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Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis

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ABSTRACT

Biochar application has been widely recommended as a potential solution to tackle the challenges of food security and climate change in agroecosystems, but the effect sizes of biochar application on crop yield, soil carbon sequestration, and global warming potential (GWP) shows great uncertainties. To explore the effect variation of biochar application alone (B) and biochar combined with chemical fertilizers (BF) on crop yield, soil organic carbon (SOC), and GWP, this study reviewed updated datasets with 455, 131, and 95 independent experiments globally to identify the key factors influencing the responses of crop yield, SOC, and GWP to B and BF, respectively. Overall, the effect sizes were different between B and BF in both improving crop yield (15.1 % and 48.4 %, respectively) and decreasing GWP (27.1 % and 14.3 %, respectively), whereas there were almost no differences in terms of increasing SOC (32.9 % and 34.8 %, respectively). In addition, the effect sizes of B and BF on crop yield were coupled with these on SOC. Increased biochar carbon to nitrogen ratio (C:N ratio) and soil pH decreased the impact of B and BF on crop yield, while increased SOC promoted the impact of BF on crop yield. The effect size on GWP increased with biochar pH increasing but soil pH decreasing under B and BF. The wetness index, soil properties (SOC, pH, and clay), and biochar properties (type, pH, C:N ratio, and application rate) jointly explained 70 %–79 %, 90 %–93 %, and 70 %–97 % of the effect variations in crop yield, SOC, and GWP, respectively. The biochar C:N ratio and soil pH were the most important factors determining the effect size of biochar application on crop yield, SOC, and GWP. Taken together, biochar application is a tripartite win-win solution for improving crop yield, increasing SOC, and decreasing GWP mainly depending on biochar properties and soil pH.

1. Introduction

Sustaining crop production to feed the growing population with limited arable soil is a great challenge for agriculture (Valin et al., 2013). In addition to its significant role in crop production, agricultural soil is also expected to contribute to mitigating climate warming by soil carbon (C) sequestration, and reduce greenhouse gas emissions through effective agricultural management practice (Lal, 2004; Wiesmeier et al., 2014). Biochar is a carbon-rich byproduct produced by the pyrolysis of agricultural waste (e.g., crop straw, wood, and manure) at high temperatures (400–700) and anoxic conditions (Smith, 2016; Sohi et al., 2010). It has a large specific surface area, stable physical and chemical properties, abundant pore structure and surface functional groups, and has been proposed as an emerging agricultural soil amendment material

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(Smith, 2016; Sohi et al., 2010). Biochar application has been regarded as an effective agricultural management practice to mitigate the threats of climate change and ensure global food security (Crane-Droesch et al., 2013; He et al., 2017; Smith, 2016).

Results on the effect of biochar on crop yield, soil organic carbon (SOC), and greenhouse gas emissions have shown wide variation and high uncertainty (Liu et al., 2016a, 2013). For example, previous results from global meta-analyses proved that biochar application could improve crop yield by 5 %–51 % and reduce soil nitrous oxide (N_2O) emissions by 28 %–60 % (Biederman and Harpole, 2013; Borchard et al., 2019; Cayuela et al., 2014; He et al., 2017; Liu et al., 2013). Moreover, biochar application increases or insignificantly affects soil CO_2 fluxes (He et al., 2017; Liu et al., 2016a), and decreases or insignificantly affects soil methane (CH_4) fluxes (He et al., 2017; Jeffery et al., 2016). The large variation and uncertainty of the effect of biochar could be attributed to anthropogenic factors, especially for biochar applied alone (B) and combined with chemical fertilizers (BF). Compared with B, BF application could not only directly provide mineral nutrients needed for crop growth but also increase greenhouse gas emissions due to the addition of chemical fertilizers (Al-Wabel et al., 2018; DeLuca et al., 2009). Therefore, to obtain a more accurate estimate of the effect of biochar, it is imperative to focus on distinguishing the effects of B and BF on crop yield, SOC, and greenhouse gas emissions.

The large effect variation of B and BF on crop yield, SOC, and greenhouse gas emissions is also dependent on different influencing variables, which can be divided into three categories: climatic factors, management practices, and soil properties (He et al., 2017; Jeffery et al., 2011; Liu et al., 2016a). Among them, climate is generally regarded as the dominant variable that regulates crop yield by directly providing temperature and precipitation for crop productivity (Crane-Droesch et al., 2013; Jeffery et al., 2017). However, the increase in crop productivity or biomass could result in a higher rate of root deposits and crop residue retention in fields and thus eventually enriching the SOC (Cai et al., 2019). With a high proportion of recalcitrant carbon, biochar has been regarded as a potential medium for soil C sequestration and greenhouse gas emissions reduction (Schmidt et al., 2002). Besides carbon substrate input, the application of biochar with a high C:N ratio results in microbial nitrogen immobilization in soil (Kirkby et al., 2014). Decreased soil microbial activities as a consequence of biochar with a high C:N ratio would lead to a decline in soil greenhouse gas fluxes and an increase in SOC (Cleveland and Liptzin, 2007; Kirkby et al., 2014). Biochar with moderate alkalinity would benefit lower SOC mineralization, while biochar with extremely high or low pH values would incur macronutrient deficiencies and finally generate low crop yield and greenhouse gas flux (Chan and Xu, 2012). Climate and biochar properties also influence the potential effect of biochar by regulating soil properties (Biederman and Harpole, 2013; Smith, 2016). Biochar application in acidic soils greatly enhances its consumption by microorganisms for balanced soil pH conditions, which may trigger a more vigorous priming effect on native SOC mineralization (Foereid et al., 2011; Jones et al., 2011). Instead, biochar amendment to neutral or alkaline soils would incur an inhibition of soil carbon mineralization with enhanced soil pH (Liu et al., 2016a). Owing to the interactions among different variables (e.g., climate, management practices, and soil properties), the practice of predicting the effect of biochar on crop yield, SOC, and greenhouse gas emissions based on individual factors (e.g., temperature, soil texture, biochar application rate, etc.) would produce considerable uncertainty (He et al., 2017; Jeffery et al., 2017, 2011; Liu et al., 2016a, 2019).

Therefore, an enhanced understanding of the relative importance of different variables influencing the effect size of biochar application on crop yield, SOC, and global warming potential (GWP), particularly B and BF application, is urgently needed to accurately predict and improve the potential benefit of biochar. In this study, 95 individual experiments derived globally from 143 published literatures were synthesized to examine the responses of crop yield, SOC, and greenhouse gas emissions to B and BF. The specific objectives of this study were to (1) quantitatively examine the effect size of B and BF on crop yield, SOC, and GWP under differently conditions, and (2) identify the key factors influencing the effect size of B and BF application on crop yield, SOC, and GWP to a better understanding of the implications of biochar application in sustainable agricultural ecosystems.

2. Materials and methods

2.1. Database collection

To establish a comprehensive database of the effect of biochar on crop yield in the global agricultural ecosystem, strict criteria (described below) were set up to obtain closely relevant data from the Web of Science (http://apps.webofknowledge.com), Google Scholar (https://scholar.google.com), and China Knowledge Resource Integrated Database (http://www.cnki.net/) with combined keywords ("biochar", "crop productivity", "crop yield", and "grain yield"). All the selected published literature and experimental data adhered to the following requirements: (a) Manipulative experiments were conducted in the field (outdoor environment), while laboratory and incubation experiments were excluded to avoid the disturbance of the growing environmental variables of crops growth from humans. Targeted experiments included control (with no biochar addition) and treatment groups (with biochar addition), and each group had no less than three plots as replicates; (b) No biochar was applied before or during the targeted experiments in the control group. For treatment groups, a study was obliged to specify whether it was the application of B or BF; (c) Studies meeting to the above two criteria and having data of SOC and GWP under B and BF were as well recorded; (d) Experimental data could be obtained directly from the figure, table, or text. For these data in figures, the GetData Graph Digitizer 2.24 was used. Relevant meta-analysis literature of previously published syntheses and the subsequent experimental data until December 2019 were included in this database.

A total of 1080 paired crop yield data under biochar addition experiments from 143 published literatures were collected, including 648 under B and 430 under BF treatments, and 333 with SOC determinations, and 298 with GWP determinations (Table 1). The spatial distribution of targeted sites was shown in Fig. 1. In addition to crop yield, information including the first author, publication year, site location (country, latitude, and longitude), climate variables (mean annual temperature (MAT) and precipitation (MAP)), crop type, biochar

Table 1
Effect size of biochar applied alone (B) and biochar combined with chemical fertilizers (BF) on crop yield, soil organic carbon (SOC), and global warming potential (GWP).

Index	Treatments	Effect size (Lower *CI*, Upper *CI* (%))	No. of independent experiments	Sampling sizes
Crop yield	Total	22.2 (18.7, 25.7)	455	1078
	B	15.1 (12.1, 18.3)	278	648
	BF	48.4 (41.8, 55.3)	177	430
SOC	Total	33.5 (23.2, 45.2)	131	333
	B	32.9 (21.7, 44.8)	86	230
	BF	34.8 (24.2, 46.5)	45	103
GWP	Total	−22.1 (−29.4, −14.9)	95	298
	B	−27.1(−32.2, −21.6)	62	162
	BF	−14.3 (−25.4, −3.2)	33	136

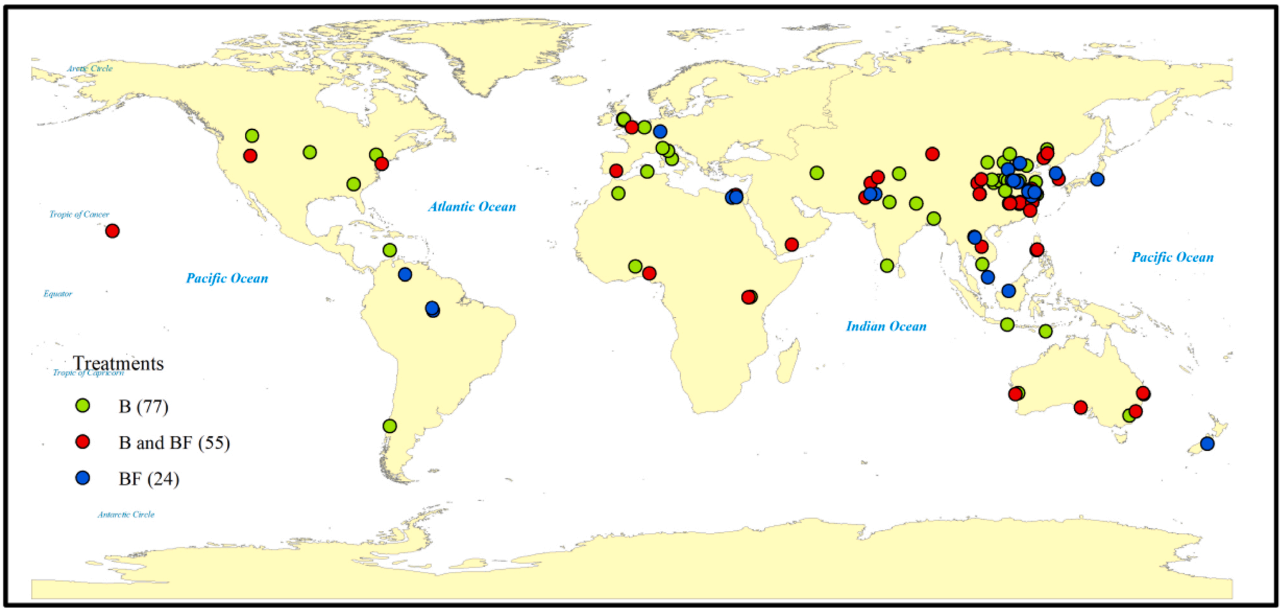

Fig. 1. Global distribution of 455 independent experiments from 156 study sites selected. Letters B (278 independent experiments) and BF (177 independent experiments) represent biochar applied alone and biochar combined with chemical fertilizers, respectively.

properties (biochar type, biochar application rate, biochar pH, biochar carbon content and biochar nitrogen content), soil physicochemical properties (SOC, soil total nitrogen, soil pH, and soil texture), and greenhouse gases (i.e., CO_2, CH_4, and N_2O) emissions were as well extracted from the targeted literature to explain the variation of crop yield.

The GWP is an indicator of the total impact of greenhouse gases on the global greenhouse effect. Based on the data of greenhouse gases (i.e., CO_2, CH_4, and N_2O) emissions, the GWP was estimated using the following equation (IPCC, 2014):

$$GWP = 25 \times R_{CH_4} + 298 \times R_{N_2O} + R_{CO_2} \tag{1}$$

where R_{CO_2}, R_{CH_4}, and R_{N_2O} are the soil CO_2, CH_4, and N_2O emissions reported in the targeted literature (kg ha^{-1}), respectively.

Finally, another database (489 paired crop yield data) was established to explore the interaction of biochar and fertilizers on crop yield because there were 41 related publications relevant to a single control, two-factor treatments (biochar and fertilizer), and combinations of factors (biochar combined with fertilizer).

2.2. Data preparation

In our study, more than half of the environmental variables (e.g., MAT (67 %), MAP (75 %), biochar properties (87 %), and soil properties (62 %)) were directly extracted from the targeted literatures (Table S1). The non-reported data (e.g., MAT, MAP, and soil texture) in the targeted literature were obtained from relevant websites. Nonetheless, such data were not included to ensure the accuracy of the database. Overall, experimental sites were spanned from −43.7° to 53.5° in latitude and from −155.7° to 172.5° in longitude, with MAT varying from 4.0 °C to 29.0 °C, and MAP ranging from 45 mm to 2870 mm. Detailed biochar and soil properties were shown in Table S1. The wetness index was a composite indicator of climate. The wetness index of each experimental site was calculated using MAT and MAP as De Martonne (1926) equation:

$$Wetness\ index = MAP/(MAT + 10) \tag{2}$$

For the comparison of the effect of biochar on crop yield, SOC, and GWP among regions, experimental sites were divided into two ways. First, experimental sites were grouped according to absolute latitude into tropic (23.5 °S to 23.5 °N), subtropic (23.5–35 °S and °N), temperate (35–50 °S and °N), and (sub)arctic (> 50 °S and °N) zones. Second, experimental sites were separated into four groups based on their wetness index: < 20.0, 20.0–40.0, 40.0–60.0, and > 60.0. The type of crop and biochar were divided into five (wheat, maize, rice, vegetable, and other) and four categories (straw, wood, manure, and other), respectively. The application rates (Mg ha^{-1}) of biochar were divided into three categories: < 10.0, 10.0–40.0, and > 40.0 Mg ha^{-1}. The pH and C:N ratio of biochar were divided into four (< 8.0, 8.0–9.0, 9.0–10.0, and > 10.0) and three categories (< 50.0, 50.0–100.0, and > 100.0), respectively. For soil properties, soil organic carbon was grouped into three categories: < 10.0, 10–20.0, and > 20.0 g kg^{-1}. If soil pH was measured by the method of $CaCl_2$ solution, the following equation was used to obtain the value of soil pH (H_2O): pH (H_2O) = 1.65 + 0.86 pH ($CaCl_2$) (Guo and Xin, 2009). Soil pH were divided into acidic soils (pH < 5.5), weak acidic soils (pH 5.5–6.5), neutral soils (pH 6.5–7.5), and alkaline soils (pH > 7.5). Soil texture was classified into sandy soil, loamy soil, and clayey soil based on the U.S. Department of Agriculture soil classification system.

2.3. Non-independence of sampling

In one experiment, the same control treatment was shared by several experimental treatments, such as different biochar application rates. These experimental treatments are treated as non-independent treatments in this experiment. Previous research results have shown that non-independent treatment plays an important role in the difference of effect size for meta-analyses, which could significantly affect the result (Hungate et al., 2009; Verhoeven et al., 2017). In this study, the application rates of biochar were considered as non-independent factors because different biochar application rates were compared with the same control. Finally, the mean and standard deviation of treatments under different application rates were weighted by the amounts of the biochar application, the weight of which could be estimated as the following equation:

$$W_B = Q \Big/ \sum_{i=1}^{N} Q_i \tag{3}$$

where Q is the amounts of the biochar application during the experiment

(Mg ha^{-1}); N is the number of treatments with the same control treatment.

With the consideration of non-independence, 455 independent experiments of crop yield, 131 independent experiments of SOC, 95 independent experiments of GWP were eventually obtained (Table 1). A meta-analysis was then performed based on these independent experiments.

2.4. Meta-analysis

This study focused on the effect size of biochar application on crop yield, SOC, and GWP at the global scale by weighting the natural log-transformed response ratio (Ln (*RR))* with the inverse variance. The Ln (*RR*) was calculated as follows:

$$Ln(RR) = ln(X_B/X_C) \tag{4}$$

where X_B and X_C are the mean under the biochar application and control, respectively.

If there was no heterogeneity among treatments ($P > 0.1$ and $I^2 < 50$ %), the fixed-effect model (FEM) would be used for analysis. Otherwise, the random effect model (REM) would be used. For that purpose, data of mean, standard deviations (SD), and sample sizes (*N*) were needed. If standard error (SE) rather than SD was obtained, SD was transformed using the following equation:

$$SD = SE\sqrt{N} \tag{5}$$

In this database, only 19 % of the data did not report SD or SE, where part of these SDs was obtained from the corresponding author, and the missing SDs were derived from the mean by the variance coefficient of all datasets (Hou et al., 2020).

The variance (V) of X was calculated as follows:

$$V = {SD^2}_B/{N_B {X^2}_B} + {SD^2}_C/{N_C {X^2}_C} \tag{6}$$

where SD_B and SD_C are the standard deviation under biochar and control, respectively. N_B and N_C are the sample number under biochar and control, respectively.

The weighting factor (W_{ij}) and standard error of S(Ln(*RR*)) were calculated using the following equations:

$$W_{ij} = {}^{1}/_{V_{ij}} \tag{7}$$

$$S(Ln(RR)) = \sqrt{1 \Big/ \sum_{i=1}^{m} \sum_{j=1}^{ki} W_{ij}} \tag{8}$$

95 % confidence interval (95 % *CI*) was calculated as the following equation:

$$95\%CI = Ln(RR) \pm 1.96S(Ln(RR)) \tag{9}$$

If 95 % *CI* overlapped with zero, biochar application would not affect crop yield, SOC, and GWP.

The effect size was transformed by using the Eq. (10):

$$RR = (e^{Ln(RR)} - 1) \times 100\% \tag{10}$$

For the effect size of interaction between biochar and fertilizer on crop yield (the interaction effect size), Ln (*RR*) and variance were calculated using the following equations:

$$Ln(RR) = Ln(X_{AB}/_{X_B}) - Ln(X_A/_{X_C}) \tag{11}$$

$$var(RR) = SD^2_{AB}/_{X_{AB}N_{AB}} + SD^2_B/_{X_BN_B} + SD^2_A/_{X_AN_A} + SD^2_C/_{X_CN_C} \tag{12}$$

where X_{AB}, SD_{AB}, and N_{AB}; X_B, SD_B, and N_B; X_A, SD_A, and N_A; X_C, SD_C, and N_C represent the mean, SD, and sample size of the group of BF, B, fertilizer alone, and control, respectively. In the BF treatment, the effect of biochar and chemical fertilizer on crop yield is to promote, inhibit or have no interaction from each other, respectively, when their interaction effect size is greater, less than or overlaps with zero.

2.5. Effect sizes

The effect size is often used the measure the effect magnitude in the Meta-analysis, which provides a statistical mean for summarizing the results of independent experiments (Hedges et al., 1999). The effect size provides comprehensive information about how much the subjects (e.g., crop yield, SOC, GWP, etc.) have been changed under the treatment group (e.g., biochar application rate, interaction between biochar and chemical fertilizer, etc.) relative to the control group across all the studies. Meanwhile, the optimal application conditions of the treatment can be obtained by comparing the effect size under different variables (e.g., temperature, rainfall, biochar type, soil texture, etc.). Meanwhile, the optimal treatment can be obtained by comparing the effect size under different treatments (e.g., biochar, biochar combined with chemical fertilizer). Furthermore, the relative contributions of different variables to the effect size could be quantified by some other statistical methods, such as a boosted regression tree (BRT) analysis.

2.6. Statistical analysis

Before conducting the meta-analysis, two ways were performed to check the quality of database, of which one was the leave-one-out meta-analysis by the "meta" packages (Supplementary Fig. 1) and the other was the frequency distribution by the Gaussian distribution function based on effect sizes:

$$y = A\ exp^{(x-\mu)^2}/_{2\sigma^2} \tag{13}$$

where y is the sample size of effect sizes; x is the mean of effect sizes; μ and σ^2 are the mean and variance across all effect sizes, respectively; A is a coefficient.

A boosted regression tree (BRT) analysis was performed to quantify the relative contributions of climate, crop type, biochar properties, and soil properties to the effect size of crop yield, SOC, and GWP under B and BF treatments. Before the BRT analyses, some variables were not included to avoid correlation based on theoretical knowledge. Specifically, (1) wetness index, rather than MAT and MAP, is adopted to represent climate because it is a composite indicator. (2) SOC, rather than soil total nitrogen, is adopted as an indicator of soil fertility because of their high correlation ($R^2 = 0.81$, $P < 0.01$, n = 326). (3) Soil clay, rather than soil sand and silt, is adopted as an indicator of soil texture. (4) Only the biochar C:N ratio is included because it is a composite indicator of high correlation with biochar carbon content and biochar nitrogen content. For each effect size, the BRT analyses were performed following the recommended parameters from previous studies (learning rate of small value (0.01−0.001), bag fraction from 0.50 to 0.75, cross-validation of 10, and tree-complexity (2–5)) to ensure the number of regression trees exceeding the sample size (Cai et al., 2020; Elith et al., 2008). The Gaussian distribution was used in the BRT analysis because of the continuous numerical variables of effect sizes. The predicted effect sizes of selected factors through the BRT analyses were compared with the observed effect sizes to check their reliability of selected factors. The package of generalized boosted regression models from Elith et al. (2008) was used in the R version 3.3.3.

3. Results

3.1. Global effect sizes of B and BF on crop yield, SOC, and WGP

This synthesis showed that the effect of biochar on crop yield, SOC, and GWP was globally distributed, which varied greatly among experimental sites and displayed normal/Gaussian distributions (Table 1 and Supplementary Figs. 1–3). Biochar had a decreased effect size with absolute latitude ($R^2 = 0.22$, $P < 0.01$, n = 85) on crop yield, but without the same occurrence on SOC and GWP (Supplementary Fig. 3). Overall, biochar with/without fertilizers significantly increased crop yield and SOC by 22.1 % (18.7%–25.7% *CI*, same as below) and 33.5 % (23.2%–45.2%), respectively, and decreased GWP by -22.1 % (-29.4 % to -14.9 %) compared with the control. The effect sizes on crop yield and GWP were substantially changed under B (15.1 % and -27.1 %) and BF (48.4 % and -14.3 %). Moreover, the effect sizes of B (Fig. 2a and b) and BF (Fig. 2c and d) on crop yield significantly and linearly correlated with that on SOC, but not significantly correlated with that on GWP (Fig. 2).

3.2. Effects sizes of B and BF on crop yield, SOC, and WGP

Crop yield significantly increased in tropic, subtropic, and temperate zones under B and BF (Fig. 3). The highest effect size of B and BF on crop yield was observed in the tropic zone and > 60 wetness index compared with other climatic zones and < 60 wetness index. The effect size of B and BF on crop yield tended to decrease with the biochar C:N ratio and soil pH increase, while an opposite trend appeared with SOC under BF. These results further revealed that the interaction between biochar and chemical fertilizers on crop yield was rare under various climates, crop types, soil properties, and biochar properties (Supplementary Fig. 4), which even revealed a negative interaction in the subtropic zone and for the crop of maize.

The application of B and BF significantly increased SOC compared with the control under various climates, crop types, soil properties, and biochar properties (Fig. 4). However, there were no significant differences in the effect size of SOC between B and BF. Meanwhile, a significant difference in the effect size on GWP among environmental variables under B and BF was shown in Fig. 5. Specifically, the effect size on GWP was significantly decreased in the subtropical zone under B and BF but not significantly decreased in the temperate zone under BF. Interestingly, the effect size of B on GWP for biochar straw in the wetness index >60 was significantly smaller than that of BF on GWP. In addition, the effect size on GWP under B and BF tended to be increased with the increase of biochar pH but decreased with the increase of soil pH.

3.3. Predicted effects sizes of B and BF on crop yield, SOC, and WGP

The responses of crop yield, SOC, and GWP to B and BF were driven by multiple environmental variables rather than a single factor (Figs. 3–6). Biochar C:N ratio, SOC, and soil pH were the three most influential variables on the effect size of crop yield under B (relative influence: 14.2 %, 15.4 %, and 15.6 %, respectively) and BF (26.0 %, 12.4 %, and 22.8 %, respectively) among the selected 9 variables. The overall influence of biochar properties to the effect size on SOC was larger than that of climate, crop type, and soil properties, with their relative influence of 55.3 % and 64.9 % under B and BF, respectively. Soil pH and biochar C:N ratio were the two relatively important factors to drive the effect size on GWP under B (33.6 % and 24.0 %, respectively) and BF (40.4 % and 11.2 %, respectively). However, some variables with the relative influence of <3% were deleted from the BRT analysis. Overall, the BRT model driven by the 9 variables could explain 70 %–79 %, 90 %–93 %, and 70 %–97 % of the variance for the effect size on crop yield, SOC, and GWP, respectively.

4. Discussion

4.1. The magnitude of biochar's effect size

According to 455 independent experiments (1078 samples) on crop yield, biochar application significantly increased crop yield by 22.2 % (Table 1), higher than an increase of 4.8 % increased crop yield from 86 samples (Jeffery et al., 2011), 8.5 % increase from 228 samples (Liu et al., 2013), 11.0 % increase from 81 samples (Liu et al., 2019), and 17.1 % increase from 30 independent experiments (Biederman and Harpole, 2013). Two reasons could be used to explain these discrepancies: (1) compared with our results, previous results mainly based on

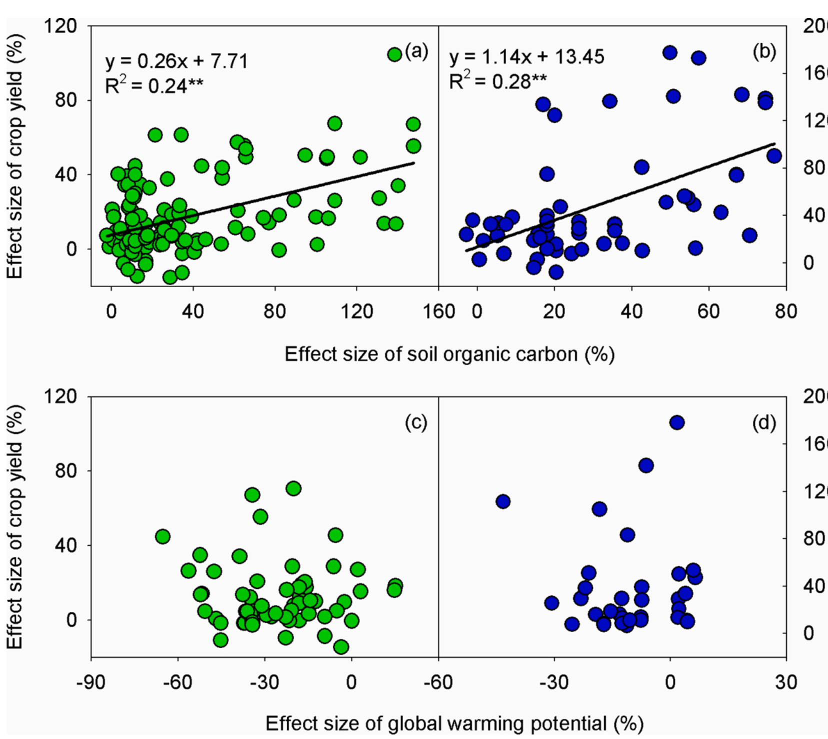

Fig. 2. Relationships between the effect size (%) of crop yield and the effect size (%) of soil organic carbon or the effect size (%) of global warming potential under biochar applied alone (a and c) and under biochar combined with chemical fertilizers (b and d).

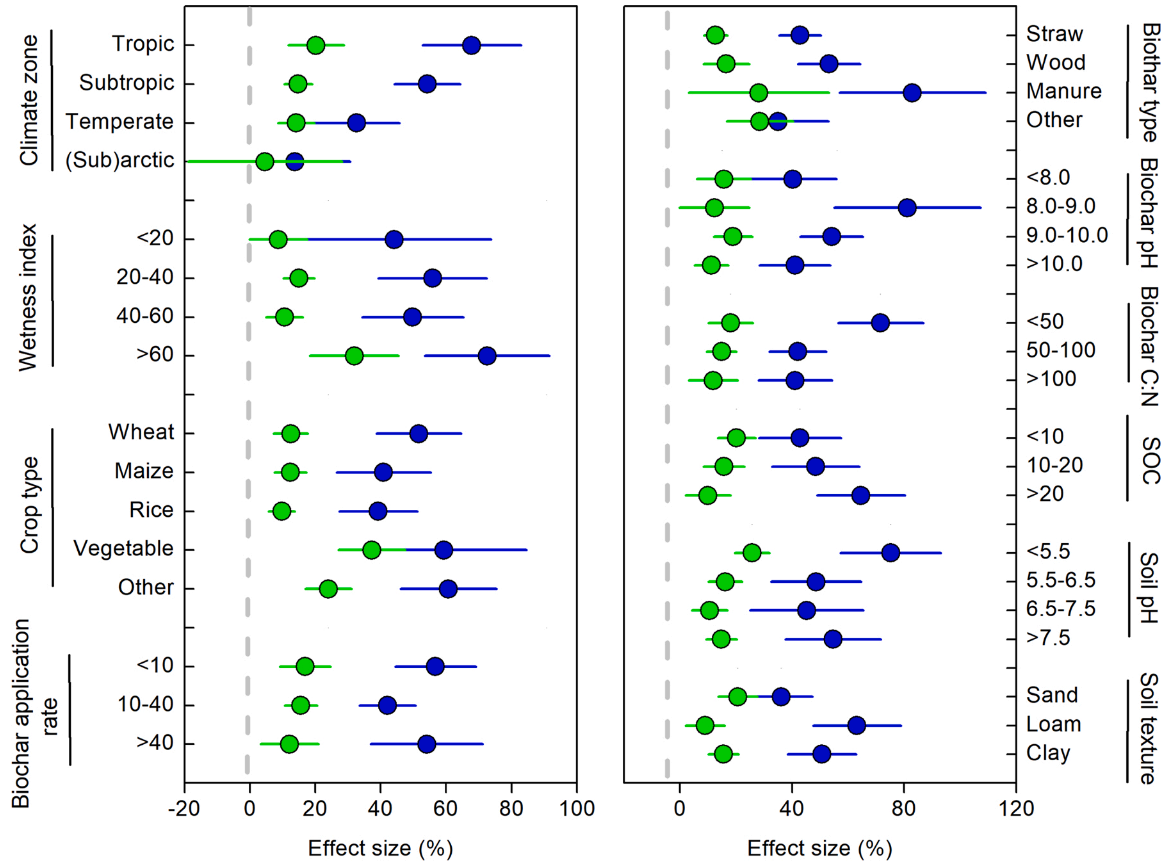

Fig. 3. Effect size (%) of crop yield at various climate zones, wetness index, crop types, biochar properties and application rates, and soil properties under biochar applied alone (green) and biochar combined with chemical fertilizers (blue). Values represent the effect sizes ± 95 % confidence intervals (see Supplementary Table 2). The dashed lines indicate the non-significant effect size. C: N is the ratio of carbon to nitrogen. SOC is the soil organic carbon. Only groups with a total sample size ≥5 are shown.

small scale samples, which might lead to a relatively greater deviation (Sutton et al., 2007); (2) the application of BF has been widely used to substantially increase crop yield due to the abundance of nutrients provided for crop growth recently (Liu et al., 2016b; Oladele et al., 2019), but while almost all previous studies did not clearly distinguish the effect size on crop yield under B and BF (rarely involving BF). Our study verified that the effect size of BF on crop yield was higher than that of B (Table 1). Compared with B, BF could further promote crop growth by enhancing nutrient supply and increase nutrient use efficiency (Agegnehu et al., 2016; Horák et al., 2017). For instance, Biederman and Harpole (2013) reported that BF could increase crop yield by 35.0 % (19.0%–51.0% *CI*) compared with the no-biochar application based on 30 samples. However, according to 177 independent experiments (430 samples), the average effect size of BF on crop yields (48.4 %) was not only higher than the Biederman and Harpole's (2013) result (35.0 %), but also with a lower variability (from 19.0 to 51.0% *CI* to 41.8–55.3 % *CI*).

Soil organic carbon sequestration by biochar application has been proposed as an effective way to increase crop yields and mitigate global warming (Smith et al., 2008). Our result was consistent with the conclusion of Liu et al. (2016a) that biochar application had a positive effect on SOC by global meta-analysis. However, the positive effect (33.5 %) revealed in this study was less than that (52.2 %) of Liu et al. (2016a). An accurate biochar's effect could be obtained by supplementing the experimental sample size and considering the experimental non-independence (Hungate et al., 2009; Verhoeven et al., 2017). Besides, the formation of SOC is a long-term process of soil retention of exogenous organic materials, which is affected by climate, management practices, and soil properties (Cai et al., 2016). Compared with B, BF could further promote crop growth and secrete more organic materials by crop roots, which contribute to SOC formation (Chew et al., 2020; Prendergast-Miller et al., 2014). The experimental time in targeted literature was relatively short, with an average of only 1.5 years, consequently resulting in no differences between the effect size of B and BF (32.9 % and 34.8 %, respectively) (Table 1).

The biochar application could significantly reduce soil N_2O emission (Borchard et al., 2019; Cayuela et al., 2014; He et al., 2017). However, the reduction (13.4 %) of soil N_2O emission reported in this present study (Supplementary Table 5) was smaller than that in the previous results (28.0 %–62.0 %) (Borchard et al., 2019; Cayuela et al., 2014; He et al., 2017). Such differences could be ascribed to the differently experimental approaches including laboratory incubation, and pot and field experiments (Cayuela et al., 2014; He et al., 2017). Compared with that in the field experiment, biochar performed better at reducing soil N_2O gas emission in laboratory incubation and pot experiment (He et al., 2017). However, the application of BF did not significantly affect soil N_2O emission compared with the no-biochar application. This might be because the reduction in soil N_2O emission from the biochar application alone offset the increase in soil N_2O emission from the chemical fertilizers (Horák et al., 2017). For soil CO_2 and CH_4 emission, Liu et al. (2016a) found biochar application having no significant effect on soil CO_2 emission. In addition, Jeffery et al. (2016) showed the potential of biochar application to mitigate soil CH_4 emission. However, the results in this present study reported that B and BF significantly increased soil CO_2 emission (13.2 % and 8.7 %, respectively) and did not significantly change soil CH_4 emission (Supplementary Table 5). These inconsistent results suggested that soil greenhouse gas emission is a complex biochemical process with internal connections (Sial et al., 2019).

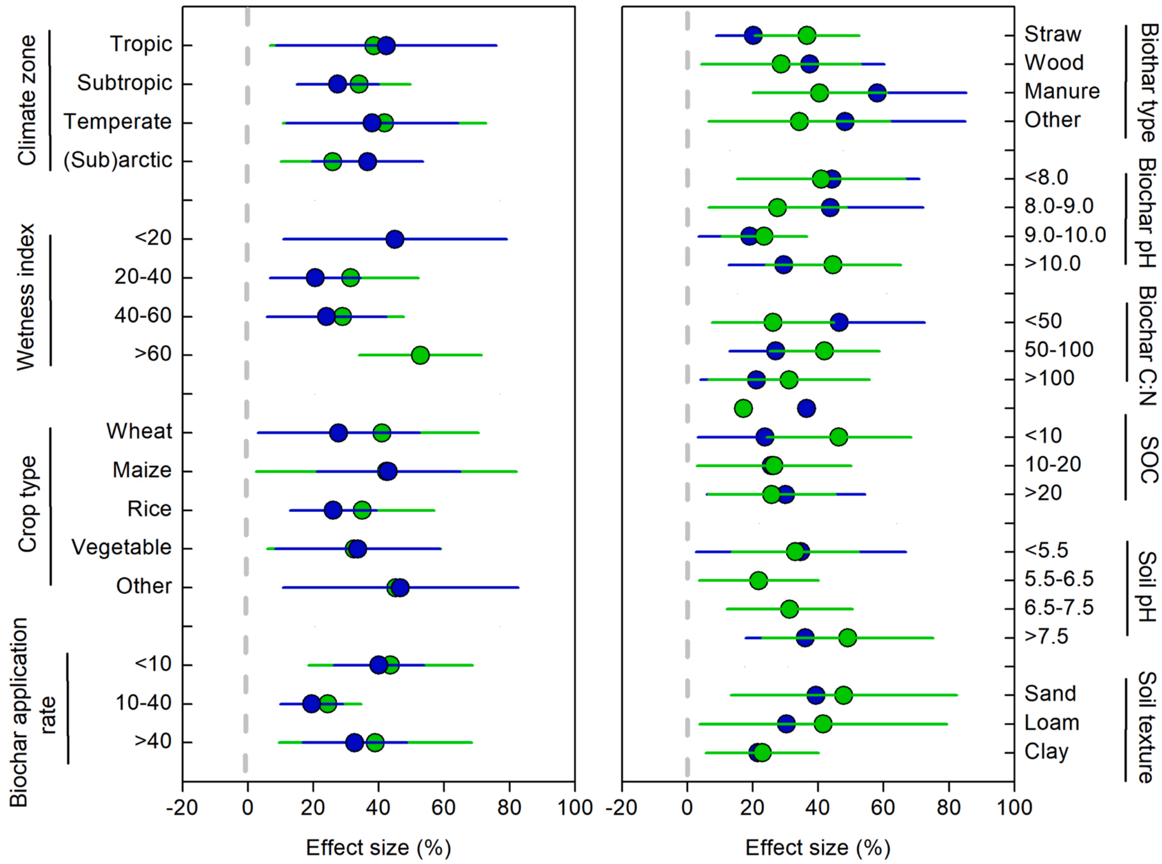

Fig. 4. Effect size (%) of soil organic carbon (SOC) at various climate zones, wetness index, crop types, biochar properties and application rates, and soil properties under biochar applied alone (green) and biochar combined with chemical fertilizers (blue). Values represent effect sizes ± 95 % confidence intervals (see Supplementary Table 3). The dashed lines indicate the non-significant effect size. C: N is the ratio of carbon to nitrogen. SOC is the soil organic carbon. Only groups with a total sample size ≥5 are shown.

Indeed, GWP has been used to evaluate the overall impact of the main greenhouse gases (i.e., CO_2, CH_4, and N_2O) (IPCC, 2014). The decrease (14.3 %) of GWP under BF was smaller than that of B (27.1 %) (Table 1), which was attributable to the fact that fertilization combined with B could reduce CO_2 and CH_4 emission but increase N_2O emission compared with B (He et al., 2017).

4.2. Mechanisms of biochar's effect

The applications of B and BF were effective management practices for increasing crop yield. However, the effects of B and BF on crop yield depended on various climatic conditions, management practices, soil properties, and biochar properties. High effect size on crop yield under B and BF occurred in the tropic climate zone with > 60 wetness index (Fig. 3), which may provide evidence for the statement that crop yield derived from nutrient effect (Haider et al., 2017; Tilman et al., 2002). Compared with the relatively fertile temperate climate zone, the addition of nutrients by B and BF was likely to have an impact on crop yield in the tropical climate zone. This may be because soil nutrients are a major limiting factor for crop growth in the tropical climate zone (Tilman et al., 2002). Some studies reported that biochar addition does not significantly increase crop yield in the temperate zone (Haider et al., 2017; Jeffery et al., 2017). This study further quantified the relationship that the effect size on crop yield under B and BF decreased with absolute latitude (Supplementary Fig. 3). In addition, the effect size of B and BF on crop yield was declined with the increase of soil pH, which was consistent with the result from Jeffery et al. (2017). Soil pH was likely to promote crop yield, especially in acidic soil (Cai et al., 2019). The positive effect of B and BF on crop yield offset the negative effect from low soil pH by the high pH and C:N ratio of the added biochar, leading to the immobilization of some nutrient elements. Interestingly, the effect size on crop yield tended to be decreased under B but increased under BF with the increase of SOC. It suggested that biochar must be combined with fertilizer to further increase crop yield in fertile soils (Agegnehu et al., 2016). That's because biochar application alone affects crop yield by mainly improving soil physical properties and then creating an optimum environment for crop growth in high-fertility soil (Biederman and Harpole, 2013). Overall, biochar C:N ratio, SOC, and soil pH were the three most influential variables on the crop yield among the selected nine variables (Fig. 6).

Biochar has a high performance in chemical and microbiological stability in soil due to its high carbon content, complex aromatization structure, and inherent chemical inertness (Lehmann et al., 2006; Sohi et al., 2010). Therefore, biochar may change the composition of soil organic matter to increase the total SOC content. By providing an abundant nutrient supply from fertilizers, the BF could significantly improve crop growth and correspondingly increase the carbon input from crops compared with B application (Chew et al., 2020). However, the response of SOC to B did not significantly differ from that to BF under various influencing variables (Fig. 4), mainly because of the too-short experiment times (1–2 years). Although more organic matter through crop roots was input into the soil under BF, the formation of SOC was still a complex and time-consuming process (Carvalhais et al., 2014; Luo et al., 2019). Meanwhile, this meta-analysis showed that the biochar C:N ratio was the most influential variable for the effect size of B and BF on SOC among all influencing variables. Biochar with a high C:N ratio may result in microbial nitrogen immobilization in soil, which is conducive to the formation of SOC (Cayuela et al., 2010). Biochar with a low C:N

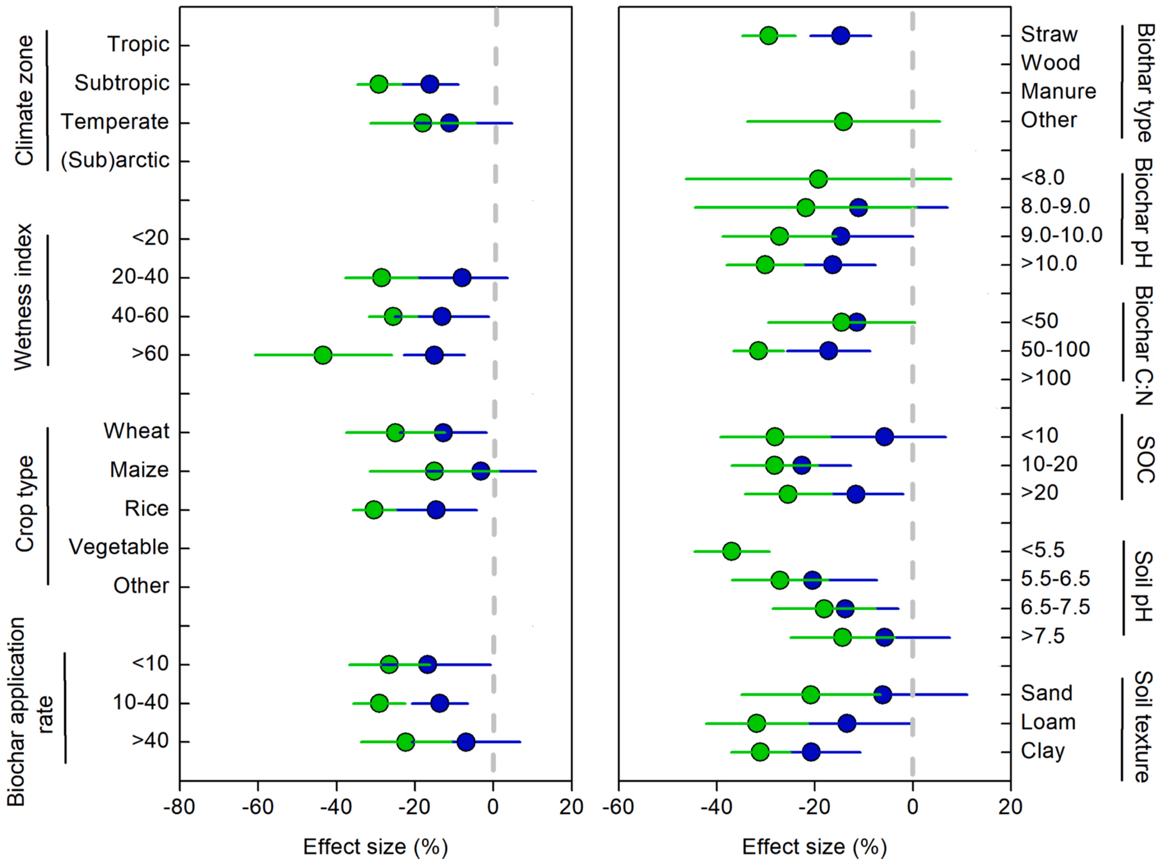

Fig. 5. Effect size (%) of global warming potential (GWP) at various climate zones, wetness index, crop types, biochar properties and application rates, and soil properties under biochar applied alone (green) and biochar combined with chemical fertilizers (blue) Values represent effect sizes ± 95 % confidence intervals (see Supplementary Table 4). The dashed lines indicate the non-significant effect size. C: N is the ratio of carbon to nitrogen. SOC is the soil organic carbon. Only groups with a total sample size ≥5 are shown.

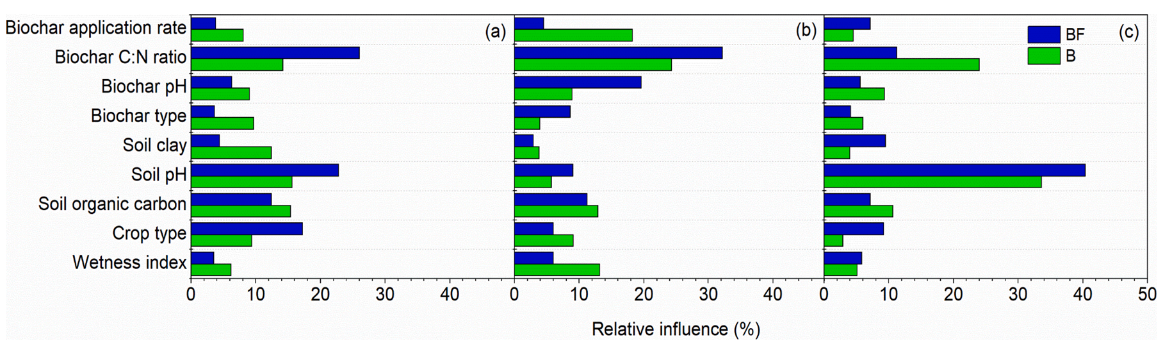

Fig. 6. The relative influence (%) of climate, crop type, edaphic factors, and biochar properties, soil properties, crop type, and wetness index to the effect sizes of biochar applied alone (B, green) and biochar combined with chemical fertilizers (BF, blue) on crop yield (a), soil organic carbon (b, SOC), and global warming potential (c, GWP) estimated by the boosted regression tree model. Notes: Biochar properties include biochar type, biochar pH, biochar carbon to nitrogen (C: N) ratio, and biochar application rate. Soil properties include SOC, soil pH, and soil clay.

ratio is generally available in microbial processes such as SOC mineralization that decreases SOC content (Singh and Cowie, 2014). The effect size of B and BF on crop yield was additionally found to increase linearly with that on SOC (Fig. 2). It directly quantified how B and BF could affect crop yield by regulating SOC and demonstrated the importance of soil fertility in crop yield (Cai et al., 2019). In a summary, more soil property indicators should be taken into account to further explore the network of biochar and soil properties in determining crop yield.

Previous results have proved that soil pH is an important variable to influence the soil's greenhouse gas emissions by altering soil properties and microbial communities under B and BF (Jeffery et al., 2016; Sheng and Zhu, 2018). The results in this study further also indicated that soil pH was the most important factor among climate, management practices, and soil properties to GWP, which quantified that soil pH could explain 33.6 %–40.4 % of the GWP variations under B and BF (Fig. 6). The application of biochar, which has high pH and C:N ratio in particular, acts as a liming effect in acidic soil (Chintala et al., 2013). Those liming effects could reflect the influence on the productions and consumptions of soil N_2O and CH_4 emissions by relevant reductases and methanotrophic communities (Clough et al., 2013; Sheng and Zhu, 2018). Therefore, the effect size of B and BF on GWP increased with the increase of biochar pH but decrease with the increase of soil pH. Moreover, our results showed that biochar C:N ratio was another important factor to drive GWP. That is because the mineralization intensity of soil nitrogen is weakened as the biochar C:N ratio increases (Cleveland and Liptzin, 2007; Kirkby et al., 2014). The biochar application increases the cation exchange capacity of soil, which then adsorbs soil NH_4^+ and NO_3^- and reduces soil N_2O emission. The GWP is mainly determined by soil N_2O flux (IPCC, 2014).

Biochar has high stability and will remain in the soil for a long time due to its slow decomposition rate (Smith, 2016). Our study further showed that the effect size of biochar application on crop yield and SOC could not be increased with the experimental time due to low nutrients content and high passive carbon content in biochar (Supplementary Fig. 6). In the early experimental stage, biochar could significantly reduce GWP due to its adsorption and related changes in microbial growth environment (Sohi et al., 2010; Sugiarto et al., 2021; Woolf and Lehmann, 2012). As the experiment time continues, the stability of biochar would be gradually altered and the effect of biochar application on GWP would become weaker and weaker (Supplementary Fig. 6). Therefore, biochar could act as a long-term soil conditioner with benefits for crop yield improvement and SOC sequestration (Woolf and Lehmann, 2012). In summary, distinguishing the effect of biochar alone and biochar combined with chemical fertilizer could reduce the variation of biochar's effect on crop yield, SOC, and GWP compared with the previous studies. Our results could improve the accuracy of estimating biochar's effect. By quantifying the relative importance of environmental variables in controlling the effect of biochar, this present study provides novel insights into the optimization of biochar application in the agroecosystem.

5. Conclusion

Evidence presented in this study showed that both B and BF application could significantly increase SOC sequestration and crop yield, but reduce GWP. Compared with B, however, BF could increase the effect size on crop yield by three times, but decrease the effect size on GWP by nearly two times, while no obviously changes in the effect size on SOC. A significant coupling relationship was found between the effect size on crop yield and that on SOC under both B and BF applications. The biochar C:N ratio and soil pH are the two most important variables controlling the effect size of B and BF application on crop yield and GWP. However, the overall influence of biochar properties on the effect size to SOC is larger than that of climate, crop types, and soil properties. Our results highlight that more economic and environmental benefits could be achieved by optimizing the properties (C:N ratio) of biochar that was applied in soil, especially in acidic soil.

Data accessibility

All data related to this manuscript are available from the Dryad Digital Repository: https://figshare.com/articles/Biochar_by_a_global_meta-analysis/12368930.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2021.105125.

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