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Effects of soil amendments on fractions and stability of soil organic matter in saline-alkaline paddy

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ABSTRACT

Soil amelioration is an effective practice to alleviate the adverse effects of soil salinization. However, increasing the fertility of salt-affected soils has been challenging, particularly in coastal saline-alkaline paddy soils. Here, we carried out a 45-day incubation experiment to evaluate the impacts of soil amendments on fractions and stability of soil organic matter (SOM) in a saline-alkaline paddy. The experiment simulates the flooding-draining practice and consists of $CaCO_3$, gypsum and biochar amendments using different fertility soils. We measured dissolved organic carbon (DOC) and nitrogen (DON) in supernatant liquids, water-soluble cations, water extractable organic carbon (WEOC) and nitrogen (WEON), and microbial biomass carbon (MBC) and nitrogen (MBN) in soils after the incubation. Results showed that water soluble sodium (Na^+) was significantly decreased under all amendments (by 17%–32%), except in high fertility soil. We found a significant decrease in DOC (by 36%–47%) under gypsum treatment, but in DON (by 18%–59%) under biochar treatment. However, there was no significant effect on DOC or DON under $CaCO_3$ treatment. Gypsum treatment led to decreased WEOC content (by 0.067%–5.4%), but increased MBC (by 0.16%–44%) and MBN (by 8.3%–37%) in all soils. Biochar treatment caused a decrease in the ratios of WEOC to soil organic carbon (SOC) and WEON to total nitrogen (TN), and an increase in MBC:SOC and MBN:TN ratios. These results suggest that gypsum and biochar amendments can enhance SOM stability in the saline-alkaline paddy. However, SOM stability was not enhanced under $CaCO_3$ treatment, probably due to the presence of a large amount of Na^+ in these soils. Our study highlights that soil amelioration has different effects on soil carbon and nitrogen cycles in the saline-alkaline paddy soils, which is associated with water-logged condition.

1. Introduction

As the largest carbon pool in the terrestrial biosphere, soil organic carbon (SOC) plays a key role in the global carbon cycle. There is evidence that SOC storage is largely influenced by not only climate and soil conditions but also land use and management practice (Lin et al., 2015; Mehra et al., 2019). It is well known that soil fertility and crop productivity are low in high-salinity soils, and soil salinization can lead to a significant decrease in SOC storage (Qadir et al., 2000; Setia et al., 2013). However, mechanisms responsible for the low fertility or low SOC levels in saline-alkaline soils are not well understood.

Environmental scientists have been seeking effective amelioration methodologies to alleviate the adverse effects of soil salinization, in which the addition of organic and inorganic amendments are common practices (Li et al., 2020a; Manasa et al., 2020). One of the most common approaches is the application of gypsum that provides calcium ions (Ca^{2+}) to replace exchangeable Na^+ in saline-alkaline soils, which can improve soil physicochemical conditions (Li and Jinman, 2018). There is evidence that gypsum amendment can increase SOC storage due to enhanced crop growth that leads to more residues in soils (Wang et al., 2017). In addition, gypsum amendment leads to improvement in soil aggregation, which is beneficial for stabilization of SOC (Inagaki et al., 2016). Recent studies have suggested that the presence of $CaCO_3$ (another Ca-containing chemical) could also promote the formation of organic-Ca-clay complexes/aggregates, which is conducive to the stability of SOC in calcareous soils (Huang et al., 2019; Rowley et al., 2017).

Over the recent decade, there is an increasing interest in using biochar as a soil amendment because of the direct input of organic carbon and effective improvement in soil physicochemical conditions (Saifullah

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et al., 2018). In particular, biochar application can improve soil porosity, water holding capacity and nutrients conditions (Singh et al., 2015; Spokas et al., 2012), which leads to enhanced crop growth and more residues into soil (Diatta et al., 2020). Apart from the direct and indirect organic carbon inputs, biochar amendment can also enhance the stability of SOC due to improved soil aggregation and low lability of SOC (Han et al., 2020), resulting in increased SOC content. For example, Dai et al. (2019) reported that SOC was more than doubled under biochar application in a saline-alkaline soil. On the other hand, biochar itself has a stronger adsorption capacity due to its high porosity and surface area, which can effectively adsorb soil salts and nutrients (Wu et al., 2019).

The stability of SOC or soil organic matter (SOM) can be assessed in many ways, e.g., using SOM fractions. Water extractable organic carbon (WEOC) and nitrogen (WEON), and microbial biomass carbon (MBC) and nitrogen (MBN) are thought to be more labile than other fractions of SOM (Choudhary et al., 2013). Thus, MBC:SOC ratio is used as a sensitive indicator for soil quality (de Brito et al., 2019). A recent study has showed that WEOC:SOC ratio (an index for SOC stability) is greater near the Yellow River, which is attributable to lower SOC stability under strong hydrological processes (Zhang et al., 2020b). There is also evidence of stronger SOC desorption in soil solution under high-salinity conditions (Zhang et al., 2020a). Thus, flooding and drainage, a common practice to remove salts in saline-alkaline paddy fields, may lead to SOC desorption/removal during this salt-washing practice.

The Yellow River Delta (YRD) is occupied by various degrees of salt-affected soils, and paddy is common in this area, particularly over saline-alkaline land (Wei et al., 2020). Although there have been various approaches to ameliorate those paddy soils or to increase soil fertility, SOC content and nutrient level remain low (Li et al., 2012; Wu et al., 2021; Xie et al., 2020), but the underlying mechanisms are not well documented. In general, the poor physical structure and chemical conditions result in low SOM stability in saline-alkaline soils (Amini et al., 2016), which could cause some losses of dissolved fractions of SOM during the salt-washing practice (i.e., flooding-drainage). On the other hand, soil amelioration approaches could reduce the losses of SOM fractions due to improved soil aggregation and SOM stability. Here, we conduct a laboratory study to assess the effects of gypsum, $CaCO_3$ and biochar amendments on Na^+ removal, microbial biomass and dissolved organic matter, and to test the hypothesis that SOM loss is reduced in association with soil amelioration during the flooding-draining practice in saline-alkaline paddy fields. The objectives of this study are to evaluate the effects of soil amendments on soluble salts, microbial biomass and water extractable fractions of SOM, and to examine if soil amelioration practice can remove more Na^+ and also reduce the loss of dissolved SOM in the YRD's paddy soil.

2. Materials and methods

2.1. Soil sampling with different soil fertility levels

A paddy field experiment was established in 2014 in a saline-alkaline soil located in the YRD (37°31′18″N,188°33′31″E) of China. The soil was developed on alluvial loess, and classified as Salic Fluvisols (FAO, 1988), which contains 21.1% sand (0.02–2 mm), 61.7% silt (0.002–0.02 mm) and 17.2% clay (<0.002 mm). The basic chemical properties in 0–20 cm soil before the field experiment were as follows: pH 8.10, SOC 4.85 g kg^{-1}, available nitrogen (AN) 40.3 mg kg^{-1}, available phosphorus (AP) 14.0 mg kg^{-1} and available potassium (AK) 229 mg kg^{-1}.

The field experiment consisted of four treatments (with three replicates): (1) non-fertilization (extremely low fertility, ELF), (2) NPK chemical fertilization (low fertility, LF), (3) NPK plus organic fertilization at 450 kg C ha^{-1} $year^{-1}$ (medium fertility, MF), (4) NPK plus organic fertilization at 900 kg C ha^{-1} $year^{-1}$ (high fertility, HF). The treatments were arranged according to a randomized blocked-plot design. The size of each plot was 15.0 m^2. The chemical fertilizers used were urea (255 N ha^{-1} $year^{-1}$), superphosphate (64 kg P ha^{-1} $year^{-1}$) and potassium sulphate (229 kg K ha^{-1} $year^{-1}$). The organic fertilizer was commercially produced from soybean litter and beans, which contained 26.1% C, 2.4% N, 1.6% P and 1.4% K. Urea was applied as follows: 20% before seeding, 40% at early tillering stage, 20% at tillering stage, and 20% at flowing stage. Half of the potassium fertilizer was applied before seeding and the other half at the earing stage. All phosphorus fertilizer and organic fertilizer were applied before seeding. The field was flooded in late May, and drained in mid-July, followed by one-week drying/sunning and then flooding. Rice was planted in mid-June and harvested in mid-October.

Top soils (~30 cm) were sampled (using 5-cm diameter auger) in October 2017, when the surface was almost dry. In each plot, 4–5 soil cores were selected randomly along a 'S' line (Lashari et al., 2013), and a composite soil was obtained. Soil samples were air-dried, thoroughly mixed, and sieved through a 2 mm mesh, which were then used for the incubation experiment. Initial soil samples (0–30 cm) after three years fertilization treatment showed similar values for soil pH (8.7–8.82) and (EC, 0.22–0.27 dS m^{-1}), but different levels for SOC and total nitrogen (TN), with significantly higher SOC (4.32 g kg^{-1}) and TN (0.50 g kg^{-1}) in HF soil (Table S1). EC levels were similar to those (0.21–0.27 dS m^{-1}) reported previously for the topsoil of cropland in the YRD (Sun et al., 2016; Zhang et al., 2020a).

2.2. Incubation experiment

The incubation experiment included one control and three amendment treatments: $CaCO_3$ (reagent grade), desulfurized gypsum and commercial biochar. The gypsum had a pH of 7.23, and contained 37.6% CaO, 49.5% SO_3 and 2.2% SiO_2. Biochar was made from corncob under incomplete combustion at ~360 °C for 24 h, which had a pH of 8.2, density of 0.30 g cm^{-3}, and contained 72.0% ash content, 65.7% C, 0.91% TN, 0.08% AP, and 1.60% AK.

Biochar application rate varied largely in previous studies, i.e., 0.5%–10% (w/w) in saline-alkaline soils (He et al., 2020; Saifullah et al., 2018; Sun et al., 2020). Other studies also used a large range (7–75 Mg ha^{-1}, i.e., 0.2%–2.7%) for the application of desulfurized gypsum in salt-affected soils (Li et al., 2012; Wang et al., 2017). Accordingly, in our study, the application rate was 2.5% for biochar, 2% for gypsum, and 4% for $CaCO_3$.

For each treatment, 50 g air-dried soil and amendment were mixed, and put into a 250 ml plastic cup. We then added 100 ml distilled water into each cup, and incubated the cups at 25 °C. After three weeks, we collected supernatant liquid using syringe, and let soil drying for three days. We then added distilled water into the cups until the total weight reached 150 g, incubated for another three weeks, and then collected the supernatant liquid and soil samples separately. The flooding-draining/drying-flooding procedure during the incubation was to simulate the flooding-draining practice during rice growing season in this region (Wu et al., 2021). All liquid and soil samples were kept frozen before chemical analyses.

2.3. Soil and solution analyses

Soil pH was measured using a soil-water (1:2.5) mixture using a pH meter (Mettler-Toledo FE 20; Switzerland). Water soluble cations (Na^+, Mg^{2+} and Ca^{2+}) in a soil-water (1:5) mixture were determined using an Atomic Absorption Spectrophotometer by inductively coupled plasma mass spectrometry (ICP-MS) (Shi et al., 2017). Water soluble Na^+, Mg^{2+} and Ca^{2+} in supernatant liquid were measured using the same method.

Concentrations of DOC and DON in the supernatant liquid were determined by using a TOC analyzer (TOC-L CPN, Shimadzu) using the high-temperature catalytic combustion method (Badr et al., 2003). For WEOC and WEON measurement, 5 g 2-mm soil samples were extracted with 25 ml 0.5 M K_2SO_4, followed by shaking the mixture for 1 h, centrifuging (4000 r min^{-1}) for 10 min, and then filtering through a

0.45-μm membrane. WEOC and WEON concentrations in filtrate were determined by using the same method for DOC and DON.

Microbial biomass was measured using the fumigation-extraction method (Brookes et al., 1985; Vance et al., 1987). Briefly, 60 g soil, adjusted to about 60% of field water-holding capacity, was put into a plastic cup and incubated for 10 days at 25 °C in the dark. After incubation, soil was divided into three parts (~20 g for each part); one part was set as control, one was fumigated for 24 h with ethanol-free $CHCl_3$, and the last one used to measure moisture content. We then added 80 ml 0.5 M K_2SO_4 into the control and fumigated subsamples, filtered the mixture after 30 min shaking, and measured DOC and DON concentrations in the filtrate. Microbial biomass C and N were calculated from the differences in DOC and DON contents between the fumigated and control samples using conversion factors of 0.38, and 0.45, respectively.

2.4. Data calculation and statistical analyses

Sodium adsorption ratio (SAR) was calculated according to Rietz and Haynes (2003):

$$SAR = \frac{[Na^+]}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{1}$$

where Na^+, Ca^{2+} and Mg^{2+} were the concentrations of their water soluble forms.

We applied linear regression analysis to assess the relationships of WEOC:SOC and MBC:SOC ratios with water soluble Ca^{2+}. Two-way ANOVA were used to analyze the influences of treatments and soil fertility on the properties of soil/liquid. Multiple comparisons were conducted using the least significant difference (LSD) at $p < 0.05$ to determine the significance of differences in soil/liquid properties among different treatments and fertility soils. All statistical analyses were carried out using SPSS 20.0, and all graphs were generated using origin 9.0.

3. Results

3.1. Effects of amendments on soil pH and soluble salts

Amendments had no significant effects on soil pH in different levels of fertility soils after six weeks of treatments (Table 1). There were considerable differences in water soluble Na^+ among different treatments and fertility soils. $CaCO_3$, $CaSO_4$ and biochar treatments caused a significant decrease in water soluble Na^+ in ELF, LF and MF soils (by 17–32%), with the greatest decrease found in ELF soil. Although the reduction of water soluble Na^+ was not significant in HF soil under all amendments, there was a modest decrease in water soluble Na^+ (by 43 mg kg^{-1}) under $CaSO_4$ treatment. Clearly, water soluble Ca^{2+} showed a significant increase under application of $CaSO_4$ (by 1156–3018 mg kg^{-1}) and biochar (by 791–1138 mg kg^{-1}), but somehow a non-significant decrease under the application of $CaCO_3$. Overall, all amendments led to a decrease in water soluble Mg^{2+} (comparing with the control), with the greatest decrease found under $CaSO_4$ (by 84–147 mg kg^{-1}) treatment. All amendments caused a decrease in SAR in all soils after six weeks incubation, with significant decreases found with $CaSO_4$ and biochar amendments and the largest decrease (by 2.4–3.6) under $CaSO_4$ treatment.

Table 1
Soil pH, water soluble cations and SAR under different amendments after six weeks incubation.

Soils	Treatments	pH	Na^+ (mg kg^{-1})	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})	SAR
ELF	Control	8.01Aa	232Aa	1418Ab	320Aa	7.79Aa
	$CaCO_3$	8.03Aa	159Bb	1409Ab	225Bb	4.86Ab
	$CaSO_4$	7.92Aa	157Ab	2736Ca	173Bb	4.16Ab
	Biochar	7.90Aa	164Bb	2556Aa	261Bab	4.37Ab
LF	Control	7.94Aa	208Aa	1563Ab	324Aa	6.79Aa
	$CaCO_3$	8.00Aa	169ABb	1352Ab	267ABab	5.91Aa
	$CaSO_4$	7.88Aa	165Ab	2719Ca	219Ab	4.36Ab
	Biochar	7.90Aa	161ABb	2354Aa	242Bab	4.45Ab
MF	Control	8.01Aa	214Aa	1708Ac	361Aa	6.66Aa
	$CaCO_3$	8.05Aa	177ABb	1476Ac	260ABab	5.94Aa
	$CaSO_4$	7.93Aa	170Ab	3406Ba	258Ab	4.00Ab
	Biochar	7.94Aa	177Ab	2562Ab	320ABab	4.67Ab
HF	Control	8.00Aa	221Aa	1783Ac	373Aa	6.75Aa
	$CaCO_3$	8.15Aa	194Aa	1617Ac	300Aab	6.21Ab
	$CaSO_4$	7.99Aa	178Aa	4801Aa	289Ab	3.55Ac
	Biochar	7.91Aa	220Aa	2617Ab	383Aa	5.68Aab

Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p < 0.05$ according to LSD test.

3.2. Effect of amendments on dissolved salts and organic matter

Concentration of soluble Na^+ in the supernatant liquid was overall higher in the first flooding (69–109 mg L^{-1}) than in the second flooding (48–80 mg L^{-1}), with considerable differences among different fertility soils. Overall, the highest Na^+ concentration was in ELF in the first flooding but in HF in the second flooding (Fig. 1a and b). Clearly, $CaSO_4$ treatment led to an increase (by 11–26 mg L^{-1}) in soluble Na^+ concentration in the first flooding with the largest increase in MF soil, but a non-significant differences in the second flooding. Overall, biochar amendment had no significant influence on soluble Na^+, but $CaCO_3$ amendment caused lower concentrations of soluble Na^+ in the second flooding with the greatest decrease in HF soil.

Soluble Ca^{2+}+Mg^{2+} in the supernatant varied largely, with much higher concentration in the second flooding than in the first flooding except under $CaCO_3$ amendment (Fig. 1c and d). Clearly, concentration of soluble Ca^{2+}+Mg^{2+} was highest under $CaSO_4$ treatment in both the first (520–692 mg L^{-1}) and second (694–1784 mg L^{-1}) floodings. There were significant differences in the response of soluble Ca^{2+}+Mg^{2+} to $CaSO_4$ treatment among soils, e.g, HF showing the lowest in the first flooding but highest in the second flooding. Biochar treatment had little effects on soluble Ca^{2+}+Mg^{2+}, but $CaCO_3$ amendment caused a significant decrease in the second flooding.

Concentration of DOC was similar between the first and second floodings, with the highest values under biochar treatment (4–4.4 mg L^{-1}) and lowest under $CaSO_4$ treatment (1.6–2.0 mg L^{-1}) (Fig. 2a and b). $CaCO_3$ treatment had little effects on DOC in all soils. However, DON concentration was much higher in the second flooding (1.3–3.6 mg L^{-1}) than in the first flooding (1.0–1.9 mg L^{-1}) under control, $CaCO_3$ and $CaSO_4$ treatments (Fig. 2c and d). Biochar amendment caused a significant decrease in DON concentration in the first (by 0.27–0.71 mg L^{-1}) and second (by 0.99–2.08 mg L^{-1}) floodings, with the greatest decrease (by 41–60%) in ELF soil.

3.3. Effects of amendments on water extractable organic matter and microbial biomass

Soil WEOC showed a significant increase under biochar treatment (by 53–81 mg kg^{-1}) in all soils, and a non-significant increase under $CaCO_3$ treatment (by 8–25 mg kg^{-1}) after six weeks incubation (Fig. 3a). However, $CaSO_4$ treatment led to a small decrease in WEOC content in ELF, LF and MF soils (by 1.3%–5.4%). Soil WEON showed a significant increase under $CaCO_3$ amendment (by 10–22 mg kg^{-1}), with the largest increase in HF soil. $CaSO_4$ treatment also caused an increase in WEON (by 7–17 mg kg^{-1}) in all soils (Fig. 3b). Biochar treatment had little effects on WEON in LF and MF soils, but caused a small increase in WEON (by 7.9%) in ELF soil, and a small decrease (by 8.1%) in HF soil.

MBC was significantly lower in the ELF (37–74 mg kg^{-1}) than in the other soils (42–139 mg kg^{-1}) without amendment (Fig. 4a). Biochar and $CaSO_4$ treatments led to an overall increase in MBC content, with greater

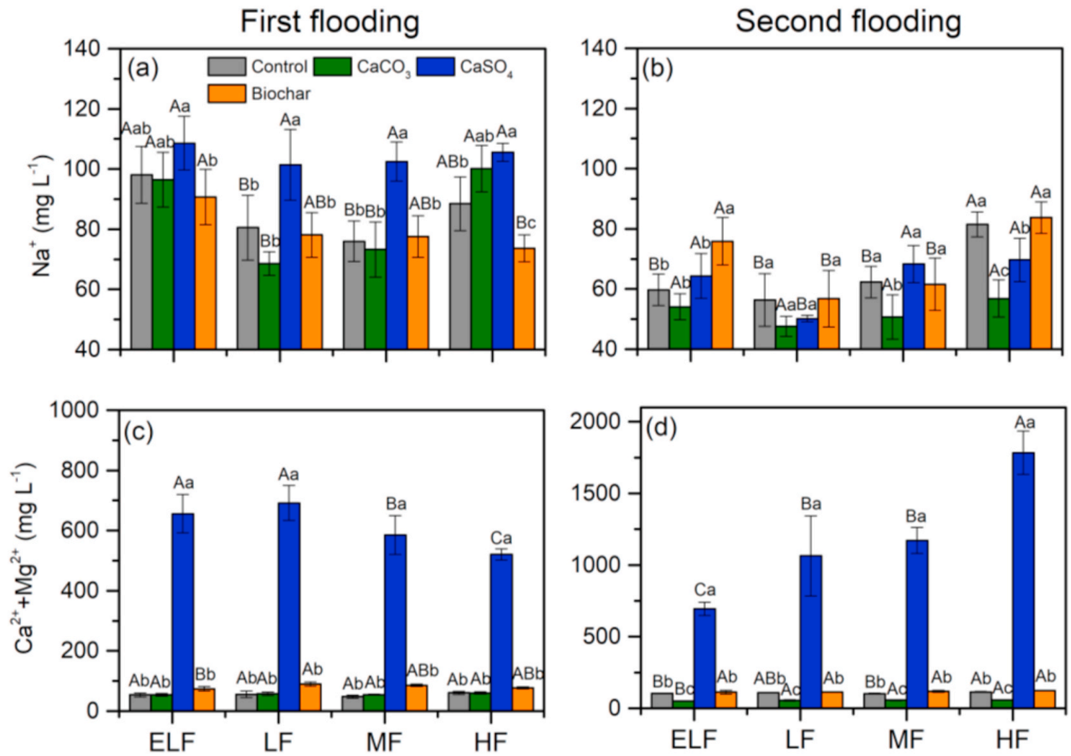

Fig. 1. Concentrations of soluble Na^{+} (a, b) and Ca^{2+}+Mg^{2+} (c, d) in supernatant liquid of the first and second flooding under different amendments. Error bars represent the standard errors. Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p < 0.05$ according to LSD test.

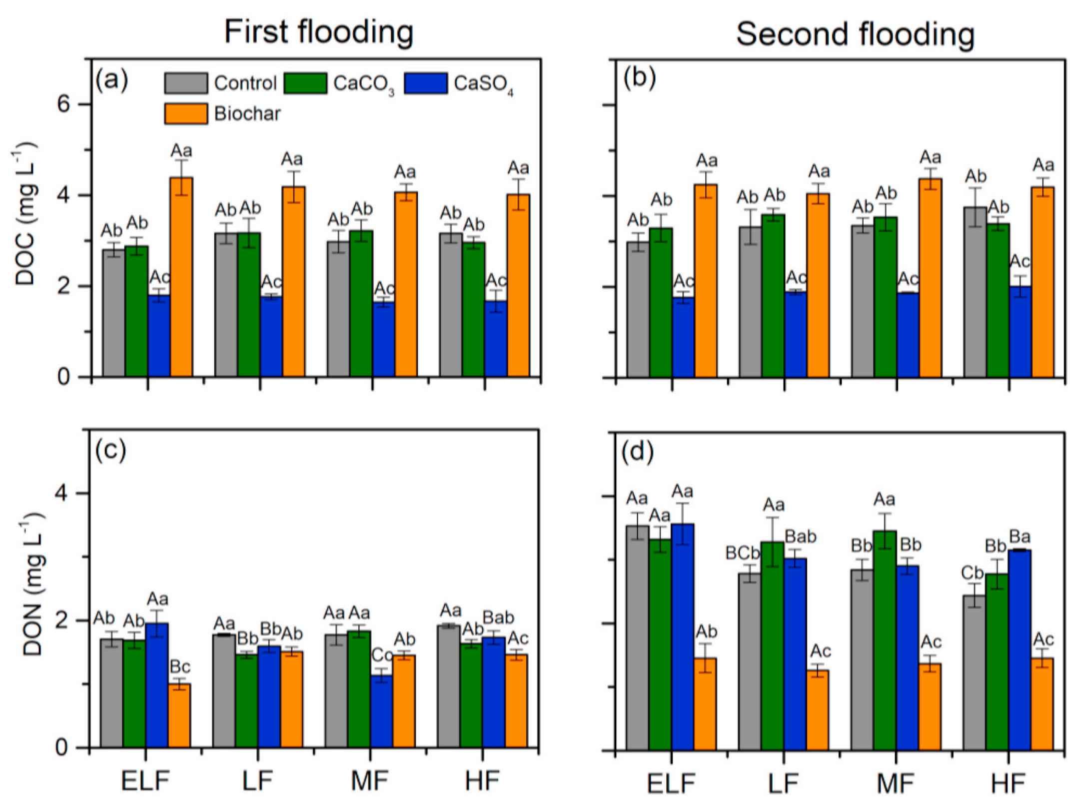

Fig. 2. Concentrations of diossolve organic carbon (DOC) (a, b) and nitrogen (DON) (c, d) in supernatant liquid of the first and second flooding under different amendments. Error bars represent the standard errors. Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p < 0.05$ according to LSD test.

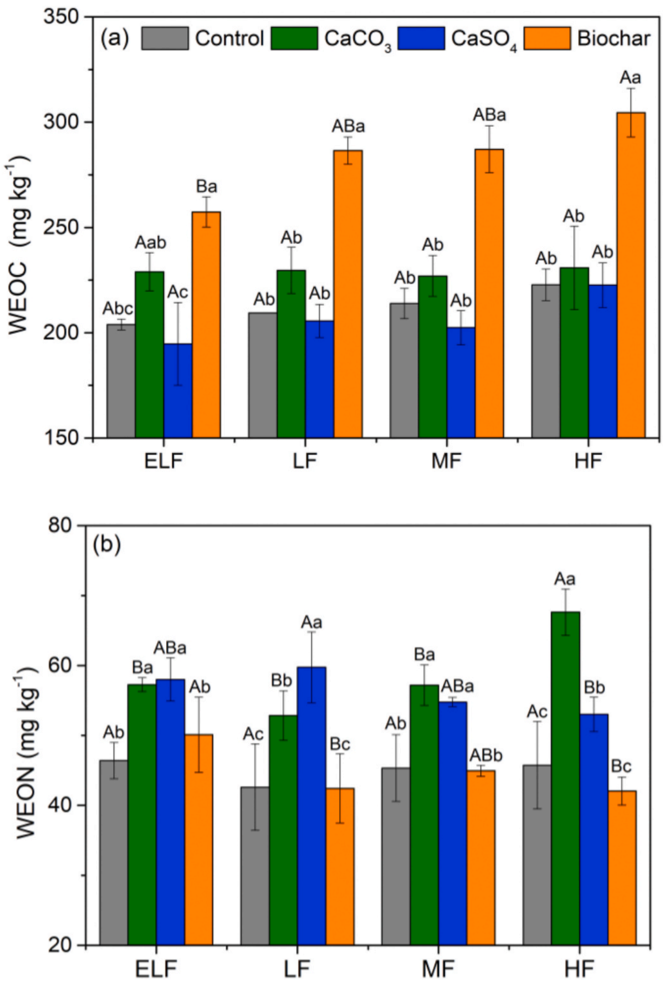

Fig. 3. Contents of water-extractable organic carbon (WEOC) (a) and organic nitrogen (WEON) (b) in soils after six weeks incubation under different amendments. Error bars represent the standard errors. Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p < 0.05$ according to LSD test.

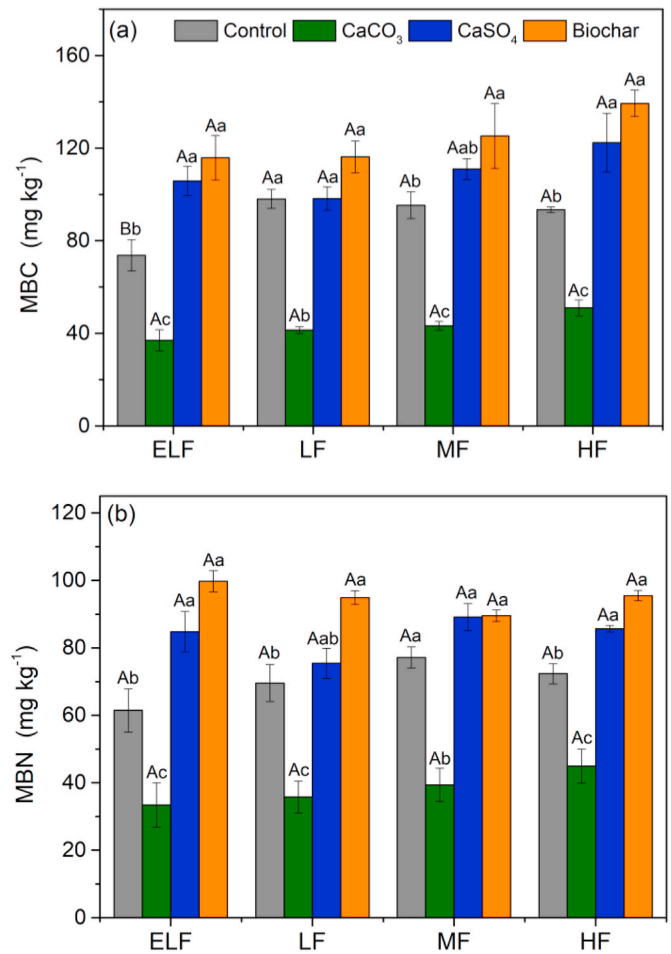

Fig. 4. Contents of microbial biomass carbon (MBC) (a) and nitrogen (MBN) (b) in soil after six weeks incubation under different amendments. Error bars represent the standard error. Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p < 0.05$ according to LSD test.

increases under biochar (by 18–46 mg kg^{-1}) than under $CaSO_4$ treatment (by 0.16–32 mg kg^{-1}). However, MBC content was much lower under $CaCO_3$ treatment (37–51 mg kg^{-1}) than under control (74–98 mg kg^{-1}). Effects of amendments on MBN were similar to those on MBC in all soils, showing an order: biochar (90–100 mg kg^{-1}) > $CaSO_4$ (75–87 mg kg^{-1}) > control (62–77 mg kg^{-1}) > $CaCO_3$ (33–45 mg kg^{-1}) (Fig. 4b).

3.4. Effects of amendments on C:N ratio in various fractions

DOC:DON ratio was generally lower (except under biochar treatment) in the second flooding (0.6–1.7) than in the first flooding (1.0–2.2) (Fig. 5a and b). Biochar treatment caused an increase in DOC:DON ratio in the first flooding (by 0.63–2.2) and the second flooding (by 1.4–2.0), with the greatest increase found in the ELF soil. Overall, $CaCO_3$ treatment led to non-significant changes in DOC:DON ratio, with an increase in the first flooding (by 0.33–0.84), but a decrease, except for the ELF soil, in the second flooding. $CaSO_4$ treatment resulted in a significant decrease of DOC:DON ratio in the first flooding (by 0.91–1.9) and second flooding (by 0.37–0.73).

Biochar amendment caused a significant increase in WEOC:WEON ratio except in ELF soil, with the largest increase (by 2.4) in HF soil (Fig. 5c). There was a decrease (by 0.4–1.5) in WEOC:WEON ratio under both $CaCO_3$ and $CaSO_4$ treatments in all soils. All amendments showed no significant effects on MBC:MBN ratio although biochar amendment seemed to led to an increase in MBC:MBN ratio in HF soil (Fig. 5d).

4. Discussion

4.1. Effects of different amendments on soil pH, salts and SAR

Studies have reported that gypsum and biochar application can often cause a decrease of soil pH in saline-alkaline soils (Luo et al., 2018; Sun et al., 2016). However, Elzobair et al. (2016) reported that biochar amendment had little effect on soil pH in an alkaline soil. There is also evidence that low rate of gypsum addition had no significant effects on soil pH in saline-alkaline soils in the northwest China (Li et al., 2012). While our study showed non-significant changes in soil pH under all amendments after six weeks incubation, there was a modest decrease in soil pH under gypsum and biochar (Table 1). There was a non-significant increase of soil pH under $CaCO_3$ treatment, which may be due to a higher insolubility of carbonate in saline-alkaline soil (Tavakkoli et al., 2015).

Previous studies have showed that gypsum amendment leads to a decrease in Na^+ in salt-affected soils due to extra Ca^{2+} that replaces exchangeable Na^+, and also the presence of extra SO_4^{2-} that promotes the formation of Na_2SO_4 complexes that are easily drained (Luo et al., 2018; Zambrosi et al., 2007). We also found that gypsum application caused an increase in soluble Na^+ concentration in the supernatant

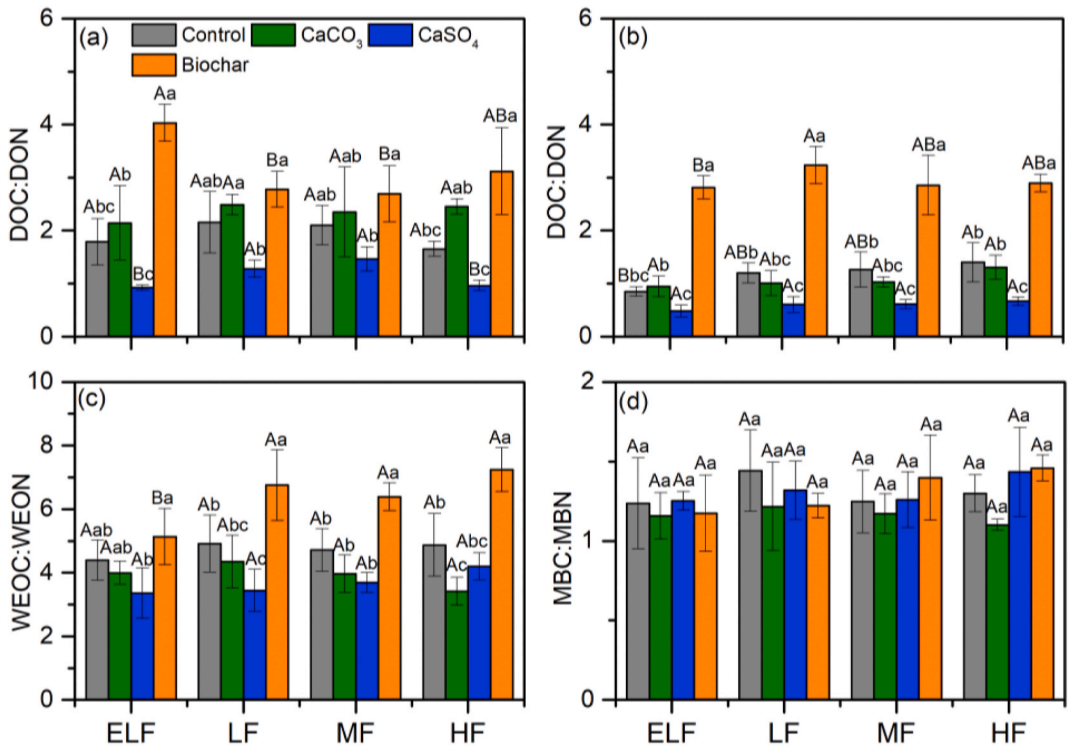

Fig. 5. DOC:DON ratio in the first (a) and second (b) flooding, and WEOC:WEON ratio (c) and MBC:MBN ratio (d) in soils under different amendments. Error bars represent the standard errors. Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p <$ 0.05 according to LSD test.

liquid, indicating that more Na^+ would be taken away during the flooding-drainage practice, which resulted in a decrease in water soluble Na^+ in salt-affected paddy soils. However, $CaCO_3$ treatment resulted in decreases in water soluble Na^+, which might be due to the changes in soil structure such as improved porosity that could retain Na^+ in soil pores (Falsone et al., 2010), leading to less desorption of Na^+. Although biochar treatment did not increase soluble Na^+ concentration in the supernatant liquid, it caused a significant decrease in water soluble Na^+ except in the high fertility soils (Table 1). An earlier study reported that there was a decrease of Na^+ content in dry cropland under biochar treatment (Lashari et al., 2013), which was due to the direct adsorption of Na^+ by biochar. In addition, biochar may also provide minerals such as Ca^{2+} and Mg^{2+} that can replace exchangeable Na^+ in saline-alkaline soils (Amini et al., 2016).

Overall, the fact of small decrease in soil pH and significant decrease in SAR under $CaSO_4$ and biochar treatments confirms that these amendments are effective for amelioration of saline-alkaline soils (Amini et al., 2016; Drake et al., 2016). Despite a slight increase of soil pH, both water soluble Na^+ and SAR showed a significant decrease under $CaCO_3$ treatment, particularly in low fertility soils, indicating some potential in using $CaCO_3$ to ameliorate saline-alkaline soils.

4.2. Effects of chemical amendments on stability of SOC

Stability of SOC is affected not only by the characteristics of SOM, but also environmental conditions such as soil pH, multivalent cations and anions bioavailability in soil solution (Setia et al., 2013). Thus, soil amendments would have impacts on stability of SOC. Our study revealed a significant decrease in DOC concentration (by 36–47%) in the supernatant liquid under gypsum treatment (Fig. 2a and b), thus proving the hypothesis that gypsum amendment can reduce the loss of DOC during the flooding-draining practice in saline-alkaline paddy fields. Previous studies have reported that gypsum amendment can lead to an increase in free forms of calcium, which promotes the formation of Ca–SOC complex (Antonangelo et al., 2017; Zambrosi et al., 2007). In addition, gypsum amendment can improve the structure of saline-alkaline soils due to enhanced clay-SOM bonding, thus enhances physicochemical protection for SOC (Rashad et al., 2010).

Our study showed an overall increase of MBC with gypsum amendment (by 0.16%–44%), with the greatest increase in the extremely low fertility soil, which was consistent with a previous study conducted in salt-affected soils (Choudhary et al., 2013). There was evidence that gypsum amendment was beneficial for microorganisms due to the improvements of soil physical and chemical conditions (Luo et al., 2018). We also found a lower WEOC:SOC ratio and a higher MBC:SOC ratio under gypsum treatment (Fig. 6a and b), which may reflect the enhancement in SOM stability due to the formation of mineral-Ca-SOM (Minick et al., 2017). Our further analyses demonstrated that there was a significant positive relationship between MBC:SOC ratio and Ca^{2+} and a significant negative relationship between WEOC:SOC ratio and Ca^{2+} (Fig. S1), further indicating that high levels of Ca^{2+} could lead to enhancement in SOM stability (Minick et al., 2017).

Previous studies suggested that the presence of carbonate might be beneficial for SOC stabilization (Fernández-Ugalde et al., 2011; Rowley et al., 2017). However, our study showed that $CaCO_3$ amendment did not decrease WEOC:SOC ratio or increase MBC:SOC ratio. Moreover, $CaCO_3$ amendment did not reduce DOC concentration in supernatant liquid, implying that SOC stability was not enhanced under $CaCO_3$ treatment in the saline-alkaline paddy soil. Interestingly, an early study reported that there was a significant negative relationship between decomposition rate of SOC and level of $CaCO_3$ in Cambisol soils of reclaimed dry cropland in the Loess Plateau (Huang et al., 2019). Moreover, there is evidence that high levels of $CaCO_3$ led to higher levels of DOC adsorption, but combined $CaCO_3$ and Na_2CO_3 addition reduced the adsorption of DOC (due to an increase in soil pH and Na^+) in an alkaline soil (Tavakkoli et al., 2015), indicating that the effect of $CaCO_3$ treatment on soil amelioration might be influenced by soil pH, and other salts such as Na^+, K^+ and Mg^{2+}.

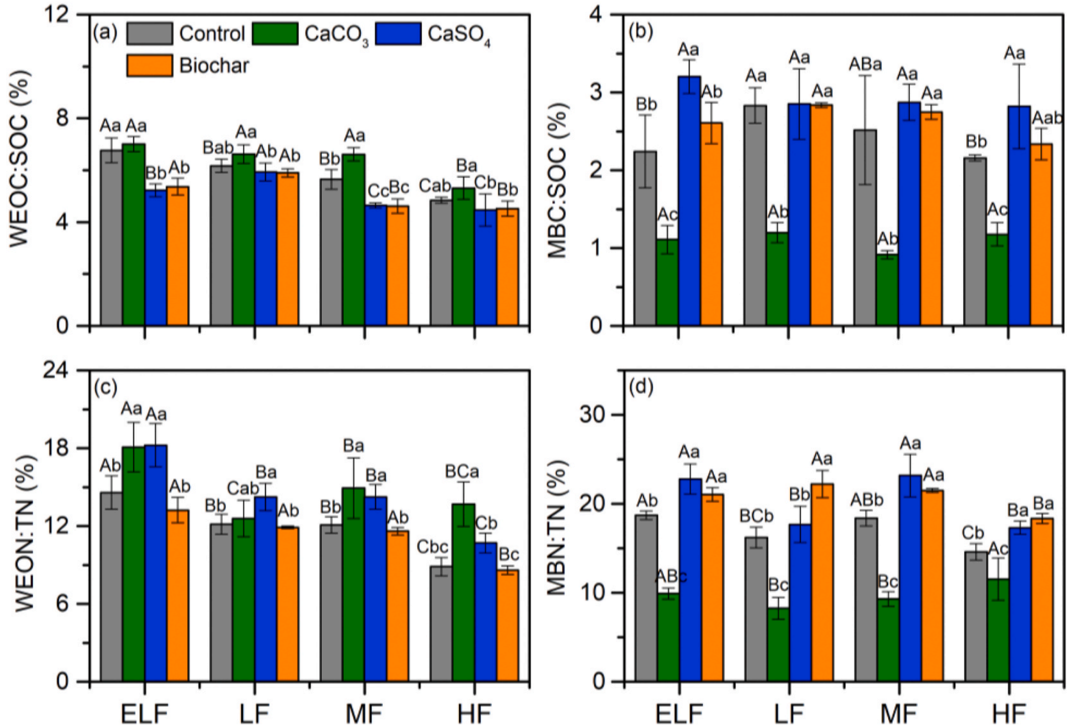

Fig. 6. Ratios of WEOC:SOC (a), MBC:SOC (b), WEON:TN (c) and MBN:TN (d) in soils under verious amendments. Error bars represent the standard errors. Values followed by different letters (lowercase among amendments and uppercase among soils) indicate significant differences at $p < 0.05$ according to LSD test.

4.3. Effects of biochar amendments on stability of SOM

A large number of studies have documented that biochar amendment is able to improve soil conditions, e.g., soil pH, soil aggregation and SOM chemical structure (Ameloot et al., 2013; Han et al., 2020), with implications for SOM stabilization. Indeed, there is evidence that biochar amendment enhances stabilization of SOC due to stronger adsorption of DOC in sandy clay soil (Eykelbosh et al., 2015).

Our study showed that biochar treatment caused a significant increase in WEOC but no significant effects on WEON, which might be related to a high C:N ratio in the crop residue derived biochar that generally contain a large amount of WEOC (Han et al., 2020). However, biochar amendment led to a significant decrease in DON concentration in supernatant liquid (comparing with other amendments), with greater decrease in extremely low fertility soil (by 41%–60%) than in high fertility soil (by 24%–40%). An earlier study also showed that biochar amendment resulted in a significant decrease in leachate DON concentrations, with greater decrease under higher rate of biochar application (Schofield et al., 2019). While their study indicated the direct retention of DON by biochar, our study suggested the possibility of greater enhancement of SOM stability for poor fertility soils under biochar amendments. Indeed, we found a decrease in WEOC:SOC (by 4–21%) and WEON:TN (2–9%) ratios under biochar treatment, with the largest decrease found in the extremely low fertility soil. Our analyses suggested that biochar amendment would have greater potential for ameliorating poor fertility soils such as saline-alkaline paddy soils in term of improving SOM stability and nitrogen retention.

Our study also showed an increase in MBC (19–57%) and MBN (16–62%) contents under biochar amendment, with the greatest decrease in extremely low fertility soil. Similarly, other studies also reported that biochar application significantly increased soil microbial biomass (Bi et al., 2020; Liu et al., 2020), which was due to the improvements in soil physio-chemical conditions (e.g., soil pH, porosity and carbon source) (Saifullah et al., 2018). Biochar treatment also caused higher MBC:SOC and MBN:TN ratios, indicating greater conversion rates of carbon and nitrogen to microbial biomass and enhanced SOM stability (Kalambukattu et al., 2013).

4.4. Carbon-nitrogen decoupling in saline-alkaline soils

Carbon and nitrogen are the main elements in SOM, and couple in many biogeochemical processes (Tong et al., 2009). However, C:N ratio varies largely between key pools (Kooch et al., 2019; Liu et al., 2008), e.g., generally higher ratios in SOM (often >10), but smaller ratios in DOC:DON (1.6–13.9) and MBC:MBN (2.8–12.8), indicating some degree of decoupling between carbon cycling and nitrogen cycling. For example, Qiu et al. (2016) reported that ratios of MBC:MBN and WEOC:WEON were less than 5 following 22 years of organic amendments in a Mollisol of northeast China. Our study revealed similar WEOC:WEON ratios (3.4–7.2) but much lower MBC:MBN ratios (1.2–1.5) in the saline-alkaline paddy soils, implying that the anaerobic environment with high salinity was stressful for soil microorganisms thus could retard the efficient conversion of organic carbon (see further discussion below). An earlier study showed that MBC:MBN ratio varied from 4.4 to 7.7 in arid saline soils of northwest China, with the lowest ratio found in the highest pH soil (Yuan et al., 2007).

Previous studies have revealed a large range of DOC (sometime also defined as WEOC, such as in our study) in agricultural soils, showing lower values in non-saline soils, e.g., 30 ± 2 mg kg^{-1} in the northern Iron (Kooch et al., 2019), 85–175 mg kg^{-1} in the North China Plain (Li et al., 2020b). Our study showed much higher levels of WEOC (194–304 mg kg^{-1}), which is close to those (248–294 mg kg^{-1}) in the coastal saline-alkaline soils (Xu et al., 2018). Similarly, we found that WEON was also higher in saline-alkaline paddy soils (42–60 mg kg^{-1}) than in non-saline soils (19–40 mg kg^{-1}) (Kooch et al., 2019; Qiu et al., 2016). The high levels of water extractable organic matter in saline-alkaline soils might be associated with flooding and draining processes that can disperse aggregates and thus enhance the dissolution of organic matter in high-salinity soil solution (Amini et al., 2016).

A number of studies have also showed a large range of MBC in agricultural soils, e.g., 15–280 mg kg^{-1} in arid saline soils of northwest China (Yuan et al., 2007), ~160–260 mg kg^{-1} in saline soils of India

(Meena et al., 2016), and 276 ± 14 mg kg^{-1} in non-saline soils of northern Iron (Kooch et al., 2019). Overall, MBC was generally low in high pH soils. While our study revealed relatively lower MBC (37–139 mg kg^{-1}) in saline-alkaline paddy soils, we also found that lower values were in higher pH soils. Interestingly, unlike MBC, MBN was much higher in our study (33–98 mg kg^{-1}) than in those (3.5–39 mg kg^{-1}) reported for non-paddy soils (Kooch et al., 2019; Yuan et al., 2007). An earlier study also reported relatively higher MBN (61 ± 15 mg kg^{-1}) in coastal saline-alkaline soils of eastern China (Xu et al., 2018). Moreover, there is evidence of decreased MBC but increased MBN content under waterlogged conditions after 60 days incubation in Hydragric Anthrosols paddy soils (Bagheri Novair et al., 2020). Apparently, water-logging condition is largely responsible for carbon and nitrogen decoupling in saline-alkaline paddy soils. Further studies are needed to better understand the coupling and de-coupling of carbon and nitrogen cycle in various environments.

5. Conclusions

Our study demonstrated that flooding-drainage practice led to losses of dissolved fraction of SOM, and some soil amendments reduced such losses. In particular, a significant decrease in DOC loss was found under gypsum treatment, but a significant decrease in DON loss was seen under biochar treatment. The reduction of DON loss under biochar amendment varied largely among different fertility soils, with the greatest reduction found in extremely low fertility soil. All soil amendments significantly reduced water soluble Na^+ and SAR except in the high fertility soil, but gypsum amendment was the most effective means for removing Na^+ from the saline-alkaline paddy soil particularly over short period. Stability of SOM was significantly higher in high fertility soil than in low fertility soils, gypsum and biochar amendments resulted in greatest enhancement of SOM stability in extremely low fertility soil. Our study also demonstrated that there was some degree of decoupling between carbon and nitrogen cycles in the saline-alkaline paddy soils. This work provides evidence that the effectiveness of soil amendments depends on both soil (e.g., salinity and fertility levels) and environment (e.g., water-logging) conditions, thus one should consider various factors for better choice of amendment and application measures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Credit statement

Lipeng Wu: Methodology, Writing – original draft, Investigation; Xiujun Wang: Conceptualization, Writing – review & editing; Haonan Zheng: Investigation.

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