0.45bc	8.82 ± 0.64ab	8.35 ± 0.81abc
Ca1	3.92 ± 0.011b	3.94 ± 0.41bc	7.77 ± 0.51abcd	6.82 ± 0.33cde
Ca2	3.95 ± 0.15b	4.76 ± 0.11ab	7.93 ± 1.01abc	7.94 ± 0.83bcd
B1	3.19 ± 0.08 cd	3.60 ± 0.47 cd	6.26 ± 0.18cde	6.37 ± 0.11de
B2	2.45 ± 0.10ef	2.67 ± 0.19d	4.80 ± 0.59ef	3.98 ± 0.54f
S1	3.72 ± 0.33bc	4.62 ± 0.16ab	5.33 ± 0.44ef	6.39 ± 0.78de
S2	3.80 ± 0.25b	4.77 ± 0.41ab	6.82 ± 0.28bcde	6.82 ± 0.35cde
S1G1	2.70 ± 0.17de	3.61 ± 0.26 cd	5.00 ± 0.48ef	5.25 ± 0.37ef
S2G2	2.92 ± 0.10de	3.20 ± 0.22 cd	5.78 ± 0.27de	6.83 ± 0.80cde

Values followed by different letters indicate significant differences among treatments ($p < 0.05$) according to LSD low-salinity soils, WEON:TN ratio showed no significant difference between gypsum and $CaCO_3$ treatments. However, $CaCO_3$ treatment resulted in a greater decrease in WEON:TN ratio (by 1.7–3.1%) relative to gypsum treatment (by 0.8–1.9%) in high-salinity soil. The decrease of WEON:TN ratio was greater under combined straw–gypsum amendment (by 1.9–4.6%) than under gypsum (0.8–1.9%) and straw amendments (by 0.8–4.2%) in all soils.

Discussion

Effects of inorganic amendments on SOC stability

Previous studies showed that inorganic amendments can enhance stability of SOM (Barreto et al. 2021; Zhang et al. 2020b), due to improvements in soil physicochemical properties and/or environment conditions. In general, application of inorganic amendment can change soil pH and salinity (Inagaki et al. 2016; Nan et al. 2016). For example, gypsum addition can provide Ca^{2+} to replace exchangeable Na^{+}, which lead to improvement in soil structure and alkalinity/salinity (Chi et al. 2012; Inagaki et al. 2016), thus enhanced SOM stability.

Our study showed that application of gypsum led to a significant decrease in WEOC (14–34%), with a greater decrease in WEOC:SOC ratio the high-salinity soils (Tables 6, 7), indicating that gypsum amendment was an effective practice for enhancing SOM stability in saline–alkaline soils. An early study also reported a decrease in WEOC under gypsum addition in short-term experiments in the alkaline soils of Australia (Tavakkoli et al. 2021). The increase of free form of Ca^{2+} from gypsum can enhance the binding capacity with organic matter, promoting the formation of Ca–SOM complexes (Wang et al. 2021). Moreover, the presence of Ca^{2+} can also inhibit clay dispersion and disruption of aggregates and increase soil structure stability, leading to enhanced SOM protection (Wuddivira and Camps-Roach 2007). These results indicate that gypsum amendment can improve soil structure and enhance SOM stability, particularly in saline–alkaline soils.

This laboratory study showed that there was no decrease in WEOC under $CaCO_3$ treatment in the salt-affected soil of North China Plain (Fig. 1). However, an early laboratory experiment reported that $CaCO_3$ addition led to a decrease in oxidizable SOC and DOC using non-salt affected soil from the Loess Plateau (Li et al. 2018). On the other hand, another laboratory study showed that DOC concentration was decreased under $CaCO_3$ treatment, but increased under combined $CaCO_3$–Na_2CO_3 treatment (Tavakkoli et al. 2015). The decrease in DOC/WEOC due to the high level of $CaCO_3$ in non-salt affected soils may be attributed to enhanced aggregation thus enhanced adsorption of SOC (Huang et al. 2019; Pihlap et al. 2021), resulting from the formation of organo-Ca complex (Yu et al. 2017). The lack of decrease in DOC/WEOC with the addition of $CaCO_3$ in saline/alkaline soils (or with high levels of Na^{+}) was probably attributed to the relatively lower levels of Ca^{2+} due to the ameliorative function of $CaCO_3$ (i.e., replacement of Na^{+} by Ca^{2+}) (Wong et al. 2010), limiting the formation of organo-Ca complex. These results indicated that the influence of $CaCO_3$ on SOM stability might be affected by soil properties and/or environment conditions (such as salinity/alkalinity and Na^{+}/K^{+} levels).

Effects of organic amendments on SOC stability

Application of carbon-rich organic materials into soil can have influences on SOC stability through changing soil physicochemical properties and microbial activities (Joseph et al. 2021; Larney and Angers 2012). In general, organic amendments can improve soil cation exchange capacity and aggregation (Karami et al. 2012; Zhang et al. 2021b), which would lead to enhanced SOM stability (Diatta et al. 2020), thus decreased desorption of SOC.

Our short-term laboratory experiment revealed various responses of WEOC:SOC ratio to straw incorporation in the Fluvo-aquic of the North Plain China (Table 6), i.e., a modest decrease only under high rate of straw addition in the low-salinity surface soil, a non-significant increase in the high-salinity surface soil, but a significant increase in the subsurface soils. Previous studies based on long-term experiments showed that straw incorporation caused a decrease in WEOC:SOC ratio in low-salinity soils (Lu et al. 2021) and non-salt affected soils (Qiu et al. 2016). In general, straw-derived organic materials such as colloids can combine with soil minerals to form macroaggregates (Jin et al. 2020), which would enhance SOM stability (thus decreased WEOC:SOC ratio) in most normal soils (such as non-salt affected soils and low-salinity soils). However, such function (of straw) might be affected by treatment duration and soil physic and chemical characteristics. There is evidence that ameliorative effects by straw incorporation are limited due to poor soil structure under high soil pH/salinity conditions (Zhang et al. 2021a), particularly in short duration (Rita and Carolina 2018). In addition, high soil salinity could hinder the procession of straw-C transforming into soil organic fractions (Xie et al. 2017), but also cause damage to old and newly formed SOM thus result in lower SOM stability. These results indicated that straw incorporation may lead to enhanced SOM stability in normal soils or under normal environment conditions, but has limited effects on improvements of SOM stability in saline–alkaline soils.

There is a significant decrease in WEOC:SOC ratio under biochar amendment, particularly in the high-salinity soil in our study. A number of studies have also reported that WEOC:SOC ratio is lower under biochar amendment in both laboratory and field studies (Demisie et al. 2014; Eykelbosh et al. 2015; Lu et al. 2021; Wu et al. 2021; Yang et al. 2017). In general, biochar has high porosity and large surface area, which is beneficial to adsorption of SOM (Blanco-Canqui 2017). In addition, biochar amendment can enhance the formation of mineral–biochar–SOM complexes, thus promote formation of macro-aggregates from micro-aggregates (Han et al. 2020; Zhang et al. 2021b), resulting in enhanced protection of SOM. On the other hand, biochar amendment can also reduce free Na^+ in salt-affected soils because of its large adsorption capacity, which can lead to improved soil structure and aggregate formation (Amini et al. 2015; Dai et al. 2019). Clearly, biochar amendment can result in enhanced SOM stability, with greater effects in saline–alkaline soils.

Effects of soil amendments on the decoupling of carbon and nitrogen cycling

Soil carbon and nitrogen are generally coupled in many biogeochemical processes in terrestrial ecosystems (Niu et al. 2023). However, C:N ratio varies largely between different pools in soils (PiÑEiro et al. 2006), indicating some degree of decoupling between carbon and nitrogen cycling. For example, C:N ratio was usually greater in SOM (9.7–14), but smaller (often < 10) and more variable in microbial biomass and water-soluble organic matter (Kooch et al. 2019; Qiu et al. 2016; Yuan et al. 2007; Zhao et al. 2017).

Our 16-week laboratory study showed a significant increase in WEOC:WEON ratio under organic amendments using Fluvic Cambisol from the North China Plain, which mainly resulted from a decrease of WEON (9.0–46%). Similarly, an 18-month experiment reported that biochar addition led to a decrease (by 22%) in DON using sandy soil from the Italy (Sorrenti and Toselli 2016). Another 35-day laboratory study found a decrease in DON under biochar and straw treatments using Cumuli-Ustic Isohumosol of Loess Plateau in northwest China (Zhu et al. 2017). The decrease of WEON or DON under biochar treatment may be associated with the high adsorption capacity of biochar (Sorrenti and Toselli 2016), due to its large porosity and surface area (Tan et al. 2017). Our further analysis showed that biochar and straw treatments caused a significant decrease (14–60%) in WEON:TN ratio (also an index for SOM stability), with a larger decrease in high-salinity soils, which was greater than the decrease in WEOC:SOC ratio. Apparently, amelioration of salt-affected soils can result in improved soil structure and SOM stability, leading to the protection of not only SOC but also N-rich organic materials.

This laboratory study showed a significant decrease in both WEON and WEOC under gypsum treatment using Fluvic Cambisol from the North China Plain. Similarly, other studies also reported a decrease in WEON and WEOC under gypsum treatment in alkaline soils in other regions (Rashad et al. 2010; Rathi et al. 2020; Tavakkoli et al. 2021). The decrease of WEON and WEOC may be due to enhanced formation of Ca–SOM complexes, resulting from the increase of free form of Ca^{2+} from gypsum (Wang et al. 2021). Interestingly, our short-term study showed a decrease in WEON, but a non-significant increase in WEOC under $CaCO_3$ treatment, which was consistent with the finding of Filep et al. (2003). A previous study based on 190 arable soils of Hungary also revealed lower levels of DON but little change in DOC in soils under higher levels of $CaCO_3$ content (Filep and Rékási 2011). There was evidence that DON and DOC decoupling (or a decrease in DOC:DON ratio) was more pronounced in soils with higher salinity or pH (Filep and Rékási 2011), due to a larger amount of N-poor or C-rich hydrophobic compounds than N-rich hydrophilic compounds in abnormal soils or unfavorable environmental conditions (Andersson et al. 2000; Filep and Rékási 2011). Our further analysis showed a significant decrease (14–31%) in WEON:TN ratio under $CaCO_3$ treatment, with a greater decrease in high-salinity soils. These limited studies indicate that $CaCO_3$ amendment could lead to enhanced SOM stability through protection of N-rich substances, particularly in saline–alkaline soils. Further studies are needed to improve our understanding of regulating mechanisms on SOM stability and carbon–nitrogen decoupling in various environments.

Conclusions

A 16-week incubation experiment was conducted to investigate the effects of soil amendments (gypsum, $CaCO_3$, straw and biochar) on the key fractions of SOM (WEOC, WEON, MBC and MBN) in low- and high-salinity soils in YRD. All soil amendments caused an increase in microbial biomass, with a greater increase found under combined gypsum–straw amendments. There was a decrease in WEOC only under gypsum amendment but an overall decrease of WEON under all the treatments. WEOC:SOC ratio (an index of SOC stability) showed a decrease under biochar and gypsum amendments but an increase with the addition of straw and $CaCO_3$. However, all amendments caused a decrease in WEON:TN ratio (also an indicator for SOM stability), with a greater decrease found under biochar and straw treatments. Clearly, there was some degree of decoupling between WEOC and WEON particularly in salt-affected soils, with a greater desorption of WEON relative to that of WEOC. This study suggested that abnormal environmental conditions (e.g., high levels of anions/cations) might have caused lower SOM stability in YRD, and soil amelioration with biochar and gypsum amendments led to enhanced SOM stability. More studies are needed to improve our understanding on regulating mechanism of SOM stability in various environments.

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Author contributions
XW provided financial support for this study, and corrected all the versions of the manuscript. LW and XZ conducted laboratory analyses; LW carried out data analyses, and prepared for the manuscript. KZ and TL collected soils, and commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The research data of this study can be obtained upon by requesting the corresponding author.

Declarations

Competing interests
All authors declare that they have no conflict of interests.

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References

Amini S, Ghadiri H, Chen C, Marschner P (2015) Salt-affected soils, reclamation, carbon dynamics, and biochar: a review. J Soils Sediments 16:939–953
Andersson S, Nilsson SI, Saetre P (2000) Leaching of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in mor humus as affected by temperature and pH. Soil Biol Biochem 32(1):1–10
Barreto MSC, Elzinga EJ, Ramlogan M, Rouff AA, Alleoni LRF (2021) Calcium enhances adsorption and thermal stability of organic compounds on soil minerals. Chem Geol 559:119804
Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81:687–711
Chi CM, Zhao CW, Sun XJ, Wang ZC (2012) Reclamation of saline-sodic soil properties and improvement of rice (Oriza sativa L.) growth and yield using desulfurized gypsum in the west of Songnen Plain, northeast China. Geoderma 187–188:24–30
Dai H, Chen Y, Liu K, Li Z, Qian X, Zang H, Yang X, Zhao Y, Shen Y, Li Z, Sui P (2019) Water-stable aggregates and carbon accumulation in barren sandy soil depend on organic amendment method: A three-year field study. J Clean Prod 212:393–400
Demisie W, Liu Z, Zhang M (2014) Effect of biochar on carbon fractions and enzyme activity of red soil. CATENA 121:214–221
Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev 30:401–422
Diatta AA, Fike JH, Battaglia ML, Galbraith JM, Baig MB (2020) Effects of biochar on soil fertility and crop productivity in arid regions: a review. Arab J Geosci 13:595
Eykelbosh AJ, Johnson MS, Couto EG (2015) Biochar decreases dissolved organic carbon but not nitrate leaching in relation to vinasse application in a Brazilian sugarcane soil. J Environ Manage 149:9–16
Filep T, Rékási M (2011) Factors controlling dissolved organic carbon (DOC), dissolved organic nitrogen (DON) and DOC/DON ratio in arable soils based on a dataset from Hungary. Geoderma 162:312–318
Filep T, Kincses I, Nagy P (2003) Dissolved organic carbon (doc) and dissolved organic nitrogen (don) content of an arenosol as affected by liming in a pot experiment. Arch Agron Soil Sci 49:111–117
Han L, Sun K, Yang Y, Xia X, Li F, Yang Z, Xing B (2020) Biochar's stability and effect on the content, composition and turnover of soil organic carbon. Geoderma 364:114184
Hardie M, Clothier B, Bound S, Oliver G, Close D (2013) Does biochar influence soil physical properties and soil water availability? Plant Soil 376:347–361
He YT, He XH, Xu MG, Zhang WJ, Yang XY, Huang SM (2018) Long-term fertilization increases soil organic carbon and alters its chemical composition in three wheat-maize cropping sites across central and south China. Soil Tillage Res 177:79–87
Huang X, Jia Z, Guo J, Li T, Sun D, Meng H, Yu G, He X, Ran W, Zhang S, Hong J, Shen Q (2019) Ten-year long-term organic fertilization enhances carbon sequestration and calcium-mediated stabilization of aggregate-associated organic carbon in a reclaimed Cambisol. Geoderma 355:113880
Inagaki TM, Sá JCDM, Caires EF, Gonçalves DRP (2016) Lime and gypsum application increases biological activity, carbon pools, and agronomic productivity in highly weathered soil. Agr Ecosyst Environ 231:156–165
Jin Z, Shah T, Zhang L, Liu H, Peng S, Nie L (2020) Effect of straw returning on soil organic carbon in rice–wheat rotation system: a review. Food Energy Secur. https://doi.org/10.1002/fes3.200
Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, Cayuela ML, Graber ER, Ippolito JA, Kuzyakov Y, Luo Y, Ok YS, Palansooriya KN, Shepherd J, Stephens S, Weng Z, Lehmann J (2021) How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. GCB-Bioenergy 13:1731–1764
Kalbitz K, Solinger S, Park JH, Michalzik B, Matzner E (2000) Controls on the dynamics of dissolved organic matter in soils: a review. Soil Sci 165:277–304
Kan ZR, Liu WX, Liu WS, Lal R, Dang YP, Zhao X, Zhang HL (2022) Mechanisms of soil organic carbon stability and its response to no-till: a global synthesis and perspective. Glob Chang Biol 28:693–710
Karami A, Homaee M, Afzalinia S, Ruhipour H, Basirat S (2012) Organic resource management: Impacts on soil aggregate stability and other soil physicochemical properties. Agric. Ecosyst Environ 148:22–28
Kooch Y, Ehsani S, Akbarinia M (2019) Stoichiometry of microbial indicators shows clearly more soil responses to land cover changes than absolute microbial activities. Ecol Eng 131:99–106
Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627
Larney FJ, Angers DA (2012) The role of organic amendments in soil reclamation: a review. Can J Soil Sci 92:19–38
Lehmann J, Kleber M (2015) The contentious nature of soil organic matter. Nature 528:60–68
Li Z, Wei B, Wang X, Zhang Y, Zhang A (2018) Response of soil organic carbon fractions and CO2 emissions to exogenous composted manure and calcium carbonate. J Soils Sediments 18:1832–1843
Lu T, Wang X, Du Z, Wu L (2021) Impacts of continuous biochar application on major carbon fractions in soil profile of North China Plain's cropland: in comparison with straw incorporation. Agric Ecosyst Environ 315:107445
Luo S, Wang S, Tian L, Shi S, Xu S, Yang F, Li X, Wang Z, Tian C (2018) Aggregate-related changes in soil microbial communities under different ameliorant applications in saline-sodic soils. Geoderma 329:108–117
Mavi MS, Marschner P (2013) Salinity affects the response of soil microbial activity and biomass to addition of carbon and nitrogen. Soil Res 51:68–75
Nan J, Chen X, Chen C, Lashari MS, Deng J, Du Z (2016) Impact of flue gas desulfurization gypsum and lignite humic acid application on soil organic matter and physical properties of a saline-sodic farmland soil in Eastern China. J Soils Sediments 16:2175–2185

Niu S, Song L, Wang J, Luo Y, Yu G (2023) Dynamic carbon-nitrogen coupling under global change. Sci China Life Sci. https://doi.org/10.1007/s11427-022-2245-y
Pihlap E, Steffens M, Kögel-Knabner I (2021) Initial soil aggregate formation and stabilisation in soils developed from calcareous loess. Geoderma 385:114854
PiÑEiro G, Oesterheld M, Batista WB, Paruelo JM (2006) Opposite changes of whole-soil vs. pools C: N ratios: a case of Simpson's paradox with implications on nitrogen cycling. Glob Chang Biol 12:804–809
Qiu S, Gao H, Zhu P, Hou Y, Zhao S, Rong X, Zhang Y, He P, Christie P, Zhou W (2016) Changes in soil carbon and nitrogen pools in a Mollisol after long-term fallow or application of chemical fertilizers, straw or manures. Soil and Tillage Res 163:255–265
Rashad M, Dultz S, Guggenberger G (2010) Dissolved organic matter release and retention in an alkaline soil from the Nile River Delta in relation to surface charge and electrolyte type. Geoderma 158:385–391
Rathi D, Devraj A, Ramprakash RS, Sharma MK (2020) Available nutrients and labile carbon fractions in soil irrigated with sodic water. Indian J Agric Sci 90:1081–1805
Rita L, Carolina V (2018) Use of organic amendments to reclaim saline and sodic soils: a review. Arid Land Res Manage 33:1–21
Rowley MC, Grand S, Verrecchia ÉP (2017) Calcium-mediated stabilisation of soil organic carbon. Biogeochemistry 137:27–49
Saffari N, Hajabbasi MA, Shirani H, Mosaddeghi MR, Mamedov AI (2020) Biochar type and pyrolysis temperature effects on soil quality indicators and structural stability. J Environ Manage 261:110190
Saifullah, Naeem D, Rengel A, Naidu R (2018) Biochar application for the remediation of salt-affected soils: challenges and opportunities. Sci Total Environ 625:320–335
Sorrenti G, Toselli M (2016) Soil leaching as affected by the amendment with biochar and compost. Agric Ecosyst Environ 226:56–64
Sowers TD, Adhikari D, Wang J, Yang Y, Sparks DL (2018) Spatial associations and chemical composition of organic carbon sequestered in Fe, Ca, and organic carbon ternary systems. Environ Sci Technol 52:6936–6944
Tan Z, Lin CSK, Ji X, Rainey TJ (2017) Returning biochar to fields: a review. Appl Soil Ecol 116:1–11
Tavakkoli E, Rengasamy P, Smith E, McDonald GK (2015) The effect of cation-anion interactions on soil pH and solubility of organic carbon. Eur J Soil Sci 66:1054–1062
Tavakkoli E, Uddin S, Rengasamy P, McDonald GK (2021) Field applications of gypsum reduce pH and improve soil C in highly alkaline soils in southern Australia's dryland cropping region. Soil Use Manage 38:466–477
Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. Soil Biol Biochem 19:703–707
Walkley A (1935) An examination of methods for determining organic carbon and nitrogen in soils. (with one text-figure.). J Agric Sci 25:598–609
Wang S, Jia Y, Liu T, Wang Y, Liu Z, Feng X (2021) Delineating the role of calcium in the large-scale distribution of metal-bound organic carbon in soils. Geophys Res Lett 48:391
Wiesmeier M, Urbanski L, Hobley E, Lang B, von Lützow M, Marin-Spiotta E, van Wesemael B, Rabot E, Ließ M, Garcia-Franco N, Wollschläger U, Vogel H-J, Kögel-Knabner I (2019) Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. Geoderma 333:149–162
Wong VNL, Greene RSB, Dalal RC, Murphy BW (2010) Soil carbon dynamics in saline and sodic soils: a review. Soil Use Manage 26:2–11
Wu L, Zheng H, Wang X (2021) Effects of soil amendments on fractions and stability of soil organic matter in saline-alkaline paddy. J Environ Manag 294:112993
Wuddivira MN, Camps-Roach G (2007) Effects of organic matter and calcium on soil structural stability. Eur J Soil Sci 58:722–727
Xie W, Wu L, Wang J, Zhang Y, Ouyang Z (2017) Effect of salinity on the transformation of wheat straw and microbial communities in a Saline Soil. Commun Soil Sci Plant Anal 48:1455–1461
Yang X, Wang D, Lan Y, Meng J, Jiang L, Sun Q, Cao D, Sun Y, Chen W (2017) Labile organic carbon fractions and carbon pool management index in a 3-year field study with biochar amendment. J Soils Sediments 18:1569–1578
Yu G, Xiao J, Hu S, Polizzotto ML, Zhao F, McGrath SP, Li H, Ran W, Shen Q (2017) Mineral availability as a key regulator of soil carbon storage. Environ Sci Technol 51:4960–4969
Yuan B, Li Z, Liu H, Gao M, Zhang Y (2007) Microbial biomass and activity in salt affected soils under arid conditions. Appl Soil Ecol 35:319–328
Zhang K, Wang X, Wu L, Lu T, Guo Y, Ding X (2020a) Impacts of salinity on the stability of soil organic carbon in the croplands of the Yellow River Delta. Land Degrad Dev 32:1873–1882
Zhang Y, Yang J, Yao R, Wang X, Xie W (2020b) Short-term effects of biochar and gypsum on soil hydraulic properties and sodicity in a saline-alkali soil. Pedosphere 30:694–702
Zhang W, Zhao Y, Wang S, Li Y, Liu J, Zhuo Y, Zhang W (2021a) Combined application of flue gas desulfurization gypsum and straw pellets to ameliorate sodicity, nutrient content, and aggregate stability of sodic soil. J Soil Sci Plant Nutr 21:1806–1816
Zhang Y, Wang J, Feng Y (2021b) The effects of biochar addition on soil physicochemical properties: a review. CATENA 202:105284
Zhao F, Zhang L, Sun J, Ren C, Han X, Yang G, Pang G, Bai H, Wang J (2017) Effect of Soil C, N and P stoichiometry on soil organic C fractions after afforestation. Pedosphere 27:705–713
Zhu LX, Xiao Q, Shen YF, Li SQ (2017) Effects of biochar and maize straw on the short-term carbon and nitrogen dynamics in a cultivated silty loam in China. Environ Sci Pollut Res Int 24:1019–1029

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