Increases of Temperature Response for CO$_2$ Emission in a Biochar-Amended Vegetable Field Soil

**Rong Huang**
Sichuan Agricultural University

**Zifang Wang**
Southwest University

**Yi Xiao**
Sichuan Agricultural University

**Luo Yu**
Chongqing Bishan District Flood Control and Drought Relief Dispatch Center

**Xuesong Gao**
Sichuan Agricultural University

**Changquan Wang**
Sichuan Agricultural University

**Bing Li**
Sichuan Agricultural University

**Qi Tao**
Sichuan Agricultural University

**Qiang Xu**
Sichuan Agricultural University

**Ming Gao** (rong19890203@163.com)
Southwest University

**Research Article**

**Keywords:** Biochar, Greenhouse gas, Temperature sensitivity, Activation energy

**Posted Date:** November 29th, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-1062376/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

To explore the effects of biochar application on CO\textsubscript{2} and CH\textsubscript{4} emission as well as the temperature response of CO\textsubscript{2} 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 CO\textsubscript{2} 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 CH\textsubscript{4} was observed in BCF treatment, and an increase CH\textsubscript{4} consumption and reduce competition with NH\textsubscript{4}\textsuperscript{+} may be responsible for the significant reduction in CH\textsubscript{4} source strength in biochar amended soil. (3) Activation energy ($E_a$) was identified as an important factor influencing the temperature sensitivity ($Q_{10}$) of CO\textsubscript{2} emission. Fertilization (CF and BCF) reduced the average $Q_{10}$ and $E_a$ values of CO\textsubscript{2} 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\textsuperscript{-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 CO\textsubscript{2} emission and temperature response of CO\textsubscript{2} emission from soil-plant system, while reduced CH\textsubscript{4} 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 CO\textsubscript{2} and N\textsubscript{2}O 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 N\textsubscript{2}O production and CH\textsubscript{4} 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 CO\textsubscript{2} 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 CO\textsubscript{2} 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 CO\textsubscript{2} 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 CO\textsubscript{2} 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 CO\textsubscript{2} 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 CO\textsubscript{2} 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 CO\textsubscript{2} and CH\textsubscript{4} emission as well as the temperature response of CO\textsubscript{2} emission. The objectives of this study were to (1) explore the effects of biochar amendment on the soil CO\textsubscript{2} and CH\textsubscript{4} emission; (2) determine the temperature response of CO\textsubscript{2} emission in biochar amended soil; and (3) trying to identify some factors that significantly influenced C emission and temperature response of CO\textsubscript{2} 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 (P\(_{2}\)O\(_5\)-eq, 12%) and muriate of potash (K\(_2\)O-eq, 60%), respectively. Biochar derived from rape straw, was purchased from Sichuan Jiusheng Agricultural Technology Development Co. Ltd., 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 CO$_2$ and CH$_4$**

The gases of CO$_2$ and CH$_4$ 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 CO$_2$ and CH$_4$ 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 CO$_2$ and CH$_4$ fluxes and cumulative CO$_2$ and CH$_4$ 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 CO$_2$ emission from plant roots, the CO$_2$ emission in this study was the net CO$_2$ emission from vegetable field, which integrated soil respiration, belowground greenhouse gas emission and the CO$_2$ 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).

$$\text{WFPS} = \frac{(\text{gravimetric moisture} \times \text{soil bulk density} \times 100)}{[1-(\text{soil bulk density} / 2.65)]},$$

with 2.65 g cm$^{-3}$ of
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):

$$y = A \cdot e^{\frac{E_a}{RT}}$$

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 mg m$^{-2}$ 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.

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

Numbers represent mean ± 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 CO\(_2\) emissions, as well as SOC and pH associated with the cumulative CH\(_4\) 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 CO\(_2\) emission through the expansion of soil C pool (Kavitha et al. 2018). In the present study, however, biochar application increased the CO\(_2\) 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 CO\(_2\) 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 CO\(_2\) 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 CO\(_2\) 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 CO\(_2\) 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; Teutscherova 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 CO\(_2\) 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 CO\(_2\) emission (Lehmann et al. 2011; Zavalloni et al. 2011). It is worth noting that CO\(_2\) emission in this study was the net CO\(_2\) emission from
soil-plant system, which integrated soil respiration, root respiration and the CO\textsubscript{2} assimilated by plants. The significant negative relationship between total vegetable yield and cumulative CO\textsubscript{2} emission may index the key roles of root respiration and plant photosynthesis in CO\textsubscript{2} 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 CO\textsubscript{2} emission.

It is well known that dryland soil in an oxic condition has a capacity of CH\textsubscript{4}-sink due to the soil methanotrophic bacteria oxidizing the CH\textsubscript{4} to CO\textsubscript{2} (Suwanwaree et al. 2005; Criscuoli et al. 2019). The flux of soil CH\textsubscript{4} is controlled by the production of CH\textsubscript{4} by methanogens and consumption of CH\textsubscript{4} 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 CH\textsubscript{4} 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 CH\textsubscript{4} emission and CO\textsubscript{2} emission (Fig. 3 and Table S2). This result suggested the increased soil CH\textsubscript{4} consumption rather than decreased CH\textsubscript{4} production dominated the influence of biochar in mitigating CH\textsubscript{4} 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 CH\textsubscript{4} 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 CH\textsubscript{4} 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 CH\textsubscript{4} 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\textsuperscript{-1} N fertilizer) treatment than in BCF (1120 kg ha\textsuperscript{-1} N fertilizer) treatments. The NH\textsubscript{4}\textsuperscript{+} containing or delivering fertilizers will compete with CH\textsubscript{4} at the binding sites, consequently, decreasing the oxidation of CH\textsubscript{4} (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. NH\textsubscript{4}\textsuperscript{+}) and reduce the competitive exclusion of CH\textsubscript{4} (Huang et al. 2020). Meanwhile, in this study, the lower content of NH\textsubscript{4}\textsuperscript{+} observed in BCF (100.7 mg kg\textsuperscript{-1}) treatment than that in CF (112.3 mg kg\textsuperscript{-1}) treatment. Therefore, short-term application of biochar showed a significant increase in CH\textsubscript{4} sink strength/reduction in CH\textsubscript{4} 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.

Funding: This work was supported by Chongqing Technology Innovation and Application Demonstration Special Key R & D Project [cstc2018jscx-mszdX0061], Chongqing key Laboratory of Soil Multi-Scale Interfacial Process, Scientific Research Project for the Follow-up Work of the Three Gorges Project from the State Major Water Conservancy Project [5001022019CF50001], National Natural Science Foundation of China [42107247], Key Program of China National Tobacco Corporation Sichuan [CYC2020004].

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

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

References

1. Anderson, C.R., Condron, L.M., Clough, T.J., Fiers, M., Stewart, A., Hill, R.A., Sherlock, R.R., 2011. Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia* 54(5–6), 309–320.

2. Ameloot, N., De Neve, S., Jegajeevagan, K., Yildiz, G., Buchan, D., Funkuin, Y.N., Prins, W., Bouckaert, L., Sleutel, S., 2013. Short-term CO₂ and N₂O emissions and microbial properties of biochar amended sandy loam soils. *Soil Biol. Biochem.* 57, 401–410.

3. Bending, G.D., Baeyens, J., Prayogo, C., Jones, J.E., 2014. Impact of biochar on mineralisation of C and N from soil and willow litter and its relationship with microbial community biomass and structure. *Biol. Fertil. Soils* 50, 695–702.

4. Carreiro, M.M., Sinsabaugh, R.L., Repert, D.A., Parkhurst, D.F., 2000. Microbial enzyme shifts explain litter decay responses to simulated nitrogen deposition. *Ecology* 81(9), 2359–2365.
5. Chen, J., Zhou, X., Wang, J., Hruska, T., Shi, W., Cao, J., Zhang, B., Xu, G., Chen, Y., Luo, Y., 2016. Grazing exclusion reduced soil respiration but increased its temperature sensitivity in a Meadow Grassland on the Tibetan Plateau. *Ecol. Evol.* 6(3), 675–687.

6. Chen, J., Li, S., Liang, C., Xu, Q., Li, Y., Qin, H., Fuhrmann, J.J., 2017. Response of microbial community structure and function to short-term biochar amendment in an intensively managed bamboo (Phyllostachys praecox) plantation soil: Effect of particle size and addition rate. *Sci. Total Environ.* 574, 24–33.

7. Cheng, C. H., Lehmann, J., Thies, J.E., Burton, S.D., Engelhard, M.H., 2006. Oxidation of black carbon by biotic and abiotic processes. *Org. Geochem.* 37(11), 1477–1488.

8. Conrad, R., 2007. Microbial ecology of methanogens and methanotrophs. *Adv. Agron.* 96(07), 1–63.

9. Criscuoli, I., Alberti, G., Baronti, S., Favilli, F., Martinez, C., Calzolari, C., Pusceddu, E., Rumpel, C., Viola, R., Miglietta, F., 2014. Carbon sequestration and fertility after centennial time scale incorporation of charcoal into soil. *PLoS One* 9(3), e91114.

10. Criscuoli, I., Ventura, M., Sperotto, A., Panzacchi, P., Tonon, G., 2019. Effect of woodchips biochar on sensitivity to temperature of soil greenhouse gases emissions. *Forests* 10(7), 1–14.

11. Conant, R.T., Ryan, M.G., Agren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., Evans, S.E., Frey, S.D., Giardina, C.P., Hopkins, F.M., Hyvonen, R., Kirschbaum, M.U.F., Lavallee, J.M., Leifeld, J., Parton, W.J., Steinweg, J.M., Wallenstein, M.D., Wet- terstedt, J.A.M., Bradford, M.A., 2011. Temperature and soil organic matter decomposition rates-synthesis of current knowledge and a way forward. *Global Change Biol.* 17, 3392–3404.

12. Dai, Z., Xiong, X., Zhu, H., Xu, G.J, Leng, P., Li, J.H., Tang, C., Xu, M.G. 2021. Association of biochar properties with changes in soil bacterial, fungal and fauna communities and nutrient cycling processes. *Biochar* 3, 239–254.

13. Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440, 165–173.

14. Dong, X.L., Singh, B.P., Li, G.T., Lin, Q.M., Zhao, X.R., 2018. Biochar application constrained native soil organic carbon accumulation from wheat residue inputs in a long-term wheat-maize cropping system. *Agric. Ecosyst. Environ.* 252, 200–207.

15. Duan, M., Wu, F., Jia, Z., Wang, S., Cai, Y., Chang, S.X., 2020. Wheat straw and its biochar differently affect soil properties and field-based greenhouse gas emission in a Chernozemic soil. *Biol. Fertil. Soils.* 56, 1023–1036.

16. FAO F., 1988. UNESCO soil map of the world, revised legend. World Resources Report 60, 138.

17. Fang, Y., Singh, B.P., Matta, P., Cowie, A.L., Van Zwieten, L., 2017. Temperature sensitivity and priming of organic matter with different stabilities in a Vertisol with aged biochar. *Soil Biol. Biochem.* 115, 346–356.

18. Fang, Y., Singh, B.P., Singh, B., 2014. Temperature sensitivity of biochar and native carbon mineralisation in biochar-amended soils. *Agric. Ecosyst. Environ.* 191, 158–167.
19. Feng, Y., Xu, Y., Yu, Y., Xie, Z., Lin, X., 2012. Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biol. Biochem.* 46, 80–88.

20. Garcia, J.L., Patel, B.K.C., Olivier, B., 2000. Taxonomic, phylogenetic, and ecological diversity of methanogenic archaea. *Anaerobe* 6(4), 205–226.

21. Ge, X., Cao, Y., Zhou, B., Xiao, W., Tian, X., Li, M.H., 2020. Combined application of biochar and N increased temperature sensitivity of soil respiration but still decreased the soil CO₂ emissions in moso bamboo plantations. *Sci. Total Environ.* 730, 139003.

22. Ghani, A., Dexter, M., Perrott, K.W., 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biol. Biochem.* 35(9), 1231–1243.

23. Guo, H., Ye, C.L., Zhang, H., Pan, S., Ji, Y.G., Li, Z., Liu, M.Q., Zhou, X.H., Du, G.Z., Hu, F., Hu, S.J., 2017. Long-term nitrogen & phosphorus additions reduce soil microbial respiration but increase its temperature sensitivity in a Tibetan alpine meadow. *Soil Biol. Biochem.* 113, 26–34.

24. Hanson, R.S., Hanson, T.E., 1996. Methanotrophic bacteria. *Microbiol. Rev.* 60(2), 439–71.

25. He, X., Du, Z., Wang, Y., Lu, N., Zhang, Q., 2016. Sensitivity of soil respiration to soil temperature decreased under deep biochar amended soils in temperate croplands. *Appl. Soil Ecol.* 108, 204–210.

26. Htun, Y.M., Tong, Y.N., Gao, P.C., Ju, X.T., 2017. Coupled effects of straw and nitrogen management on N₂O and CH₄ emissions of rain fed agriculture in Northwest China. *Atmos. Environ.* 157, 156–166.

27. Huang, R., Tian, D., Liu, J., Lv, S., He, X. H., Gao, M., 2018. Responses of soil carbon pool and soil aggregates associated organic carbon to straw and straw-derived biochar addition in a dryland cropping mesocosm system. *Agric. Ecosys. Environ.* 265, 576–586.

28. Huang, R., Wang, Y.Y., Liu, J., Li, J.C., Xu, G.X., Luo, M., Xu, C., Ci, E., Gao, M., 2019. Variation in N₂O emission and N₂O related microbial functional genes in straw- and biochar-amended and non-amended soils. *Appl. Soil Ecol.* 137, 57–68.

29. Huang, R., Liu, J., He, X., Xie, D., Ni, J., Xu, C., Zhang, Y., Ci, E., Wang, Z., Gao, M., 2020. Reduced mineral fertilization coupled with straw return in field mesocosm vegetable cultivation helps to coordinate greenhouse gas emissions and vegetable production. *J. Soils Sediment.* 20(4), 1834–1845.

30. Jeffery, S., Verheijen, F.G., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* 144, 175–187.

31. Jeffery, S., Verheijen, F.G., Kammann, C., Abalos, D., 2016. Biochar effects on methane emissions from soils: a meta-analysis. *Soil Biol. Biochem.* 101, 251–258.

32. Kan, Z. R., Liu, Q.Y., Wu, G., Ma, S.T., Virk, A.L., Qi, J.Y., Zhao, X., Zhang, H.L., 2020. Temperature and moisture driven changes in soil carbon sequestration and mineralization under biochar addition. *J. Clean. Prod.* 265, 121921.
33. Kasozi, G.N., Zimmerman, A.R., Nkedi-Kizza, P., Gao, B., 2010. Catechol and humic acid sorption onto a range of laboratory-produced black carbons (biochars). *Environ. Sci. Technol.* 44, 6189–6195.

34. Kavitha, B., Reddy, P.V.L., Kim, B., Lee, S.S., Pandey, S.K., Kim, K.H., 2018. Benefits and limitations of biochar amendment in agricultural soils: A review. *J. Environ. Manage.* 227, 146–154.

35. Keeler, B.L., Hobbie, S.E., Kellogg, L.E., 2009. Effects of long-term nitrogen addition on microbial enzyme activity in eight forested and grassland sites: implications for litter and soil organic matter decomposition. *Ecosystems*, 12, 1–15.

36. Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. *Soil Biol. Biochem.* 27, 753–760.

37. Kuzyakov, Y., 2010. Priming effects: interactions between living and dead organic matter. *Soil Biol. Biochem.* 42, 1363-1371.

38. Kuzyakov, Y., Friedel, J.K., Stahr, K., 2000. Review of mechanisms and quantification of priming effects. *Soil Biol. Biochem.* 32, 1485-1498. Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. *Eur. J. Soil Biol.* 37, 25–50.

39. Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – a review. *Soil Biol. Biochem.* 43, 1812–1836.

40. Li, L.J., Han, X.Z., You, M., Horwath, W.R., 2013. Nitrous oxide emissions from Mollisols as affected by long-term applications of organic amendments and chemical fertilizers. *Sci. Total Environ.* 452-453, 302–308.

41. Liu, B., Mou, C., Yan, G., Xu, L., Jiang, S., Xing, Y., Wang, Q., 2016a. Annual soil CO$_2$ efflux in a cold temperate forest in northeastern China: effects of winter snowpack and artificial nitrogen deposition. *Sci. Rep.* 6(1), 18957.

42. Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., Zou, J., 2016. Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. *GCB Bioenergy* 8(2), 392–406.

43. Liu, L., Greaver, T.L., 2010. A global perspective on belowground carbon dynamics under nitrogen enrichment. *Ecol. Lett.* 13(7), 819–828.

44. Lu, W., Ding, W., Zhang, J., Li, Y., Luo, J., Bolan, N., Xie, Z., 2014. Biochar suppressed the decomposition of organic carbon in a cultivated sandy loam soil: a negative priming effect. *Soil Biol. Biochem.* 76, 12–21.

45. Masto R.E., Kumar S., Rout T.K., Sarkar P., George J., Ram L.C., 2013. Biochar from water hyacinth (*Eichornia crassipes*) and its impact on soil biological activity. *Catena*, 111, 64-7.

46. Pei, J.M., Zhuang, S., Cui, J., Li, J.Q., Li, B., Wu, J.H., Fang, C.M., 2017. Biochar decreased the temperature sensitivity of soil carbon decomposition in a paddy field. *Agric. Ecosys. Environ.* 249, 156–164.

47. Paul, E.A., Clark, F.E., 1989. Soil Microbiology and Biochemistry, Academic Press, San Diego.
48. Qin, X., Li, Y.e., Wang, H., Liu, C., Li, J., Wan, Y., Gao, Q., Fan, F., Liao, Y., 2016. Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: a four-year case study in south China. *Sci. Total Environ.* 569, 1390–1401.

49. Singh, B.P., Fang, Y., Boersma, M., Collins, D., Van Zwieten, L., Macdonald, L.M., 2015. In situ persistence and migration of biochar carbon and its impact on native carbon emission in contrasting soils under managed temperate pastures. *PLoS One, 10*, e0141560.

50. Spokas, K.A., Reicosky, D.C., 2009. Impacts of sixteen different biochars on soil greenhouse gas production. *Annals of Environmental Science, 3*, 179–193.

51. Sun C.X., Chen X., Cao M.M., Li M.Q., and Zhang Y.L., 2017. Growth and metabolic responses of maize roots to straw biochar application at different rates. *Plant Soil, 416*, 487–502.

52. Suwanwaree, P. Robertson, G.P., 2005. Methane oxidation in forest, successional, and no-till agricultural ecosystems: Effects of nitrogen and soil disturbance. *Soil Sci. Soc. Am. J. 69(6)*, 1722–1729.

53. Teutscherova, N., Vazquez, E., Masaguer, A., Navas, M., Scow, K.M., Schmidt, R., Benito, M., 2017. Comparison of lime- and biochar-mediated pH changes in nitrification and ammonia oxidizers in degraded acid soil. *Biol. Fertil. Soils 53*, 811–821.

54. Thiessen, S., Gleixner, G., Wutzler, T., Reichstein, M., 2013. Both priming and temperature sensitivity of soil organic matter decomposition depend on microbial biomass – An incubation study. *Soil Biol. Biochem. 57*, 739–748.

55. Treseder, K.K., 2008. Nitrogen additions and microbial biomass: a meta-analysis of ecosystem studies. *Ecol. Lett. 11*, 1111–1120.

56. von Lützow, M., Kögel-Knabner, I., 2009. Temperature sensitivity of soil organic matter decomposition: what do we know? *Biol. Fertil. Soils 46*, 1–15.

57. Wang, C., Liu, J., Shen, J., Chen, D., Li, Y., Jiang, B., Wu, J., 2018. Effects of biochar amendment on net greenhouse gas emissions and soil fertility in a double rice cropping system: a 4-year field experiment. *Agric. Ecosyst. Environ. 262*, 83–96.

58. Wang, J., Xiong, Z., Kuzyakov, Y., 2016. Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy, 8(3)*, 512–523.

59. Wang, X.J., Chen, G.H., Wang, S.Y., Zhang, L.Y., Zhang, R.D., 2019. Temperature sensitivity of different soil carbon pools under biochar addition. *Environ. Sci. Pollut. Res. 26*, 4130–4140.

60. Wu Z., Song Y., Shen H., Jiang X., Li B., Xiong Z., 2019. Biochar can mitigate methane emissions by improving methanotrophs for prolonged period in fertilized paddy soils. Environmental Pollution. 253, 1038-1046. Yang, J.H., Wang, C.L., Dai, H.L. (2008). Agricultural Soil Analysis and Environmental Monitoring (in Chinese). Beijing: China Land Press.

61. Yang, X., Wang, D., Lan, Y., Meng, J., Jiang, L., Sun, Q., Cao, D., Sun, Y., Chen, W., 2018. Labile organic carbon fractions and carbon pool management index in a 3-year field study with biochar amendment. *J. Soils Sediment. 18(4)*, 1569–1578.
62. Zhang, F.S., Chen, X.P., Duan, B.W., 2009. Guide to Fertilization of Major Crops in China. Beijing: China Agricultural University Press. (in Chinese)

63. Zhou, G.Y., Zhou, X.H., Zhang, T., Du, Z.G., He, Y.H., Wang, X.H., Shao, J.J., Cao, Y., Xue, S.G., Wang, H.L., Xu, C.Y., 2017. Biochar increased soil respiration in temperate forests but had no effects in subtropical forests. *Forest Ecol. Manag.* **405**, 339–349.

64. Zhou, T., Shi, P., Hui, D., Luo, Y., 2009. Global pattern of temperature sensitivity of soil heterotrophic respiration (Q10) and its implications for carbon-climate feedback. *J Geophys. Res. Biogeoch.* **114**(2), 1–9.

65. Zhou, X., Wan, S.Q., Luo, Y.Q., 2007. Source components and interannual variability of soil CO₂ efflux under experimental warming and clipping in a grassland ecosystem. *Glob. Chang. Biol.* **13**, 761–775.

66. Zavalloni, C., Alberti, G., Biasiol, S., Vedove, G. D., Fornasier, F., Liu, J., Peressotti, A., 2011. Microbial mineralization of biochar and wheat straw mixture in soil: A short-term study. *Appl. Soil Ecol.* **50**(1), 45–51.

67. Zimmerman, A.R., 2010. Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environ. Sci. Technol.* **44**, 1295–1301.

68. Zimmerman, A.R., Gao, B., Ahn, M.Y., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biol. Biochem.* **43**, 1169–1179.

**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 CO2 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 Ea as determined by automatic linear modeling (Right).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementinformation20211010.docx