Effects of biochar application on soil greenhouse gas fluxes: a meta-analysis

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Abstract

Biochar application to soils may increase carbon (C) sequestration due to the inputs of recalcitrant organic C. However, the effects of biochar application on the soil greenhouse gas (GHG) fluxes appear variable among many case studies; therefore, the efficacy of biochar as a carbon sequestration agent for climate change mitigation remains uncertain. We performed a meta-analysis of 91 published papers with 552 paired comparisons to obtain a central tendency of three main GHG fluxes (i.e., CO2, CH4, and N2O) in response to biochar application. Our results showed that biochar application significantly increased soil CO2 fluxes by 22.14%, but decreased N2O fluxes by 30.92% and did not affect CH4 fluxes. As a consequence, biochar application may significantly contribute to an increased global warming potential (GWP) of total soil GHG fluxes due to the large stimulation of CO2 fluxes. However, soil CO2 fluxes were suppressed when biochar was added to fertilized soils, indicating that biochar application is unlikely to stimulate CO2 fluxes in the agriculture sector, in which N fertilizer inputs are common. Responses of soil GHG fluxes mainly varied with biochar feedstock source and soil texture and the pyrolysis temperature of biochar. Soil and biochar pH, biochar applied rate, and latitude also influence soil GHG fluxes, but to a more limited extent. Our findings provide a scientific basis for developing more rational strategies toward widespread adoption of biochar as a soil amendment for climate change mitigation.

Keywords: biochar, carbon dioxide, global warming potential, methane, nitrous oxide, soil greenhouse gas

Received 16 March 2016; accepted 22 April 2016

Introduction

The global average surface temperature has increased by 0.85 °C over the period 1880–2012 based on multiple independently produced datasets, and current projections suggest that the temperature is likely to increase by another 0.3–4.8 °C by the end of this century (IPCC, 2013). Global warming is mostly attributable to the increasing atmospheric concentrations of greenhouse gases (GHGs) due to human activities. The three main GHGs (i.e., CO2, CH4, and N2O) in combination contribute to more than 90% of anthropogenic climate warming (Hansen et al., 2000; IPCC, 2013).

Greenhouse gas mitigation strategies include reducing and avoiding emissions as well as enhancing the removal of GHGs from the atmosphere (Smith et al., 2008). Soil carbon (C) sequestration through biochar amendment has been proposed as an effective countermeasure for the rising concentration of atmospheric GHGs (Lal, 1999; Pan et al., 2004; Smith et al., 2008). Biochar is a carbon-rich, charcoal-like product produced by burning biomass in the absence of oxygen (Lehmann, 2009); it contains a high proportion of recalcitrant organic C and is stable for hundreds to thousands of years after it is applied to soil (Schmidt et al., 2002). Biochar application to soils has the potential to mitigate global warming via soil C sequestration, and provide other benefits, such as improving soil fertility, retaining soil moisture, and increasing crop yields (Marris, 2006; Lehmann, 2007a; Laird, 2008; Woolf et al., 2010; Mukherjee et al., 2014; Reverchon et al., 2014; Bai et al., 2015a,b; Xu et al., 2015a,b; Darby et al., 2016).
However, the precise effects of biochar application on soil GHG emissions remain controversial and appear very variable among many case studies (Cayuela et al., 2014; Lorenz & Lal, 2014). Soil CO₂, CH₄, and N₂O fluxes increased significantly in some studies (Yanai et al., 2007; Van Zwieten et al., 2010; Jones et al., 2011; Wang et al., 2012), but substantially decreased or remained unchanged in others (Rogovska et al., 2011; Feng et al., 2012; Zheng et al., 2012; Case et al., 2014; Quin et al., 2015). For example, a field trial in paddy soils amended with biochar produced from wheat straw induced a 12% increase in CO₂ emissions, but a 41.8% decrease in N₂O emissions (Zhang et al., 2012b). Another field experiment in pasture showed no significant effects of biochar amendment on soil CO₂ and N₂O emissions in a pasture ecosystem (Scheer et al., 2011). Thus, the efficacy of biochar for climate change mitigation is largely uncertain due to these variable effects on soil GHG emissions.

There are many hypotheses to explain why biochar may increase or decrease soil GHG fluxes. For example, increases in soil CO₂ emissions induced by biochar might be due to the labile C input and positive priming effects of biochar as well as increased belowground net primary productivity (BNPP) (Zimmerman et al., 2011; Zhang et al., 2012a), while the suppression of soil CO₂ emissions may be due to reduced enzymatic activity and the precipitation of CO₂ onto the biochar surface (Case et al., 2014). Elevated CH₄ emissions could be attributed to the inhibitory effect of chemicals in the biochar on soil methanotrophs (Spokas, 2010). Reduced CH₄ emissions might be associated with decreased ratios of methanogenic archaea to methanotrophic proteobacteria, as the increase in oxygen supply due to biochar application supports a group of aerobic methanotrophs (Feng et al., 2012).

There are also contradictory reports with respect to N₂O emissions. For example, increases in N₂O emissions may be ascribed to biochar-induced increases in soil water content, which favors denitrification, or the release of biochar embodied-N (Lorenz & Lal, 2014). In contrast, mechanisms that explain decreased N₂O emissions include (1) improved soil aeration, (2) increased soil pH, (3) enhanced N immobilization, and (4) a toxic effect induced by biochar organic compounds (poly-cyclic aromatic hydrocarbons) on nitrifier and denitrifier communities (Clough et al., 2010, 2013; Taghizadeh-Toosi et al., 2011; Hale et al., 2012).

The contradictory reports of changes in size and even direction of soil GHG emissions when biochar is applied, and the diversity of mechanisms proposed, suggest that biochar effects may depend on many factors, including soil properties, experimental methods, artificial cultivation management, biochar application rate, and biochar physicochemical properties (Hilscher & Knicker, 2011; Lorenz & Lal, 2014). These factors may determine to what extent biochar alters soil C and N transformation processes and consequently soil GHG emissions. However, how these factors contribute to the variable responses of soil GHG emissions to biochar application across the globe still remains unclear. If these factors are not adequately addressed, the effects of biochar application on mitigating global warming cannot be fully understood.

Recently, three meta-analyses on the effects of biochar application on soil GHG fluxes have been conducted. Two of them (i.e., Cayuela et al., 2014, 2015) only emphasized the central tendency of soil N₂O fluxes under biochar addition, and the other by Liu et al. (2016) examined the response of CO₂ fluxes, soil organic C (SOC), and soil microbial biomass C (MBC) to biochar amendment. However, there is limited information on the simultaneous effects of biochar amendments on soil GHG fluxes and their global warming potential (GWP). It is necessary to compile all available data to synthesize results from individual studies to reveal the patterns of biochar-induced changes in soil GHG fluxes and to identify the major drivers for responses of GHG fluxes to biochar addition.

In this study, we compiled data from individual experimental studies that quantified the effect of soil biochar application on GHG fluxes across various ecosystems and then quantitatively evaluated the responses of soil CO₂, CH₄, and N₂O fluxes to biochar application under different environmental and experimental conditions using meta-analysis techniques. Our objectives were to (1) quantify the effect size of biochar amendment on soil GHG fluxes across studies; (2) examine whether environmental conditions, experimental methods, and biochar characteristics would influence the responses of soil GHG fluxes to biochar application; and (3) evaluate the response of GWP of soil GHGs to biochar application.

Materials and methods

Data sources

Publications were searched using Web of Science (1900–2015) with the following search terms: (biochar or black carbon or charcoal) and [soil greenhouse gases (GHGs) or CO₂ or CH₄ or N₂O or global warming potential (GWP)]. The selection criteria were as follows: (i) Experiments had at least one pair of data (control and treatment) and measured soil CO₂, CH₄, or N₂O fluxes; (ii) the method of biochar application was clearly described, including experimental duration, amount of biochar application, physico-chemical characteristics of biochar, and soil properties such as pH and C/N ratio; (iii) the means, standard deviations/errors, and sample sizes of variables in the

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control and treatment groups could be extracted directly from tables, graphs, or contexts. In total, 91 research papers on biochar application were selected from more than 2000 published papers. The geographic distribution of the selected studies over the world is presented in Fig. 1. The studies contained multiple biochar application levels (Case et al., 2012; Stewart et al., 2013), biochar types (Spokas & Reicosky, 2009; Ameloot et al., 2013), soil types (Wang et al., 2011; Gomez et al., 2014), or N fertilization levels (Barbosa De Sousa et al., 2014; Sun et al., 2014), which were treated as multiple independent studies.

Four categories of data were extracted from the literature of biochar application experiments: (1) soil GHG fluxes, including CO₂, CH₄, and N₂O fluxes; (2) soil properties, including pH, total C, total N, and C/N ratio; (3) biochar properties, including biochar feedstock types, pyrolysis temperature, rate of biochar applied, pH, total C, total N, and C/N ratio; and (4) other auxiliary variables, including latitude, longitude, experiment types (field, pot, and incubation), experimental duration, and N fertilization (whether or not). The variables listed in categories (2), (3), and (4) were used as explanatory factors (either categorical or continuous) of the variation in GHG fluxes in response to biochar application.

Analysis

We followed the methods used by Hedges et al. (1999) and Luo et al. (2006) to evaluate the responses of soil CO₂, CH₄, and N₂O fluxes to biochar application. A response ratio (RR, natural log of the ratio of the mean value of a variable in biochar treatment plots to that in control) was used to calculate effect sizes as below:

\[ RR = \ln \frac{X_t}{X_c} = \ln(X_t) - \ln(X_c) \]  \hspace{1cm} (1)

where \( X_t \) and \( X_c \) are means in the treatment and control groups, respectively. The variance (\( v \)) of each individual RR is estimated as:

\[ v = \frac{S_t^2}{n_t X_t^2} + \frac{S_c^2}{n_c X_c^2} \]  \hspace{1cm} (2)

where \( n_t \) and \( n_c \) are the sample sizes of the variable in treatment and control groups, respectively; \( S_t \) and \( S_c \) are the standard deviations for the treatment and control groups.

The mean response ratio (\( RR_{++} \)) was calculated from RR of individual pairwise comparisons between treatment and control as below,

\[ RR_{++} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{k} W_{ij} RR_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{k} W_{ij}} \]  \hspace{1cm} (3)

where \( m \) is the number of groups and \( k \) is the number of comparisons in the \( i \)th group. The reciprocal of its variance (\( W \)) was considered as the weight (\( W \)) of each RR.

We used a bootstrapping method to obtain the 2.5% and 97.5% percentiles as the lower and upper limits of our 95% bootstrap confidence interval (CI) based on 5000 iterations (Adams et al., 1997; Zhou et al., 2014). When the 95% CI of \( RR_{++} \) for soil GHG emissions overlapped with zero, biochar application had no significant impact on the variable. Otherwise, the biochar-induced response was considered as significance (Luo et al., 2006). The percentage change of variables was calculated on the basis of \( \exp(\text{RR}_{++}) - 1 \times 100\% \).

The frequency distribution of the individual response ratio (RR) was tested by a normal test and fitted by a Gaussian function using Eqn (5) in SIGMAPLOT software (Systat Software Inc., San Jose, CA, USA).

\[ y = x \exp \left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \]  \hspace{1cm} (4)
where $x$ is RR of a variable; $y$ is the frequency (i.e., the number of RR values); $a$ is a coefficient showing the expected number of RR values at $x = y$; and $\mu$ and $\sigma$ are the mean and variance of the frequency distributions of RR, respectively.

In addition, global warming potential (GWP) was calculated when three soil GHG (i.e., CO$_2$, CH$_4$, and N$_2$O) fluxes were extracted simultaneously from one study (IPCC, 2007). It should be noted that the units of soil CO$_2$, CH$_4$, and N$_2$O fluxes were unified before the calculation of the GWP. The GWP (t CO$_2$ equivalent ha$^{-1}$) was then determined as follows:

$$\text{CO}_2 \times 1 + \text{CH}_4 \times 25 + \text{N}_2\text{O} \times 298$$

(5)

The between-group heterogeneity ($Q_b$) across all data for a given response variable was calculated to further analyze the biochar effect among different subgrouping categories. A random-effect model was used to explore the soil and biochar properties and other auxiliary variables that may explain the response of soil GHG fluxes to biochar application. We also conducted meta-regression analysis to examine the relationships between RR (GHGs) and continuous forcing factors. The correlations of RR (GHGs) among different variables were examined by correlation analysis applied in R (R Core Team, 2015).

The publication bias was tested by funnel plot method and assessed using Kendall’s Tau (Moller & Jennions, 2001). If the mean effect had significant difference from zero (i.e., indicating the existence of publication bias), Rosenthal’s fail-safe number was calculated (MetaWin 2.1; Rosenberg et al., 1997) to estimate whether our conclusion is likely to be affected by the nonpublished studies (Rosenberg, 2005).

**Results**

**Effects of biochar application on soil greenhouse gas (GHG) fluxes**

The individual response ratios (RRs) of soil GHG fluxes (i.e., CO$_2$, CH$_4$, and N$_2$O) all displayed normal/Gaussian distributions (Fig. S1). On average, biochar application significantly increased soil CO$_2$ fluxes by 22.14% with a mean weighted RR$_{+}$ of 0.20 [CI = (0.12, 0.31)], but decreased soil N$_2$O fluxes by 30.92% with a RR$_{-}$ of 0.37 [CI = (−0.48, −0.28)]. Soil CH$_4$ fluxes were not significantly affected by biochar application [RR$_{-}$ = −0.03, CI = (−0.35, 0.23)] (Fig. 2, Table S2). Publication bias for this analysis was not suggested by Rosenthal’s method (Table S3).

The response of soil CO$_2$ flux to biochar application depended significantly on biochar properties, experimental method, nitrogen (N) fertilization, and latitude. Soil texture and biochar pH were the two most critical parameters affecting the response of soil CH$_4$ flux to biochar addition. Biochar-induced changes in soil N$_2$O fluxes were significantly associated with soil and

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**Fig. 2** The effect of biochar application on soil CO$_2$ (a), CH$_4$ (b), and N$_2$O (c) emissions differed with experimental method [including field studies (F), laboratory incubation (I), and pot experiments (P)] in unfertilized soils and N-fertilized soils, shown as weighted response ratio (RR$_{+}$). Mean effect and 95% CIs are shown. If the CI did not overlap with zero, the response was considered significant (*). Numerals indicate the number of observations. ‘Overall’ indicates the integrated biochar effect across N fertilization as compared with controls.

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Table 1  Between-group variability (Qb) among observations (n) suggesting their potential as predictive variables influencing soil greenhouse gas (GHG) emissions responses to biochar application

| Variables                  | CO2  | CH4  | N2O  |
|----------------------------|------|------|------|
|                            | n    | Qb   | n    | Qb   | n    | Qb   |
| All studies                | 402  | 25.08*** | 103  | 14.22*** | 317  | 0.30*** |
| Role of N fertilization    | 402  | 13.43*** | 121  | 7.70**  | 371  | 0.37   |
| Experimental method        | 402  | 19.52*** | 121  | 9.33**  | 371  | 2.34   |
| Feedstock source           | 402  | 4.28   | 121  | 10.60** | 371  | 19.37*** |
| Soil texture               | 277  | 9.95*** | 86   | 115.98*** | 256  | 14.34** |
| Pyrolysis temperature (°C) | 385  | 37.27*** | 110  | 6.85**  | 354  | 1.94   |
| Biochar pH                 | 327  | 25.08*** | 103  | 14.22*** | 317  | 3.05   |
| Soil pH                    | 390  | 0.55   | 117  | 1.62    | 351  | 10.19** |
| Applied rate [Lg (t ha⁻¹)] | 400  | 15.65*** | 120  | 4.53*   | 371  | 39.05*** |
| Latitude (°)               | 401  | 50.44*** | 121  | 0.00    | 371  | 2.50   |
| Soil C/N ratio             | 212  | 0.25   | 58   | 0.02    | 183  | 2.35   |
| Duration (day)             | 402  | 0.02   | 121  | 0.51    | 371  | 1.62   |
| Biochar C/N ratio          | 387  | 0.06   | 120  | 0.64    | 363  | 0.53   |

A variable with larger Qb is a better predictor than a variable with smaller Qb.

Statistical significance of Qb: *P < 0.05; **P < 0.01; ***P < 0.001.

Effects of biochar applying methods on GHG fluxes

Experimental methods (i.e., field studies, laboratory incubations, and pot experiments) had a significant effect on the response of soil CO₂ and CH₄ fluxes to biochar application, while it was not pronounced for N₂O fluxes (Table 1, Fig. S3). On average, biochar application significantly increased soil CO₂ fluxes by 30.34% in laboratory incubations, but had no changes under field studies and pot experiments. Biochar application significantly increased soil CH₄ fluxes by 25.4% in field studies, but did not change in laboratory incubations and pot experiments. In addition, experimental duration showed no significant effect on responses of soil GHG fluxes to biochar application (Fig. S4).

Interestingly, the effect of fertilization on GHG fluxes in biochar-amended soil appears closely related to experiment methodology. Only laboratory incubations showed a significant increase in CO₂ fluxes to biochar application in unfertilized soils compared to those in field and pot experiments, while there were no responses in fertilized soils. For CH₄ fluxes, only field studies showed significant positive responses to biochar application in fertilized soils, and other treatments did not exhibit any significant effects (Fig. 2).

Effects of soil and biochar properties on soil GHG emissions

The response of soil GHG fluxes to biochar application differed for biochar feedstock source (i.e., wood, herb, and biowaste, Table 1, Fig. 3a–c). Among all biochar feedstock sources, wood source had the smallest positive effect for CO₂ fluxes and negative effect for N₂O fluxes. Meanwhile, biowaste source induced the largest positive effect and negative effect for CO₂ and N₂O fluxes, respectively. The effects of biochar application on soil CH₄ fluxes were not significant among different feedstock sources.

The response of soil GHG fluxes to biochar application also varied with soil texture (Table 1, Fig. 3d–f). For CO₂ fluxes, positive effects of biochar application occurred in soils with coarse and medium texture, while no significant effects were found in fine texture. CH₄ fluxes showed a significant negative response to biochar amendment only in coarse soils. N₂O fluxes significantly decreased by biochar application in all soil types, but the smallest negative response occurred in medium soils.

Response ratios of soil GHG fluxes across all the studies were significantly correlated with biochar pyrolysis temperature (Tem), biochar pH (BpH), soil pH, and biochar application rate (App), and latitude (Lat) (Table 1, Fig. 4). The response of soil CO₂ and CH₄ fluxes to
biochar amendment slightly decreased with pyrolysis temperature and biochar pH \((P < 0.001)\), but increased with application rate and latitude of the study for soil CO2 fluxes \((P < 0.001)\). In addition, the responses of soil N2O fluxes to biochar application revealed negative trends with soil pH \((P = 0.001)\) and application rate \((P < 0.001)\). Although these correlations were statistically significant, their contributions in explaining the variation in GHG flux responses were low \((0.04 < R^2 < 0.11, \text{Fig. 4})\).

**Discussion**

**Responses of CO2, CH4, and N2O fluxes to biochar application**

On average, our meta-analysis showed that biochar application significantly increased soil CO2 fluxes by 22.14%. Among individual studies, biochar application affected soil CO2 fluxes with diverse magnitudes and even directions (Scheer et al., 2011; Augustenborg et al., 2012; Zhang et al., 2012a). The stimulating effects of biochar application on soil CO2 fluxes were usually ascribed to higher labile C mineralization and/or inorganic C release from biochar (Fig. 6; e.g., Jones et al., 2011; Smith et al., 2010; Zimmerman et al., 2011). Furthermore, as suggested by Liu et al. (2016), biochar application enhanced soil organic C (SOC) by 40% and soil microbial biomass C (MBC) content by 18%. This
indicates that the stimulation of soil CO2 fluxes might be associated with the higher SOC status and the more active soil microbial activities (Fig. 6).

Soil CO2 fluxes declined with biochar pyrolysis temperature. Low pyrolysis temperature results in more microbial available C and nutrients in biochar than a high pyrolysis temperature, which promotes high soil microbial activities to decompose soil organic matter (SOM) and release more CO2 from soil (Chan et al., 2008; Novak et al., 2010; Hale et al., 2012). This results in the negative relationship between RR (CO2) and biochar pyrolysis temperature and a positive relationship between RR (CO2) and application rate (Fig. 4a, d). Meanwhile, high-temperature biochars may contain higher relative concentrations of toxic compounds (i.e., polycyclic aromatic hydrocarbons) (Nakajima et al., 2007), which can affect soil microbial biomass and activity. In addition, the RR (CO2) exhibited a negative correlation with biochar pH probably because biochar with pH < 7 had a relatively high input of labile C fractions and triggered a higher priming effect on soil C mineralization (Crombie et al., 2015). Our results indicated that CO2 fluxes did vary over time after biochar application. However, mechanisms involved in soil CO2 stimulation after biochar application may differ in short term compared to long term. In short term, soil CO2 stimulation may have been originated from the breakdown of organic C and the release of inorganic C contained in the biochar (Jones et al., 2011). In the long term, biochar can promote the rapid loss of humus and belowground C (Wardle et al., 2008). Meanwhile, increased belowground NPP induced by biochar amendment may also cause the stimulation of CO2 emissions during the long-time experiments (Major et al., 2010).

In addition, biochar-induced changes in soil CO2 fluxes significantly increased with latitude, which may be related to increase in soil temperature after biochar application (Bozzi et al., 2015). The increasing temperature may induce the larger stimulation on soil microbes and thereby CO2 fluxes, in the high-latitude soils, where microbial activities and soil respiration are strongly limited by temperature (Mikan et al., 2002).

Biochar application had no significant effect on soil CH4 fluxes in our meta-analysis, although individual studies showed diverse effects. In experimental studies, multiple factors (e.g., soil aeration and porosity, methanogens, and methanotrophs) have been proposed to explain the different effects of biochar application on soil CH4 fluxes (Lehmann & Rondon, 2006; Karhu et al., 2011), but the underlying mechanisms are still poorly understood (Lorenz & Lal, 2014). Soil CH4 fluxes are largely determined by methanogens and methanotrophs at a microbial scale (Bodelier & Laanbroek, 2004). Therefore, decreased soil CH4 fluxes under biochar application might be due to the higher ratios of methanogenic to methanotrophic bacteria observed in some studies.

Fig. 4 Effects of biochar pyrolysis temperature, biochar pH, soil pH, applied rate, and latitude on response ratios of soil CO2 emissions (a–e), CH4 emissions (f–j), and N2O emissions (k–o) to biochar application.
and others suggested that improved soil aeration and CH$_4$ oxidation after biochar application suppressed soil CH$_4$ fluxes (Fig. 6; Karhu et al., 2011). In contrast, the increased soil CH$_4$ fluxes under biochar application could be attributed to biochar compounds that inhibit the activity of methanotrophs (Spokas, 2013).

Biochar application decreased CH$_4$ fluxes in coarse soils, whereas it increased CH$_4$ fluxes in fine soils. Biochar application to the coarse soils is likely to improve soil aeration, thus making the soils more favorable for the aerobic methanotrophs communities and increases CH$_4$ oxidation (Van Zwieten et al., 2009). However, in the fine-textured soils, the porous structure of biochar may be filled with a clay and fine silt fraction, which could offset the aeration effect. A weak stimulation of CH$_4$ fluxes induced by biochar amendment may be due to enhancing soil methanogenic archaea (Feng et al., 2012). In addition, the biochar-induced effects on soil CH$_4$ fluxes decreased with biochar pH, probably resulting from altered soil microbial community structure, especially the ratio of soil methanogenic to methanotrophic abundance (Anders et al., 2013).

Our meta-analysis showed that biochar application decreased soil N$_2$O fluxes by 30.92%, consistent with another meta-analysis reported by Cayuela et al. (2014). This response was probably driven by the changes in the activity of the nitrifiers and denitrifiers that produce N$_2$O. Biochar application enhances soil aeration (absorbing/holding an excess of soil moisture) and reduces N leaching as a result of NH$_4^+$ and NO$_3^-$ adsorption by biochar (Fig. 6; Bai et al., 2015a; Reverchon et al., 2014; Rogovska et al., 2011; Steiner et al., 2008; Yanai et al., 2007). The enhanced soil aeration and reduced compaction may inhibit denitrification due to more oxygen being present, and the diminished N leaching may decrease the inorganic N pool available for soil nitrifiers and denitrifiers (Fig. 6). Moreover, biochar amendment stimulates the nosZ transcription (i.e., denitrifying bacteria gene markers), which suggests

![Fig. 5 Frequency distributions of response ratio (RR) of global warming potential (GWP, panel a) to biochar application, GWP in unfertilized soils (b) and N-fertilized soils (c). The sample size (n), weighted response ratio (RR$_+$), and 95% CIs are shown. The effect of biochar application on GWP differed with experimental method (d), and GWP differed with experimental method in unfertilized soils (d$_1$) and N-fertilized soils (d$_2$). Mean effect and 95% CIs are shown. If the CI did not overlap with zero, the response was considered significant (**). Numerals indicate the number of observations.](image-url)
that biochar mitigates N₂O fluxes by further reducing it to N₂ (Xu et al., 2014). In addition, biochar facilitates the transfer of electrons to soil denitrifying microorganisms, which promotes the reduction of N₂O to N₂ (Fig. 6; Cayuela et al., 2013).

Furthermore, our study found that biochar-induced decreases in N₂O fluxes were enhanced with increasing biochar application rate. Larger amounts of microbial available and active nutrients due to high biochar application rates may promote the complete denitrification to N₂ (Lorenz & Lal, 2014), which may largely contribute to the suppression of soil N₂O fluxes as well as high molar H : Corg ratio (Cayuela et al., 2015).

Regulation of nitrogen (N) fertilization on biochar impacts

Our results showed that biochar application increased soil CO₂ fluxes by 43.33% in unfertilized soils, but decreased by 8.61% in N-fertilized soils, consistent with the meta-analysis of Liu et al. (2016). More available inorganic N source for soil microbes and/or plant roots could stimulate soil microbial C mineralization after N is added (Lu et al., 2011; Zhou et al., 2014), but the absorption of NH₄⁺ and NO₃⁻ by biochar would decrease the soil inorganic N pool after N fertilizers were applied (Steiner et al., 2008; Clough et al., 2013). Therefore, immobilization of soil inorganic N induced by biochar application may be the main reason for the slight suppression of soil CO₂ fluxes in N-fertilized soils. In unfertilized soils, the significant stimulation of soil CO₂ fluxes was mainly explained by the relatively higher nutrient availability for soil microbes and/or the priming effect on native soil C decomposition after biochar application (Wardle et al., 2008; Smith et al., 2010).

Biochar application increased soil CH₄ fluxes by 11.67% in N-fertilized soils, but had no significant effect on unfertilized soils. Soil CH₄ fluxes increased weakly under corn and strongly under rice cultivation with N fertilization, respectively, during the entire growing season (Zhang et al., 2010, 2012b). Biochar input under N addition is likely to alleviate C limitation to microbes. Therefore, the activities of soil methanogenic archaea are enhanced and more CH₄ is produced. Alternatively, some studies showed that decrease in soil CH₄ fluxes could be partly explained by the facilitated CH₄ oxidation after biochar application (Karhu et al., 2011; Yu et al., 2012), and a more stimulatory effect of biochar on methanotrophic proteobacteria than on methanogenic archaea in unfertilized soils (Feng et al., 2012).

The biochar-induced decrease in soil N₂O fluxes was not significantly different in unfertilized [28.82%, CI = (39.95%, 16.47%)] soils from those of N-fertilized soils [32.97%, CI = (41.14%, 24.42%)]. As N addition increased N₂O fluxes by 216% on average across the globe (Liu & Greaver, 2009), the quantity of soil N₂O fluxes mitigated by biochar application in N-fertilized soils is much larger than that in unfertilized soils. As mentioned above, this might be due to more soil NH₄⁺ and NO₃⁻ absorbed by biochar after N fertilizer application, likely causing denitrification to decline (Russow et al., 2008) and/or a facilitation of N₂O reduction to N₂ (Dalal et al., 2003).
The effects of biochar application on soil CO$_2$ fluxes differed with experimental types. Our study found a significant positive response in unfertilized soils mainly in laboratory incubations, but not in field and pot experiments. The positive response of soil CO$_2$ fluxes in laboratory incubation is most likely due to the mineralization of the labile C fractions existed in biochar (Zimmerman et al., 2011), as well as increased soil surface area due to pore structures which promotes microbial activity (Chia et al., 2014). In field experiments, the nonsignificant difference in CO$_2$ fluxes between control and biochar treatments largely resulted from low application rates and/or high biochar labile C leaching due to rainfall (Kuzyakov et al., 2009; Spokas & Reicosky, 2009). In N-fertilized soils, there were no significant differences in biochar-induced changes in soil CO$_2$ fluxes among field studies, pot experiments, and laboratory incubations. The positive effects of biochar application on soil CO$_2$ fluxes as mentioned above may be offset by the absorption of soil inorganic N (NH$_4^+$ and NO$_3^-$) when biochar is applied (Steiner et al., 2008; Wardle et al., 2008; Smith et al., 2010). Therefore, no changes were observed in soil CO$_2$ fluxes.

Across all studies, soil CH$_4$ fluxes showed a positive response to biochar application in field studies, but no significant changes in laboratory incubations and pot experiments. The positive effects in field studies mainly reported from the treatments with N fertilization. The increase in soil CH$_4$ fluxes under N addition probably resulted from the stimulation of soil microbial activities, especially the methanogenic archaea and methanotrophic bacteria (Bodelier & Laanbroek, 2004). As reported by Liu et al. (2016), biochar amendment significantly increased soil microbial biomass C (MBC) in the field experiments, whereas MBC decreased in controlled studies. This likely resulted from improving the availability of microbial habitats and the accessibility of microbial food resources in the field-based experiments compared to the controlled conditions especially under biochar amendment (Pietikainen et al., 2000).

In contrast, the responses of soil N$_2$O fluxes to biochar application showed a consistent trend across all treatments (Fig. 4a–c). However, laboratory incubations showed greater N$_2$O flux decreases than field studies with respect to biochar application in unfertilized soils (Fig. 4b), likely due to the difference in mixing of biochar with soil in controlled and field studies. Biochar is mixed thoroughly with soils in most controlled studies, which enhances soil aeration, but in field studies biochar is applied to the soil surface (e.g., Scheer et al., 2011; Wang et al., 2012; Bamminger et al., 2014; Case et al., 2014).

Responses of GWP of soil GHGs to biochar application

Global warming potential (GWP) is a simplified index to estimate the potential future impacts of GHGs on the global climate system based on their radiative forcing and lifetimes (IPCC, 2013). Overall, biochar application significantly increased GWP by 46.22% [CI = (19.72%, 82.20%)]. The fluxes are governed by different mechanisms (Fig. 6), but largely resulting from the significant stimulation of soil CO$_2$ fluxes. The increased amount of soil CO$_2$ fluxes induced by biochar application was nearly a one thousand times the size of CH$_4$ or N$_2$O fluxes in most studies (e.g., Scheer et al., 2011; Wang et al., 2012; Zhang et al., 2012a). In addition, biochar increased the GWP of soil GHGs in unfertilized soils, but decreased it in N-fertilized soils due to the suppression of soil CO$_2$ and N$_2$O fluxes under N addition.

Significant amounts of CO$_2$, CH$_4$, and N$_2$O were released to the atmosphere from agriculture, which accounted for nearly one-fifth of the annual increase in radiative forcing of climate change (Cole et al., 1997). Soil GHG fluxes would increase substantially after N fertilizers were applied, especially in croplands (Hall & Matson, 1999; McSwiney & Robertson, 2005; Liu & Greaver, 2009; Zhou et al., 2014). Agricultural GHG emissions from crop and livestock production were 5.3 Pg of carbon dioxide equivalents (CO$_2$ eq) in 2011 (FAO 2014). Tian et al. (2016) estimated that CH$_4$ and N$_2$O emissions in the agricultural ecosystems were 169 ± 26 and 4.9 ± 0.3 Tg N yr$^{-1}$, respectively. According to our estimates with a decrease of 7.69% for GWP under N fertilization, 0.41 Pg CO$_2$ eq yr$^{-1}$ could potentially be mitigated by biochar applied to agricultural soils in combination with N fertilizers. Moreover, biochar application would increase the average yield of 10% and nearly 14% in acidic soils (Jeffery et al., 2011). Given that our study elicits that biochar application reduces CO$_2$ fluxes and GWP in N-fertilized soil, biochar therefore appears to be a good strategy to mitigate global warming in fertilized agro-ecosystems.

Implications for future experiments and land surface models

The compiled database in our meta-analysis was mainly obtained from laboratory incubations, and the results were different for the responses of soil GHG fluxes to biochar application compared to those from field studies (Scheer et al., 2011; Spokas et al., 2009; Fig 4). The lack of field-scale studies, especially those lasting at least two successive seasons (Lorenz & Lal, 2014), may

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hampers our evaluation of soil GHG fluxes in response to biochar application in the longer term. In addition, most biochar application experiments had been conducted in North America, Europe, and China. There remains a dearth of field studies in other regions, including Africa, South-East Asia, and South America. Thus, long-term field experiments with biochar amendments are especially needed in these regions.

Nitrogen fertilization mediated the responses of soil GHG fluxes and their GWP to biochar application. Because N deposition increased from 34 Tg N yr⁻¹ in 1860–100 Tg N yr⁻¹ in 1995 and is predicted to reach 200 Tg N yr⁻¹ in 2050 (Galloway et al., 2008; IPCC, 2013), the interactive effects between biochar and N addition may dramatically influence soil microbial community structure and ecosystem functioning as well as soil GHG fluxes in the future (Liu et al., 2016). To address this issue, biochar experiments with diverse types of N fertilization (e.g., fertilizer type and level) are needed to examine the potential nonlinear responses to biochar application.

In the nature, biochar is often produced by wildfire, and currently, industrially produced biochar application becomes more common, especially in agriculture. Our meta-analysis results from laboratory, pot, and field studies found significant effects of biochar application on soil GHG fluxes and their GWPs. These results may provide some insights into how the fire-generated biochar affects net climate forcing from soil GHG fluxes and offers recommendations for the development and improvement of land surface models. Tempo-spatial variability of soil GHG fluxes is mostly attributed to soil temperature, soil moisture, fire severity, aspect, and time since fire in wildfire models (Cathany & Burke, 2011). However, wildfire-produced and industrial biochar may play critical roles in shaping terrestrial ecosystem processes and affecting soil GHG fluxes. Thus, future land surface models may need to incorporate biochar-induced effects to natural ecosystem processes, especially soil GHG fluxes and their GWPs for better forecasting the feedback of terrestrial ecosystems to climate change. Additionally, the combined or interactive effects of N fertilization with biochar amendments can be incorporated into future land surface models to improve the predictions about N-mediated feedback of ecosystem C cycles to climate systems from soil GHG fluxes.

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (Grant No. 31370489), the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning, and ‘Thousand Young Talents’ Program in China. We would like to acknowledge the work carried out by the researchers whose published data were used for this meta-analysis.

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**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article:

**Figure S1.** Frequency distributions of response ratios (RR) of soil CO2, CH4, and N2O emissions to biochar application.

**Figure S2.** Frequency distributions of response ratios (RR) of soil CO2, CH4, and N2O emissions to biochar application on unfertilized soils and N-fertilized soils.

**Figure S3.** The effect of biochar application on soil CO2, CH4, and N2O emissions differed with experimental method.

**Figure S4.** Effects of experimental duration on response ratios of GHG emissions to biochar application.

**Table S1.** Response ratio (RR) and number of paired observations extracted from each of the papers.

**Table S2.** Percentage changes of soil greenhouse gas (GHG) emissions in response to biochar application.

**Table S3.** The Kendall’s Tau for RR(CO2), RR(CH4), RR(N2O) and RR(GWP) in different treatments.

**Data S1.** A list of 91 papers from which the data were extracted for this meta-analysis.