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Impacts of biochar amendment and straw incorporation on soil heterotrophic respiration and desorption of soil organic carbon

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Abstract

While biochar amendment and straw incorporation in soil have received great attention due to the potential of carbon sequestration and improvements in soil physicochemical properties, there were limited studies addressing their impacts on soil heterotrophic respiration over a seasonal cycle. Here, we conducted a field experiment to evaluate the effects of biochar amendment and straw incorporation on the temporal variations of soil heterotrophic respiration and desorption of soil organic carbon (SOC) in the North China Plain. We measured CO_2 efflux over 1-year period in the field, together with water extractable organic carbon (WEOC) and soil microbial biomass carbon (SMBC). Our study showed a significant exponential relationship ($P < 0.001$) between CO_2 efflux and temperature, with Q_{10} values in a range of 2.6–3. CO_2 efflux was significantly higher in summer under straw incorporation (5.66 μmol m^{-2} s^{-1}) than under biochar amendments (3.54–3.92 μmol m^{-2} s^{-1}) and without amendment (3.76 μmol m^{-2} s^{-1}). We found significantly lower WEOC:SOC ratio and SMBC:SOC ratio under biochar amendments than with straw incorporation and without amendment. Our study indicated that biochar amendment had a greater potential for reducing SOC desorption and CO_2 efflux in the cropland of North China Plain.

Keywords Soil heterotrophic respiration, CO_2 efflux, Desorption of soil organic carbon, Straw incorporation, Biochar amendment, Seasonal variability

Introduction

Soil carbon pool is the largest carbon pool on land, which is much greater than the sum of total carbon stored in the atmosphere and biosphere (Tang et al. 2018; Tifafi et al. 2018). Soil organic carbon (SOC), as a main component of soil carbon pool, acts as both a source and a sink of carbon dioxide (CO_2) in the terrestrial ecosystem. In particular, soil heterotrophic respiration (decomposition of SOC) is a major CO_2 source to the atmosphere.

Soil heterotrophic respiration is largely regulated by natural factors such as climate conditions and soil characteristics (Moonis et al. 2021). In general, high temperature can stimulate microbial activities thus enhances soil heterotrophic respiration (Allison et al. 2010). However, extremely high temperature may cause water stress thus decrease microbial activities, leading to low rates of soil respiration (Bradford et al. 2008). The effect of precipitation on soil respiration is complex due to its effects on various processes that regulate soil properties and microbial activity (Moyano et al. 2013; Novak et al. 2010). Generally, precipitation could increase microbial activities

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in drylands, which would enhance SOC decomposition (Shen et al. 2008; Wang et al. 2021b). But, sustained heavy rainfall could lead to hypoxia conditions that inhibit soil microbial activity, leading to low rates of soil respiration (Waring and Hawkes 2015).

Soil heterotrophic respiration is also affected by soil physical (e.g., porosity and texture), and chemical properties (e.g., soil pH, salinity and ion concentration) (Ferrara et al. 2017; He et al. 2009). There was evidence that high levels of clay in soils were beneficial for soil organic matter (SOM) protection (Xu et al. 2019). In addition, studies also showed that soil heterotrophic respiration was generally weak in saline–alkaline soils because of reduced soil osmotic potential and substrate availability that inhibit soil microbial activity (Ghollarata and Raiesi 2007; Wang et al. 2021a).

Land use managements can have large influences on soil heterotrophic respiration or CO_2 efflux (Artemyeva et al. 2021; Guimarães et al. 2013). Straw incorporation, a comment practice, is not only beneficial for maintaining soil fertility, but also provides easily degradable organic materials (Wang et al. 2021b), which often results in more CO_2 efflux. Over the past decade, biochar has been applied to improve soil physical and chemical conditions and to enhance carbon sequestration. An early study showed that biochar amendment significantly increased the numbers of macropores (>75 μm) and medium pores (30–75 μm) in a clayey soil (Sun and Lu 2014), due to biochar's loose and porous characteristics, which improved soil structure (Ventura et al. 2013). There was evidence that biochar amendment can increase cation exchange capacity (CEC) content in both acidic and alkaline soils due to a larger mount of anions on the biochar's surface, and "biochar promotes the polymerization of small organic molecules through surface catalytic activity to form soil organic matter, and macropores can adsorb small organic molecules in soil" (Zhang et al. 2021). In addition, biochar addition results in improvement in soil pH (Novak et al. 2010). The improvements in soil physical and chemical conditions led to enhanced microbial activity and diversity, which can cause high rates of SOC decomposition (Zhang et al. 2021).

Our recent study revealed that long-term applications of biochar and straw led to enhanced SOM stability in wheat–maize cropping system, with greater enhancement under biochar amendment (Lu et al. 2021). Thus, one may hypothesize that biochar amendment can reduce rate of CO_2 efflux, and desorption of SOC is stronger under straw incorporation than under biochar amendment. However, there were few relevant studies conducted over a seasonal cycle. The objectives of this 1-year field study were to examine the temporal variation of CO_2 efflux under straw incorporation and biochar amendment in a Fluvo-aquic soil, and to evaluate the effects of soil amendments on the desorption of SOC in the main seasons.

Materials and methods

Site description

The study was conducted at the Huantai Agroecosystem Experimental Station (36° 58′ N, 117° 59′ E, elevation 17 m) of the China Agricultural University. This area is dominated by warm temperate continental monsoon climate with obvious seasonal characteristics: low temperature and drought in spring, hot and rainy in summer and autumn, cold and dry in winter. We obtained weather data from a local weather station, which showed a clear seasonality in both air temperature and precipitation (Fig. 1). Mean monthly temperature was highest in August (26.58 °C) and lowest in January (0.28 °C). Annual mean precipitation was 523 mm, with ~70% in summer. The soil was developed on alluvial loess, and classified as Fluvo-aquic. No crops have been planted in the experimental soil for nearly 15 years. The topsoil (0–20 cm) has 70.8% sand (0.02–2 mm), 26.9% silt (0.002–0.02 mm) and 2.3% clay (<0.002 mm) (Du et al. 2014). Soil pH, SOC and total nitrogen (TN) were 8.29, 6.02 g kg^{-1} and 0.71 g kg^{-1}, respectively.

Experimental design

We collected topsoil (0–25 cm) from a fallow plot at the experimental station in September 2019, and mixed the soil thoroughly to ensure homogeneity, then passed through a 5-mm sieve. Empty PVC tubes (80 cm in height, 50 cm in diameter) were buried in the field (~50 cm deep), then filled with well-mixed soil with or without amendment. Five treatments were set up: no amendment (CK), biochar addition at 1% (B1) and 2%

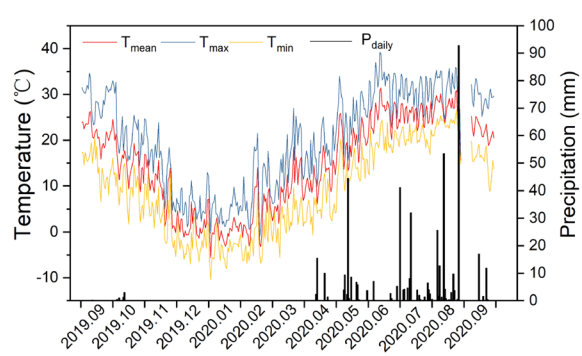

Fig. 1 Temperature and precipitation data for whole year from September 2019 to September 2020. The solid lines in red, blue and yellow denote the daily mean, maximum and minimum temperatures,respectively. The black columns denote daily precipitation

(B2), and wheat straw incorporation at 1% (S1) and 2% (S2). Each treatment was repeated in two sets. Wheat straw was cut into 1–2 cm in length. Application rates of soil amendments were in compliance with local agricultural practice. Biochar was produced from corncob by pyrolysis at 360 °C (by Jinfu Biochar Company in Liaoning). Basic properties of biochar were as follows: pH value 8.20, 72.0% ash content, 5.70% total carbon, 0.91% total nitrogen, 0.08% available-P and 1.60% available-K.

CO_2 efflux measurements and soil sample analyses

We measured CO_2 efflux every 2 weeks in summer and once a month in other seasons using Li-8100A CO_2 system (20 cm chamber, Li-COR, Inc, Lincoln, NE, USA). A soil collar was inserted in the center of PVC tube. The periodic measurements were conducted from 09:00 a.m. to 11:00 a.m. We also carried out 24-h CO_2 efflux measurement in July and November 2019, July and October 2020, with an interval of ~2 h during the day and ~3 h over night.

Topsoil (0–15 cm) samples were collected in April, July and October 2020, which were used to analyze relevant properties. Soils samples were air-dried, mixed thoroughly and sieved through a 2-mm screen. We prepared soil–water mixtures (1:2.5) for measurements of soil pH, and electrical conductivity (EC) using Conductivity Meter (Mettler-Toledo FE 20; Switzerland). For the measurements of WEOC and SMBC, we used 10 g 2-mm soil which was treated with 40 ml 0.05 M K_2SO_4 solution for 6 h at 25 °C. We shook the mixture for 40 min by oscillating machine, then followed it through centrifugation. The supernatant was filtered through a 0.45-μm membrane. Last, then analyzing WEOC and SMBC using a TOC analyzer (TOC-VCPH, Shimadzu) (Salazar et al. 2019).

Subsamples were crushed less than 0.25 mm, which were used for the measurements of SOC and TN. SOC content was determined by $K_2Cr_2O_7$ oxidation titration (Walkley and Black 1934). TN content was determined by Kjeldahl method of nitrogen determination (Speirs and Mitchell 1936).

Empirical model for CO_2 efflux and statistical analyses

We used observed CO_2 efflux (R) and temperature (T) to derive a relationship for each treatment, using a simple empirical exponential model:

$$R = \alpha e^{\beta T} \tag{1}$$

where α and β are respiration rate at 0 °C and temperature-depend coefficients, respectively. An indicator for the temperature sensitivity to soil respiration, Q_{10}, is calculated as:

$$Q_{10} = \frac{R_{T0+10}}{R_{T0}} \tag{2}$$

We use one-way analysis of variance (ANOVA) and Fisher' protected least significant difference (LSD) to assess the significance of differences in soil carbon fractions between treatments (e.g. WEOC and SMBC). The statistical tests were conducted using the SPSS Statistics 19.0 (SPSS Inc., Chicago, IL, USA). Temperature and precipitation data were obtained from local weather stations.

Results

Temporal variations of soil CO_2 efflux

Diurnal variation of CO_2 efflux showed a large similarity to that of soil temperature under all treatments (Fig. 2). Despite some differences among treatments, overall, soil CO_2 efflux was highest around 12 o'clock and lowest around 24 o'clock. However, there were some differences in the magnitude of diurnal variation. For example, the highest and lowest values of CO_2 efflux were 2.98 and 0.62 μmol m^{-2} s^{-1} in July, 2019, but 4.57 and 1.92 μmol m^{-2} s^{-1} in July 2020 without amendment (Fig. 2a, c). Clearly, diurnal variation was greater in October (from ~0.8–2.1 to 3.2–5.5 μmol m^{-2} s^{-1}) than in November (from ~0.5–1.2 to 1.4–2.9 μmol m^{-2} s^{-1}), 2019 under all treatments (Fig. 2b, d). As expected, straw incorporation resulted in an increase in CO_2 efflux, with greater increase under higher rate. CO_2 efflux under biochar amendments showed an overall weaker diurnal variation, and/or lower rates comparing with the control.

CO_2 efflux showed an obvious seasonal variation with a similar pattern under all treatments (Fig. 3). CO_2 efflux was lowest in January 2020 in all treatments (< 0.20 μmol m^{-2} s^{-1}), and highest in early July 2020 (3.40–3.90 μmol m^{-2} s^{-1}) without straw incorporation but in September 2019 (> 5.66 μmol m^{-2} s^{-1}) with straw incorporation. There was a sharp decline in CO_2 efflux (by 3.07–5.42 μmol m^{-2} s^{-1}) from September to December in 2019 in all treatments, and a modest increase (by 1.19–2.83 μmol m^{-2} s^{-1}) from April to July in 2020. CO_2 efflux was lower in September in 2020 (2.71–3.22 μmol m^{-2} s^{-1}) than in 2019 (3.31–3.53 μmol m^{-2} s^{-1}) without straw incorporation, which was similar to the variation of temperature (23.4 °C vs. 20.3 °C). CO_2 efflux was extremely low in August 2020, without (< 0.53 μmol m^{-2} s^{-1}) and with (1.70 μmol m^{-2} s^{-1}) straw incorporation, which was in association with the large rainfall. Overall, there was little difference between CK and biochar treatments in terms of the seasonal variation of CO_2 efflux.

Relationship between CO_2 efflux and temperature

We evaluated the relationship of CO_2 efflux with two mean temperatures (i.e., 3-day mean and 7-day

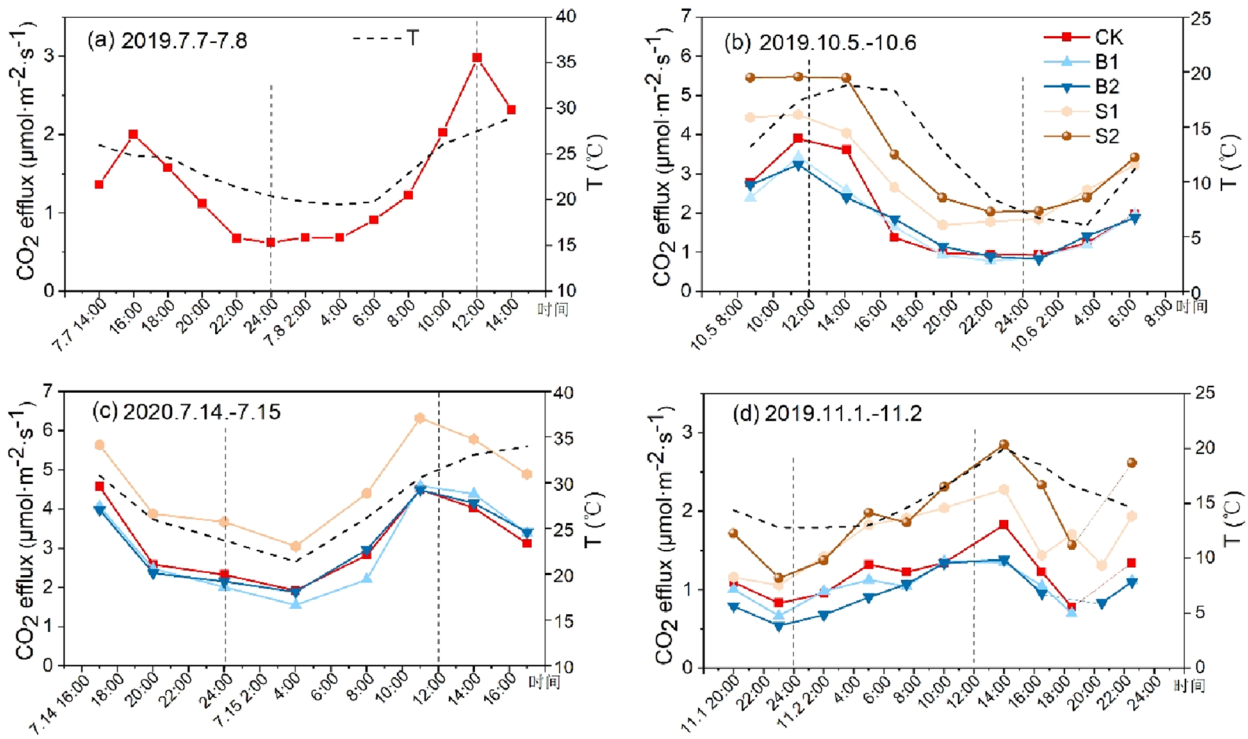

Fig. 2 Diurnal variation of CO_2 efflux under no amendment (CK), 1% biochar (B1), 2% biochar (B2), 1% wheat straw (S1) and 2% wheat straw (S2) application. Dashed black lines denote daily mean temperature

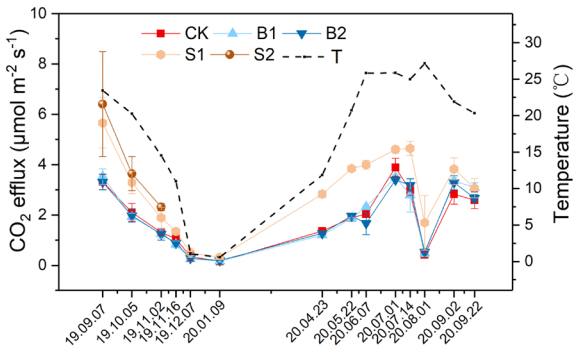

Fig. 3 Seasonal variation of CO_2 efflux under no amendment (CK), 1% biochar (B1), 2% biochar (B2), 1% wheat straw (S1) and 2% wheat straw (S2) application. Dashed line denotes 7-day mean temperature prior to the day of CO_2 measured (no date in February and March due to the Covid-19 epidemic)

mean prior to CO_2 efflux measurement). Our analyses showed that CO_2 efflux and temperature had a significant exponential relationship under all treatments, with R^2 value ranging from 0.85 to 0.92 ($P < 0.001$) (Fig. 4). The respiration coefficient (α) showed the highest value (0.570) under S1 treatment and the lowest value (0.285) under B1 treatment, with relatively high values when using 3-day mean temperature. The respiration coefficient was greater under B2 treatment (0.261–0.322) than under B1 treatment (0.229–295) with two temperatures. The temperature-dependent coefficient (β) showed the highest value (0.108) under B1 treatment, and the lowest value under S1 treatment (0.096), with relatively high values when using 7-day mean temperature. Q_{10} was consistent with the change in temperature-depend coefficients under all treatments (Table 1). For example, the highest temperature-depend coefficient was 0.093 and Q_{10} was 2.948 under B1 treatment. While the lowest value was 0.081 and Q_{10} was 2.620 under straw incorporation when using 3-day mean temperature.

We estimated CO_2 efflux caused by straw decomposition by calculating the difference in CO_2 efflux between straw incorporation and no amendment, and found that there was also a significant exponential relationship between straw caused CO_2 efflux and temperature (Fig. 5). The respiration coefficient was higher which fitted at 3-day mean temperature than 7 days (0.210 vs. 0.162), while the R^2 value was lower (0.57 ($P < 0.05$) vs. 0.65 ($P < 0.01$)). The temperature-depend coefficients were higher by 7-day mean than 3 days (0.089 vs. 0.072).

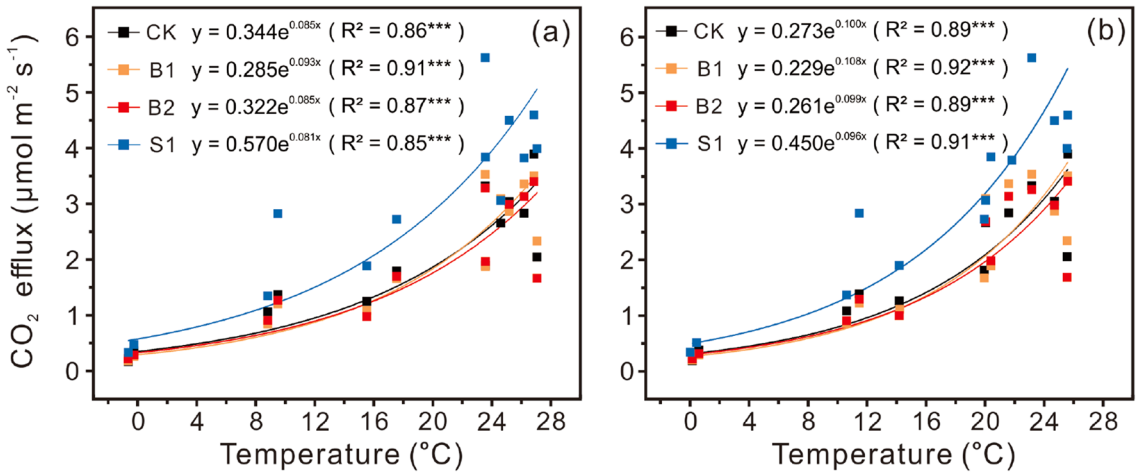

Fig. 4 Relationship between CO_2 efflux and temperature under no amendment (CK), 1% biochar (B1), 2% biochar (B2) and 1% wheat straw (S1) application. **a** Using 3-day mean temperature prior to the day of CO_2 measured, and **b** using 7-day mean temperature prior to the day of CO_2 measured

Table 1 Parameters for the relationship between CO_2 efflux and temperature under no amendment (CK), 1% biochar (B1), 2% biochar (B2) and 1% wheat straw (S1) application

Treatment	3-day mean temperature				7-day mean temperature			
	α	β	R^2	Q_{10}	α	β	R^2	Q_{10}
CK	0.34	0.085	0.86***	2.71	0.27	0.100	0.89***	2.33
B1	0.28	0.093	0.91***	2.95	0.23	0.108	0.92***	2.53
B2	0.32	0.085	0.87***	2.70	0.26	0.099	0.89***	2.33
S1	0.57	0.081	0.85***	2.62	0.45	0.096	0.91***	2.24

Three asterisks denote a significance at $P < 0.001$

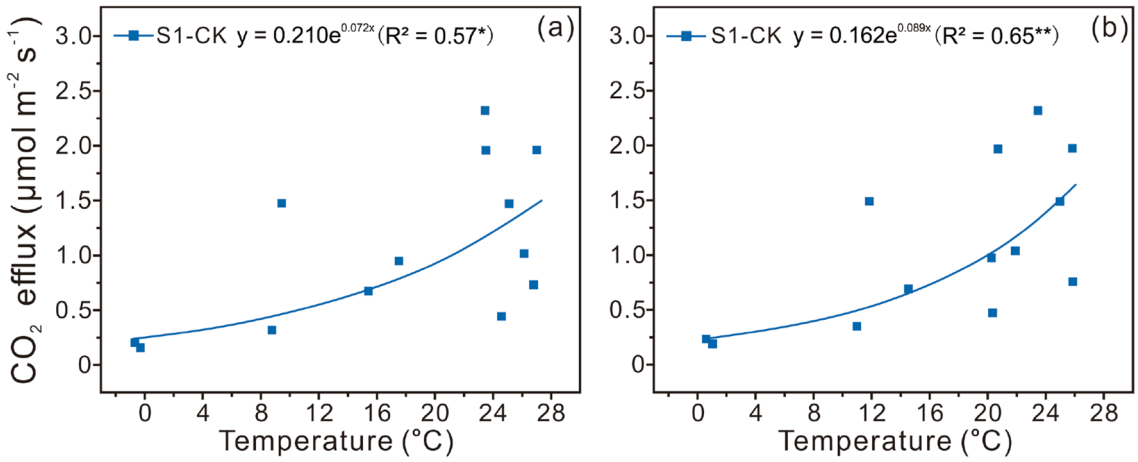

Fig. 5 Relationship between increased CO_2 efflux due to straw addition and temperature. **a** Using 3-day mean temperature prior to the day of CO_2 measured, and **b** using 7-day mean temperature prior to the day of CO_2 measured

Seasonal variations of CO_2 efflux under different organic amendments

We used the parameters derived for the relationship between CO_2 efflux and 7-day temperature (Table 1) to estimate the decomposition rate of SOC, straw and biochar over an entire year (Fig. 6). The decomposition rate of SOC showed a decline from early autumn (~3 μmol m^{-2} s^{-1}) to winter (~0.5 μmol m^{-2} s^{-1}) in 2019, followed by a modest increase until early spring then a sharp increase from April (~1 μmol m^{-2} s^{-1}) to June (~4.5 μmol m^{-2} s^{-1}) in 2020 and remained high until August (Fig. 6a). The decomposition rate of straw revealed a similar but much strong seasonality, i.e., the lowest (0.15 μmol m^{-2} s^{-1}) in winter 2019 and the highest (~2.40 μmol m^{-2} s^{-1}) in summer 2020 (Fig. 6b).

The seasonal change in CO_2 efflux was different between low rate and high rate biochar application. There was an increase in CO_2 efflux under 1% biochar application in summer 2020 (by ~0.1–0.3 μmol m^{-2} s^{-1}), but a small decrease (~0.05 μmol m^{-2} s^{-1}) in all other seasons (Fig. 6c). However, high rate of biochar application caused a decrease in CO_2 efflux during the entire year, with the greatest decrease found in summer (~0.3 μmol m^{-2} s^{-1}) and the smallest decrease in winter (0.02 μmol m^{-2} s^{-1}) (Fig. 6d).

Effects of soil amendments on WEOC and SMBC

There was little change in WEOC content during incubation without amendment. Organic amendments led to a significant increase in WEOC content, with the greatest increase in April and the smallest increase in October (Fig. 7a). Overall, the increase of WEOC content was significantly greater under biochar amendment (by 25–31 mg kg^{-1}) than under straw incorporation (by 17–23 mg kg^{-1}). SMBC content showed little change in April and July but a significant increase in October without amendment (Fig. 7b). Overall, biochar amendment had no clear effect on SMBC whereas stesulted in a significant increase of SMBC content (by 29–73 mg kg^{-1}).

There was a slight decrease in WEOC:SOC ratio over time without amendment (Fig. 7c). Biochar amendment led to a decrease in WEOC:SOC ratio but straw incorporation had little effect on WEOC:SOC ratio (slight increase in April and July but decrease in October).

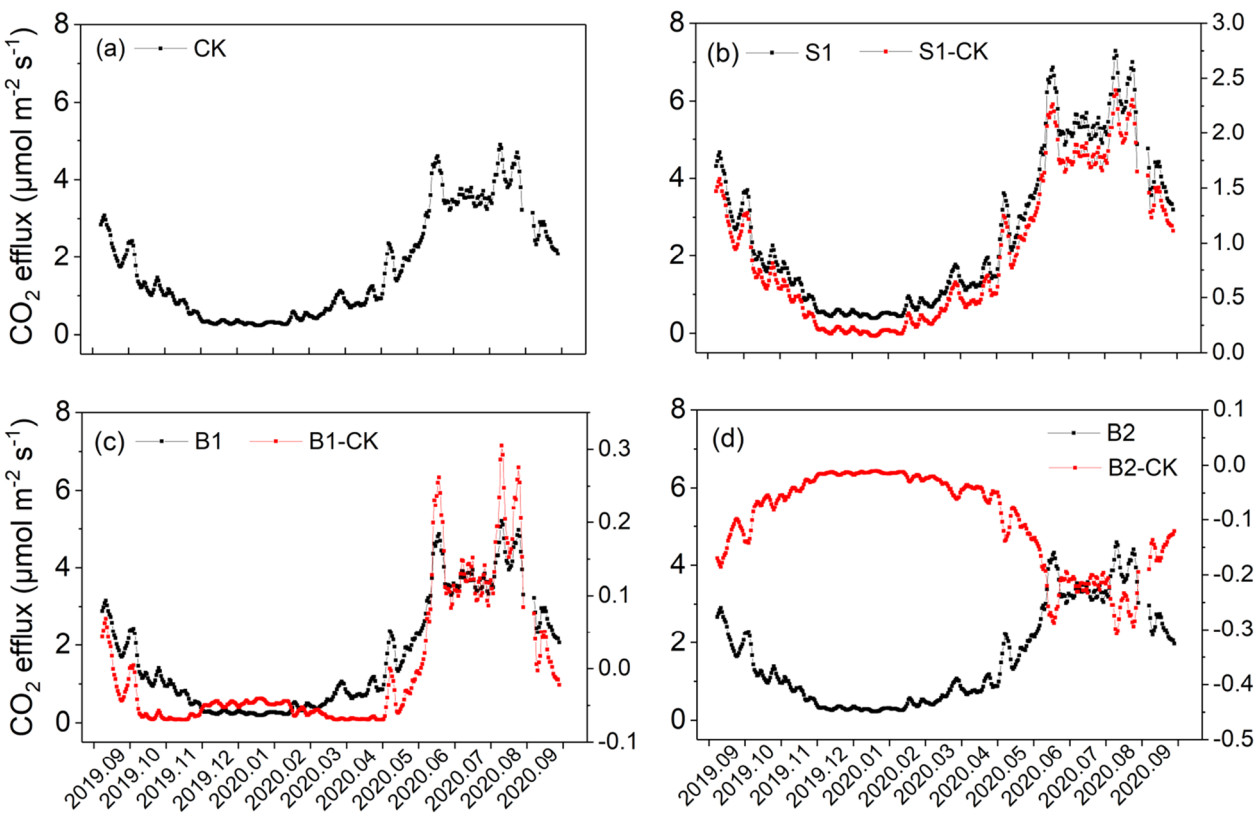

Fig. 6 Seasonal variations of estimated CO_2 efflux (black lines) under no amendment (CK), 1% wheat straw (S1) application, 1% biochar (B1), and 2% biochar (B2) and decomposition rate of **a** soil organic carbon (i.e., CO_2 efflux in CK) and **b** straw under 1% application (i.e., the difference in CO_2 efflux between S1 and CK, red line), and changes in CO_2 efflux (red lines) due to biochar amendment under **c** biochar 1% application (B1-CK) and (d) 2% application (B2-CK)

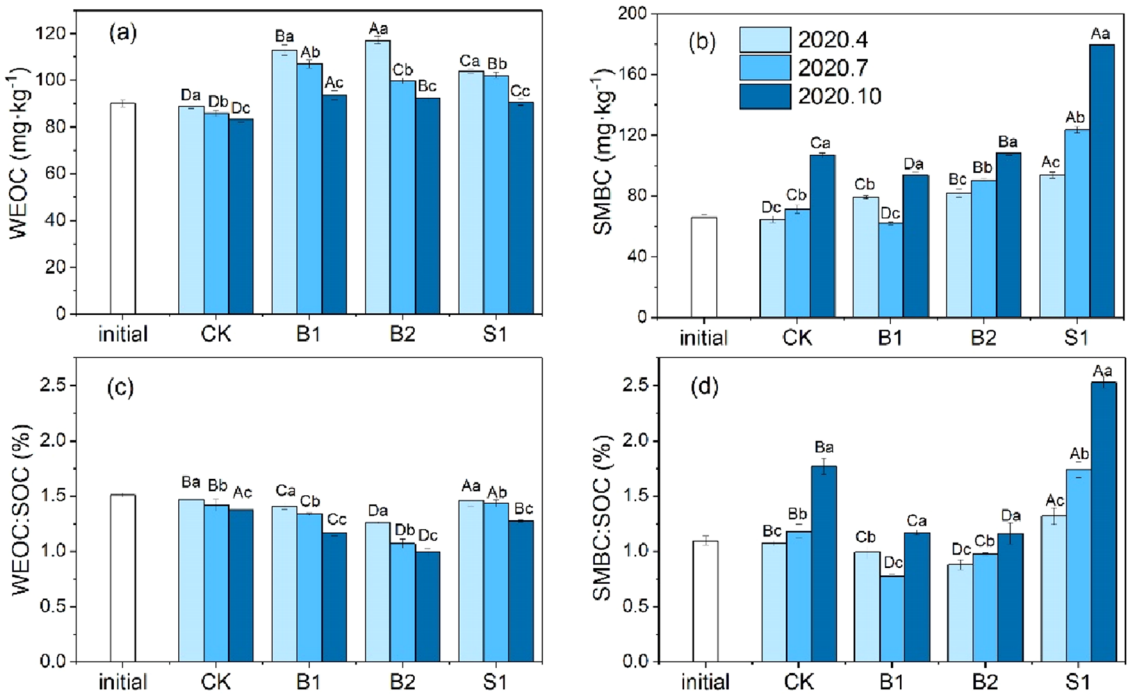

Fig. 7 Contents of (**a**) water extractable organic carbon (WEOC) and (**b**) soil microbial biomass carbon (SMBC), (**c**) WEOC:SOC ratio, and (**d**) SMBC:SOC ratio in initial samples, and under no amendment (CK), 1% biochar (B1), 2% biochar (B2) and 1% wheat straw (S1) application. Error bars denote the standard errors. Values followed by the same letter (upper case between treatments or lower case between months) are not significantly different at $P < 0.05$

Clearly, the lowest WEOC:SOC ratio was found in October under all treatments. However, SMBC:SOC ratio was highest in October under all treatments (Fig. 7d). There was a significant decrease in SMBC:SOC ratio under biochar amendments but an increase under straw incorporation.

Discussion

Response of CO_2 efflux to environmental conditions

Soil respiration and CO_2 efflux are regulated by environmental conditions, such as temperature and soil moisture (Delgado-Baquerizo et al. 2017; Gray et al. 2019; Rojas et al. 2017). Higher temperature can stimulate soil microbial activity, thus increase soil heterotrophic respiration (La Scala et al. 2010; Li et al. 2018). Many studies showed that soil respiration rate was significantly correlated with temperature in a certain range (Chen and Wu 2019; Kirschbaum 2006; Mahecha et al. 2010). Our study shows clear diurnal and seasonal patterns in CO_2 efflux, which are largely related to the changes in temperature (Figs. 2 and 3).

There was evidence that Q_{10} value for soil heterotrophic respiration was generally higher in boreal and temperate regions (2.0–2.6) than in tropical and subtropical regions (1.0–2.0) (Zhou et al. 2009), reflecting temperature limitation in mid-attitudes. The Q_{10} value was 2.33–2.71 in our study, which was close to those (2.3–2.9) under similar soil conditions (i.e., in alkaline sandy loam) in Fierer's study (Fierer et al. 2006). A field study conducted in arid farmland of northwest China yielded a much higher Q_{10} value (4.3) for SOC decomposition (Li et al. 2011). The large differences in Q_{10} value might reflect the influence of other factors (such as soil moisture) on soil heterotrophic respiration.

There is evidence that soil moisture has various effects on soil respiration and CO_2 efflux (Inglima et al. 2009; Pabst et al. 2016). While soil respiration generally increases with the increase of soil moisture in a certain range under controled environmental conditions, such as in laboratory experiments (Zhou et al. 2014) (Moonis et al. 2021), soil respiration is low when soil moisture is too high such as in tropical forestlands, because of the water-log conditions that retard microbial activities (Zimmermann et al. 2015). The effect of precipitation on CO_2 efflux is more complex (Chayawat et al. 2012; Ma et al. 2012) due to the impacts of soil moisture change on both microbial activities and soil porosity. CO_2 efflux is affeted by both the timing and intensity of precipitation (Luo et al. 2017). Previous studies reported enhanced CO_2 efflux with an increase of precipitation at an earlier stage or in a short period in arid and

semi-arid areas and then followed by a decline, e.g., in a desert shrubland in Gansu (Song et al. 2015) and in semi-arid grasslands of Inner Mongolia (Qi et al. 2014). The initial increase of CO_2 efflux was due to enhanced microbial activity that led to increased decomposition of SOM (Tan et al. 2021) whereas the decrease of CO_2 efflux was probably caused by reduced soil porosity in arid and semi-arid areas (Xu et al. 2019).

On the other hand, there was evidence of reduced CO_2 efflux with an increase of rainfall in humid and subhumid areas (Chen et al. 2003). Our study showed that CO_2 efflux reduced to near 0 after 2-week continuous heavy rainfall in summer (Fig. 3). Similarly, other field studies also showed a decrease in CO_2 efflux with an increase of rainfall, e.g., in summer and autumn at a forest site in Beijing (Zhu et al. 2020) and in summer in a coastal reed wetland (Han et al. 2018). In general, hypoxia condition induced by heavy rainfall could inhibit microbial activity (thus decrease the decomposition of SOM) in humid and subhumid regions (Yoon et al. 2014). In addition, heavy rainfall could reduce soil porosity thus restrain CO_2 diffusion from soil profile to the atmosphere (Liu et al. 2017).

Effects of organic amendments on soil heterotrophic respiration and CO_2 efflux

Soil management measures (straw incorporation and biochar amendment) can affect soil respiration by changing soil physicochemical properties and activity of soil microorganisms (Battaglia et al. 2021; Oertel et al. 2016). Our study showed increased CO_2 efflux with straw incorporation, which was consistent with many other studies (Li et al. 2019). In general, straw incorporation can directly input organic carbon, thus increases substrate concentration for microorganisms (Feng et al. 2012; Liu et al. 2021). In addition, straw incorporation can improve soil structure and provide extra nutrients and energy for microorganisms (Singh et al. 2007; Wang et al. 2015), which facilitates microbial activity, thus increases SOC decomposition and CO_2 efflux.

There were limited studies addressing the effects of biochar amendment on soil respiration and CO_2 efflux, which showed inconsistent findings. For example, some indoor experiments showed enhanced CO_2 efflux under biochar amendments in pH neutral soils over the duration from 3 days to ~3 months (Jones et al. 2011; Shah and Shah 2017; Zavalloni et al. 2011) whereas a 24-day indoor trial revealed a decrease in CO_2 efflux under biochar amendment in sandy loam with a pH of 7.6 (Lu et al. 2014). Our field incubation experiment showed that despite of ~10% decrease in CO_2 efflux under 1–2% biochar treatments, there were no significant differences over 1-year period in the sandy loam with a high pH (8.2) (Fig. 6).

The ratio of WEOC:SOC (desorption potential) showed little change under straw incorporation, but a significant decrease under biochar amendment. A number of studies also revealed that biochar amendment led to a significant decrease in WEOC:SOC ratio, including in Fluvo-aquic of North China Plain (Lu et al. 2021; Wu et al. 2021) in Hapli-Udic Cambisol soil of Northeast China (Yang et al. 2017), Solonchacks soil of East China (Ma et al. 2021) and Ferrosol soil of Southeast China (Yin et al. 2014). There was evidence that biochar amendment could increase CEC due to biochar's negative charge, thus enhance the formation of SOC-cation complex (Chintala et al. 2014; Zhang et al. 2021). In addition, biochar amendment could also enhance the formation of macro-aggregates from micro-aggregates due to the formation of mineral-biochar-SOM complexes (Han et al. 2020) (Zhang et al. 2021). The formation of these complexes would result in enhanced protection of SOM, thus reduce soil heterotrophic respiration and CO_2 efflux.

Seasonal variation of CO_2 efflux from different organic materials

It is widely observed that there is a strong seasonality in soil respiration or CO_2 efflux in varous ecosystems across most climate zones, which appears in association with temperature change. However, there is a large range in the temperature sensitivity parameter Q_{10} value for soil heterotrophic respiration (Del Grosso et al. 2005); our results show some differences in Q_{10} value among different treatments, with the smallest value under straw treatment. The differences in Q_{10} value may reflect the partial influence of other environmental conditions (such as soil moisture) on soil heterotrophic respiration (Inglima et al. 2009; Pabst et al. 2016). In addition, the characteristics of SOM and other organic materials have large influences on SOM stability (Kan et al. 2022; Wu et al. 2023) thus soil respiration with implications for the seasonal variation of CO_2 efflux.

Our study showed a strong seasonality in straw decomposition (i.e., 1.9 μmol m^{-2} s^{-1} in summer, and 0.2 μmol m^{-2} s^{-1} in winter, Table 2), which was similar

Table 2 Seasonal means of CO_2 efflux (μmol m^{-2} s^{-1}) under no amendment (CK), 1% biochar (B1), 2% biochar (B2) and 1% wheat straw (S1) application

Treatment	Autumn	Winter	Spring	Summer	Total
CK	1.46b	0.32b	1.10b	3.76b	6.64b
B1	1.42b	0.27c	1.05b	3.92b	6.66b
B2	1.38b	0.30b	1.04b	3.54c	6.26c
S1	2.27a	0.52a	1.73a	5.66a	10.18a
S1-CK	0.79	0.20	0.63	1.90	3.52

Values followed by the same letter are not significantly different at $P < 0.05$

that of SOM decomposition. Overall, biochar application caused a reduction of CO_2 efflux year-around except in summer under lower rate of biochar application. The response of CO_2 efflux to straw or biochar addition was consistent with that of SMBC:SOC ratio, i.e., increase with straw and decrease with biochar (Fig. 7d), which reflected enhanced microbial activity (Singh et al. 2007; Wang et al. 2015) and reduced microbial/enzyme activity (Yang et al. 2022), respectively. The differences in magnitude and seasonality of CO_2 efflux between straw and biochar were probably attributable to the differences in their own physicochemical properties and their influences on the stability of old SOM (Abiven et al. 2009; Diacono and Montemurro 2010; Han et al. 2020; Tan et al. 2017).

Our previous study demonstrated that biochar amendment had a greater influence on enhancement of SOM stability than straw incorporation in cropland of North China Plain (Lu et al. 2021). There was evidence that biochar amendment could increase soil porosity due to the large surface area of biochar, which could lead to greater adsorption capacity of soil, thus more SOC trapped in soils (Burrell et al. 2016). Biochar was also able to form macroaggregates by acting as a persistent organic binder (Abel et al. 2013). Moreover, biochar amendment can increase CEC due to biochar's negative charge, thus promote the formation of SOC-cation complex, which is beneficial to SOC stability (Chintala et al. 2014; Zhang et al. 2021). Further studies are needed to investigate the interactive responses of physical and chemical properties to various organic amendments and the subsequent effects on soil microorganisms, which aims to better understand the impacts of land use management on soil quality and carbon sequestration.

Conclusions

This field study showed a strong seasonality in CO_2 efflux, with the lowest in January 2020 (< 0.20 μmol m^{-2} s^{-1}) in all treatments, and the highest in early July 2020 (3.40–3.90 μmol m^{-2} s^{-1}) without straw incorporation. CO_2 efflux was significantly higher under straw incorporation, but overall lower under biochar amendment. Both WEOC:SOC ratio (an indicator for SOC desorption or SOC stability) and SMBC:SOC ratio were significantly lower under biochar amendment than under straw incorporation. The study suggested that biochar amendment had a greater potential for enhancing SOC stability, and biochar amendment was more effective than straw incorporation in soil improvement in farmland of north China. More studies are still needed to advance our understanding the complex influences of organic amendments on soil physical and chemical properties and the carbon cycle in croplands under changing environments.

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Author contributions
XW provided supervision and financial support for this study, and corrected all the versions of the manuscript. ZZ collected field experiment and laboratory measurement, and prepared for the manuscript. NH provided financial support, and commented on later versions of the manuscript. TL and LW helped with sampling and analyses, and commented on later versions of the manuscript. ZH provided support for the field experiment.

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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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