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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 CO_2 emission by 10.1%, but decreased N_2O emission by 14.7%. Meanwhile, N addition increased both soil CO_2 and N_2O emissions by 11.6% and 288%, respectively. The combination of biochar and N addition also exhibited significant positive effect on CO_2 (+18.0%) and N_2O (+148%) emissions, but there were non-significant changes in CH_4 fluxes. Consequently, antagonistic interaction between biochar and N addition was observed in soil GHG fluxes and their global warming potential (GWP), except for CH_4 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., CO_2, CH_4, and N_2O; 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 CO_2 emissions by 3%–22% on average, but reduced N_2O emissions by 31%–54%, and had no effect on CH_4 fluxes (Cayuela et al., 2014; He et al., 2017; Jeffery et al., 2016; Liu et al., 2016). Increases in soil CO_2 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 N_2O 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 CH_4 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 CO_2 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 CO_2, N_2O, and/or CH_4 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 N_2O 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 CO_2 OR CH_4 OR N_2O". 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 CO_2, CH_4, and/or N_2O 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 (CO_2, N_2O, and/or CH_4); (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 that in control as the following equation:

$$RR = \ln\left(\frac{x_t}{x_c}\right) = \ln x_t - \ln x_c, \quad (1)$$

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 weighed *RR* (RR_{++}) is described in He et al. (2017).

We also quantified global warming potential (GWP) as follows:

$$\text{GWP} = CO_2 + 298 \times (N_2O) + 25 \times (CH_4), \quad (2)$$

All fluxes were converted to CO_2 equivalents according to the 100-year GWP (t CO_2 equivalent ha^{-1}) of 298 for N_2O and 25 for CH_4 (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}).

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

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

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

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:

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

$$m = n_C + n_B + n_N + n_{BN} - 4, \quad (7)$$

$$J(m) = 1 - \frac{3}{4m - 1}, \quad (8)$$

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.

$$v = \left[\frac{1}{n_C} + \frac{1}{n_B} + \frac{1}{n_N} + \frac{1}{n_{BN}} + \frac{d_{BN}^2}{2(n_C + n_B + n_N + n_{BN})} \right] /4, \quad (9)$$

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 $d_{++} \pm C_{\alpha/2} \times s\ (d_{++})$ and $RR_{++} \pm C_{\alpha/2} \times s\ (RR_{++})$, respectively. The $C_{\alpha/2}$ 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 CO_2 emission by 10.1% with a mean weighted RR_{++} of 0.10 [CI = (0.03, 0.17)], but decreased soil N_2O emission by 14.7% with a RR_{++} of −0.14 [CI = (−0.25, −0.03)] and had no significant effects on soil CH_4 emission [CI = (−0.12, 0.34)] and CH_4 uptake [CI = (−0.27, 0.92)]. Meanwhile, N addition significantly increased soil CO_2 and N_2O emissions by 11.6% and 288%, respectively, but did not affect soil CH_4 emission and uptake (Figure 1). Similarly, the combined biochar and N addition significantly increased soil CO_2 and N_2O emissions by 18.0% and 148%, respectively, but induced no changes on soil CH_4 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 CH_4 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 CO_2 emission was significantly positive, but negative on soil N_2O emission. Similarly, N addition significantly increased soil CO_2 and N_2O emissions and GWP, but decreased CH_4 uptake (Figure S2). Interactive effects of biochar and N addition on soil GHG fluxes were mainly antagonistic, with the exception of soil CH_4 uptake showing an additive interaction (Figure 2a). Although antagonistic effects for soil CO_2, N_2O, CH_4 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 CO_2, N_2O, CH_4 emission, CH_4 uptake, and GWP, respectively (Figure 2b). Furthermore, the antagonistic interactions on soil CO_2 (19.4% vs. 1.9%) and N_2O 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 CO_2 and N_2O fluxes, with the deviation of 28.5% and 17.8%, respectively. However, no significant differences were observed in soil CH_4 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 CO_2 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

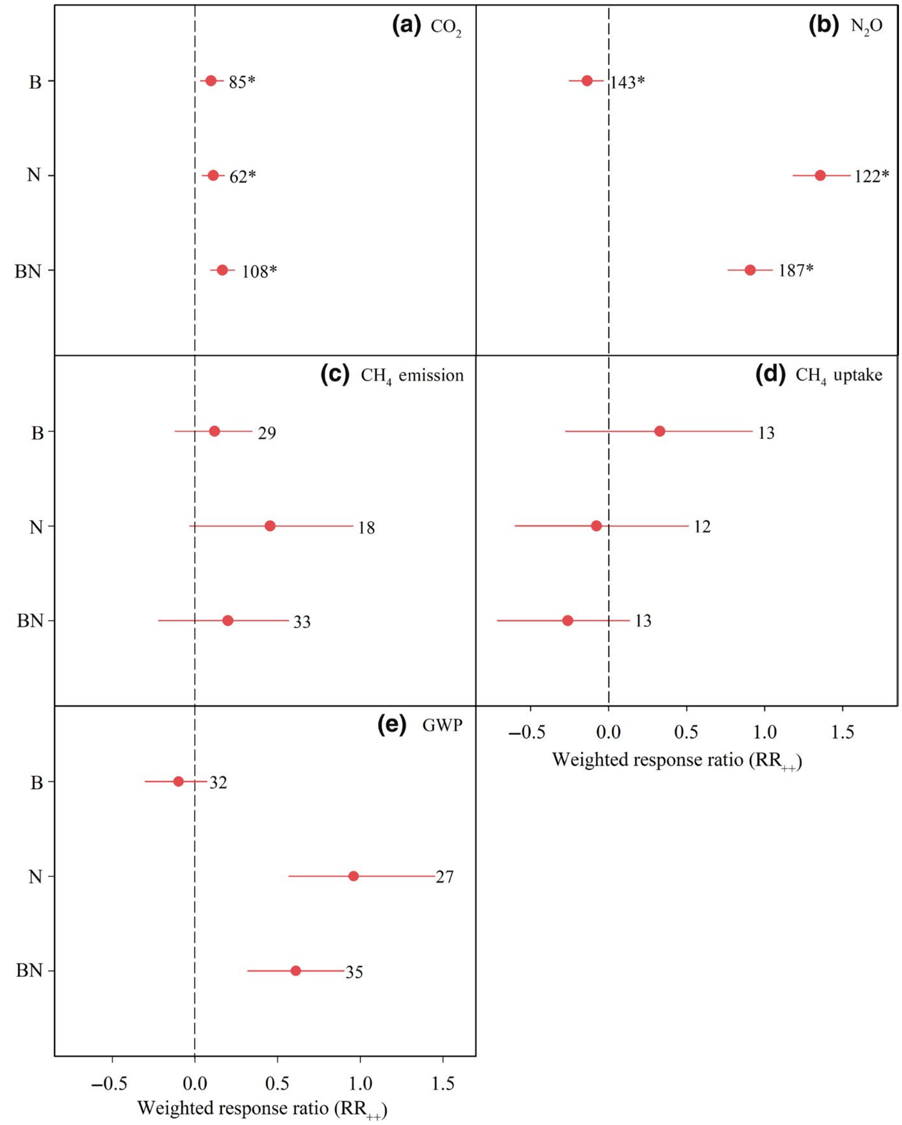

FIGURE 1 Effects of biochar (B), N addition (N) and their combination (BN) on soil GHG fluxes (CO_2, N_2O, and CH_4), and their global warming potential (GWP) are shown as mean response ratio (RR_{++}). Mean effect and 95% confidence interval (CI) are shown. If the CI did not overlap the zero, the response was considered as significant ('*'). Numerals mean the number of observations

C/N ratio ($R^2 = 0.06$, $p < 0.05$). Meanwhile, negative correlation between biochar TN and soil N_2O 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_2O 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_2O 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_2O emission and induced no significant effects on soil CH_4 emission and uptake (Figure 1). Meanwhile, N addition facilitated soil CO_2 and N_2O 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

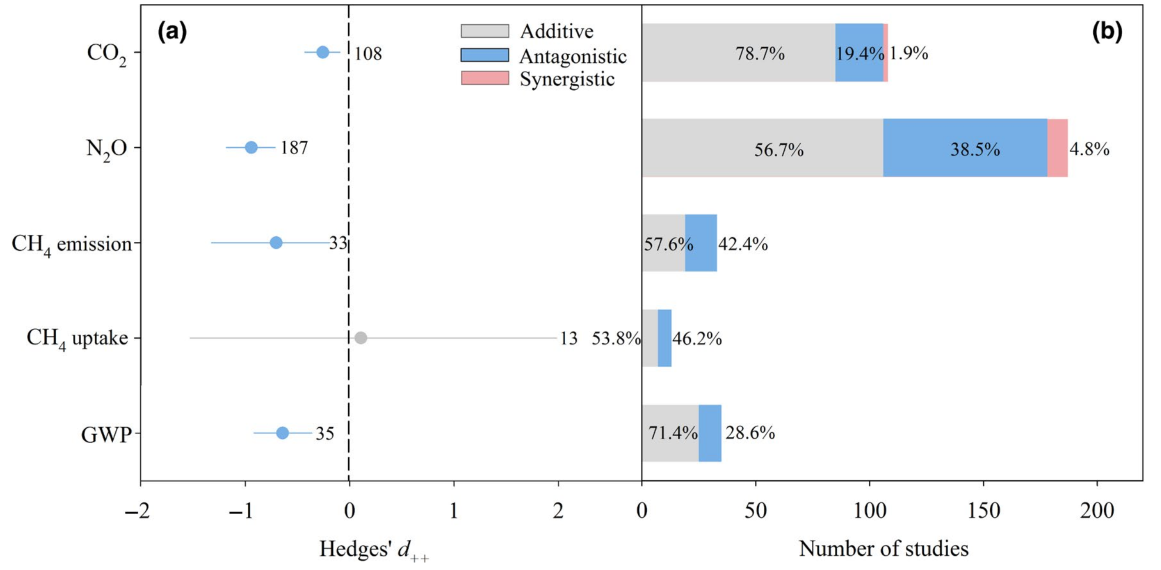

FIGURE 2 The interaction types of biochar and nitrogen in soil GHG (CO_2, N_2O, and CH_4) fluxes and their global warming potential (GWP, a). The percentage of the three interaction types in all studies is shown (b)

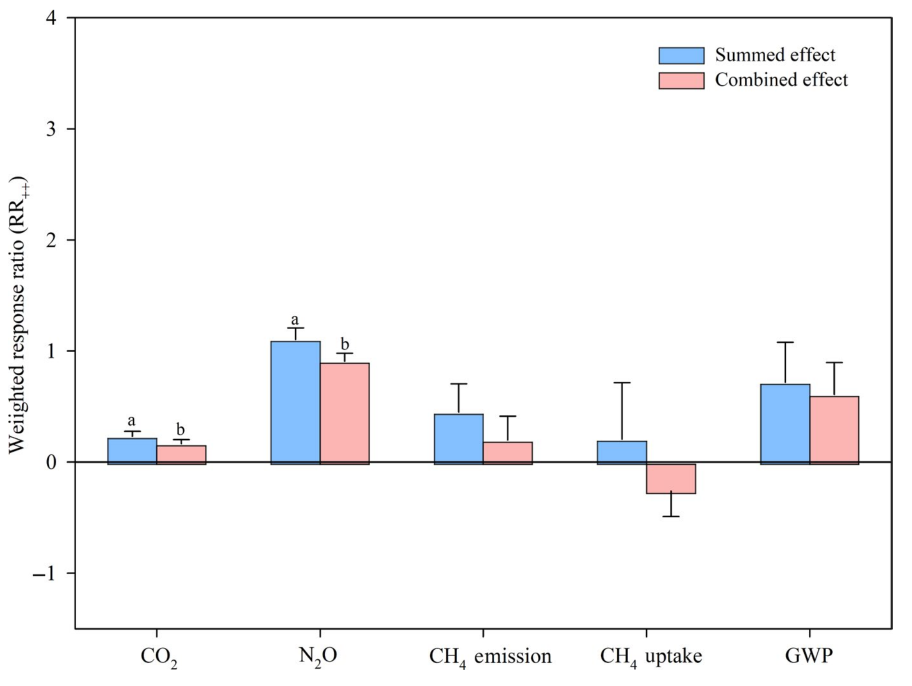

FIGURE 3 The weighted response ratio (RR_{++}) of the summed and combined effects on GHG (CO_2, N_2O, and CH_4) fluxes and global warming potential (GWP). Different lower case letters mean significant different between the summed effect (B+N) and the combined effect (BN) at $p < 0.05$. Summed effect represents the sum of individual biochar and N addition effect, where the combined effect means the effect of biochar co-applied with N addition

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 NO_3^- and 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

TABLE 1 Between-group variability (Q_b) among observations (n) suggesting their potential as predictive variables influencing soil GHG fluxes to biochar combined with N addition

		CO_2		N_2O		CH_4-emission		CH_4-uptake	
	Variables	Q_b	n	Q_b	n	Q_b	n	Q_b	N
Experimental factors	Exp. Method	24.91***	108	13.57**	187	2.31	33	1.74	13
	Exp. Duration	0.14	108	0.01	178	0.28	33	0.43	13
	Latitude	0.05	108	4.00*	187	0.70	33	1.27	13
	With plant	0.01	108	2.81	187	1.06	33	1.74	13
Nitrogen	N addition rate (t ha^{-1})	15.24***	98	0.06	172	0.34	31	0.01	12
Soil properties	Soil texture	7.7*	85	2.66	148	5.67	21	9.90**	9
	Soil pH	1.98	104	4.78*	180	0.06	33	0.35	11
	Soil C/N	0.34	80	1.37	124	7.36**	23	0.003	10
Biochar properties	Source	1.34	108	2.24	187	0.94	33	1.54	13
	Pyrolysis temp. (°C)	0.18	108	0.73	181	13.57***	29	3.80	13
	Biochar C/N	2.32	86	6.37*	178	13.54***	33	1.48	11
	Biochar pH	2.00	101	0.01	182	1.05	33	0.77	11
	Biochar addition rate (t ha^{-1})	0.85	92	0.46	161	0.22	27	0.26	10
	Biochar TN (g kg^{-1})	8.84**	100	9.10**	175	5.25*	33	0.06	7

Note: A variation with larger Q_b can be a better predictor than the small one. Statistical significance of Q_b: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

microorganisms, leading to the increase in soil N_2O 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). Meanwhile, the interactions between biochar and N addition also exhibited a significant antagonistic influence on GWP because of the significant antagonistic effect of soil CO_2 and N_2O emissions. Our findings indicate that the combined biochar and N addition is potentially sustainable to improve crop yields (Alburquerque et al., 2013; Ali et al., 2020), and simultaneously negate soil GHG emissions compared with N addition.

Specifically, 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. Furthermore, 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_2O 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_2O 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_2O reductase genes (*NosZ*) might

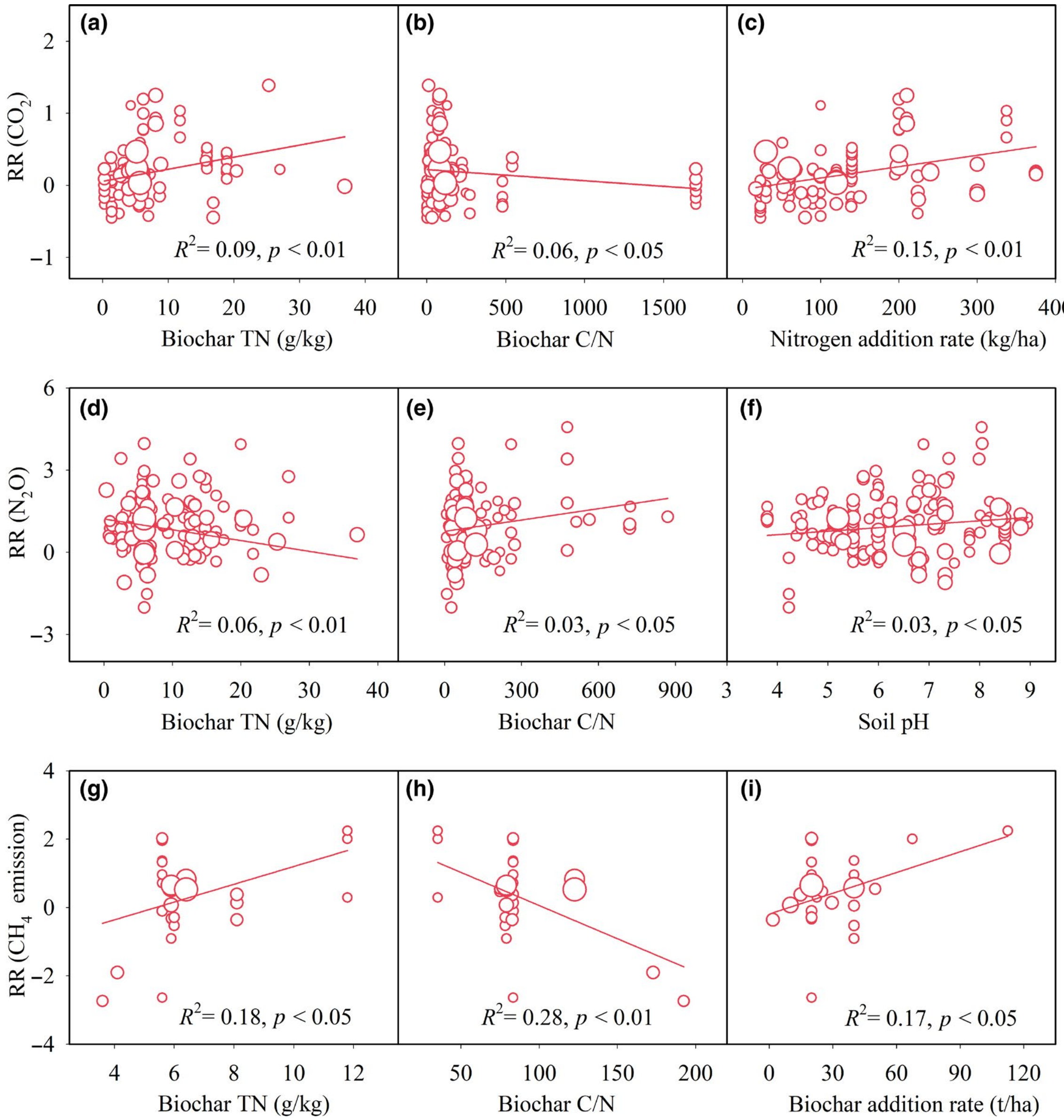

FIGURE 4 Bubble plots of the meta-regression results between the response ratio of soil greenhouse gas fluxes and biochar properties (biochar TN, biochar C/N), biochar and N addition rate, and soil pH. Sizes of circles represent the weights of each observation in meta-regressions. Weights for each observation are the inverses of sum of variance and tau^2

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 CO_2 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 CO_2 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 N_2O 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 N_2 (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 N_2O emission across experimental methods, with the lowest positive response of N_2O 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 N_2O emissions could be due to more available N (NO_3^- and NH_4^+) being immobilized by biochar. Additionally, the combined effect of biochar and N addition on soil CH_4 emission largely depends on biochar characteristics and its application rate. Soil CH_4 emission mainly depends on the balance between methanogenic archaeal and methanotrophic communities (Bodelier & Lannbroek, 2004). Therefore, soil CH_4 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 CO_2 and N_2O 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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SUPPORTING INFORMATION

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

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