Antagonistic interaction between biochar and nitrogen addition on soil greenhouse gas fluxes: A global synthesis

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Abstract
Both biochar and nitrogen (N) addition have been proposed for enhancing plant productivity and increasing carbon (C) sequestration. Although numerous studies have been conducted to examine responses of soil greenhouse gas (GHG) fluxes to biochar or N addition, biochar is often co-applied with N fertilizer and the interactive effects of the two factors still remain unclear. In this study, we performed a meta-analysis of manipulative experiments with 267 two-factor observations to quantify the main and interactive effects of biochar and N addition on soil GHG fluxes at a global scale. Our results showed that biochar addition significantly increased soil CO2 emission by 10.1%, but decreased N2O emission by 14.7%. Meanwhile, N addition increased both soil CO2 and N2O emissions by 11.6% and 288%, respectively. The combination of biochar and N addition also exhibited significant positive effect on CO2 (+18.0%) and N2O (+148%) emissions, but there were non-significant changes in CH4 fluxes. Consequently, antagonistic interaction between biochar and N addition was observed in soil GHG fluxes and their global warming potential (GWP), except for CH4 uptake showing an additive interaction. This synthesis highlights the importance of the interactive effects between biochar and N addition, providing a quantitative basis to develop sustainable strategies toward widespread application of biochar to preserve cropping system and mitigate climate change.

KEYWORDS
biochar, carbon sequestration, global warming potential, interactive effect, nitrogen addition, soil greenhouse gas
1 | INTRODUCTION

The Earth has experienced approximately 0.85°C of elevated temperature relative to the pre-industrial levels, which was mainly caused by the ever-increasing greenhouse gas (GHG) emissions from anthropogenic activities (IPCC, 2013). To mitigate the global warming, timely and effective negative emission technologies are urgently needed to negate GHG emissions (i.e., CO₂, CH₄, and N₂O; Meinshausen et al., 2009; Smith, 2016; Sykes et al., 2020). Conversion of plant biomass into biochar, a carbon (C)-rich product derived from biomass by pyrolysis in the absence of oxygen, and its application to soils seem to be a promising strategy for improving C sequestration to mitigate climate change (Lehmann, 2007; Smith et al., 2016; Woolf et al., 2010). Meanwhile, biochar amendment also plays an important role in improving soil quality, plant productivity, soil water holding capacity, and nutrient availability (Deluca et al., 2015; Gao et al., 2019; He, Yao, et al., 2020; Hui et al., 2018; Jeffery et al., 2011).

Previous studies have demonstrated that biochar amendment has substantially altered soil GHG emissions (Sarauer et al., 2019; Zhang et al., 2012; Van Zwieten et al., 2009). Global meta-analyses of diverse studies conducted at the global scale indicated that biochar amendment enhanced soil CO₂ emissions by 3%–22% on average, but reduced N₂O emissions by 31%–54%, and had no effect on CH₄ fluxes (Cayuela et al., 2014; He et al., 2017; Jeffery et al., 2016; Liu et al., 2016). Increases in soil CO₂ emission have been linked to the biochar-induced changes in soil physical properties and labile C inputs as well as growth stimulation of roots and microorganisms (Jones et al., 2011; Mukherjee et al., 2014; Xiang et al., 2017). In contrast, decreases in soil N₂O emission by biochar amendment have been a result of increases in soil aeration, pH alteration, and N immobilization (Case et al., 2012; Liu et al., 2019; Yanai et al., 2007). Additionally, biochar amendment induced either positive or negative effects on soil CH₄ fluxes in individual studies, which were largely determined by the biochar-incurred changes in soil methanogenic archaea and methanotrophs (e.g., α- and γ-proteobacteria; Feng et al., 2012; Jeffery et al., 2016; He, Yuan, et al., 2020). Consequently, it is likely that biochar addition may increase the global warming potential (GWP) due to the large stimulation of soil CO₂ efflux (He et al., 2017).

Nitrogen (N) deposition, mainly from agricultural activities and fossil fuel combustion, has increased more than threefold over the past century (Davidson, 2009; Galloway et al., 2008), which may interactively affect soil GHG fluxes with biochar amendment. Recently, a large number of studies have examined the responses of soil CO₂, N₂O, and/or CH₄ fluxes to biochar in combination with N addition, showing inconsistent results with increase (Sui et al., 2016; Wu et al., 2019), decrease (Azeem et al., 2019; Ge et al., 2020), or no significant change (Sherman & Coleman, 2020). These contradictory reports of soil GHG fluxes with respect to biochar and N addition may be caused by the changes in soil properties, environmental factors, biochar characteristics, and N addition rate (Fernández et al., 2014; Fungo et al., 2019; He et al., 2016; Sigua et al., 2016). For example, biochar and N addition stimulated soil N₂O emission in the mid of maize-growing season, but decreased it in the late season. The difference may result from changes in the underlying microbial processes largely determined by soil moisture and inorganic N availability (Edwards et al., 2018). However, how these factors influence soil GHG fluxes in response to the combined biochar and N addition across the globe remains unclear.

Biochar and N addition may interactively (including additive, synergistic, or antagonistic) affect soil GHG fluxes (He, Yuan, et al., 2020; Lan et al., 2018; Zheng et al., 2012). Substantial data from field manipulative experiments have demonstrated that the combined effects of biochar and N addition on soil GHG fluxes were equal to the sum of the single-factor effects (additive), but synergistic and antagonistic interactions have also been observed in other studies (Jiang et al., 2016; Maestrini et al., 2014; Zhang et al., 2019). It is essential to compile all the available data to obtain the central tendency of the interactive effects of biochar and N additions on soil GHG fluxes, which could help us to mitigate GHG emissions and develop C sequestration strategies in the changing world (Chen et al., 2019; Edwards et al., 2018; Shakoor et al., 2021).

In this study, we compiled biochar and N addition studies across various ecosystems and quantitatively examined general patterns of their interactions on soil GHG fluxes and GWP over a 100-year time frame using a meta-analysis approach. The objectives were to (1) quantify the interactive effects of biochar and N addition on soil GHG fluxes and their GWP and (2) identify the key factors, including soil and biochar characteristics that influence responses of soil GHG fluxes to the combined biochar and N addition. Our study would test whether biochar combined with N addition can be effectively used to mitigate soil GHG emissions when the optimal yield was sustained.

2 | MATERIALS AND METHODS

2.1 | Data sources

Publications were searched in Web of Science, China National Knowledge Infrastructure, and Google scholar (1900–2020) with the keywords “biochar OR char OR pyrogenic carbon (C) AND nitrogen (N) fertilizer AND greenhouse gases OR CO₂ OR CH₄ OR N₂O”. To minimize publication bias, the following criteria were used to select the publications:
(i) experiments had at least one pair of data (including control, biochar amendment, N fertilizer addition, and the combined biochar and N fertilizer treatments) and measured soil CO₂, CH₄, and/or N₂O fluxes; (ii) the methods of the experiments were clearly stated, such as experimental duration, the amendment rate of biochar and N fertilizer, biochar and soil properties; (iii) plots for these treatment groups had the same experimental conditions as the control at the beginning of experiments; and (iv) the means, standard deviations/errors, and the sample sizes of the variables in both control and treatment pairs could be extracted from the context, tables, or digitized graphs. In total, 66 publications (Data S1) with 267 two-factor observations were selected from more than 800 peer-reviewed publications, which were mainly distributed in the Northern Hemisphere (Figure S1). The studies with multiple biochar types, biochar amendment rates, soil textures, or N fertilizer addition levels were considered as the different individual studies. We did not differentiate the responses of soil GHG fluxes among different N fertilizer type (e.g., organic and inorganic materials), since the N fertilizer in many publications was not provided.

Five categories of data were collected from the papers of biochar and N fertilizer amendment experiments: (1) soil GHG fluxes (CO₂, N₂O, and/or CH₄); (2) soil properties, including soil organic C, soil total N, C/N ratio, pH, and soil texture; (3) biochar properties, including C and N content, C/N ratio, pH, feedstock types (wood, herb, and biowaste), pyrolysis temperature, and addition rate (t ha⁻¹); (4) N fertilizer addition rate (kg N ha⁻¹); and (5) additional auxiliary variables, including latitude and longitude, experimental types (field studies, pot experiments, and laboratory incubations), plants (with or not), and experimental duration. The above variables mentioned in (2), (3), (4), and (5) were used to explain the variation in soil GHG fluxes in response to biochar and N fertilizer addition.

### 2.2 Data analysis

#### 2.2.1 Individual and combined effects

The individual effect of biochar, N addition, and the combined two factors was calculated by the response ratio (RR), which was described in the Hedges et al. (1999) and Luo et al. (2006). Specifically, the RR was calculated using the natural log of the ratio of the mean value in treatment than in control as the following equation:

\[
RR = \ln \left( \frac{x_t}{x_c} \right) = \ln x_t - \ln x_c, \tag{1}
\]

where \(x_c\) and \(x_t\) represent the means of the control and treatment groups, respectively. The detailed calculation of the variance (v) and the weight (w) of RR and the weighted RR (RR⁺) is described in He et al. (2017). We also quantified global warming potential (GWP) as follows:

\[
GWP = CO₂ + 298 \times (N₂O) + 25 \times (CH₄), \tag{2}
\]

All fluxes were converted to CO₂ equivalents according to the 100-year GWP (t CO₂ equivalent ha⁻¹) of 298 for N₂O and 25 for CH₄ (IPCC, 2007).

#### 2.2.2 Interactive effects

In this synthesis, main effect of biochar addition refers to the difference by comparing its net effect in the presence and absence of N addition, which is similar to main effect tests in ANOVA (Crain et al., 2008; Zhou et al., 2016). The interactive effects are the simultaneous effects of biochar and N addition on soil GHG fluxes, in which their joint effect is more or less than the sum of the single effect, including synergistic, antagonistic, and additive effects (Crain et al., 2008; Zhou et al., 2016). The Hedge’s \(d\), which was employed by Gurevitch et al. (1992) and Zhou et al. (2019), was used to evaluate the main effect size of two factors and their interactive effects on the variables. We used the following equations to estimate the main effect of biochar \(d_B\) and N addition \(d_N\) as well as their interactions \(d_{BN}\).

\[
d_B = \frac{(\bar{X}_B + \bar{X}_{BN}) - (\bar{X}_N + \bar{X}_C)}{2s} J(m), \tag{3}
\]

\[
d_N = \frac{(\bar{X}_N + \bar{X}_{BN}) - (\bar{X}_B + \bar{X}_C)}{2s} J(m), \tag{4}
\]

\[
d_{BN} = \frac{(\bar{X}_{BN} + \bar{X}_B) - (\bar{X}_N + \bar{X}_C)}{2s} J(m), \tag{5}
\]

where \(\bar{X}_C, \bar{X}_B, \bar{X}_N\), and \(\bar{X}_{BN}\) were the means of a variable in control, biochar, N addition, and their combination treatment groups, respectively. Pooled standard deviation \(s\), degree of freedom \(m\), and correction term for small sample bias \(J(m)\) were estimated using Equations 6, 7, and 8, respectively:

\[
s = \sqrt{\frac{(n_C - 1)(s_C)^2 + (n_B - 1)(s_B)^2 + (n_N - 1)(s_N)^2 + (n_{BN} - 1)(s_{BN})^2}{n_C + n_B + n_N + n_{BN} - 4}}, \tag{6}
\]

\[
m = n_C + n_B + n_N + n_{BN} - 4, \tag{7}
\]

\[
J(m) = 1 - \frac{3}{4m - 1}, \tag{8}
\]
where \( n_C, n_B, n_N, \) and \( n_{BN} \) were the sample sizes of control, biochar, N addition, and their combination treatment groups, respectively. \( S_C, S_B, S_N, \) and \( S_{BN} \) were the standard deviation of control, biochar, N addition, and their combination treatment groups, respectively. The variance \( (v) \) of the main effects and interactions was estimated by Equation 9.

\[
v = \left[ \frac{1}{n_C} + \frac{1}{n_B} + \frac{1}{n_N} + \frac{1}{n_{BN}} + \frac{d^2_{BN}}{2(n_C+n_B+n_N+n_{BN})} \right]/4,
\]

The weight \( (w) \) is the reciprocal of the variance. The detailed weighted \( d (d_{++}) \) and standard error \( s [s(d_{++})] \) were described in Zhou et al. (2016).

When the number of sampling points was more than 20, the 95% confidence interval (CI) of \( d_{++} \) and \( RR_{++} \) was calculated as \( d_{++} \pm C_{a/2} \times s (d_{++}) \) and \( RR_{++} \pm C_{a/2} \times s (RR_{++}) \), respectively. The \( C_{a/2} \) is the two-tailed critical value of the standard normal distribution. While the number was less than 20, a bootstrapping method was used to resample data based on 5000 iterations to obtain the highest and lowest 2.5% value. Three types of interactive effects were identified as additive, synergistic, and antagonistic. If the 95% CI overlapped with zero, the interactive effects were classified as additive. When the individual effects were both positive, the interactive effect size is greater than zero recognized as synergistic (<0 is antagonistic). In case the individual effects were either both negative or one positive and one negative, the interactions were established in the reverse pattern (>0 is antagonistic). In addition, the between-group heterogeneity \( (Q_b) \) was used to investigate the combined effect of biochar and N addition among different sub-grouping categories. Publication bias was tested using funnel plot and Kendall’s Tau methods (Møller & Jennions, 2001; Rosenberg, 2005).

3 | RESULTS

3.1 | Effects of biochar and/or nitrogen addition on soil GHG fluxes

On average, biochar amendment significantly increased soil CO2 emission by 10.1% with a mean weighted \( RR_{++} \) of 0.10 \([CI = (0.03, 0.17)]\), but decreased soil N2O emission by 14.7% with a \( RR_{++} \) of −0.14 \([CI = (-0.25, -0.03)]\) and had no significant effects on soil CH4 emission \([CI = (-0.12, 0.34)]\) and CH4 uptake \([CI = (-0.27, 0.92)]\). Meanwhile, N addition significantly increased soil CO2 and N2O emissions by 11.6% and 288%, respectively, but did not affect soil CH4 emission and uptake (Figure 1). Similarly, the combined biochar and N addition significantly increased soil CO2 and N2O emissions by 18.0% and 148%, respectively, but induced no changes on soil CH4 fluxes (Figure 1).

Biochar amendment had no significant effect on global warming potential (GWP) but N addition increased GWP by 160% with a \( RR_{++} \) of 0.96 \([CI = (0.57, 1.44)]\) (Figure 1e). Meanwhile, the combined biochar and N addition significantly increased GWP by 83.7% \([RR_{++} = 0.61, CI = (0.32, 0.90)]\) (Figure 1e). In addition, publication bias was not found for soil GHG fluxes and GWP in response to biochar, N addition, and their combination, except for CH4 uptake under single biochar addition with only 13 samples (Table S1).

3.2 | Interactive effects of biochar and N addition on soil GHG fluxes

The main effect of biochar addition, which represents the difference between its net effect in the presence and absence of N addition, on soil CO2 emission was significantly positive, but negative on soil N2O emission. Similarly, N addition significantly increased soil CO2 and N2O emissions and GWP, but decreased CH4 uptake (Figure S2). Interactive effects of biochar and N addition on soil GHG fluxes were mainly antagonistic, with the exception of soil CH4 uptake showing an additive interaction (Figure 2a). Although antagonistic effects for soil CO2, N2O, CH4 fluxes, and GWP were observed, additive interaction still showed a dominance for the number of studies as revealed by the frequency distribution of interaction types among individual observations (Figure 2b). Specifically, the additive interactions accounted for 78.7%, 56.7%, 57.6%, 53.8%, and 71.4% on soil CO2, N2O, CH4 emission, CH4 uptake, and GWP, respectively (Figure 2b). Furthermore, the antagonistic interactions on soil CO2 (19.4% vs. 1.9%) and N2O emissions (38.5% vs. 4.8%) were more frequent than synergistic ones (Figure 2b).

The summed effects of biochar and N addition were calculated and compared with the combined biochar and N addition for soil GHG fluxes and their GWP. Our results showed that the summed effects were higher than the combined effects for soil CO2 and N2O fluxes, with the deviation of 28.5% and 17.8%, respectively. However, no significant differences were observed in soil CH4 fluxes and GWP (Figure 3).

3.3 | Regulation of moderator variables on soil GHG fluxes

The responses of soil GHG fluxes to the combined biochar and N addition treatment were significantly influenced by experimental methods (e.g., field studies, pot experiments, and laboratory incubations), N addition rates, soil and biochar properties (Table 1). Specifically, the responses of soil CO2 emission to the combined biochar and N addition increased with biochar TN \( (R^2 = 0.09, p < 0.01) \) and N addition rate \( (R^2 = 0.15, p < 0.01) \), but decreased with biochar
C/N ratio ($R^2 = 0.06, p < 0.05$). Meanwhile, negative correlation between biochar TN and soil N$_2$O emission was observed ($R^2 = 0.06, p < 0.01$), but positive correlations of both biochar C/N ($R^2 = 0.03, p < 0.05$) and soil pH ($R^2 = 0.03, p < 0.05$) with soil N$_2$O emission were found in this study. Likewise, the responses of soil CH$_4$ emission increased with biochar TN ($R^2 = 0.18, p < 0.05$) and addition rate ($R^2 = 0.28, p < 0.01$), but decreased with biochar C/N ratio ($R^2 = 0.17, p < 0.05$; Figure 4).

Experimental method and soil texture induced a significant effect on soil GHG fluxes with respect to the combined biochar and N addition treatment (Table 1). Among the field, pot and laboratory studies, pot studies showed the highest increases in soil CO$_2$ emission, but the lowest increases in soil N$_2$O emission in the combined biochar and N addition treatment (Figure S3). Positive effects of the combined biochar and N addition on soil CO$_2$ emission occurred in soils with fine texture, but no significant effect was observed in soils with coarse and medium texture (Figure S4).

4 | DISCUSSION

4.1 | Individual effects of biochar or N addition on soil GHG fluxes

Both biochar and N addition generally increase soil GHG fluxes (Deng et al., 2020; He et al., 2017; Liu & Greaver, 2009). In this study, biochar addition stimulated soil CO$_2$ emission, but depressed soil N$_2$O emission and induced no significant effects on soil CH$_4$ emission and uptake (Figure 1). Meanwhile, N addition facilitated soil CO$_2$ and N$_2$O emissions, but had no changes on CH$_4$ fluxes (Figure 1). The significant positive effects of biochar and N addition on soil GHG fluxes are supported by the findings of previous meta-analyses (Cayuela et al., 2014; Jeffery et al., 2016; Shcherbak et al., 2014; Zhou et al., 2014).

The potential mechanisms underlying the stimulation of soil CO$_2$ emission by biochar amendment were well synthesized in previous studies, largely due to positive responses...
of leaf photosynthesis rate, shoot and root biomass, soil microbial activities, and soil organic C (SOC) status, and then increasing root and/or microbial respiration (Bai et al., 2015; He, Yao, et al., 2020; Laird, 2008; Nguyen et al., 2016; Olmo et al., 2016). The biochar-induced suppression of soil \( N_2O \) emission was probably driven by the reduction of electron donors and acceptors for denitrification, which might be attributed to sorption and/or immobilization of \( \text{NO}_3^- \) and \( \text{NH}_4^+ \) onto biochar, and the decrease in microbial denitrification induced by the improved soil aeration (Cayuela et al., 2015; Harter et al., 2014; Xu et al., 2014). Furthermore, the decrease in soil \( N_2O \) emission following biochar addition might stem from the stimulation of \( N_2O \)-reducing bacteria community with the increased soil pH and dissolve organic C (Ameloot et al., 2016; Ji et al., 2020).

The stimulation of soil \( CO_2 \) emissions in response to N addition might be due to the increased plant productivity and soil C pools, enlarging the size and activity of soil microbial population, especially in cropland and grassland biomes (Lu, Yang, et al., 2011; Ye et al., 2018; Zhou et al., 2014). Likewise, additional N inputs would enhance the readily N supply for nitrifying and denitrifying
microorganisms, leading to the increase in soil N$_2$O emission (Deng et al., 2020; Fu et al., 2015; Liu & Greaver, 2009). In this study, the responses of soil CH$_4$ emission and uptake to N addition were much more uncertain due to the small sample size and the great heterogeneity in biochar and N addition treatments.

### 4.2 Combined and interactive effects of biochar and N addition on soil GHG fluxes

Understanding the combined and interactive effects of biochar and N addition on soil GHG fluxes is crucial for developing a more optimized strategy towards biochar addition worldwide to mitigate global climate change. In this study, we found that the interactive effects of biochar and N addition on soil GHG fluxes were generally antagonistic (i.e., the combined effect is weaker than the sum of the two individual effects), rather than additive or synergistic (Figure 2).

#### 4.2.1 Combined and interactive effects of biochar and N addition on soil CO$_2$ emission

The combined biochar and N addition significantly stimulated soil CO$_2$ emission by 18%, which was significantly smaller than the sum of two individual effects (26%, Figure 3). The antagonistic interaction on soil CO$_2$ emission could be ascribed to the sorption of exogenous N ($NO_3^-$ and $NH_4^+$) to biochar with high surface area and porosity (Clough et al., 2013; Li et al., 2020; Nguyen et al., 2017), thus reducing N availability for microorganisms. Moreover, biochar amendment would stimulate soil organic matter (SOM) mineralization, causing a positive priming effect (Wang et al., 2016; Yu et al., 2018). With alleviating N limitation for soil microbes following N inputs, the priming effects on SOM decomposition are diminished (Feng & Zhu, 2021), thereby having a decline in CO$_2$ emission.

Soil N$_2$O emission showed a more dominant antagonism interactions compared with synergism (Figure 2b). It could be because biochar amendment counteracted the significant positive effects of additional N inputs on soil N$_2$O emission. Previous studies have suggested that the combined biochar and N addition remarkably boosted plant productivity, which, in turn, increased plant N demands (Backer et al., 2017; Song et al., 2020). Thus, the increase in N uptake by plants and N immobilization by biochar particles probably decreased soil N availability for nitrification and denitrification, resulting in an antagonistic interaction between biochar and N addition. Additionally, N addition to biochar-treated soil can sustain increases in plant productivity, and thus maintain organic C inputs to soils (Liao et al., 2020; Van Zwieten et al., 2010). The inputs of readily available C substrate would accelerate both nitrification and denitrification processes while the increased transcription of N$_2$O reductase genes ($NOSZ$) might
enhance further reduction of soil $N_2O$ to $N_2$ (Anderson et al., 2011; Xu et al., 2014).

Although the combined effects of biochar and N addition showed non-significant effect on soil CH$_4$ emission (Figure 1c), the interaction between these two drivers was exhibited as antagonism (Figure 2b). The combined biochar and N addition induced higher rhizodeposition, above- and belowground biomass, which have been reported in recent studies (He, Yuan, et al., 2020; Shaukat et al., 2019). Thus, the increased available C substrates further stimulate activity of methanotrophs and CH$_4$ oxidation (Feng et al., 2012; Wang et al., 2019), resulting in an antagonistic interaction. However, the interactive effects of biochar and N addition on soil CH$_4$ uptake were found to be additive, which may be attributed to the small sample sizes for these two drivers to conceal potential antagonistic or synergistic effects.

4.3 | Influences of moderator variables

Biochar and soil properties have been widely demonstrated to influence soil C and N cycling in response to biochar and/or N addition (Cayuela et al., 2015; Farrar et al., 2021; He et al., 2017). Our results showed that effects of the combined biochar and N addition on soil CO$_2$ emission exhibited a positive correlation with N addition rate and biochar total N content (TN), but a negative relationship with biochar C/N.
ratio (Figure 4). These suggested that soil CO₂ emission increased with soil available N, which was consistent with the results from Zhou et al. (2014). Meanwhile, the combined biochar and N addition induced a positive effect on CO₂ emission in fine-textured soils while no significant effects were observed in coarse and medium texture soils (Figure S4). It might be attributed to the fact that soil aeration increased in the biochar treatment, which was exceptionally porous with a high cation exchange capacity (CEC) and surface area, hence improving soil retention of water and nutrients. In addition, biochar and N addition may enhance the growth of aerobic microorganisms, thereby stimulating SOC decomposition (Chan & Xu, 2009; McCormack et al., 2019; Wardle et al., 2008).

Surprisingly, our study showed that the responses of N₂O emissions to the combined biochar and N addition displayed no significant correlation with N addition rate (Table 1), probably resulting from the biochar-induced facilitation of complete denitrification to N₂ (Anderson et al., 2011; Wei et al., 2020; Xu et al., 2014). Moreover, the combined biochar and N addition exerted a consistent and significant positive effect on soil N₂O emission across experimental methods, with the lowest positive response of N₂O emission observed in pot experiments (Figure S3). Biochar addition rates in pot experiments were generally higher than those in laboratory or field studies (Liu et al., 2016). Hence, the reduction in soil N₂O emissions could be due to more available N (NO₃⁻ and NH₄⁺) being immobilized by biochar. Additionally, the combined effect of biochar and N addition on soil CH₄ emission largely depends on biochar characteristics and its application rate. Soil CH₄ emission mainly depends on the balance between methanogenic archaeal and methanotrophic communities (Bodelier & Lannbroek, 2004). Therefore, soil CH₄ emission increased with biochar TN and addition rate, probably resulting from the increased ratio of soil methanogenic to methanotrophic abundance (Jeffery et al., 2016; Singla et al., 2014).

### 4.4 Implications for future studies and management

Over the past two decades, several meta-analyses have reported the responses of plant performance, ecosystem C and N-cycles to biochar or N addition (Biederman & Harpole, 2013; He, Yao, et al., 2020; He et al., 2017; Lu, Yang, et al., 2011; Lu, Zhou, et al., 2011; Nguyen et al., 2017; Zhou et al., 2014), but relatively few studies have examined their combined and interactive effects. This synthesis offers some insights for future manipulative experiments and management towards biochar widespread application. First, our findings reveal an antagonistic effect of biochar and N addition on soil GHG fluxes at the global scale. To achieve the targets of limiting global warming to 1.5°C above pre-industrial levels, which was launched at the 21st session of the Conference of the Paris to the United Nations Framework Convention on Climate Change (UNFCCC, 2015), negative emissions technologies (including biochar amending to land) were deployed at the large scale. Since the antagonistic effect of biochar and N addition on GWP was mainly attributed to the significant antagonistic effect of soil CO₂ and N₂O emissions, biochar amendment with N fertilizer may be one of the good strategies for both the crop yield and the mitigation of climate change.

Second, we found that the responses of soil GHG fluxes to biochar and N addition were influenced by biochar and soil properties, implying that biochar combined with relatively low N addition rate appears to be a good strategy to mitigate climate warming in acidic soils on the basis of crop yield being guaranteed. Meanwhile, the influence of biochar and N addition on soil GHG fluxes is site- and ecosystem-specific, suggesting that more field experiments from several hotspot regions (e.g., Africa, South America, and Australia areas) are urgently needed to improve the global perspective. Third, the majority of current studies focus on individual and combined effect of biochar and N addition to ecosystem function and nutrients cycling (Borchard et al., 2019; Oladele et al., 2019; Shi et al., 2020). How and to what extent the interactive effects of biochar and N addition combined with other global change factors (e.g., warming, precipitation changes, and land-use change) on C and N cycling is still a knowledge gap to be addressed in the near future.

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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### REFERENCES

Alburquerque, J. A., Salazar, P., Barrón, V., Torrent, J., del Campillo, M. D. C., Gallardo, A., & Villar, R. (2013). Enhanced wheat yield by biochar addition under different mineral fertilization levels.
Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of The Total Environment*, 654, 463–472. https://doi.org/10.1016/j.scitotenv.2018.11.124

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. *Science of The Total Environment*, 730. https://doi.org/10.1016/j.scitotenv.2020.139003

Gurevitch, J., Morrow, L. L., Wallace, A., & Walsh, J. S. (1992). A meta-analysis of competition in field experiments. *The American Naturalist*, 140, 539–572. https://doi.org/10.1086/285428

Harter, J., Krause, H.-M., Schuettler, S., Ruser, R., Fromme, M., Scholten, T., Kappler, A., & Behrens, S. (2014). Linking N2O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. *The ISME Journal*, 8, 660–674. https://doi.org/10.1038/ismej.2013.160

He, L., Zhao, X., Wang, S., & Xing, G. (2016). The effects of rice straw biochar addition on nitrification activity and nitrous oxide emissions in two Oxisols. *Soil and Tillage Research*, 164, 52–62. https://doi.org/10.1016/j.still.2016.05.006

He, T., Yuan, J., Luo, J., Lindsey, S., Xiang, J., Lin, Y., Liu, D., Chen, Z., & Ding, W. (2020). Combined application of biochar with urease and nitrification inhibitors have synergistic effects on mitigating CH4 emissions in rice field: A three-year study. *Science of The Total Environment*, 743. https://doi.org/10.1016/j.scitotenv.2020.140500

He, Y., Yao, Y., Ji, Y., Deng, J., Zhou, G., Liu, R., Shao, J., Zhou, L., Li, N., Zhou, X., & Bai, S. H. (2020). Biochar amendment boosts photosynthesis and biomass in C3 but not C4 plants: A global synthesis. *GCB Bioenergy*, 12, 605–617. https://doi.org/10.1111/gcbb.12720

He, Y., Zhou, X., Jiang, L., Li, M., Du, Z., Zhou, G., Shao, J., Wang, X., Xu, Z., Hosseini Bai, S., Wallace, H., & Xu, C. (2017). Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy*, 9, 743–755. https://doi.org/10.1111/gcbb.12376

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, 80, 1150–1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2

Hui, D., Yu, C.-L., Deng, Q., Saini, P., Collins, K., & Koff, J. (2018). Weak effects of biochar and nitrogen fertilization on switchgrass photosynthesis, biomass, and soil respiration. *Agriculture*, 8, 143. https://doi.org/10.3390/agriculture8090143

IPCC. (2007). Technical summary. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 19–91). Cambridge University Press.

IPCC. (2013). Summary for policymakers. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 3–29). Cambridge University Press.

Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biology and Biochemistry*, 101, 251–258. https://doi.org/10.1016/j.soilbio.2016.07.021

Jones, D. L., Murphy, D. V., Khalid, M., Ahmad, W., Edwards-Jones, G., & DeLuca, T. H. (2011). Short-term biochar-induced increase in soil CO2 release is both biotically and abiotically mediated. *Soil Biology and Biochemistry*, 43, 1723–1731. https://doi.org/10.1016/j.soilbio.2011.04.018

Laird, D. A. (2008). The charcoal vision: A win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, 100, 178. https://doi.org/10.2134/agronj2007.0161

Lan, Z., Chen, C., Rezaei Rashiti, M., Yang, H., & Zhang, D. (2018). High pyrolysis temperature biochars reduce nitrogen availability and nitrous oxide emissions from an acid soil. *GCB Bioenergy*, 10, 930–945. https://doi.org/10.1111/gcbb.12529

Lehmann, J. (2007). A handful of carbon. *Nature*, 447, 143–144. https://doi.org/10.1038/447I43a

Li, S., Wang, S., Fan, M., Wu, Y., & Shangguan, Z. (2020). Interactions between biochar and nitrogen impact soil carbon mineralization and the microbial community. *Soil and Tillage Research*, 196. https://doi.org/10.1016/j.still.2019.104437

Liao, X., Niu, Y., Liu, D., Chen, Z., He, T., Luo, J., Lindsey, S., & Ding, W. (2020). Four-year continuous residual effects of biochar application to a sandy loam soil on crop yield and N2O and NO emissions under maize-wheat rotation. *Agriculture, Ecosystems & Environment*, 302. https://doi.org/10.1016/j.agee.2020.107109

Liu, L., & Greaver, T. L. (2009). A review of nitrogen enrichment effects on three biogenic GHGs: The CO2 sink may be largely offset by stimulated N2O and CH4 emission. *Ecology Letters*, 12, 1103–1117. https://doi.org/10.1111/j.1461-0248.2009.01351.x

Liu, Q., Liu, B., Zhang, Y., Hu, T., Lin, Z., Liu, G., Wang, X., Ma, J., Wang, H., Jin, H., Ambus, P., Amonette, J. E., & Xie, Z. (2019). Biochar application as a tool to decrease soil nitrogen losses (NH3 volatilization, N2O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective. *Global Change Biology*, 25, 2077–2093. https://doi.org/10.1111/gcb.14613

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, 392–406. https://doi.org/10.1111/gcbb.12265

Lu, M., Yang, Y., Luo, Y., Fang, C., Zhou, X., Chen, J., Yang, X., & Li, B. (2011). Responses of ecosystem nitrogen cycle to nitrogen...
addition: A meta-analysis. New Phytologist, 189, 1040–1050. https://doi.org/10.1111/nph.1469-8137.2010.03563.x

Lu, M., Zhou, X., Luo, Y., Yang, Y., Fang, C., Chen, J., & Li, B. (2011). Minor stimulation of soil carbon storage by nitrogen addition: A meta-analysis. Agriculture, Ecosystems & Environment, 140, 234–244. https://doi.org/10.1016/j.agee.2010.12.010

Luo, Y., Hui, D., & Zhang, D. (2006). Elevated CO₂ stimulates net accumulations of carbon and nitrogen in land ecosystems: A meta-analysis. Ecology, 87, 53–63. https://doi.org/10.1890/04-1724

Maestrini, B., Herrmann, A. M., Nanni, P., Schmidt, M. W. I., & Abiven, S. (2014). Ryegrass-derived pyrogenic organic matter changes organic carbon and nitrogen mineralization in a temperate forest soil. Soil Biology and Biochemistry, 69, 291–301. https://doi.org/10.1016/j.soilbio.2013.11.013

McCormack, S. A., Ostle, N., Bardgett, R. D., Hopkins, D. W., Pereira, M. G., & Vanbergen, A. J. (2019). Soil biota, carbon cycling and crop plant biomass responses to biochar in a temperate mesocosm experiment. Plant and Soil, 440, 341–356. https://doi.org/10.1007/s11104-019-04062-5

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., & Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. Nature, 458, 1158–1162. https://doi.org/10.1038/nature08017

Møller, A. P., & Jennions, M. D. (2001). Testing and adjusting for publication bias. Trends in Ecology & Evolution, 16, 580–586. https://doi.org/10.1016/S0169-8137(01)02235-2

Nguyen, D. H., Scheer, C., Rowlings, D. W., & Grace, P. R. (2016). Rice husk biochar and crop residue amendment in subtropical cropping soils: Effect on biomass production, nitrogen use efficiency and greenhouse gas emissions. Biochar and Fertility of Soils, 52, 261–270. https://doi.org/10.1007/s00374-015-1074-4

Nguyen, T. T. N., Xu, C.-Y., Tahmashian, I., Che, R., Xu, Z., Zhou, X., Wallace, H. M., & Bai, S. H. (2017). Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. Geoderma, 288, 79–96. https://doi.org/10.1016/j.geoderma.2016.11.004

Oladele, S. O., Adeyemo, A. J., & Awodun, M. A. (2019). Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils. Geoderma, 336, 1–11. https://doi.org/10.1016/j.geoderma.2018.08.025

Olmo, M., Villar, R., Salazar, P., & Alburquerque, J. A. (2016). Changes in soil nutrient availability explain biochar’s impact on wheat root development. Plant and Soil, 399, 333–343. https://doi.org/10.1007/s11104-015-2700-5

Rosenberg, M. S. (2005). The file-drawer problem revisited: A general weighted method for calculating fail-safe numbers in meta-analysis. Evolution, 59, 464–468. https://doi.org/10.1111/j.0014-3820.2005.tb01004.x

Sarauer, J. L., Page-Dumroese, D. S., & Coleman, M. D. (2019). Soil greenhouse gas, carbon content, and tree growth response to biochar amendment in western United States forests. GCB Bioenergy, 11, 660–671. https://doi.org/10.1111/gcbb.12595

Shakoor, A., Shakoor, S., Rehman, A., Ashraf, F., Abdullah, M., Shahzad, S. M., Farooq, T. H., Ashraf, M., Manzoor, M. A., Altuf, M. M., & Altuf, M. A. (2021). Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils – A global meta-analysis. Journal of Cleaner Production, 278. https://doi.org/10.1016/j.jclepro.2020.124019

Shaukat, M., Samoy-Pascual, K., Maas, E. D. L., & Ahmad, A. (2019). Simultaneous effects of biochar and nitrogen fertilization on nitrous oxide and methane emissions from paddy rice. Journal of Environmental Management, 248. https://doi.org/10.1016/j.jenvman.2019.07.013

Shcherbak, I., Millar, N., & Robertson, G. P. (2014). Global metaanalysis of the nonlinear response of soil nitrous oxide (N₂O) emissions to fertilizer nitrogen. Proceedings of the National Academy of Sciences of the United States of the America, 111, 9199–9204. https://doi.org/10.1073/pnas.1322434111

Sherman, L., & Coleman, M. D. (2020). Forest soil respiration and exoenzyme activity in western North America following thinning, residue removal for biofuel production, and compensatory soil amendments. GCB Bioenergy, 12, 223–236. https://doi.org/10.1111/gcbb.12668

Shi, W., Ju, Y., Bian, R., Li, L., Joseph, S., Mitchell, D. R. G., Munroe, P., Taherymoosavi, S., & Pan, G. (2020). Biochar bound urea boosts plant growth and reduces nitrogen leaching. Science of The Total Environment, 701. https://doi.org/10.1016/j.scitenv.2019.134424

Singla, A., Dubey, S. K., Singh, A., & Inubushi, K. (2014). Effect of biogas digested slurry-based biochar on methane flux and methanogenic archaeal diversity in paddy soil. Agriculture, Ecosystems & Environment, 197, 278–287. https://doi.org/10.1016/j.agee.2014.08.010

Smith, P. (2016a). Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22, 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016b). Biophysical and economic limits to negative CO₂ emissions. Nature Climate Change, 6, 42–50. https://doi.org/10.1038/nclimate2870

Song, X., Razavi, B. S., Ludwig, B., Zamanian, K., Zang, H., Kuzyakov, Y., Dippold, M. A., & Gunina, A. (2020). Combined biochar and nitrogen application stimulates enzyme activity and root plasticity. Science of The Total Environment, 735. https://doi.org/10.1016/j.scitotenv.2020.139393

Sui, Y., Gao, J., Liu, C., Zhang, W., Lan, Y., Li, S., Meng, J., Xu, Z., & Tang, L. (2016). Interactive effects of straw-derived biochar and N fertilization on soil C storage and rice productivity in rice paddies of Northeast China. Science of The Total Environment, 544, 203–210. https://doi.org/10.1016/j.scitotenv.2015.11.079

Sykes, A. J., Macleod, M., Eory, V., Rees, R. M., Payen, F., Myrgiotis, V., Williams, M., Sohi, S., Hillier, J., Moran, D., Manning, D. A. C., Goglio, P., Seghetta, M., Williams, A., Harris, J., Dondini, M., Walton, J., House, J., & Smith, P. (2020). Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. Global Change Biology, 26, 1085–1108. https://doi.org/10.1111/gcb.14844
UNFCCC. (2015). Adoption of the Paris Agreement, Report No. FCCC/CP/2015/L.9/Rev.1. Retrieved from http://unfccc.int/resource/docs/2015/cop21/eng/09r01.pdf

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, 327, 235–246. https://doi.org/10.1007/s11104-009-0050-x

Van Zwieten, L., Singh, B. P., Joseph, S., Kimber, S., Cowie, A., & Chan, K. Y. (2009). Biochar and emission of non-CO2 greenhouse gases from soil. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management science and technology* (pp. 227–249). Earthscan.

Wang, C., Shen, J., Liu, J., Qin, H., Yuan, Q., Fan, F., Hu, Y., Wang, J., Wei, W., Li, Y., & Wu, J. (2019). Microbial mechanisms in the reduction of CH4 emission from double rice cropping system amended by biochar: A four-year study. *Soil Biology and Biochemistry*, 135, 251–263. https://doi.org/10.1016/j.soilbio.2019.05.012

Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8, 512–523. https://doi.org/10.1111/gcbb.12266

Wardle, D. A., Nilsson, M.-C., & Zackrisson, O. (2008). Fire-derived charcoal causes loss of forest humus. *Science*, 320, 629. https://doi.org/10.1126/science.1154960

Wei, W., Yang, H., Fan, M., Chen, H., Guo, D., Cao, J., & Kuzyakov, Y. (2020). Biochar effects on crop yields and nitrogen loss depending on fertilization. *Science of The Total Environment*, 702. https://doi.org/10.1016/j.scitotenv.2019.134423

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, 1–9. https://doi.org/10.1038/ncomm s1053

Wu, Z., Zhang, X., Dong, Y., Li, B., & Xiong, Z. (2019). Biochar amendment reduced greenhouse gas intensities in the rice-wheat rotation systems: Six-year field observation and meta-analysis. *Agricultural and Forest Meteorology*, 278. https://doi.org/10.1016/j.agrmet.2019.107625

Xiang, Y., Deng, Q., Duan, H., & Guo, Y. (2017). Effects of biochar application on root traits: A meta-analysis. *GCB Bioenergy*, 9, 1563–1572. https://doi.org/10.1111/gcbb.12449

Xu, H. J., Wang, X. H., Li, H., Yao, H. Y., Su, J. Q., & Zhu, Y. G. (2014). Biochar impacts soil microbial community composition and nitrogen cycling in an acidic soil planted with rape. *Environmental Science & Technology*, 48, 9391–9399. https://doi.org/10.1021/es5021058

Yanai, Y., Toyota, K., & Okazaki, M. (2007). Effects of charcoal addition on N2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Science and Plant Nutrition*, 53, 181–188. https://doi.org/10.1111/j.1747-0765.2007.00123.x

Ye, C., Chen, D., Hall, S. J., Pan, S., Yan, X., Bai, T., Guo, H., Zhang, Y., Bai, Y., & Hu, S. (2018). Reconciling multiple impacts of nitrogen enrichment on soil carbon: Plant, microbial and geochemical controls. *Ecology Letters*, 21, 1162–1173. https://doi.org/10.1111/ele.13083

Yu, Z., Chen, L., Pan, S., Li, Y., Kuzyakov, Y., Xu, J., Brookes, P. C., & Luo, Y. (2018). Feedstock determines biochar-induced soil priming effects by stimulating the activity of specific microorganisms: Feedstock of biochar determines priming effects. *European Journal of Soil Science*, 69, 521–534. https://doi.org/10.1111/1365-2442.12542

Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L., Zheng, J., & Zhang, X. (2012). Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. *Plant and Soil*, 351, 263–275. https://doi.org/10.1007/s11104-011-0957-x

Zhang, J., Li, Q., Wu, J., & Song, X. (2019). Effects of nitrogen deposition and biochar amendment on soil respiration in a Torreya grandis orchard. *Geoderma*, 355. https://doi.org/10.1016/j.geoderma.2019.113918

Zheng, J., Stewart, C. E., & Cotrufo, M. F. (2012). Biochar and nitrogen fertilizer alters soil nitrogen dynamics and greenhouse gas fluxes from two temperate soils. *Journal of Environmental Quality*, 41, 1361–1370. https://doi.org/10.2134/jeq2012.0019

Zhou, G., Luo, Q., Chen, Y., Hu, J., He, M., Gao, J., Zhou, L., Liu, H., & Zhou, X. (2019). Interactive effects of grazing and global change factors on soil and ecosystem respiration in grassland ecosystems: A global synthesis. *Journal of Applied Ecology*, https://doi.org/10.1111/1365-2664.13443

Zhou, L., Zhou, X., Shao, J., Nie, Y., He, Y., Jiang, L., Wu, Z., & Hosseini Bai, S. (2016). Interactive effects of global change factors on soil respiration and its components: A meta-analysis. *Global Change Biology*, 22, 3157–3169. https://doi.org/10.1111/gcb.13253

Zhou, L., Zhou, X., Zhang, B., Lu, M., Luo, Y., Liu, L., & Li, B. (2014). Different responses of soil respiration and its components to nitrogen addition among biomes: A meta-analysis. *Global Change Biology*, 20, 2332–2343. https://doi.org/10.1111/gcb.12490

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.