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Review

Impact of biochar application on yield-scaled greenhouse gas intensity: A meta-analysis

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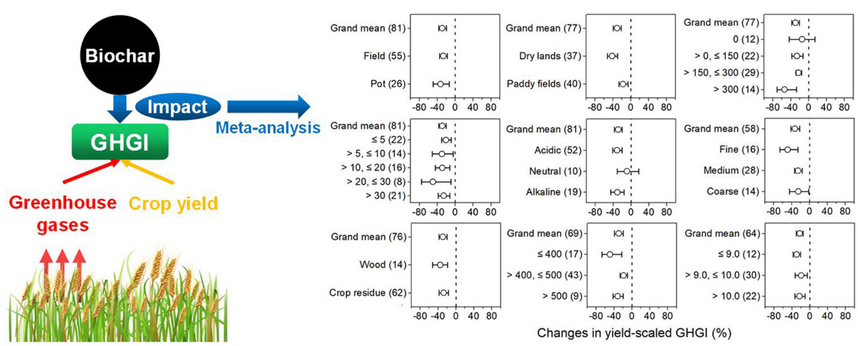
HIGHLIGHTS

- Overall, biochar significantly reduced GHGI by 29%.
- The effect of biochar on reducing GHGI was significantly affected by cropping system.
- Biochar had no effect on GHGI when no nitrogen fertilizer was applied.
- Properties of soil and biochar have little impact on the response of GHGI to biochar.

GRAPHICAL ABSTRACT



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ABSTRACT

The application of biochar to agricultural ecosystems is a potential solution to mitigate climate change and guarantee food security. However, the impacts of biochar on greenhouse gas emissions and crop yield are usually evaluated separately and the results are contradictory in individual studies. In this study, a meta-analysis was conducted based on data from 28 peer-reviewed studies to quantify the impacts of biochar application on greenhouse gas emissions and crop yield using yield-scaled greenhouse gas intensity (GHGI). Potential factors (experimental conditions and properties of soil and biochar) influencing the effect of biochar on yield-scaled GHGI were explored. The results showed that overall, biochar significantly reduced yield-scaled GHGI by 29%. The reductions in yield-scaled GHGI induced by biochar varied with different experimental conditions and properties of soil and biochar. However, the difference was only significant between the two cropping systems, with significantly greater reduction being observed in dry lands (−41%) than in paddy fields (−17%). Therefore, it is suggested that biochar amendment in dry lands may bring more environmental and agronomic benefits than that in paddy fields. The response of crop yield to biochar application further implied that biochar made from crop residue, biochar produced at low pyrolysis temperatures (≤400 °C), and biochar with high pH (>9.0) might contribute to save the production cost of biochar while promoting crop yield in agricultural ecosystems. Long-term field trials are required to elucidate the persistence of the impact of biochar on reducing yield-scaled GHGI and to clarify the underlying mechanisms. The balance between the price of biochar production and the benefits brought by biochar should also be focused in further studies.

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Contents

1. Introduction

Agriculture serves as one of the major contributors of atmospheric greenhouse gases, accounting for approximately 52% and 84% of global anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions, respectively (Smith et al., 2008). Despite its significant role in influencing global climate change, agriculture also faces the great challenge of providing enough food for the growing population by using limited land resources (Smith et al., 2013; Valin et al., 2013). Therefore, effective agricultural management practices are urgently needed to promote both greenhouse gas mitigation and food security.

Biochar, the carbonaceous residue of pyrolyzed organic materials (e.g. crop residue) at relatively low temperatures (<700 °C) in the partial or total absence of O_2 (Lehmann et al., 2011; Nguyen et al., 2017), has drawn an increasing attention in the last decade due to its potentially environmental and agronomic benefits such as mitigating greenhouse gas emissions, improving soil fertility, and increasing crop yield after its application to agricultural soils (Sohi et al., 2010; Lehmann et al., 2011; Cornelissen et al., 2018). However, such effects are highly variable because of the differences in experimental conditions and the nature of soil and biochar in individual studies (Jeffery et al., 2011; Liu et al., 2016). Empirical evidence showed that biochar could stay in soils for a long time due to its high biochemical stability (Atkinson et al., 2010; Wang et al., 2016). Therefore, biochar may have irreversible impacts on soil properties and ecosystem functions (Sohi et al., 2010). Before the large-scale implementation of biochar as a soil amendment, a great deal of work still need to be conducted in order to provide more rational information for policy-makers when dealing with global warming and food production through biochar application (Jeffery et al., 2011). In this case, a systematic synthesis of biochar effects on greenhouse gas emissions and crop yield based on the results from published literature may provide suggestions and implications for further research (Cayuela et al., 2014). Since both global warming and food security are great challenges that humans must face (Lal, 2004), the responses of greenhouse gas emissions and crop yield to biochar application should better be assessed together rather than separately.

Greenhouse gas intensity (GHGI), defined as the ratio of global warming potential (GWP) to crop yield, has been used to relate agricultural production to greenhouse gas emissions (Mosier et al., 2006; Zhang et al., 2012). A smaller value of GHGI indicates that a lower GWP is produced to obtain a same crop yield, whereas a lager value implies that producing a same crop yield induces a higher GWP. Hence, GHGI can be an effective indicator when optimizing agricultural management practices for simultaneously mitigating climatic impacts and ensuring food security (Huang et al., 2013; van Groenigen et al., 2013). Although some previous studies pointed out that yield-scaled GHGI could be reduced by biochar application (Zhang et al., 2012; Liu et al., 2014; Li et al., 2015), no response or even an increase of GHGI after biochar application were also reported (Koyama et al., 2015; Ly et al., 2015). Factors influencing the response of GHGI to biochar application are currently poorly understood.

In this study, 81 experimental observations derived from 28 peer-reviewed publications were synthesized to quantitatively examine the impact of biochar application on yield-scaled GHGI in agricultural ecosystems using meta-analysis procedures. Potential factors regulating the impact of biochar on yield-scaled GHGI were also explored. The results would provide implications for future studies which aim to evaluate the effectiveness of biochar application on greenhouse gas mitigation and crop yield promotion.

2. Materials and methods

2.1. Data sources and compilation

A literature search was conducted through ISI Web of Science and Google Scholar using the keywords "biochar" OR "charcoal" AND "greenhouse gas intensity" OR "greenhouse gas" OR "nitrous oxide" OR "methane" OR "N_2O" OR "CH_4" AND "crop yield" OR "crop productivity" (cut-off data: 18th September 2018). Since most of the related studies separately assessed the effects of biochar application on greenhouse gas emissions and crop yield, only 81 observations from 28 peer-reviewed studies were collected based on the following criteria: (1) data of yield-scaled GHGI must be reported or could be calculated through GWP and crop yield for control and biochar treatment; (2) sample size must be given for each treatment with a minimum of three replications. It should be noted that the only difference between control and biochar treatment was the application of biochar. In this meta-analysis, GWP (t carbon dioxide (CO_2)-eq ha^{-1}) was defined as the sum of cumulative CO_2-equivalent emission in a 100-year horizon for CH_4 and N_2O using a conversion factor of 25 for CH_4 and 298 for N_2O (IPCC, 2007), respectively, which were used to calculate GWP in most of the selected studies. For studies which used different conversion factors, the GWP was recalculated to make the results comparable. Yield-scaled GHGI (t CO_2-eq t^{-1} grain yield) was defined as the GWP divided by the grain yield (t ha^{-1}). When the raw data was presented in graphs rather than in tables, the GetData Graph Digitizer (version 2.25, Russian Federation) was used to extract numerical data (Liu et al., 2018). For each study, information on the location of the experimental site (country), application rates of nitrogen (N) fertilizer and biochar, planted crop species as well as the feedstock and pyrolysis temperature of biochar was also compiled (Table S1).

The compiled dataset was grouped by categories including experimental conditions (type of experiment, cropping system and application rates of N fertilizer and biochar), properties of soil (pH and texture), and properties of biochar (feedstock, pyrolysis temperature and pH) to explore the potential factors affecting the response of yield-scaled GHGI to biochar application (Table 1). The three categories of soil texture were based on USDA classifications (Soil Survey Staff, 2014), which grouped the soil texture of clay, silt clay and sandy clay into fine; the soil texture of clay loam, loam, silty clay loam, silt and silt loam into medium; and the soil texture of sandy loam, sandy clay loam and loamy sand into coarse, respectively (Cayuela et al., 2014).

2.2. Meta-analysis

In this study, the natural log-transformed response ratio (R) was used as a measure of effect size for the meta-analysis (Lam et al., 2012):

$$\ln R = \ln\left(\frac{X_t}{X_c}\right) \tag{1}$$

where X_t and X_c represent the mean yield-scaled GHGI of biochar treatment and control group, respectively. The results were back transformed to percentage change ((R-1) × 100) to present the effect of biochar application on yield-scaled GHGI. Negative values indicate that GHGI values were reduced by biochar application, and positive values indicate increases in GHGI after biochar application.

In previous meta-analyses, effect sizes were weighted by the inverse of pooled variance (Ainsworth and Long, 2005), replication (Lam et al., 2012) or unweighted (Shi et al., 2016). Since not all the collected studies reported variances, the effect sizes in this study were weighted by a function of sample size (Lam et al., 2012; Xia et al., 2017; Liu et al., 2018):

$$\text{weight} = \frac{n_t \times n_c}{n_t + n_c} \tag{2}$$

where n_t and n_c are the numbers of replications of the biochar treatment and control, respectively.

Mean effect sizes and 95% confidence intervals (CIs) were generated through bootstrapping (4999 interactions) using MetaWin 2.1 (Rosenberg et al., 2000). Although a mixed-effects model or a fixed-effects model was technically not applicable for non-parametric meta-analytic procedure based on weighting by replication, a fixed-effects model must be selected when performing a correct bootstrapping using MetaWin (Lam et al., 2012; Xia et al., 2017; Liu et al., 2018). The impact of biochar application on yield-scaled GHGI was considered significant if the 95% CIs did not overlap with zero. Means of categorical variables were considered significantly if their 95% CIs did not overlap.

Table 1
Factors categorized as predictive variables in this meta-analysis.

Factor		Levels
Experimental conditions	Type of experiment	Field; pot
	Cropping system	Dry lands; paddy fields
	Application rate of nitrogen fertilizer (kg N ha^{-1})	0; >0, ≤150; > 150, ≤300; >300
	Application rate of biochar (t ha^{-1})	≤5; >5, ≤10; >10, ≤ 20; >20, ≤30; >30
Soil properties	Soil pH	Acidic (≤6.5); neutral (>6.5, ≤7.5); alkaline (>7.5)
	Soil texture	Fine; medium; coarse
Biochar properties	Feedstock	Wood; crop residue
	Pyrolysis temperature (°C)	≤400; >400, ≤500; >500
	Biochar pH	≤9.0; >9.0, ≤10.0; >10.0

3. Results

3.1. Changes in yield-scaled GHGI after biochar application as affected by experimental conditions

Overall, biochar application significantly reduced yield-scaled GHGI by 29%. The reduction in pot experiments was higher (−33%) than that in field experiments (−27%), but the difference between them was not significant (Fig. 1a). By contrast, the reductions in GHGI induced by biochar differed significantly between the two cropping systems. The reduction in dry lands (−41%) was significantly higher compared to that in paddy fields (−17%) (Fig. 1b). When no N fertilizer was applied, biochar application had no effect on GHGI. In contrast, GHGI was significantly reduced by 23–54% as a result of biochar application when N fertilizer was applied, and the reductions decreased in the order: high application rate (>300 kg N ha^{-1}) > low application rate (>0, ≤150 kg N ha^{-1}) > moderate application rate (>150, ≤300 kg N ha^{-1}). However, the differences in reductions in GHGI among the three application rates were not significant (Fig. 1c). Biochar significantly reduced GHGI by 21% when the application rate of biochar did not exceed 5 t ha^{-1}. The reductions in GHGI varied in a range of 26–50% when the application rate of biochar was higher than 5 t ha^{-1}, but the differences among different treatments were also not significant (Fig. 1d).

3.2. Changes in yield-scaled GHGI after biochar application as affected by soil properties

Significant reductions (−31%) in yield-scaled GHGI were observed when incorporating biochar into acidic and alkaline soils. In contrast, applying biochar to neutral soils had no effect on GHGI. Although the reductions in GHGI in acidic and alkaline soils were 3.4 times greater than that in neutral soils after biochar application, the differences among them were not significant (Fig. 2a). As shown in Fig. 2b, applying biochar to soils with different textures significantly reduced GHGI by 25–49%, and the reduction in soils with fine texture was almost twice

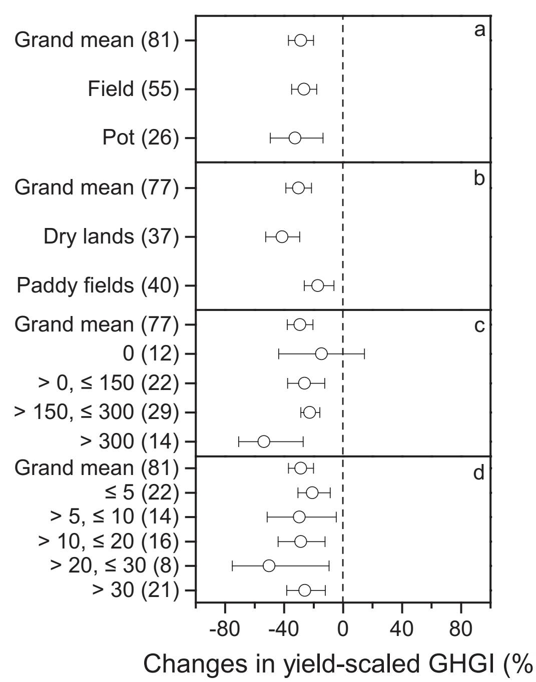

Fig. 1. Changes in yield-scaled greenhouse gas intensity (GHGI) after biochar application as influenced by type of experiment (a), cropping system (b), application rate of nitrogen fertilizer (kg N ha^{-1}) (c) and application rate of biochar (t ha^{-1}) (d). The dash reference lines indicate no change in GHGI after biochar application. Points are means with 95% confidence intervals. Numbers of experimental observations are in parentheses.

as large as those in soils with medium and coarse textures. Nevertheless, the differences did not differ significantly among the three soil textures.

3.3. Changes in yield-scaled GHGI after biochar application as affected by biochar properties

On average, biochar made from wood and biochar made from crop residue significantly reduced yield-scaled GHGI by 35% and 28%, respectively, but the difference between them was not significant (Fig. 3a). No difference in reduction in GHGI was detected after applying biochar with different pyrolysis temperatures, although biochar produced at low pyrolysis temperatures (≤400 °C) led to a higher reduction in GHGI (−49%) than those produced at moderate (>400, ≤500 °C) (−19%) and high (>500 °C) (−32%) pyrolysis temperatures (Fig. 3b). As presented in Fig. 3c, significant reductions in GHGI were observed after biochar amendment regardless of the different pH of biochar. The highest reduction in GHGI (−29%) was observed when the pH of applied biochar did not exceed 9.0, but the reduction did not differ significantly with those after applying biochar with higher pH (−19 to −23%).

4. Discussion

4.1. Potential mechanisms of biochar affecting GWP and crop yield

Overall, the present meta-analysis showed that biochar application significantly decreased GWP by 21% (Fig. S1a), while significantly increasing crop yield by 11% (Fig. S2a). Therefore, a significant reduction in yield-scaled GHGI (29%) was detected after biochar application (Fig. 1a). The results were in line with findings of previous meta-analyses (Jeffery et al., 2011; Liu et al., 2013; Cayuela et al., 2014; Jeffery et al., 2016), which indicated that biochar played significant roles in mitigating N_2O and CH_4 emissions and improving crop productivity. To date, a number of mechanisms have been proposed to explain how biochar influences the production and consumption of N_2O and CH_4 in soils. In general, the mechanisms by which biochar may suppress soil N_2O emissions include: (1) biochar liming effect leading to an increase in soil pH, which may shift the product stoichiometry of denitrification to increased production of N_2 rather than N_2O; (2) enhanced soil aeration restraining denitrification as more O_2 being present in soils; (3) the adsorption of NO_3^- and/or NH_4^+ by biochar decreasing the substrate availability of nitrification and denitrification; (4) labile organic carbon (C) of biochar increasing the availability of dissolved organic C pool, which leads to a complete denitrification; and (5) the inhibitory or toxic compounds of biochar releasing into soils and inhibiting nitrification or denitrification (Clough et al., 2013; Cayuela et al., 2014). The potential mechanisms of how biochar decreases CH_4 emissions from soils include: (1) biochar improving soil aeration, which may stimulate CH_4 oxidation and/or suppress CH_4 production (Karhu et al., 2011; Jeffery et al., 2016); (2) biochar has the capacity to adsorb CH_4 on its surface (Yaghoubi et al., 2014); and (3) biochar increasing methanotrophic abundances and decreasing the ratios of methanogenic to methanotrophic abundances under anoxic conditions (Feng et al., 2012). The positive effect of biochar on increasing crop productivity is mainly attributed to that biochar improves soil fertility through enhancing the retention and availability of soil nutrients (e.g. N, Ca and Mg) and water (Atkinson et al., 2010; Major et al., 2010; Liu et al., 2013; Agegnehu et al., 2016). In acidic soils, the liming effect of biochar can also alleviate Al and P stress by regulating soil pH for better growth of crops (Steiner et al., 2007; Pandit et al., 2018). In addition, empirical evidence indicated that biochar was effective in reducing the bioavailability, phytotoxicity, and plant uptake of potentially toxic elements (e.g. As, Cd and Pb), which not only promotes the growth of crops, but also reduces the risk of potentially toxic elements to human health (Park et al., 2011; Khan et al., 2014). However, most of the above-mentioned mechanisms are only assumed or speculated. Further research is required to discern the underlying mechanisms of biochar impacts on greenhouse gas emissions and crop productivity.

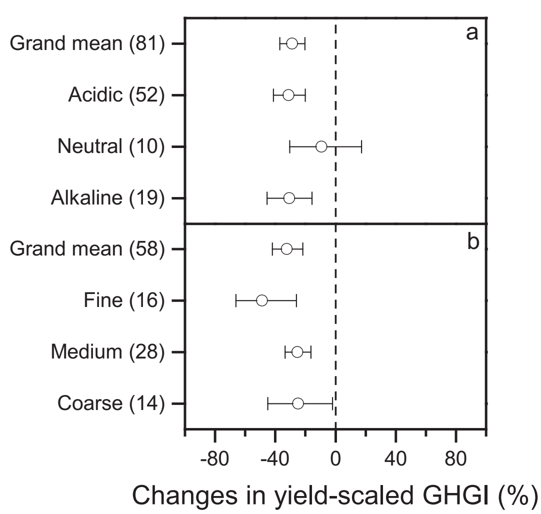

Fig. 2. Changes in yield-scaled greenhouse gas intensity (GHGI) after biochar application as influenced by soil pH (a) and soil texture (b). The dash reference lines indicate no change in GHGI after biochar application. Points are means with 95% confidence intervals. Numbers of experimental observations are in parentheses.

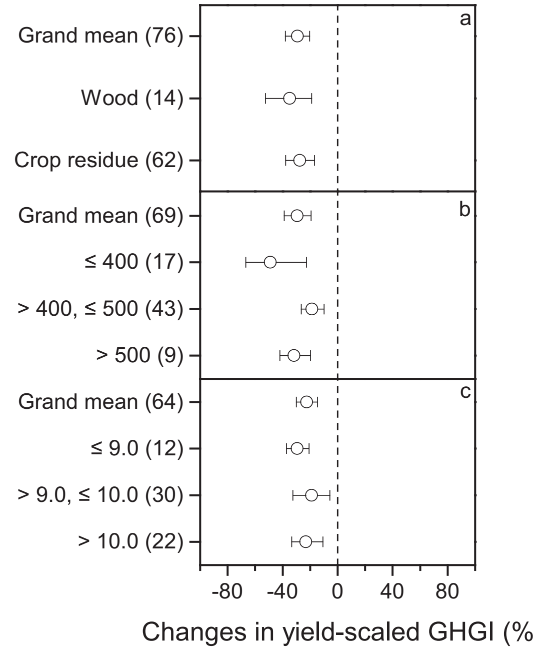

Fig. 3. Changes in yield-scaled greenhouse gas intensity (GHGI) after biochar application as influenced by feedstock (a), pyrolysis temperature (°C) (b) and pH (c) of biochar. The dash reference lines indicate no change in GHGI after biochar application. Points are means with 95% confidence intervals. Numbers of experimental observations are in parentheses.

4.2. Experimental conditions

Biochar significantly reduced yield-scaled GHGI in both field and pot studies, but the difference between them was not significant (Fig. 1a). The results, which were in agreement with observations of previous meta-analyses (Liu et al., 2013; He et al., 2017), indicated that the positive effects of biochar on mitigating global warming and improving crop yield were not changed by the experimental method. However, the collected observations were generally short-term trials with periods of <4 years for field studies and ≤4 months for pot studies. Although both the environmental and agronomic benefits produced by biochar have been discussed in previous studies, the long-term benefits of using biochar as a soil amendment are still unclear because the trial lengths were generally within 5 years (Dong et al., 2019). What is certain is that biochar is irretrievable once applied to soils, implying that biochar may have irreversible effects on soil function, greenhouse gas balance, and crop productivity (Sohi et al., 2010). A recent model study pointed out that biochar had negligible effect on long-term (32 years) corn yields in the US Midwest, suggesting that biochar had limited impact on improving crop productivity after remaining in soils for a long time (Aller et al., 2018). Therefore, long-term trials, particularly those under field conditions, are needed to clarify the persistence of the impact of biochar on reducing yield-scaled GHGI. In contrast, the effect of biochar on GHGI differed significantly between the two cropping systems (Fig. 1b). The difference was due to the soils of paddy fields being usually under anoxic conditions, which favored methanogens while inhibiting methanotrophs (Conrad, 2007), making paddy fields a significant source of CH_4 and resulting in a higher GWP than dry lands. In this case, even though biochar exerted a positive effect on reducing GWP in paddy fields, the reduction (−10%) was not significant and was considerably lower than that in dry lands (−34%) (Fig. S1b). Since the increases in crop yield induced by biochar did not differ significantly between the two cropping systems (12% for dry lands and 11% for paddy fields, respectively) (Fig. S2b), the reduction in GHGI caused by biochar was thus greater in dry lands than that in paddy fields. A recent meta-analysis indicated that biochar did not influence carbon dioxide (CO_2) emissions in dry lands, but significantly increased CO_2 emissions by 18% in paddy fields (Liu et al., 2016). Consequently, biochar amendment in dry lands may have a better performance on mitigating global warming and improving crop production than that in paddy fields.

Biochar amendment had no effect on yield-scaled GHGI without the application of N fertilizer, but significantly reduced GHGI by 23–54% when N fertilizer was applied (Fig. 1c). In practice, N fertilizer is necessary for agricultural production because the original level of available N in soils cannot meet the requirement of crop growth. However, the application of N fertilizer also induces many environmental issues, one of which is the high emissions of soil N_2O (Shcherbak et al., 2014). It is estimated that N_2O emissions from agricultural soils are responsible for 84% of the global anthropogenic N_2O emissions, mainly due to the application of N fertilizer (Smith et al., 2008). Although N_2O emissions usually increase with the application rate of N fertilizer (Shcherbak et al., 2014), as illustrated above, biochar can suppress soil N_2O emissions through affecting the microbial processes of nitrification and denitrification, which are two major sources of soil N_2O (Clough et al., 2013; Cayuela et al., 2014). As shown in Fig. S2c, the increases in crop yield induced by biochar increased with the application rate of N fertilizer, possibly due to that biochar enhanced N use efficiency through adsorbing NO_3^- and/or NH_4^+ (Atkinson et al., 2010; Clough et al., 2013). Hence, significant reductions in both GWP (−13 to −43%) (Fig. S1c) and GHGI were observed after biochar amendment in soils with N application. In a previous meta-analysis, Cayuela et al. (2014) pointed out that the effectiveness of biochar on reducing N_2O emissions could also be affected by the chemical form of N fertilizer, with the greatest effect (80% reduction) being detected when the applied form of N was NO_3^-. However, the impact of N fertilizer form on GHGI was not assessed in the present study because most of the selected studies did not give the form of applied N fertilizer, which should be focused in further studies.

The reductions in yield-scaled GHGI generally increased with biochar application rate when the application rate of biochar did not exceed 30 t ha^{-1}, but showed a decreasing trend when the application rate of biochar was higher than 30 t ha^{-1} (Fig. 1d). The results implied that the environmental and agronomic benefits brought by biochar did not always increase with biochar application rate. The finding was consistent with observations of previous meta-analyses (Liu et al., 2013; Jeffery et al., 2011; He et al., 2017). The reasons why the positive effects of biochar on mitigating greenhouse gas emissions and improving crop yield weakened at certain application rates are still unclear, likely as a result of the differences in management practices, planted crop species, and properties of soil and biochar in individual studies (Kloss et al., 2014; Laghari et al., 2015). Since the production of biochar not only consumes biomass and energy, but also leads to greenhouse gas emissions, the balance between the price of biochar production and the benefits brought by biochar should be paid closer attention to in the future (Pandit et al., 2018).

4.3. Soil properties

Previous meta-analyses observed that soil pH was an important factor that influenced the performance of biochar in agricultural ecosystems (Jeffery et al., 2011; Cayuela et al., 2014; Jeffery et al., 2016; Liu et al., 2016). Results of the present study indicated that biochar amendment in acidic and alkaline soils could significantly reduce GHGI. However, biochar had no effect on GHGI in neutral soils (Fig. 2a). In general, biochar has a higher pH than the soil in which it is applied (Zhang et al., 2012; Koyama et al., 2015), thereby a liming effect is often induced by biochar application (van Zwieten et al., 2010; Chintala et al., 2014). In the collected studies, the acidic soils were mostly from tropical and subtropical regions, where crop growth was often limited by low availability of P, K, Ca, Mg and by low level of soil organic matter (Glaser et al., 2002). The increase in soil pH after biochar amendment could not only enhance the availability of soil nutrients (e.g. P and K), but also reduce the toxicity of metal ion (e.g. Al^{3+}), contributing to better crop growth in these regions (Jeffery et al., 2011; Liu et al., 2013). Therefore, a significant increase in crop yield (14%) was observed after biochar amendment in acidic soils (Fig. S2e). Biochar's liming effect might also influence the production and consumption of N_2O and CH_4 in acidic soils. The increase in soil pH induced by the liming effect could create a favorable environment for N_2O reductase and methanotrophic communities, which contributed to the formation of N_2 and the oxidation of CH_4, respectively (Clough et al., 2013; Jeffery et al., 2016). The reduced toxicity of Al^{3+} to methanotrophs might also lead to the mitigation of CH_4 (Jeffery et al., 2016). Consequently, it is suggested that the liming effect of biochar is the main reason for the reduced yield-scaled GHGI in acidic soils. In alkaline soils, the significantly decreased GHGI after biochar application was unlikely to be a result of the liming effect due to the high soil pH (8.3 on average). Based on the above-mentioned mechanisms, it is hypothesized that the changes in soil labile organic C pool and nutrient status (e.g. the adsorption of mineral N), which have considerable impacts on soil microbial activities and crop growth, are possible explanations for the decreased GHGI in alkaline soils after biochar amendment. However, the hypothesized mechanisms need to be tested in further studies.

Soil texture is an important factor that influences soil aeration as well as soil water and nutrient availability (Silver et al., 2000). Empirical evidence showed that the effects of biochar on greenhouse gas emissions and crop growth varying with soil texture (Butnan et al., 2015; He et al., 2017). Unfortunately, there is currently no consensus on how soil texture affects the performance of biochar in soils. Biochar has a highly porous structure, which can improve a range of soil physical properties such as porosity and pore size distribution (Hardie et al., 2014). In general, it is speculated that particles in coarse soils are easier to mix with biochar compared to those in fine and medium soils, resulting in a better aeration condition in coarse soils (Liu et al., 2016). The improved soil aeration may further stimulate the decomposition of soil organic C and the activity of methanotrophs (Liu et al., 2016; He et al., 2017). Therefore, higher CO_2 emissions and lower CH_4 emissions are usually observed in coarse soils than those in fine and medium soils after biochar application (Liu et al., 2016; He et al., 2017). In contrast, the effectiveness of biochar on mitigating N_2O emissions and promoting crop yield is often not influenced by soil texture (Liu et al., 2013;

Cayuela et al., 2014). Similarly, results of the present study indicated that the response of yield-scaled GHGI to biochar application was not affected by soil texture (Fig. 2b). It is likely that the impacts of biochar on N_2O emissions and crop yield depend more on microbial activity and nutrient availability than soil physical properties (Atkinson et al., 2010; Clough et al., 2013).

4.4. Biochar properties

The feedstock of biochar, which is a key factor determining the compositional constituents of biochar, has received much attention during the last decade when evaluating the performance of biochar in greenhouse gas mitigation and crop yield promotion (Mukome et al., 2013). The most commonly used materials for biochar production are crop residue (e.g. rice husk and wheat straw) and wood, both of which can be easily obtained in most areas of the world (Mukome et al., 2013). Other feedstocks of biochar include, but are not limited to sewage sludge, manure, and municipal wastes (Ronsse et al., 2013). In the collected studies, the applied biochars were mainly made from crop residue or wood. Therefore, only two feedstocks of biochar were considered in this study. The results showed that the feedstock of biochar did not alter the response of yield-scaled GHGI to biochar (Fig. 3a). In contrast, the response of crop yield to biochar was significantly affected by the biochar feedstock, with no response (−3%) after applying biochar made from wood but a significant increase (15%) after applying biochar made from crop residue (Fig. S2g). Using meta-analysis, Nguyen et al. (2017) found that the decreases in NH_4^+ and NO_3^- were greater in soils with crop residue derived biochar than those in soils with woody biochar, suggesting that biochar made from crop residue might have a better impact on the retention of available N than biochar made from wood. After reviewing the effects of biochar on soil hydrological properties, Omondi et al. (2016) observed that crop residue derived biochar induced greater increases in soil porosity, water holding capacity, and saturated hydraulic conductivity compared to wood derived biochar. Hence, crop residue derived biochar may have a better performance on increasing the availability of N and water than woody biochar, creating a better soil environment for crop growth. Taking the performance of biochar and the cost of biochar production into consideration (Mukome et al., 2013), it is suggested that crop residue may be a better option for producing biochar than wood in agricultural ecosystems.

The pyrolysis temperature of biochar has been recognized as another important factor that affects biochar properties (Hossain et al., 2011; Al-Wabel et al., 2013). Results of the present study show that the effect of biochar on yield-scaled GHGI was not influenced by the pyrolysis temperature of biochar (Fig. 3b). In contrast, crop yield significantly increased after applying biochar produced at low (22%) and moderate pyrolysis temperatures (13%), and showed no response to biochar produced at high pyrolysis temperatures (−1%) (Fig. S2h). The results were inconsistent with those of Liu et al. (2013), who reported that biochars made from wood and crop residue at low pyrolysis temperatures (<350 °C) had no effect, or even significantly decreased crop productivity, whereas biochar produced at high pyrolysis temperatures (≥350 °C) resulted in significant increases in crop productivity. The contradictory results were due to that the assessed indexes were different in the two studies. In the present study, only the impact of biochar on crop yield was considered. In contrast, the impacts of biochar on both crop yield and aboveground biomass were assessed by Liu et al. (2013). In general, as pyrolysis temperature increased, the pH, electrical conductivity, ash content, C stability, and nutrient contents of biochar show increasing trends, whereas the yield of biochar decreases (Hossain et al., 2011; Al-Wabel et al., 2013; Yuan et al., 2015). Consequently, biochar produced at low pyrolysis temperatures may contribute to save the production cost of biochar while promoting crop yield.

The results showed that the effectiveness of biochar on reducing yield-scaled GHGI was not affected by biochar pH (Fig. 3c). In contrast, biochar application had no impact on crop yield (0%) if the pH of biochar was lower than 9.0, whereas it significantly increased crop yield by 13–16% if the biochar pH was higher than 9.0 (Fig. 2i). Previous studies indicated that biochar generally had a higher pH than the soil in which it was applied (Zhang et al., 2012; Koyama et al., 2015). In the collected studies, the pH of biochar varied from 6.3 to 10.4 with an average value of 9.5. By contrast, the average pH of soils was only 6.5. In this case, biochar was able to induce a liming effect after being applied to soils, especially acidic soils (Chintala et al., 2014). As illustrated above, biochar's liming effect not only improves mineral nutrient supply for crop growth, but can also alleviate Al and P stress for better crop health in acidic soils (Steiner et al., 2007; Asai et al., 2009; Schulz and Glaser, 2012). Consequently, biochars with high pH might have a better performance on improving soil fertility than those with low pH due to their stronger liming effects, resulting in significant increases in crop yield.

Based on the results of this meta-analysis, it is suggested that biochar application in dry lands may produce more environmental and agronomic benefits than that in paddy fields. Since the effectiveness of biochar on reducing yield-scaled GHGI does not always increase with the application rate of biochar, an appropriate application rate of biochar should be explored to maximize the benefits brought by biochar from a regional perspective. Soil pH and texture generally have little impact on the response of GHGI to biochar application, for which the reasons are currently unclear and require further studies to elucidate. The performance of biochar on reducing yield-scaled GHGI is also not influenced by biochar properties including feedstock, pyrolysis temperature, and pH. However, the response of crop yield to biochar amendment indicates that biochar made from crop residue, biochar produced at low pyrolysis temperatures (≤400 °C), and biochar with high pH (>9.0) may contribute to save the production cost of biochar while promoting crop yield in agricultural ecosystems. Long-term field trials are required to examine the persistence of the impact of biochar on reducing yield-scaled GHGI in the future.

5. Conclusion

Results of this meta-analysis showed that biochar application significantly reduced yield-scaled GHGI by 29%, indicating that biochar application might be an effective soil amendment for mitigating greenhouse gas emissions and simultaneously increasing crop yield in agricultural ecosystems. Although the reductions in GHGI after biochar application varied with different experimental conditions and properties of soil and biochar, the difference was only significant between the two cropping systems. In dry lands, the reduction in GHGI was significantly higher than that in paddy fields after biochar amendment, implying that biochar amendment in dry lands might produce more environmental and agronomic benefits than that in paddy fields. Taking the impacts of biochar on crop yield into consideration, it is suggested that biochar made from crop residue, biochar pyrolyzed at low temperatures (≤400 °C), and biochar with high pH (>9.0) are potentially effective soil amendments for saving the production cost of biochar while promoting crop yield in agricultural ecosystems. More studies, particularly long-term field studies, should be conducted to obtain a robust conclusion on how these factors regulate the effect of biochar on yield-scaled GHGI and to clarify the underlying mechanisms. Optimizing the impacts of biochar on greenhouse gas mitigation and crop yield promotion and evaluating the balance between the price of biochar production and the benefits brought by biochar should also be paid closer attention to in the future.

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Appendix A. Supplementary data

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