Increases of Temperature Response for CO₂ Emission in a Biochar-Amended Vegetable Field Soil

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Abstract

To explore the effects of biochar application on CO₂ and CH₄ emission as well as the temperature response of CO₂ emission, an one-year experiment was conducted with three treatments (Control; CF, chemical fertilizer only; BCF, biochar combined with chemical fertilizer) in a vegetable field. Results shown that (1) compared with CF, short-term application of biochar significantly enhancing the cumulative CO₂ emission by 27.5% from soil-plant system, *via* increasing the soil microbial biomass (e.g., MBC) and C substrates (e.g., SOC). (2) A lowest emission of CH₄ was observed in BCF treatment, and an increase CH₄ consumption and reduce competition with NH₄⁺ may be responsible for the significant reduction in CH₄ source strength in biochar amended soil. (3) Activation energy (E_a) was identified as an important factor influencing the temperature sensitivity (Q_{10}) of CO₂ emission. Fertilization (CF and BCF) reduced the average Q_{10} and E_a values of CO₂ emission by 9.0-26.7% and 23.5-10.1%, relative to the control, respectively. Besides, the average of E_a value in BCF treatment (51.9 KJ mol⁻¹) was significantly higher than those in control and CF treatment. The increase in Q_{10} and E_a values following biochar application possibly contributed to the supplement of limit labile C and nutrient but highly resistant C following biochar application. Soil pH and crop cultivation may play key roles in influencing the change of E_a . Our study concludes that biochar amendment increased CO₂ emission and temperature response of CO₂ emission from soil-plant system, while reduced CH₄ emission.

1 Introduction

Biochar, as a soil amendment has been incorporation into soil to improve soil properties and soil structure, increase nutrient available and microbial activities (Anderson et al. 2011; Criscuoli et al. 2014; Duan et al. 2020; Dai et al. 2021). As a stable amendment, biochar currently has been an attractive measure to enhance C sequestration in the long-term field scale (Singh et al. 2015; Kan et al. 2020). Therefore, there has been growing call to add biochar into soil to promote C sequestration and improve soil quality. However, in short periods of time (i.e. months), biochar will undergo structural changes, primarily the oxidation of surface, and can be utilized by microbes as a C source (Cheng et al. 2006; Zavalloni et al. 2011). As a result, biochar could be an ecosystem C source, instead of sink, within a short-term period in soil. For example, Ameloot et al. (2013) determined that the increase of short-term CO₂ and N₂O emissions (117 days) were observed in biochar-amended soils due to the rapid degradation of labile compounds in the biochar (Zimmerman et al. 2011). Alternatively, new substrates addition would stimulate the “priming effects”, defined as the changes in the mineralization of native soil organic matter (Kuzyakov, et al. 2000; Kuzyakov, 2010). The negative priming effects, such as reduced N₂O production and CH₄ oxidation have been reported in the soil treated with biochar (Spokas and Reicosky, 2009; Wu et al. 2019; Duan et al. 2020), due to biochar’s porous native and high affinity for natural organic matter (Kasozi et al. 2010; Zimmerman et al. 2011). However, biochar could also promote the mineralization of soil C due to the positive priming effect (Dong et al. 2018; Kan et al. 2020; Dai et al. 2021). Meanwhile, biochar incorporation can increase the root biomass, net photosynthesis and grain yield, and then

influence the net CO₂ emission from the soil-plant system (Masto et al. 2013; Sun et al. 2017). Hence, the short-term response of greenhouse gas emission on the biochar application in agriculture systems should be received more attention.

Temperature plays a vital role in affecting soil organic C (SOC) mineralization and result in variability in the C pool (Criscuoli et al. 2019; Kan et al. 2020; Wang et al. 2019). The response to temperature changes, such as temperature sensitivity (Q_{10} , defined as the rate of change of soil CO₂ emission as a consequence of temperature increase of 10 °C) (Kirschbaum 1995) and activation energy (E_a , defined as the necessary energy for reacting molecules to break and form new bonds after a collision) (Thiessen et al. 2013), could be used to evaluate the feedback intensity between CO₂ emission and global warming (Zhou et al. 2009), as well as the response of SOC to global warming (Fang et al. 2014). Exogenous C input (e.g. biochar) may alter the chemical recalcitrance of organic matter and environmental conditions, and resulted in changing the temperature response of CO₂ emission (Fang et al. 2014, 2017; Wang et al. 2019). According to the fundamental enzymatic kinetic theory, organic compounds with higher molecule weights showed lower rates of decomposition, higher values of Q_{10} and E_a relative to organic compounds with lower molecule weights. However, the decreases and increases in the Q_{10} and E_a were observed in biochar added soils (He et al. 2016; Fang et al. 2017; Pei et al. 2017; Wang et al. 2019). The contradictory of results may be caused by the interactions of physical–chemical protection and substrate C quality change (Conant et al. 2011). Biochar application in short-term period may introduce the more C including stable and labile C, which is related to the temperature response. However, there is a lack of knowledge about the temperature response of CO₂ emission from soil-plant systems in biochar amended vegetable field soil.

Here, we hypothesized that biochar incorporated to soil would increase the C gas loss and enhanced the temperature response of CO₂ emission due to the exogenous C, especially in the short-term time. In this study, we conducted a short-term experiment (about one year) in vegetable cultivation to investigate the response of biochar amendment on the CO₂ and CH₄ emission as well as the temperature response of CO₂ emission. The objectives of this study were to (1) explore the effects of biochar amendment on the soil CO₂ and CH₄ emission; (2) determine the temperature response of CO₂ emission in biochar amended soil; and (3) trying to identify some factors that significantly influenced C emission and temperature response of CO₂ emission in short-term application of biochar.

2 Materials And Methods

2.1 Study site description

The experiment was conducted in the National Monitoring Station of Soil Fertility and Fertilizer Efficiency on Purple Soils (30°26'N, 106°26'E) in the Beibei district of Chongqing, southwestern China. The *in-situ* soil is classified as Regosol in the Food and Agriculture Organization classification scheme (FAO, 1988).

The details of this trail site were described in study of Huang et al. (2018, 2019). The basic property of soil was shown in Table 1.

Table 1
Properties of background soil and biochar used in this study

	Soil	Biochar
pH	5.8	8.9
Organic carbon (g kg ⁻¹)	11.12	625.8
Total N (g kg ⁻¹)	0.82	4.4
Total P (g kg ⁻¹)	0.76	1.0
Total K (g kg ⁻¹)	20.7	10.4
C/N	13.6	142.2
Available N (mg kg ⁻¹)	83.0	
Available P (mg kg ⁻¹)	44.1	
Available K (mg kg ⁻¹)	208.8	
CEC (cmol(+) kg ⁻¹)	23.2	
<0.002 mm	31.30%	
0.05-0.002 mm	39.10%	
0.05-2 mm	29.60%	
Soil texture	Clay loam	

2.2 Experimental design

Nine 2 m × 1 m plots were selected for this study from 2016-2017. Three treatments (one treatment per plot), including no fertilizer (control), chemical fertilizer only (CF), and biochar combined with chemical fertilizer (BCF), were arranged in a completely randomized design with three replicates (total 9 plots). The same amount of total nitrogen (N), phosphorus (P) and potassium (K) was applied in CF and BCF treatments. Chemical fertilizers were applied as urea (N-eq, 46%), single superphosphate (P₂O₅-eq, 12%) and muriate of potash (K₂O-eq, 60%), respectively. Biochar derived from rape straw, was purchased from Sichuan Jiusheng Agricultural Technology Development Co. Lid., China. The property of biochar was given in Table 1.

Four vegetable crops were grown in rotation during the experimental period from November 2016 to November 2017. The cultivated vegetable crops were lettuce (*Lactuca sativa* L. var. *Angustana Irish*, November 2016 to January 2017), cabbage (*Brassica oleracea* L. var. *Capitata* L., January 2017 to May 2017), chili (*Capsicum annuum* L., May 2017 to September 2017) and lettuce (*Lactuca sativa* L. var. *Angustana Irish*, September 2017 to November 2017). In CF treatment, the amount of chemical fertilizer was applied according to the Fertilization Guide for Major Crops in China (Zhang et al. 2009), shown in our previous study (Huang et al. 2019). In BCF treatment, 10 t hm⁻² biochar was applied to soil before transplanting lettuce (October 20, 2016) and chili (May 5, 2017) for each addition. The deficient nutrient in BCF treatment was supplemented with chemical fertilizer basing on the same amount of total N, P and K. Chemical fertilizers in CF and BCF treatments were applied through basal fertilization and topdressing. The fertilization procedures were described in our previous study (Huang et al. 2019). The time schedule for fertilization and vegetable cultivation for different vegetables are described in Table S1.

2.3 Measurement of CO₂ and CH₄

The gases of CO₂ and CH₄ were sampled though the static closed chamber method during the experiment period. The setup of chamber and method of gas collection were given in the study of Huang et al. (2019). Briefly, gas samples were collected one time every week (between 9:00 and 11:00), and every two or three days for one week following basal fertilizer and topdressing. After gas sample collection, the fluxes of CO₂ and CH₄ were measured simultaneously via the gas chromatography facility (Agilent 7890A, Agilent Inc., USA). During the entire experiment, gas samples were collected 63 times in total. The calculations used to determine CO₂ and CH₄ fluxes and cumulative CO₂ and CH₄ emissions were similar to the study reported by Huang et al. (2019). Air and soil temperature (5 cm depth in soil) and soil moisture content were recorded at the beginning and the end of sampling, and average of the two values was calculated. Due to the greenhouse gas chamber measurement cannot exclude the CO₂ emission from plant roots, the CO₂ emission in this study was the net CO₂ emission from vegetable field, which integrated soil respiration, belowground greenhouse gas emission and the CO₂ assimilated by plants.

2.4 Soil sampling and measurements

Topsoil (0-20 cm) were sampled on November 23, 2017. In each plot, five soil cores were randomly sampled and mixed to form a pooled sample. The pooled samples were placed in the sterile plastic bags and transported to the laboratory. Meanwhile, soil bulk density was obtained via the cutting ring method. Sampled soil was thoroughly mixed and passed through a 2-mm sieve after all the visible roots and stones had been removed. Fresh soil was used for the analysis of soil dissolved organic carbon (DOC) and microbial biomass carbon (MBC), and the final concentrations of DOC and MBC were normalized by the dry mass of soil. The remaining soil was air-dried for measuring the total soil organic carbon (SOC) and other soil properties.

Soil water-filled pore space (WFPS) was calculated according to the following equation (Li et al. 2013). $WFPS = (\text{gravimetric moisture} \times \text{soil bulk density} \times 100) / [1 - (\text{soil bulk density} / 2.65)]$, with 2.65 g cm⁻³ of

particle density.

Soil DOC content was extracted with water and then measured via the Multi N/C® 2100 Analyzer (ANALYTIKJENA, Germany) (Ghani et al. 2003). After being extracted by chloroform fumigation with 0.5 mol L⁻¹ K₂SO₄, the extracts was used to measure the soil MBC content through the method of K₂Cr₂O₇ external heating with titrating FeSO₄ (Yang et al. 2008).

2.5 Temperature response

Temperature sensitivity (Q_{10}) and activation energy (E_a) of CO₂ emission were used to describe the relationship between temperature and CO₂ emission.

The Q_{10} was calculated with the following equation (Zhou et al. 2007; Chen et al. 2016):

$$y = a \cdot e^{bT}$$

1

$$Q_{10} = e^{10b}$$

2

Where, y is the flux of CO₂ over time (mg m⁻² h⁻¹), a and b are the exponential fit parameters. Parameter “ a ” is the intercept of CO₂ flux when the temperature is 0 °C. T is the soil temperature (°C).

The activation energy was calculated via using the exponential Arrhenius function according to Thiessen et al. (2013):

$$y = A \cdot e^{\frac{-E_a}{R \cdot T}}$$

3

Where, y is the flux of CO₂ over time (mg m⁻² h⁻¹), A is the constant, E_a is the activation energy (J mol⁻¹), R is the universal gas constant (8.314 J mol⁻¹ K⁻¹), T is the soil temperature in Kelvin (K). In chemical kinetics, E_a is defined as the necessary energy for reacting molecules to break and form new bonds after a collision. For calculating the daily E_a , a maximum likelihood estimate of the slope of the linear regression of the natural logarithms of CO₂ flux against the reciprocal of absolute soil temperature. To estimate the average E_a during the experiment period, we multiplied the slope values by the gas constant R .

2.6 Statistical analysis

The data were statistically analyzed using the SPSS 23.0 and Origin 8.5 software. The Kolmogorov-Smirnov test was used to test the normality of all data. Both parametric and non-parametric approaches

were used to test the differences. For the normal distributed data, comparisons of data among treatments were performed by one-way analysis of variance analysis (ANOVA) in combination with the least significant difference (LSD) test. For non-normal distributed data, the comparisons of data were performed by Kruskal-Wallis test. The variables related to soil properties, Q_{10} , E_a and cumulative CO_2 , CH_4 emission were subjected to principal component analysis (PCA) to identify key factors for Q_{10} , E_a and cumulative CO_2 , CH_4 emission using Origin 8.5. Automatic linear modeling was performed at the 95% confidence level using SPSS 18.0. The Spearman's coefficient was used in the non-parametric correlation analysis. The statistical significance was determined at $p = 0.05$ and $p = 0.01$.

3 Results

3.1 CO_2 and CH_4 emission

As shown in Fig. 1a, there were two peaks of CO_2 flux during the experimental period, which were observed in April and August, respectively. The highest CO_2 flux with the value of 3254.8 and 3201.9 $\text{mg m}^{-2} \text{h}^{-1}$ were both found in the BCF treatment on April 13 and August 9, respectively. Compared with the control, fertilization (CF and BCF) increased the flux of CO_2 , except for the period of higher air temperature (from July to August). The higher CO_2 fluxes were observed in the BCF treatment, relative to CF treatment, when the air temperature was over 18 °C. Additionally, the second peak of CO_2 flux in the BCF treatment (on August 9) was later than that in the CF treatment (on July 26). During the experimental period (Fig. 1b), BCF significantly increased the cumulative CO_2 emission by 27.5% and 37.1%, relative to the control and CF treatment, respectively.

Different from CO_2 flux, variation of CH_4 flux during the experiment period was not significant (Fig. 1c). However, after the application of biochar, the significant fluctuation of CH_4 flux was observed, especially after the second time of biochar application. Compared with control, CF and BCF both reduced the cumulative CH_4 emission, and the cumulative CH_4 emission in the BCF treatment was -1.09 kg hm^{-2} (Fig. 1d).

3.2 Temperature sensitivity (Q_{10}) and activation energy (E_a) of CO_2 emission

Because of the negative value of CH_4 flux, only temperature sensitivity (Q_{10}) and activation energy (E_a) of CO_2 emission were calculated in this study. The flux of CO_2 has an exponential relationship with the soil temperature (Fig. S1a-c). The dynamic of Q_{10} over time was shown in Fig. 2a. Fertilizer application (CF and BCF) reduced the Q_{10} values during the experimental period. When the first time of biochar application, BCF reduced the Q_{10} values relative to the CF treatment, while increased the values when the second time of biochar application. In each season of vegetable growing, the peak of Q_{10} values were observed, especially in April. As shown in Fig. 2b, the lowest value of average Q_{10} was observed in CF

treatment, which significantly reduced by 29.2% relative to the control. However, there were no significant difference between CF and BCF treatments, even if the higher value of average Q_{10} ($Q_{10} = 2.1$) was observed in the BCF treatment.

Similar to the Q_{10} dynamic of CO_2 emission, peaks of E_a value were all found in each vegetable growing season, especially in the initial time of vegetable growing (Fig. 2c). Compared with the CF, BCF increased the E_a values by 33.7-49.5%, regardless of times of biochar application. Besides, the average of E_a value in BCF treatment (51.9 KJ mol^{-1}) was significantly higher than those in control (60.4 KJ mol^{-1}) and CF (36.2 KJ mol^{-1}) treatments (Fig. 2d).

3.3 Soil property

Compared with CF, BCF increased the contents of DOC, MBC and SOC by 800.7% ($p < 0.05$), 33.3% ($p < 0.05$) and 68.9% ($p > 0.05$), respectively (Table 2). In addition, the highest values of soil pH and WFPS were both found in the control, following by those in BCF treatment.

Table 2
Soil properties in different treatments

	DOC (mg kg^{-1})	MBC (mg kg^{-1})	SOC (g kg^{-1})	pH	WFPS (%)
Control	247.5 $\pm$ 86.9a	27.5 $\pm$ 8.2a	7.5 $\pm$ 0.8b	6.0a	68.1 $\pm$ 1.7a
CF	18.3 $\pm$ 3.9b	23.0 $\pm$ 16.7a	7.8 $\pm$ 0.2b	4.6c	48.4 $\pm$ 5.0b
BCF	164.5 $\pm$ 71.2a	30.7 $\pm$ 20.7a	13.1 $\pm$ 1.9a	5.0b	53.6 $\pm$ 7.6b

Numbers represent mean $\pm$ standard error ($n = 3$); different lowercase letters within the same column indicate significant differences ($P < 0.05$). Control, no fertilizer; CF, chemical fertilizer only; BCF, biochar combined with chemical fertilizer; DOC, dissolved organic carbon; MBC, microbial biomass carbon; SOC, soil organic carbon; WFPS, soil water-filled pore space.

3.4 Correlation of soil properties, Q_{10} , E_a and carbon emission

The first two principal components (PC1 and PC2) accounted for 50.0% and 31.3% of the total variation in principle component analysis (PCA), respectively (Fig. 3). Variation of cumulative CO_2 emission has a positive relationship with SOC, but a negative relationship with the cumulative CH_4 emission (Fig. 3). Soil DOC was the key factor influencing the variation of Q_{10} and E_a according to the results of PCA analysis. Correlations among soil properties, Q_{10} , E_a and carbon emission (CO_2 and CH_4) were listed in Table S2. The cumulative CO_2 and CH_4 emission was both significantly associated with SOC ($r = 0.887$, $r = -0.888$, respectively). The value of Q_{10} was correlated with E_a ($r = 0.837$), soil DOC ($r = 0.732$) and pH ($r = 0.765$) ($p < 0.05$ or 0.01). The value of E_a has a significant relationship with soil DOC ($r = 0.933$), pH ($r = 0.873$)

and WFPS ($r = 0.792$). Besides, automatic linear modeling revealed that soil SOC, together with MBC were the primary factors associated with the cumulative CO₂ emissions, as well as SOC and pH associated with the cumulative CH₄ emissions (Fig. 3). Activation energy (E_a) and soil DOC was the key factor influencing the Q_{10} and E_a , respectively.

4 Discussion

4.1 Biochar application influencing the carbon emission

Biochar, as a soil amendment, plays a key role in C utilization as well as in decreasing the greenhouse gasses emissions. In general, biochar reduces the CO₂ emission through the expansion of soil C pool (Kavitha et al. 2018). In the present study, however, biochar application increased the CO₂ emission from soil-plant system during short-term experiment, relative to the no-biochar (control and CF) treatments (Fig. 1b). The observation of increased cumulative CO₂ emission in biochar (BCF) treatment were inconsistent with the previous literatures (Lu et al. 2014; Bending et al. 2014; Chen et al. 2017), which demonstrated that biochar application significantly decreased the soil CO₂ emission during the short-term incubations. Similarly, the studies of Zhou et al. (2017) and Ge et al. (2020) shown that biochar (produced from bamboo) addition decreased the cumulative soil CO₂ emission in the field experiment. The inconsistent results may be caused by the different biochar feedstock, pyrolysis temperature and addition rate (Ameloot et al. 2013; Lu et al. 2014; Bending et al. 2014). Firstly, the pyrolysis temperature of 450-500°C in this study was incomplete oxidization, which may increase volatile matter content and then promote the abiotic release of inorganic C in biochar (Ameloot et al. 2013; Yang et al. 2018). Besides, greater positive priming effect of biochar was observed immediately at the low pyrolysis temperature (Zimmerman et al. 2011). Secondly, short-term application of biochar may induce the priming effects, causing the native soil organic C or labile compounds of biochar readily decomposed by microorganisms (Zimmerman, 2010; Wang et al. 2016; Yang et al. 2018). Meanwhile, combined application of biochar and N fertilization could stimulate the CO₂ releasing from biochar with the increased value of 28.3% (Lu et al. 2014). Thirdly, biochar application in a short period of time provided the labile C for soil microbes (especially for the 'r-strategist' microbes that are adapted to respond quickly to newly available C sources) and then stimulated soil respiration (Paul and Clark, 1989; Zimmerman et al. 2011; Teutscheroova et al. 2017; Duan et al. 2019). This hypothesis is supported by the higher contents of soil DOC and MBC in biochar treatment (Table 2). Besides, the result of automatic linear modeling also verify that the enhanced microbial biomass (e.g. MBC) and C substrates (e.g. SOC) in soils may lead to the greater CO₂ emission (Fig. 3). Although, the adsorption and/or encapsulation of biochar can protect the native soil labile C from microbial utilization and inhibit the decomposition of native SOC (Zimmerman et al. 2011; Lu et al. 2014; Bending et al. 2014; Chen et al. 2017), the co-location of microorganisms and various nutrients on biochar surfaces and/or in pores may provide a highly suitable habitat for microbes and increase microbial C use efficiency, and subsequently higher CO₂ emission (Lehmann et al. 2011; Zavalloni et al. 2011). It is worth noting that CO₂ emission in this study was the net CO₂ emission from

soil-plant system, which integrated soil respiration, root respiration and the CO₂ assimilated by plants. The significant negative relationship between total vegetable yield and cumulative CO₂ emission may index the key roles of root respiration and plant photosynthesis in CO₂ emission (Table S2), especially for the root respiration. Additionally, biochar application obtained high total vegetable yields than no-biochar (Table S3). Therefore, short-term biochar and N combined application cannot offset, at least partly, the negative effect of biochar or plant photosynthesis on the CO₂ emission.

It is well known that dryland soil in an oxic condition has a capacity of CH₄-sink due to the soil methanotrophic bacteria oxidizing the CH₄ to CO₂ (Suwanwaree et al. 2005; Criscuoli et al. 2019). The flux of soil CH₄ is controlled by the production of CH₄ by methanogens and consumption of CH₄ by methanotrophs, as well as the soil conditions which can impact the growth of methanogens and methanotrophs (Le Mer and Roger 2001; Conrad 2007). Consisted with reported literatures (Jeffery et al. 2011; Feng et al. 2012; Qin et al. 2016; Liu et al. 2016b), biochar application in this study significantly reduced the cumulative CH₄ emissions relative to the control and CF treatments (Fig. 1d). A potential explanation is the fact that the enhanced soil aeration would increase the activity of methanotrophs due to the biochar's large surface area and pore volume (Wang et al. 2018), which supported by the negative relationship of cumulative CH₄ emission and CO₂ emission (Fig. 3 and Table S2). This result suggested the increased soil CH₄ consumption rather than decreased CH₄ production dominated the influence of biochar in mitigating CH₄ emission from dryland soil-plant system. Another potential explanation, as discussed above, is that the progressive protection of biochar may prevent SOC from being used by methanogens (Zimmerman et al. 2011), resulting in the decreased CH₄ production. The higher contents of SOC observed in BCF treatment may be attributed by the protection of biochar in this study (Table 2). Soil pH plays a key role in affecting both methanogenesis and methanotrophy (Hanson and Hanson, 1996; Jeffery et al. 2016). Generally, the pH ranging from 6 to 8 was optimum for most methanogens (Garcia et al., 2000), and high acidity was not favor to increase the microbial habitability of methanogens (e.g. reducing the abundance of methanogens) (Jeffery et al. 2016). Therefore, a significant increase of CH₄ sink strength was observed in biochar-treated soil with the pH of 5.0, which is consisted with the findings of Jeffery et al. (2016). However, we observed a CH₄ source in CF treatment, even if the soil pH is lower than that in BCF treatment (Table 2). Except for the negative effect of biochar, a possible explanation is that the more N fertilizer amount in CF (1200 kg ha⁻¹ N fertilizer) treatment than in BCF (1120 kg ha⁻¹ N fertilizer) treatments. The NH₄⁺ containing or delivering fertilizers will compete with CH₄ at the binding sites, consequently, decreasing the oxidation of CH₄ (Htun et al. 2017; Huang et al. 2020). Besides, the incorporation of biochar with the high C/N ratio of 142.2 may increase immobilization of inorganic N (e.g. NH₄⁺) and reduce the competitive exclusion of CH₄ (Huang et al. 2020). Meanwhile, in this study, the lower content of NH₄⁺ observed in BCF (100.7 mg kg⁻¹) treatment than that in CF (112.3 mg kg⁻¹) treatment. Therefore, short-term application of biochar showed a significant increase in CH₄ sink strength/reduction in CH₄ source strength.

4.2 Biochar application influencing the temperature response of CO₂ emission

In this study, fertilization incorporation reduced the temperature response of CO₂ emission (expressed as Q_{10} or E_a), compared to the control (Fig. 2a-b). It may be caused by the fact that nutrients (e.g. N, P) from fertilizers changed the substrate C quality, which is linked to the soil C emission (Guo et al. 2017). Previous studies determined that the N addition potentially increased those microbial abundance using labile C and elevated the cellulose-decomposing enzymes activity (Carreiro et al. 2000; Keeler et al. 2009). Thus, increased Q_{10} was observed following fertilization or artificial N deposition in the previous studies (Liu et al. 2016a; Guo et al. 2017; Ge et al. 2020). The inconsistency of literatures with this study is likely attributed to the different fertilization time (e.g. long-term fertilization (> 10 years) in the study of Guo et al. (2017), short-term fertilization (about 1 years) in this study). Long-term N inputs may change the substrate quality characterized with C complexities and increase the recalcitrant C, leading to the enhanced Q_{10} value (Guo et al. 2017). Generally, the temperature sensitivity of resistant C was higher than labile C due to the former needing more activation energy (E_a) and time, according to the enzyme kinetic theory (Davidson and Janssens 2006; Conant et al. 2011). Our observation of the positive relationship between E_a and Q_{10} (Fig. 3 and Table S2) possibly supported the enzyme kinetic hypothesis. Therefore, the reduced Q_{10} under short-term fertilizer inputs may be well explained by the lower E_a in CF and BCF treatment.

Compared with CF treatment, biochar addition increased the Q_{10} and E_a , especially in the second time of application, which is consistent with the report of Wang et al. (2019). Multiple reasons may be responsible for this increase in Q_{10} and E_a . For example, the biochar-induced increase in temperature sensitivity may be attributed to the accumulation of resistant C pools in soil organic matter due to the biochar aromatic properties (Zhou et al. 2017; Wang et al. 2019). On the other hand, the increase in Q_{10} and E_a values following biochar application may contribute to the enhanced nutrient availability and microbial activities, leading to the decomposition of soil organic matter (Lehmann et al. 2011; Criscuoli et al. 2014), as evidenced by the increased MBC (Table 2), CO₂ flux (Fig. 1a) and N (or P, K) fertilizer utilization efficiency (unpublished data) in BCF treatment. The increased nutrient availability may reduce the degradability of resistant C, possibly *via* decreasing the affinity of microbial enzymes (such as phenol oxidase and peroxidase) to substrates (Guo et al. 2017), and thus increased Q_{10} and E_a following biochar application (Fig. 2). Besides, resistant C pools might increase in dry farmland (as in our study) under high microbial activities after biochar addition, contributing to an increase in Q_{10} values (Wang et al. 2019). However, the fact that biochar applications reduced Q_{10} values was also reported in some studies (Pei et al. 2017). These discrepancies may be attributed to the high rate of biochar application in the study of Pei et al. (2017) (i.e. 40-100 t ha⁻¹), which is significantly higher than the rates used in the studies of Zhou et al. (2017) (i.e. 10-30 t ha⁻¹), Kan et al. (2020) (i.e. 1.8-7.2 t ha⁻¹) and our study (i.e. 10-20 t ha⁻¹). More biochar incorporated into soil can increase the non-biochar labile dissolvable C of native soil, which

would be entrapped in the porous structure of biochar (Bending et al. 2014). While the co-location of microorganisms and entrapped C, as mentioned above, may enhance the availability of soil decomposable C, thus reducing the Q_{10} values (Pei et al. 2017). Though the higher DOC content was observed in soil treated with biochar (Table 2), the low ratio of DOC to SOC (i.e. 1.25%) may indicate the more resistant C remained in soil treated with biochar in short-term period. Meanwhile, more recalcitrant C with higher E_a dominated in soil since the limited labile C being depleted quickly, especially in the second time of biochar addition.

Temperature response of CO_2 emission is directly affected by external factors that limit decomposition, except for the direct factor (such as substrate availability and microbial enzyme affinity) (Davidson and Janssens 2006; von Lützow and Kögel-Knabner, 2009; Fang et al. 2017). Soil pH play a key role in the temperature response of CO_2 emission in this study due to the significant association of soil pH with Q_{10} and E_a (Table S1 and Fig. 3). Acidifying soil causing by fertilization is characterized with high osmotic pressures, low soil minerals and high aluminum toxicity, which would reduce the microbial activity and consequently decreasing the temperature response (Treseder 2008; Liu and Greaver 2010). Thus, the higher soil pH in BCF treatment may be partly responsible for the higher temperature response, relative to the CF. Besides, the peak of E_a with time was observed within one week of crop transplant in each grow season, regardless of treatments (Fig. 2c). We speculate that the crop cultivation measures may influence the E_a possibly due to inducing the change of the external and/or direct factors (e.g., root biomass). Unfortunately, the soil indexes with time have not been detected in this study. However, the significant relationship of E_a and vegetable yields may index the important effect of vegetable cultivation on the temperature response of CO_2 emission (Table S2). As mention above, biochar application may impact the CO_2 emission due to the root respiration. Overall, short-term application of biochar increased the temperature response of CO_2 emission in the soil-plant system.

5 Conclusion

Short-term application of biochar significantly increased the CO_2 emission from soil-plant system. However, biochar addition showed a significant reduction in CH_4 source strength in dryland soil, possibly via increasing CH_4 consumption and reducing competition with NH_4^+ . Fertilization reduced the temperature sensitivity (Q_{10}) of CO_2 emission through decreasing activation energy (E_a). Besides, biochar significantly increased the temperature response (Q_{10} and E_a) of CO_2 emission, relative to solely chemical fertilizer application, which is related to the supplement of limit labile C and nutrient but highly resistant C following biochar application. External factors (e.g. pH, crop cultivation) play key roles in influencing the change of E_a . Thus, our study suggests that short-term response of biochar on C gas emission and temperature should be obtained attention to better understand the long-term effect of biochar on C release and sequestration.

Statements & Declarations

Declarations

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: Not applicable

Availability of data and materials: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Authors' contributions:

Rong Huang: Conceptualization, Methodology, Investigation, Writing - Original Draft; Zifang Wang: Conceptualization, Methodology, Validation; Yi Xiao: Investigation, Methodology, Validation; Luo Yu: Methodology, Validation; Xuesong Gao: Formal analysis, Writing - Review & Editing; Changquan Wang: Supervision, Funding acquisition; Bing Li: Formal analysis, Writing - Review & Editing; Qi Tao: Methodology, Writing - Review & Editing; Qiang Xu: Methodology, Validation; Ming Gao: Supervision, Funding acquisition

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Figures

Figure 1

CO₂ and CH₄ fluxes with time (a, c) and cumulative CO₂ and CH₄ (b, d) in different treatments. Control, no fertilizer; CF, chemical fertilizer only; BCF, biochar combined with chemical fertilizer. Different lowercase letters indicate the differences are significant ($P < 0.05$).

Figure 2

Temperature sensitivity (Q_{10}) (a, b) and activation energy (E_a) (c, d) of CO_2 emission in different treatments. Control, no fertilizer; CF, chemical fertilizer only; BCF, biochar combined with chemical fertilizer. Different lowercase letters indicate the differences are significant ($P < 0.05$).

Figure 3

Principal component analysis (PCA) of soil properties, Q₁₀ and cumulative carbon emissions (Left); predictive importance of selected soil properties on cumulative carbon emission Q₁₀ and E_a as determined by automatic linear modeling (Right).

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