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A global synthesis of biochar's sustainability in climate-smart agriculture - Evidence from field and laboratory experiments

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ABSTRACT

Biochar amendment has been proposed as a promising solution to mitigate greenhouse gas (GHG) emissions from agriculture and sustainably enhance crop yield. However, the net GHG mitigation potential of biochar remains uncertain, especially the controversial results from field and laboratory experiments. Using 9970 published observational data derived from 592 peer-reviewed papers, this study highlighted the effects of biochar in field experiments on crop yield, soil organic carbon (SOC) stocks, carbon dioxide (CO_2) and methane (CH_4) fluxes, and soil nitrogen (N) dynamics (i.e., soil inorganic N stocks, nitrous oxide [N_2O] emissions, ammonia [NH_3] volatilization, and inorganic N leaching). Overall, field data indicated that biochar significantly increased gross SOC stocks (26.6%) and crop yield (15.7%), reduced soil CH_4 (−14.8%) and N_2O (−23.1%) emissions, and ammonium (−24.9%) and total inorganic N leaching (−23.2%) but had no effect on soil CO_2 emissions. Whereas laboratory data generally showed greater effect sizes of biochar on these indictors. Global warming potential was decreased only in field experiments, but both experiments showed similar reductions in GHG intensity. Both experiments suggested that soil and biochar cation exchange capacity, pH, biochar application rate, and nitrogen fertilization interactively regulated biochar effects on crop yield and GHG emissions. The unrealistically high rates of biochar in laboratory experiments may overestimate its benefit on soil C sequestration and/or underestimate its mitigation potential. These findings provide a comprehensive view that biochar amendment may serve as a viable climate-smart agricultural practice that can help in partial achievement of multiple sustainable development goals.

1. Introduction

Biochar amendment is considered a promising management practice of climate-smart agriculture (CSA) that aims to simultaneously boost crop productivity, enhance resilience to climate variability, and reduce greenhouse gas (GHG) emissions [1–3]. However, the effects of biochar on crop yield, soil properties, and GHG emissions are highly variable, depending on biochar feedstock and pyrolysis conditions, biochar amendment rates, experiment duration, soil and environmental conditions [4–6]. An improved understanding of how biochar amendment can contribute to achieving CSA's goals is needed to develop the optimized design and use of biochar amendment for multiple benefits [7].

Biochar contains recalcitrant organic carbon (C) and is produced by pyrolysis of organic matter at temperatures usually between 300 °C and 1000 °C [8]. The stability of biochar makes it a distinct soil amendment to abate climate change by reducing atmospheric carbon dioxide (CO_2) and promoting long-term soil C sequestration [9–11]. In addition, biochar can improve soil quality and soil fertility, thereby enhancing crop productivity [4,12,13]. Studies have reported a wide range of responses of physical, chemical, and biological soil properties to biochar, primarily due to variations in biochar properties [14]. Generally, biochar increases soil pH and cation exchange capacity (CEC), enhances water and nutrient retention and aggregate stability, and reduces soil bulk density

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List of abbreviations

Ammonia (NH_3)
Ammonium (NH_4^+)
Carbon dioxide (CO_2)
Cation exchange capacity (CEC)
Climate-smart agriculture (CSA)
Global warming potential (GWP)
Greenhouse gas (GHG)
Greenhouse gas intensity (GHGI)
Methane (CH_4)
Nitrate (NO_3^-)
Nitrous oxide (N_2O)
Soil organic carbon (SOC)
Total nitrogen (TN)
Total inorganic nitrogen (TIN)

[13,15–17]. Biochar addition can directly affect soil microbial communities and their activities [18]. For example, meta-analyses have shown that biochar addition increases microbial biomass C, nitrogen (N)-acquisition enzyme activities, and symbiotic biological N_2 fixation [19,20].

Biochar amendment may increase crop yield [4,21,22], although adverse yield effects have been reported [23,24]. The positive responses were commonly reported in nutrient-poor and acidic soils [23], with no responses found in nutrient-rich soils and negative yield responses for alkaline soils [24].

When it comes to GHG (i.e., CO_2, methane [CH_4], and nitrous oxide [N_2O]) emissions from biochar-amended soils, the responses are highly variable due to the complex soil microbial processes determining GHG fluxes and the interrelated biotic and abiotic regulating factors [5,14]. Yet, in most cases [25], biochar amendment has been demonstrated to reduce N_2O emissions ranging from 12% to 49% [19,26–30], especially when applied in combination with fertilizer or manure. Biochar amendment might have no effects [31], or result in an increase [32] or a decrease [33] in CO_2 emissions. For CH_4 emissions, biochar might have no effects [32] or serve as a mitigation strategy [34].

The responses of GHG intensity (i.e., GHG emissions per unit yield, GHGI) to biochar addition have been synthesized to address the trade-offs between GHG emissions and crop yield. On average, biochar addition reduces GHGI by 29% [35]. Biochar has other interactions with the N cycle, such as reductions in NO_3^- leaching and stimulation of NH_3 volatilization [19]. Such interactions, together with associated indirect N_2O emissions, play an essential role in evaluating the suitability of biochar amendment to enhance N use efficiency and reduce eutrophication under climate change.

A systematic quantitative review and thorough investigation of comprehensive biochar effects (e.g., meta-analysis) are helpful for synthesizing biochar effects on the soil C and N cycles to reveal the common response patterns among individual studies. Previous studies have been conducted on various topics, ranging from crop yields to soil nutrient dynamics, SOC sequestration, and GHG emissions. However, a comprehensive understanding of biochar effects on the trade-offs among C sequestration, GHG emissions, and soil N dynamics is lacking. This knowledge gap has hindered the efforts of fulfilling the three objectives of CSA [5]. Previous meta-analyses on biochar generally considered a mix of laboratory and field experiment data, although some treated experimental methods as an influential factor [32,33,35]. Field trials represent more realistic *in-situ* responses to biochar amendment, while laboratory experiments (including pot, greenhouse, and incubation experiments) may have a bias for specific target variables, e.g., GHG emissions [36]. Plant roots that are absent from incubation studies have an important role in soil aggregation and biogeochemical processes. Whereas plant root autotrophic respiration is often included in field CO_2 flux measurements. Some studies have illustrated contradictory results between laboratory experiments and field observations, which reduce the robustness of extrapolations and predictions across systems [14]. For example, Shakoor et al. [33] reported that biochar application led to decreased and increased CO_2 emissions from field and laboratory experiments, respectively. Nevertheless, they did not split the dataset into different experimental categories while analyzing the other influencing factors, such as biochar and soil properties.

This study compiled data from peer-reviewed studies to evaluate the effects of biochar on crop yield and soil C and N cycles, including GHG emissions, SOC, soil total N (TN), soil inorganic N pools (i.e., NO_3^-, NH_4^+, and total inorganic N [TIN]), NH_3 volatilization, and inorganic N leaching. Specifically, this study differentiated between observations from field trials and laboratory experiments, emphasizing results from field trials. Therefore, objectives of this study were to (1) compare the responses of the variables mentioned above to biochar amendment from field and laboratory experiments, and (2) identify the factors regulating such responses. This study was expected to lead to the development of tailored biochar management practices for accomplishing CSA objectives.

2. Materials and methods

2.1. Data compilation

A literature search was performed for publications before 2021 through the Web of Science and Google Scholar on Jan 7, 2021, using the keywords "biochar", "carbon dioxide/CO_2", "methane/CH_4", "nitrous oxide/N_2O″, "crop production/yield/productivity", "soil carbon", "soil nitrogen", "nitrogen leaching", "SOC", "ammonium", and "nitrate". The screen criteria were applied as follows:

1) The studies reported GHG emissions, soil C stock, crop production, or soil N loss in response to biochar;
2) The research was conducted on cropland soils excluding orchard, pasture, and tea plantation;
3) The biochar was produced by pyrolyzing organic materials, i.e., hydrochar and post-physiochemically modified biochar were not considered;
4) The control and biochar treatments were subjected to the same management (e.g., similar tillage practice, irrigation management, fertilization, or residue addition);
5) The means, standard deviations/errors, and sample sizes of variables in the control and treatment groups could be extracted directly from tables, graphs, text, or supplementary information.

The resulting overall dataset consists of 592 papers with 9970 observations for the target variables, including crop yield, SOC, GHG emissions (i.e., CO_2, CH_4, and N_2O), NH_3 volatilization, soil inorganic N (i.e., NO_3^-, NH_4^+, TIN) and TN, and inorganic N leaching (details are listed in Table S1 and Supplementary database). Data for this meta-analysis were either derived from tables or extracted from figures using WebPlotDigitizer [37]. Auxiliary information regarding the influencing factors was recorded.

Biochar application rates expressed in weight percentage were transformed to Mg ha^{-1} if the incorporation depth and soil bulk density were available. Otherwise, a 10-cm application depth and a mean soil bulk density of 1.3 Mg m^{-3} [38] were adopted following the method by Liu et al. [36]. All data on SOC concentration changes were converted to stock changes in Mg C ha^{-1} by multiplying the soil depth with the bulk density and the given change in SOC concentration. If bulk density was not reported, the SoilGrids dataset was used, which provides global estimates at a 250-m resolution based on approximately 150,000 soil profilers [39,40]. This study assumed that bulk density decreased on average by 7.6% under biochar treatment [41]. A conversion factor of

0.5 was used to calculate SOC content when only soil organic matter (SOM) content was reported [42]. The pH values of soil and biochar measured with $CaCl_2$ were transformed to pH measured in water following the method from Biederman and Harpole [21].

The global warming potential (GWP) was calculated when CO_2, CH_4, and N_2O fluxes were measured simultaneously in a study. GWP with a 100-year time horizon was converted into CO_2-equivalent emissions by multiplying the cumulative emissions of CH_4 and N_2O by 34 and 298, respectively, with climate-carbon feedback [43]:

GWP (Mg CO_2 equivalents ha^{-1} yr^{-1}) = 1 × CO_2 emission + 298 × N_2O emission + 34 × CH_4 emission.

The yield-scale GWP (or GHG intensity, GHGI) is related to grain yield and defined as follows:

GHGI (Mg CO_2 equivalents Mg^{-1} grain yield) = GWP/crop yield.

2.2. Meta-analysis

A random-effect meta-analysis was performed to investigate the partial dependence of biochar effects as a function of different variables. The effect size was calculated as a natural logarithmic-transformed response ratio (R) as follows [44]:

$$lnR = \ln\left(\frac{X_t}{X_c}\right),$$

where, X_t and X_c are the mean value of the target variables (e.g., crop yield, GHG emissions, GWP, NO_3 leaching, and SOC) for the biochar treatment and control, respectively. The variance (υ) of lnR was calculated as follows:

$$\upsilon = \frac{SD_t^2}{n_t X_t^2} + \frac{SD_c^2}{n_c X_c^2},$$

where, SD and n are the standard deviations and sample size in the biochar treatment and control. The weight (ω) of each effect size is defined as the inverse of the variance [45]. The mean effect size was then calculated as follows:

$$\overline{lnR} = \frac{\sum(lnR_i \times \omega_i)}{\sum \omega_i},$$

where, lnR_i and ω_i are the effect size and weight from the ith comparison, respectively. The 95% confidence interval (CI) of $\overline{lnR}$ was computed to determine the statistical significance. Comparisons between the biochar treatment and control were significantly different if the 95% CIs did not overlap with zero. Results were converted to percentage change [$(e^{\overline{lnR}}-1) \times 100\%$] for facilitating interpretation.

Factors influencing the effect size were grouped into different subcategories. Biochar feedstock type was classified as "biosolids" (e.g., slurry, distillation waste, kitchen waste), "herbaceous" (e.g., crop residues, grass, leaves), "manure" (e.g., animal waste), and "wood" (e.g., wood, sawdust, nutshell, bamboo). Biochar pyrolysis temperature (T, 150–1200 °C in the dataset) was grouped into $T \le 400$, $400 < T \le 550$, $550 < T \le 700$, and $T > 700$ °C. Biochar pH (4.2–12.8) included $pH \le 7$, $7 < pH \le 8$, $8 < pH \le 9$, $9 < pH \le 10$, and $pH > 10$. Biochar CEC (0.65–1025 cmol kg^{-1}) was grouped as $CEC \le 10$, $10 < CEC \le 20$, $20 < CEC \le 40$, $40 < CEC \le 80$, and $CEC > 80$ cmol kg^{-1}. Biochar application rate (R) (0.2–260 Mg ha^{-1}) was grouped as $R \le 10$, $10 < R \le 20$, $20 < R \le 40$, $40 < R \le 80$, $80 < R \le 120$, and $R > 120$ Mg ha^{-1}. Experiment duration (D) was grouped into $D \le 1$, $1 < D \le 2$, $2 < D \le 3$, $3 < D \le 5$, $D > 5$ years. Soil pH (3.7–10.2, was classified into three categories following Havlin et al. [46]: acidic ($pH < 6.6$), neutral ($6.6 \le pH \le 7.3$), and alkaline ($pH > 7.3$). Soil texture was classified according to the USDA soil texture triangle. Clay, sandy clay, and silty clay classes were considered "fine-textured; " silt, silt loam, silty clay loam, loam, sandy clay loam, and clay loam were designated as "medium-textured; " and sand, loamy sand, and sandy loam were grouped as "coarse-textured" [47,48]. Initial SOC content (0.005–181 g C kg^{-1}) was grouped as $SOC \le 5$, $5 < SOC \le 10$, $10 < SOC \le 20$, and $SOC > 20$ g C kg^{-1} soil. Soil CEC (0.5–356.3 cmol kg^{-1}) was classified as $CEC \le 5$, $5 < CEC \le 10$, $10 < CEC \le 20$, and $CEC > 20$ cmol kg^{-1}. Nitrogen fertilizer was grouped as "yes" or "no". Climate regions were grouped as "arid cold", "arid hot", "cold with dry winter", "cold humid", "temperate with dry summer", "temperate humid", "temperate with dry winter", and "tropical", based on the Köppen-Geiger climate classification maps at 1-km resolution (Table S2) [49]. Land cover types were grouped as "bare soil" (fallow period in field studies and incubation with soil samples in laboratory studies), "dryland" (vegetables and crops excluding paddy rice), and "paddy" (paddy rice).

Publication bias was tested by the funnel plot method and assessed using Kendell's rank correlation [50]. If the Kendell's Tau exhibited a significant difference from zero (i.e., indicating publication bias), Rosenthal's fail-safe or file drawer number was calculated (METAFOR package in R) to estimate if the results were likely affected by non-published studies (Tables S3–5) [51]. Each categorical factor was treated as a moderator for analyzing the whole dataset. The between-group variability was evaluated using the Chi-square test (Tables S6–7).

3. Results

3.1. Biochar effects on crop yield, SOC, TN, GHG emissions, and soil inorganic N dynamics

Overall, crop yield responses to biochar amendment were positive, with a significantly higher yield increase in laboratory experiments (25.4%) than in field trials (15.7%, Fig. 1). Similar patterns were found for SOC and TN (67.8% *vs.* 26.6% and 26.6% *vs.* 13.7%, respectively). Generally, biochar amendment reduced CH_4 (−21.9% *vs.* −14.8%) and N_2O emissions (−23.8% *vs.* −23.1%), NH_4^+ (−26.3% *vs.* −24.9%) and TIN leaching (−26.7% *vs.* −23.2%) compared to non-amended soils in laboratory and field experiments (Fig. 1). However, CO_2 emissions were 15.3% higher after biochar addition in laboratory experiments but were not significantly different in field trials. Biochar-induced decrease in NO_3^- leaching was only significant in laboratory experiments, while a decreasing trend was observed in field trials. As for biochar-induced changes in soil NO_3^-, NH_4^+, and TIN, there were opposite trends between field trials and laboratory experiments, with an increasing trend for the former and a decreasing trend for the latter. Biochar-induced changes in NH_3 volatilization tended to decrease in field trials but increase in laboratory experiments, although such responses were not statistically significant.

3.2. Factors influencing biochar effects on crop yield, SOC, GHG emissions, and nitrate leaching

The effects of biochar application on crop yield, SOC, GHG emissions, and NO_3^- dynamics depend on multiple factors, including biochar properties and application strategies, soil properties, climatic conditions, and agronomic practices. For each categorical factor, the subgroups with less than three pairwise comparisons were not included in the description and interpretation of the results. This section compared the results from field and laboratory experiments with a highlight of the former. Detailed results regarding field experiments were present here, and those from laboratory experiments were provided in supplementary files.

3.2.1. Biochar properties, application rates and experiment duration

Biochar feedstock. Biochar feedstock type played an important role in determining biochar effects on crop yield (Tables S6–7). Manure-based biochar increased crop yield the most (18.3% in field trials and 68.0% in laboratory experiments), followed by herbaceous-based biochar (Figs. 2 and S1). The responses of SOC to biochar addition were

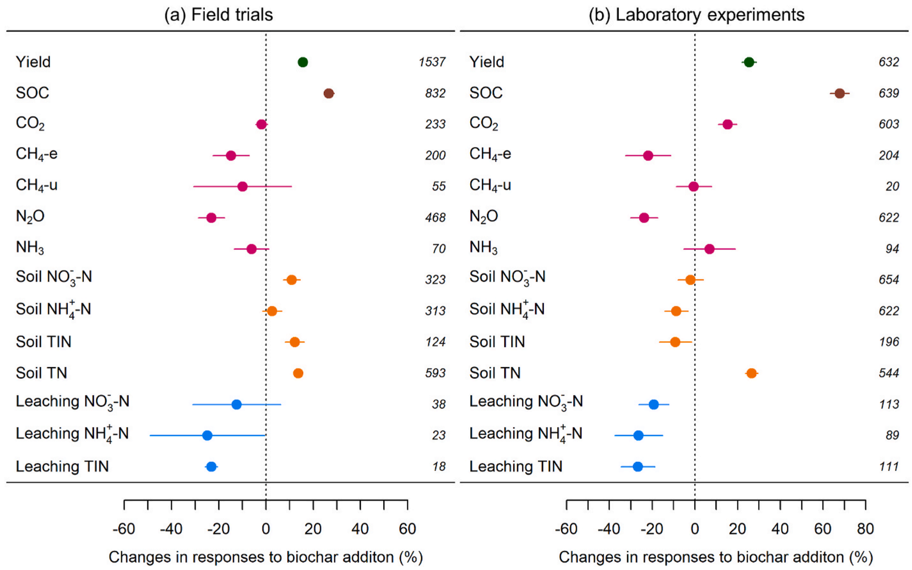

Fig. 1. Biochar effects on crop yield, GHG (i.e., CO_2, CH_4, and N_2O) emissions, NH_3 volatilization, inorganic soil N storage and leaching (i.e., NO_3^-, NH_4^+, and TIN), and SOC and TN storage in (a) field trials and (b) laboratory experiments. CH_4-e and CH_4-u represent the net positive and negative fluxes of CH_4 from the soil, respectively. Points represent the mean effect, and bars represent 95% confidence intervals. The right column shows the number of data pairs.

significantly affected by feedstock type in laboratory experiments but not field trials (Tables S6–7), although the responses were all positive. In laboratory experiments, wood-based biochar led to the highest increase in SOC stock (94.5%), while biosolid-based biochar led to the least (Fig. S2). Field trials had large variability regarding the effects of feedstock type on NO_3^- leaching. Laboratory experiments indicated that wood- and herbaceous-based biochar could significantly reduce NO_3^- leaching (Fig. S3).

The responses of CO_2 and N_2O emissions were not affected by feedstock type (Tables S6–7). Biochar effects on CO_2 emissions were neutral in all feedstock types from field trials (Fig. 3) but either neutral (biosolids) or positive (other types) from laboratory experiments (Fig. S4). The effects on N_2O emissions were either neutral (biosolids) or negative (other types) in both experimental scales (Figs. 3 and S6). Feedstock type significantly affected the effect size of CH_4 emissions in laboratory experiments but not field trials (Tables S6–7). In laboratory conditions, herbaceous- and wood-based biochar significantly reduced CH_4 emissions by 26.0% and 24.6%, respectively, but biosolids-based biochar increased CH_4 emissions by 71.9% (Fig. S5). Herbaceous-based biochar decreased CH_4 emissions in field trials (−15.5%, Fig. 3). There was only one data pair for biosolids but no data for manure regarding CH_4 emissions in field trials.

Biochar application rate. Positive crop yield responses increased with increasing biochar application rate and peaked at rates between 20 and 40 Mg ha^{-1} in field trials (Fig. 2). Similar yield responses were reported in laboratory experiments, but biochar-induced yield benefit peaked at lower rates between 10 and 20 Mg ha^{-1} (Fig. S1). Biochar increased SOC stock, and it peaked at rates between 40 and 80 Mg ha^{-1} in field trials. However, in laboratory experiments, biochar-induced increase in SOC stock consistently increased with biochar application rate (Fig. S2). After biochar amendment, CO_2 emissions decreased by 4.4% when the application rate was lower than 10 Mg ha^{-1} in field trials (Fig. 3). No significant effects were observed at higher rates; there were no data pairs in the 80–120 Mg ha^{-1} range and only one data pair for application rate >120 Mg ha^{-1}. In contrast, laboratory experiments showed that biochar stimulated CO_2 emissions with increased application rates (Fig. S4). Biochar amendment significantly decreased CH_4 emissions by 16.4% and 51.3% at rates lower than 10 Mg ha^{-1} and 40–80 Mg ha^{-1}, respectively, in field trials, while no data were available for 80–120 Mg ha^{-1} and >120 Mg ha^{-1} (Fig. 3). In laboratory experiments, biochar only significantly reduced CH_4 emissions by 45.8% at rates between 20 and 40 Mg ha^{-1}, while there were no data pairs for 80–120 Mg ha^{-1} (Fig. S5). Biochar amendment significantly decreased N_2O emissions when application rates were <10 Mg ha^{-1}, 10–20 Mg ha^{-1}, and 20–40 Mg ha^{-1} in field trials, but limited information was found for field application rates in the ranges of 80–120 and > 120 Mg ha^{-1} (Fig. 3). Observations in laboratory experiments indicated that the reduction in N_2O emissions and NO_3^- leaching increased with increasing biochar application rate (Figs. S3 and S6).

Biochar pH. Laboratory experiments showed that biochar benefited crop yield more when biochar pH was low (Fig. S1). However, field trials did not exhibit such a trend, and biochar was found to enhance crop yield the most when biochar pH > 10 (Fig. 2). The responses of SOC to biochar addition were not affected by biochar pH in field trials but significantly different in laboratory experiments (Tables S6–7). The SOC stocks increased the most when biochar pH was 7–8 in laboratory experiments (129.8%, Fig. S2). Field trials showed that biochar significantly decreased CO_2 emissions by 22.4% and 6.6% when biochar pH was ≤ 7 and 8–9, respectively, and increased CO_2 emissions by 11.4% and 4.3% when biochar pH was 7–8 and 9–10, respectively (Fig. 2). In contrast, laboratory experiments indicated no effects on CO_2 emissions when biochar pH was 8–9, but increases in CO_2 emissions were observed at other biochar pH values, with the largest increase recorded when biochar pH was ≤ 7 (Fig. S4). Biochar amendment significantly decreased CH_4 emission when biochar pH was 9–10 (−18.7%) in field trials and 8–9 (−25.4%) or > 10 (−31.9%) in laboratory experiments (Figs. 3 and S5). The responses of N_2O emissions were not affected by biochar pH (Tables S6–7), showing negative effect sizes in all sub-groups at both experimental scales. Laboratory experiments showed that biochar amendment significantly decreased NO_3^- leaching by 38.2% and 17.3% when biochar pH was 8–9 and 9–10, respectively (Fig. S3). The responses of NO_3^- were not affected by biochar pH in field trials.

Biochar CEC. Field trials showed that biochar-induced yield benefit was generally increased with biochar CEC and peaked at 40–80 cmol kg^{-1} (Fig. 2). In contrast, laboratory experiments indicated that the yield benefit initially decreased with biochar CEC, with no significant effects at 20–40 cmol kg^{-1}, and then increased with biochar CEC, with the largest increase observed when biochar CEC was > 80 cmol kg^{-1} (Fig. S1). The largest increase in SOC stocks was found when biochar CEC was > 80 cmol kg^{-1} (63.7%) and 10–20 cmol kg^{-1} (152.1%) in field trials and laboratory experiments, respectively. Biochar addition increased CO_2 emissions by 10.9% in field trials only when biochar CEC

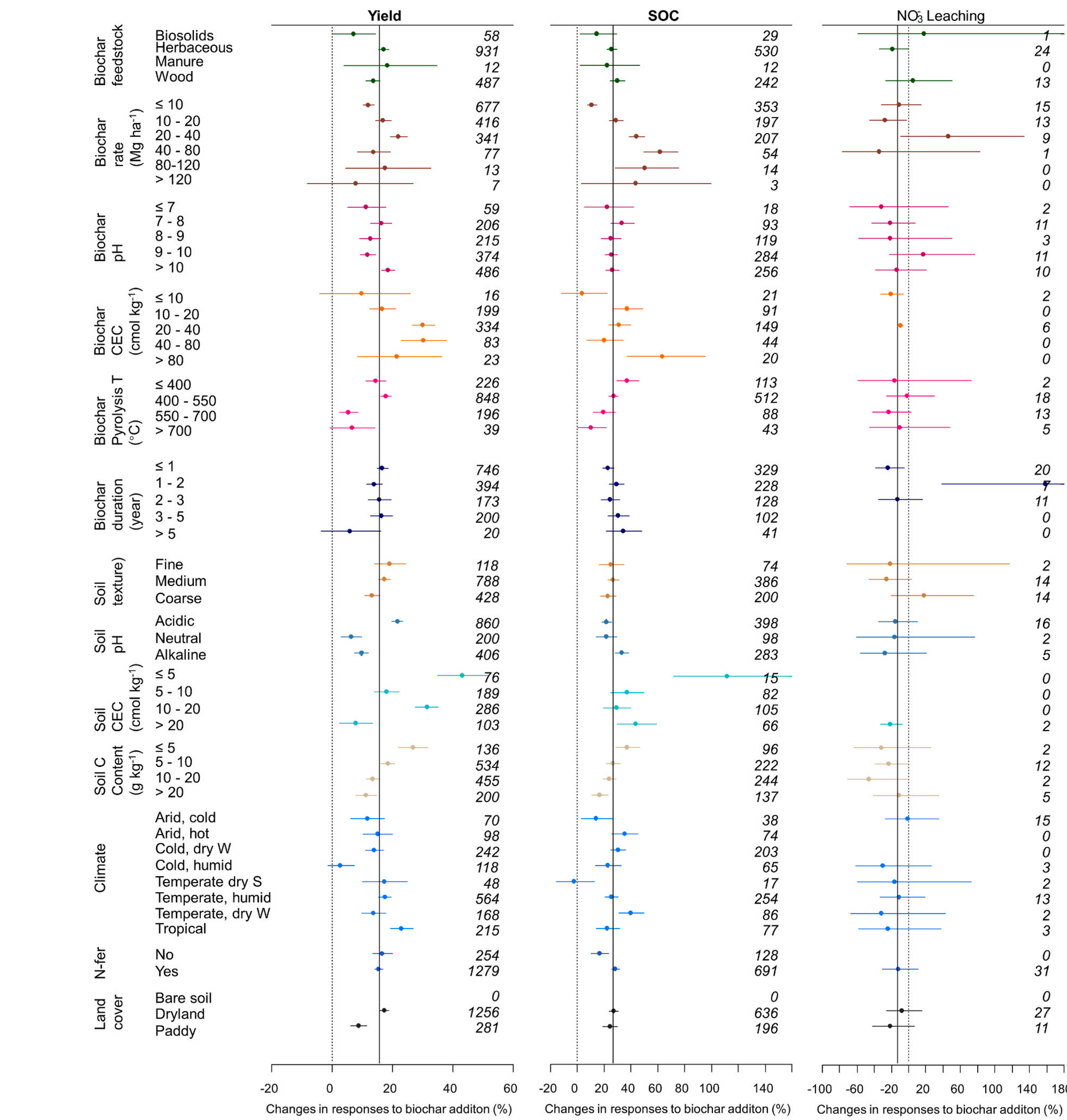

Fig. 2. The responses of crop yield, SOC stocks, and NO_3^- leaching to biochar amendment as affected by biochar properties and application strategies, soil characteristics, climate, and N fertilization in field trials. Solid vertical lines represent the grand mean % changes responding to biochar addition. Points represent the mean effect, and bars represent 95% confidence intervals. The right column shows the number of data pairs (N-fer: nitrogen fertilization; S: summer; T: temperature; W: winter).

was 40–80 cmol kg^{-1} (Fig. 3). Biochar addition in laboratory experiments decreased CO_2 emissions by 22.3% when biochar CEC was 10–20 cmol kg^{-1} and increased CO_2 emissions by 42.1% and 30.0% when biochar CEC was 20–40 and 40–80 cmol kg^{-1}, respectively (Fig. S4). Biochar amendment decreased CH_4 emissions by −27.1% and −34.1% when biochar CEC was 10–20 and 40–80 cmol kg^{-1}, respectively, in field trials (Fig. 3). Laboratory experiments indicated a decrease of 55.7% in CH_4 emissions when biochar CEC was 20–40 cmol kg^{-1} (Fig. S5). The responses of N_2O emissions and NO_3^- leaching were significantly affected by biochar CEC in laboratory but not field trials (Tables S6–7). Relatively higher reduction in N_2O emissions was generally found with biochar CEC at 40–80 cmol kg^{-1} (Figs. 3 and S6). Reduction in NO_3^- leaching was only significant with biochar at 10–20 cmol kg^{-1} in laboratory experiments (Fig. S3).

Biochar pyrolysis temperature. Biochar pyrolyzed at 400–550 °C exhibited the highest yield benefit in field trials, while biochar pyrolyzed at > 700 °C led to the largest yield increase in laboratory experiments (Figs. 2 and S1). Field trials showed that the gross SOC stock increase was more pronounced when biochar was pyrolyzed at a lower temperature (≤ 400 °C). However, laboratory experiments showed that biochar pyrolyzed at medium temperature (400–550 °C) led to the largest SOC stock increase. Biochar pyrolyzed at ≤ 400 °C significantly reduced CO_2 emissions by 12.2% in field trials (Fig. 3). But in laboratory experiments, biochar increased CO_2 in all pyrolysis temperature groups,

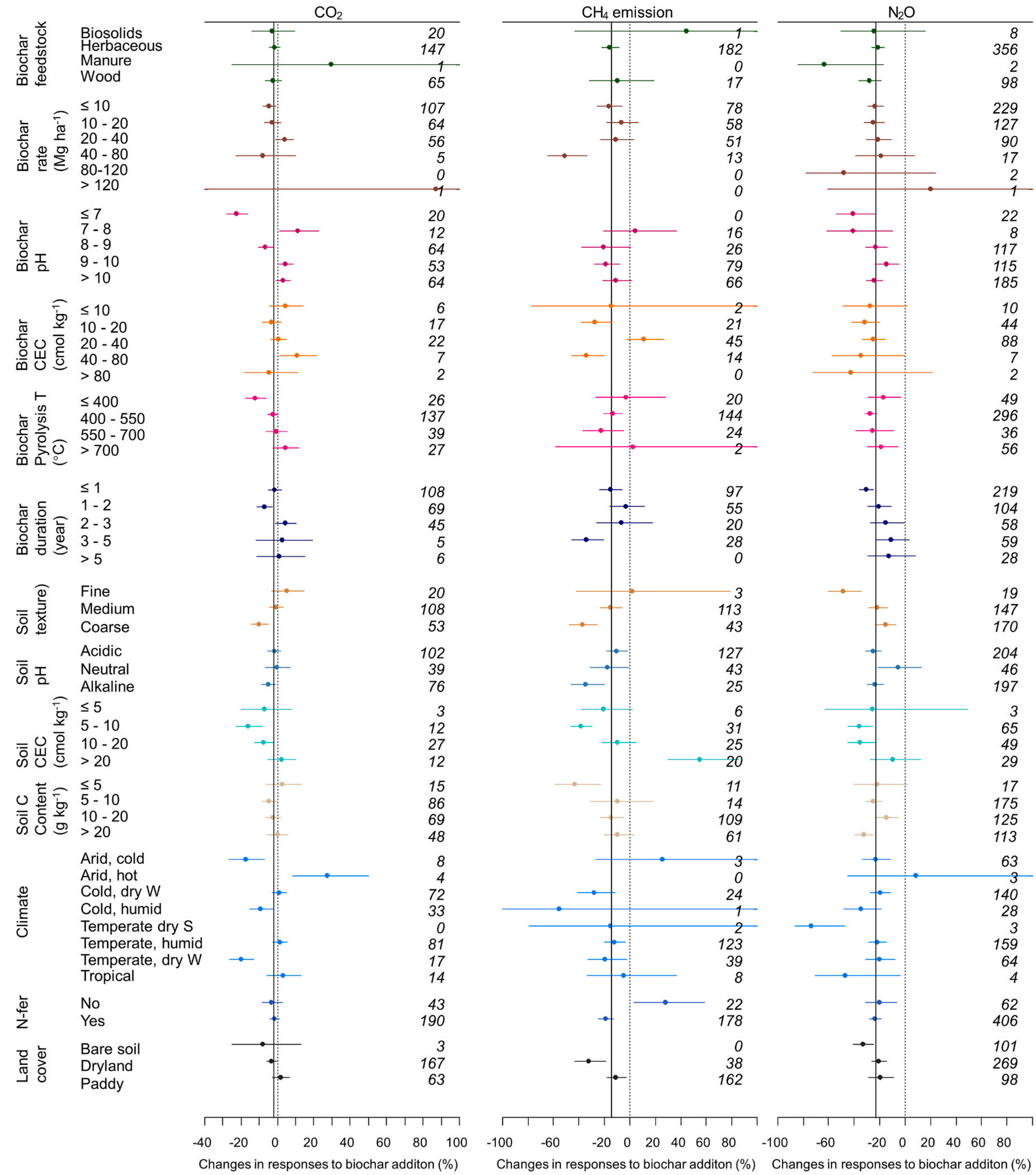

Fig. 3. The responses of GHG emissions to biochar amendment as affected by biochar properties and application strategies, soil characteristics, climate, and N fertilization in field trials. Solid vertical lines represent the grand mean % changes responding to biochar addition. Points represent the mean effect, and bars represent 95% confidence intervals. The right column shows the number of data pairs (N-fer: nitrogen fertilization; S: summer; T: temperature; W: winter).

with higher increases when the temperature was ≤ 400 °C and > 700 °C (Fig. S4). Biochar pyrolyzed at 550–700 °C, and 400–550 °C led to the largest reduction in CH_4 and N_2O emissions, respectively, under laboratory conditions (Figs. S5 and S6). Laboratory experiments showed that biochar pyrolyzed at 400–550 °C and 550–700 °C caused a significant decrease in NO_3^- leaching.

Experiment duration. Results from field trials suggested that the yield benefit can last in the medium-term (3–5 years), and the increase in SOC stock can last in the long-term (> 5 years). The benefit of decreasing NO_3^- leaching was only evident within one year after biochar addition (Figs. 2 and S3). It should be noted that long-lasting (>1 year) biochar experiments regarding NO_3^- leaching were scarce. Field trials suggested that biochar significantly reduced CO_2 emissions in the second year (Fig. 3). Laboratory experiments indicated an increase in CO_2 emissions within two years and a decrease in the third year (Fig. S4). Both experiments agreed that biochar reduced CH_4 emissions in the short (≤ 1 year) and medium (3–5 years) terms (Figs. 3 and S5). The reduction in N_2O emissions was only evident in the short term (≤ 3 and ≤ 2 years under field and laboratory conditions, respectively) (Figs. 3 and S6).

3.2.2. *Initial soil properties*

Soil texture. Biochar's yield benefit was more pronounced in fine-textured than in coarse-textured soils in field trials (Fig. 2, Table 1).

Table 1
The responses (percentage change, %) of crop yield to biochar amendment in field trials and laboratory experiments as affected by soil properties.

Moderator	Category$^{\Delta}$	Crop yield	
		Field	Laboratory
Soil texture	Fine	19.1 (14.0, 24.3) (118)[a]	21.6 (10.4, 34.0) (48)
	Medium	17.4 (15.5, 19.32) (788)	20.79 (15.1, 34.0) (211)
	Coarse	13.2 (10.7, 15.78) (428)	22.82 (17.0, 26.8) (287)
Soil pH	Acidic	21.6 (19.8, 23.47) (860)	37.86 (31.0, 45.0) (88)
	Neutral	6.4 (3.0, 9.9) (200)	8.89 (−0.5, 19.2) (218)
	Alkaline	9.7 (7.5, 12.0) (406)	19.12 (12.5, 26.2) (45)
Soil CEC (cmo kg^{-1})	≤ 5	43.2 (34.9, 52.0) (76)	42.47 (19.0, 70.5) (57)
	5–10	18.1 (14.0, 22.3) (189)	28.04 (9.5, 49.8) (57)
	10–20	31.4 (27.7, 35.2) (286)	32.26 (13.0, 54.8) (59)
	>20	7.9 (2.5, 13.5) (103)	57.81 (35.0, 84.4) (59)
Soil C content (g kg^{-1})	≤ 5	26.9 (22.1, 31.8) (136)	32.08 (24.7, 39.9) (160)
	5–10	18.5 (16.2, 20.9) (534)	15.87 (9.4, 22.8) (157)
	10–20	13.5 (11.2, 16.0) (455)	16.89 (10.7, 23.5) (184)
	> 20	11.2 (7.8, 14.7) (200)	54.78 (39.9, 71.2) (52)

ΔClay, sandy clay, and silty clay classes were considered "fine-textured; " silt, silt loam, silty clay loam, loam, sandy clay loam, and clay loam were designated as "medium-textured; " and sand, loamy sand, and sandy loam were grouped as "coarse-textured" [47,48].

[a] The first number represents the mean values, numbers in the first pair of parentheses are the 95% confidence intervals, and numbers in the second pair of parentheses are the number of data pairs.

Biochar amendment significantly reduced CO_2 emissions by 9.8% in coarse-textured soils (Fig. 3). However, in laboratory experiments, biochar increased CO_2 emissions the most in coarse-textured soils (Fig. S10). Biochar caused the largest decrease in CH_4 emissions in coarse-textured soils in field trials (−37.2%, Fig. 3) and in medium-textured soils in laboratory experiments (−15.9%, Fig. S11). As for the biochar-induced reduction in N_2O emissions, both experimental conditions agreed that such benefit was more pronounced in fine-textured soils (Figs. 3 and S12). Laboratory experiments indicated that the benefit of reducing NO_3^- leaching was significant in medium- and coarse-textured soils (−27.4% and −17.6%, respectively; Fig. S9).

Soil pH. The benefit of yield increase due to biochar application was more significant in acidic soils, and the SOC gains were more pronounced in alkaline soils (Figs. 2 and S7–8). Field trials showed that biochar application significantly reduced CO_2 emissions by 4.9% in alkaline soils (Fig. 3), while the largest increase in CO_2 emissions was in neutral soils under laboratory conditions (Fig. S10). The highest reduction in CH_4 emissions was −34.6% in alkaline soils under field conditions (Fig. 3). Although the three-level factor of soil pH as a whole did not significantly alter biochar effects on reducing N_2O emissions (Fig. 3), the N_2O responses were significantly different between neutral and alkaline soils. Additionally, laboratory experiments showed that the reduction in NO_3^- leaching was more significant in acidic soils (−28.4%, Fig. S9).

Soil CEC and initial C content. The largest yield and SOC increases were found in soils with low CEC (≤ 5 cmol kg^{-1}) and initial C content (≤ 5 g kg^{-1}) (Fig. 2). In field experiments, the SOC benefit was less with increasing initial soil C content. Biochar amendment decreased CO_2 emissions by 4.5% when soil CEC was 5–10 or 10–20 cmol kg^{-1} and soil initial C was 5–10 g kg^{-1} under field conditions (Fig. 3). However, laboratory experiments showed that biochar increased CO_2 emissions the most when soil CEC was ≤ 5 cmol kg^{-1} and initial soil C was 5–10 g kg^{-1} (Fig. S10), such effects generally decreased with increasing soil CEC or soil initial C. The reduction in CH_4 emissions was significant when soil CEC was 5–10 and 10–20 cmol kg^{-1} in field trials (−38.4%) and laboratory experiments (−34.4%), respectively (Figs. 3 and S11). There was a 55.0% increase in CH_4 emissions when soil CEC was > 20 cmol kg^{-1} in field trials (Fig. 3). The reduction in N_2O emissions was remarkable in soils with CEC of 5–10 and 10–20 cmol kg^{-1}. The reduction in N_2O emissions was more pronounced when initial soil C content was high (> 20 g kg^{-1}) in field trials (Fig. 3). The reduction in NO_3^- leaching was only significant in soils with CEC of 10–20 cmol kg^{-1} or initial C of 5–10 and 10–20 g kg^{-1} in laboratory experiments (Fig. S9).

3.2.3. Climate, land cover and nitrogen fertilization

All field studies were from 19 climate zones according to the Köppen-Geiger climate classification [49]. In this study, the climate zones were grouped into eight types (Fig. 4a). Biochar's benefits in increasing crop yield and SOC were generally consistent across the eight climate zones considered in this study (Fig. 2). Tropical climate areas showed a higher yield increase (23.0%) due to biochar amendment than other climate zones (Fig. 2). A significant reduction in CO_2 emissions was found in arid cold, cold humid, and temperate dry winter zones. Whereas a significant increase in CO_2 emissions was found in arid, hot zones (Fig. 3). The reductions in CH_4 and N_2O emissions due to biochar amendment were not significantly affected by climate conditions.

Yield increase due to biochar addition was higher in dryland (27.4%) than in paddy land (16.1%) from field trials (Fig. 2). Both field and laboratory experiments showed that significant reductions in CO_2 emissions only occurred in dryland (Figs. 3 and S14). Biochar added to dryland led to greater CH_4 emissions reductions than that added to paddy land (Fig. 3). Biochar added to bare soils led to the most N_2O emissions reductions (Fig. 3 and S16). Although laboratory experiments showed more SOC gains occurred in bare soils and dryland than in paddy land (Fig. S17), SOC gains from the field trials were not different between dryland and paddy land (Fig. 2).

Nitrogen fertilizer did not affect biochar's response on crop yield, CO_2 emissions, N_2O emissions, or NO_3^- leaching in field trials (Figs. 2 and 3). Biochar with N fertilizer resulted in more SOC increase than biochar without N fertilizer (Fig. 2). The biochar effect on CH_4 emissions was significantly affected by N fertilization. There was a decrease in CH_4 emissions (−18.9%) with N fertilizer but an increase in CH_4 emissions (27.8%) without it (Fig. 3).

3.3. Biochar effects on GWP and GHGI

Overall, biochar application did not affect GWP but significantly reduced yield-scale GWP (GHGI) by 16.2% based on the whole dataset (Fig. 5). However, biochar application significantly reduced GWP by 7.1% in field trials. Herbaceous- and wood-based biochar significantly decreased GWP by 5.5% and 12.0%, respectively, in field trials (Fig. S18). The reductions in GWP were significant when the biochar application rate was 10–20 Mg ha^{-1} (−11.5%), biochar pH was 8–9 (−24.6%), and biochar pyrolysis temperature was 400–550 °C (−9.1%) and 550–700 °C (−18.9%). Biochar application significantly reduced GWP by 20.0% in coarse-textured soils but not in fine- or medium-textured soils. The reductions in GWP were similar in acidic and alkaline soils but not significant in neutral soils. Soils with lower CEC responded to biochar addition with larger reductions in GWP than soils with higher CEC. Soils with high initial C content exhibited higher reductions in GWP with biochar addition. The reductions in GWP were only significant in the short term (≤2 years). The reductions in GWP were only significant in the arid cold (−26.3%) and cold humid (−19.2%) climate zones. Biochar application significantly reduced GWP by 9.9% when N fertilizer was applied but had no effect on GWP when N

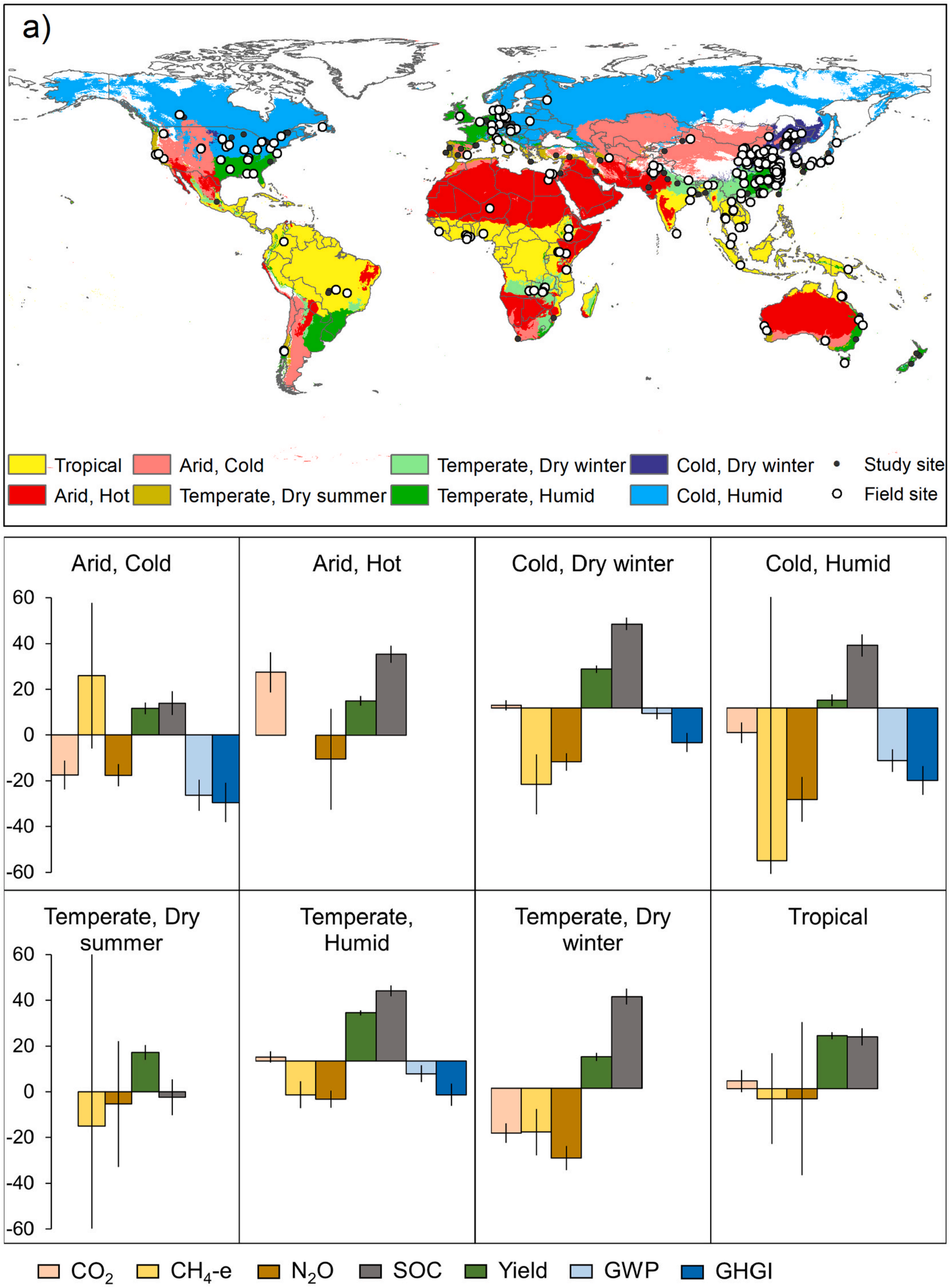

Fig. 4. a) Global distribution of study sites and climate zones based on the Köppen-Geiger climate classification; b) Biochar effects on greenhouse gas emissions (GHG, i.e., CO_2, CH_4, and N_2O. CH_4-e represents the net positive fluxes of CH_4 from the soil), Global warming potential (GWP), greenhouse gas intensity (GHGI), soil organic C (SOC), and yield in different climate zones.

fertilizer was not applied.

The reductions in GHGI were significant in both field trials and laboratory experiments. Field trials showed that the reductions in GHGI were higher with wood-based biochar (−24.3%) than with herbaceous-based biochar (−14.7%). Its difference among different biochar application rates was not significant. Biochar with a pH of 8–9 led to the largest reductions in GHGI (Fig. S19). Biochar pyrolyzed at 550–700 °C caused a higher reduction in GHGI (−25.7%) than biochar pyrolyzed at 400–550 °C (−17.2%). Biochar application significantly reduced GHGI by 10.4% and 31.7% in medium- and coarse-textured soils, respectively, but had no effect in fine-textured soils. The reductions in GHGI were similar in acidic and alkaline soils. The reductions in GHGI had similar response trends as the reductions in GWP did to soil CEC, initial C content, and N fertilization. Biochar application significantly reduced GHGI in four climate zones (i.e., arid cold; cold with dry winter; cold humid; and temperate humid), with the range between 12.3% and 29.5% (Fig. 4b).

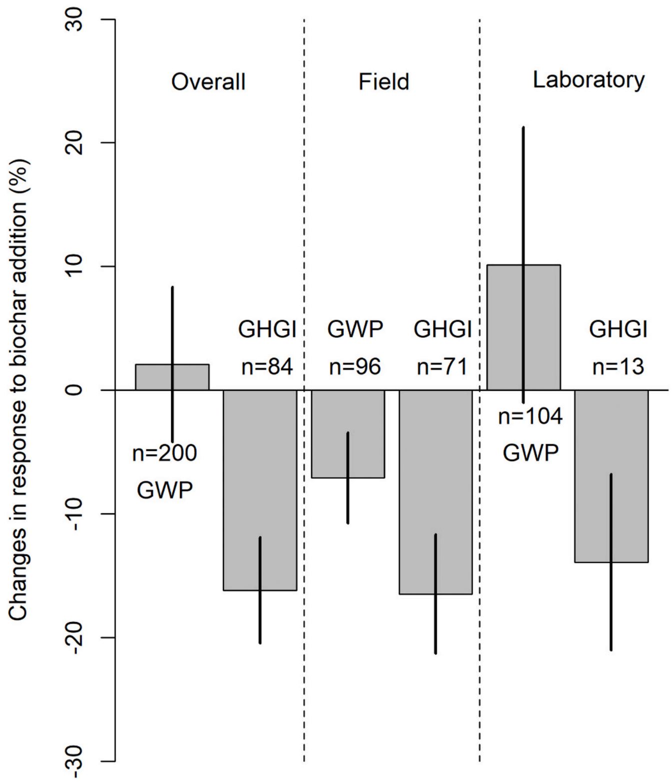

Fig. 5. Effects of biochar addition on global warming potential (GWP) and greenhouse gas intensity (GHGI).

4. Discussion

4.1. Biochar effects on crop yield

The results showed a consistent enhancement of crop yield due to biochar application in field (15.7%) and laboratory (25.4%) experiments. This finding is in line with the results reported in previous meta-analyses (10%–42%) [4,21–24]. The crop yield responses to biochar addition as affected by multiple moderating factors were neutral to positive, indicating that biochar amendment can be a reliable practice to mitigate crop production risks under climate change, although the variability could be introduced by biochar properties, soil conditions, climate, and N fertilization.

The most distinct effect of biochar properties on crop yield was caused by biochar CEC, with the groups of 20–40 and 40–80 cmol kg^{-1} causing the greatest increase in crop yield (~30%). Results presented herein showed a greater yield increase occurred in soils with lower CEC (especially when soil CEC < 5 cmol kg^1) and lower initial C content, which is inconsistent with previous studies [24,52]. Biochar is usually featured by its porous structure, large surface area, and negative surface charge [53,54]. When applied to soil, it helps improve soil CEC and enhance nutrient retention in soils, such as K [55] and P [56], promoting plant growth. In addition, as higher CEC soils are usually associated with greater soil water holding capacity, biochar can improve soil water retention [13] and facilitate crop biomass accumulation [57]. It could explain the higher yield increase from dryland crops than paddy rice in this study.

This study agreed with previous findings that biochar's yield benefit was more pronounced in acidic soils [23,24], primarily due to the liming effects of biochar. An interactive analysis of biochar pH and soil pH suggested that the largest yield increase occurred when alkaline biochar (pH > 10) was applied to acidic soils (25.4%, Table S8). In acidic soils, liming agents reduce the mobility of toxic elements like Al and increase the availability of P for better crop growth [58,59]. Yield responses were the highest in the tropical climate zone (~23%) where soils are often acidic and P deficient [60]. Crop yield benefit due to biochar could persist for up to five years (Fig. 2), and only 6/20 data pairs from experiments longer than five years showed negative responses. Biochar can stay in soils for a long time due to its biochemical stability [11,61]; it may have irreversible effects on soil properties [62]. Glaser and Lehr [56] indicated that the enhancement of plant-available P in biochar-amended soils could last at least five years. The interactions of biochar with soil minerals and microbes enhance the formation of organo-mineral microagglomerates, which can increase nutrient holding capacity in the long term [5]. A recent six-year field experiment indicated that long-term biochar increased both macro- and micro-aggregates, especially the C transfer from macro-aggregates to micro-aggregates [63].

4.2. Biochar effects on climate change mitigation

4.2.1. Carbon sequestration and CO_2 emissions

This meta-analysis showed an average increase of 26.6% in gross SOC stocks in biochar-amended soils (with an average application rate of 20.9 Mg ha^{-1} across the field database, Fig. S36) and enhanced SOC stocks with higher biochar application rates. The laboratory data exhibited greater SOC gains than the field data. It is not surprising because biochar is a C-rich material, and the majority of biochar-associated C is recalcitrant in soils, with a residence time ranging from hundreds to thousands of years [64]. This study showed the co-occurrence of the most significant increase in SOC pools and the most yield stimulation in biochar-amended soils, suggesting a great potential of biochar for improving soil health. Like results reported by Liu et al. [31], biochar amendment resulted in higher SOC gains in controlled laboratory experiments than in field studies. The compiled data showed that the average biochar addition rate was higher in laboratory-based than that in field studies, with even unrealistically high rates occurring in laboratory experiments (Fig. S36). These high application rates may lead to an overestimation of the influence of other biochar properties (e.g., biochar pH) on SOC from laboratory experiments: high biochar application rate (80–120 and > 120 Mg ha^{-1}) with biochar pH between 7 and 8 from laboratory led to high effect sizes of SOC (Tables S7 and S9). Another possible reason is that biochar applied in the field could be lost through wind and water erosions [15,65] or moved vertically into deeper soil layers [65].

It should be noted that biochar produced at lower pyrolysis temperatures resulted in higher SOC gains than that pyrolyzed at higher temperatures. These results are in accordance with the findings of machine-learning analysis that reported a negative relationship between pyrolysis temperature and SOC response ratios [66]. Although the total C content of biochar increased with increasing pyrolysis temperature [54], higher temperatures can lead to lower biochar yields from feedstocks [67]. Biochar pyrolyzed at 350–550 °C had greater effects on microbial biomass and enzymatic activities [20], implicating a better soil quality for crop production. The greater crop yield increase when biochar was pyrolyzed at a temperature <550 °C echoed this hypothesis (Fig. 2).

Biochar application did not affect soil CO_2 emissions in field trials. But increased CO_2 emissions occurred in laboratory experiments (15.3%), indicating that caution should be taken in the interpretation/extrapolation of laboratory results to field-scale settings. Compared to laboratory experiments, field trials are usually conducted with actively growing plants and involve the interactions of several environmental factors that are difficult to control, such as soil moisture and temperature, and that can have significant effects on soil microbial activity [68]. The stabilization of root exudates by the formation of organo-mineral complexes in biochar-amended soils could reduce root exudate-derived CO_2 emissions [69]. Biochar amendment can initially increase soil CO_2 emissions due to microbial decomposition of the labile biochar C [70] and a positive priming effect (i.e., enhanced decomposition of SOM) [71]. Available data showed that biochar typically contained a small amount of labile C (~3% overall) [61] and tended to initially induce a positive priming after biochar addition [72, 73] and then a negative priming effect in the long-term [61]. For example, a recent study showed that biochar addition to maize field stimulated soil CO_2 emissions in the initial 66 days and decreased it afterward, leading to an overall reduction for the entire growing season [74]. While some studies suggested that biochar suppressed CO_2 emissions consistently during the growing season [75,76]. One possible explanation for this discrepancy could be that priming direction and magnitude in the short term varied with soil and biochar type [77].

4.2.2. Non-CO_2 soil GHG emissions

This meta-analysis showed a similar reduction in soil N_2O emissions between field and laboratory data (−23.1% *vs.* −23.8%), falling within the range of previous studies (−49% to −12.4%) [19,27,28,30]. The average responses of N_2O emissions were generally neutral to negative despite the variability in biochar proprieties and application strategies, soil conditions, climate, and N fertilization. Results from laboratory experiments showed the reduction in N_2O emissions increased with the biochar addition rate. However, results from field trials showed similar responses when the biochar application rate was <40 Mg ha^{-1} but no effect with higher application rates. The possible reason could be that soil moisture and temperature regimes were usually under control in laboratory experiments but were more variable under field conditions. Aerobic nitrification and anaerobic denitrification are the main N_2O formation pathways [78]. Soil moisture status largely determines the dominant N_2O production pathway [79]. Biochar reduced N_2O emissions mainly by affecting the denitrification processes [80]. For example, biochar can increase soil pH, thus encouraging N_2O-reducing microbial activities [81]. Biochar exhibits adsorption ability to NO_3^- and/or NH_4^+ [82,83], and thus could reduce the availability of these mineral N species for nitrification and denitrification. This study showed that a higher reduction in N_2O emissions occurred in fine-textured soils. One possible reason could be the development of anaerobic condition in water-saturated capillary pores in these soils [84], thus facilitating complete denitrification (that is conversion of N_2O to N_2). Biochar decreased N_2O emissions more in soils with high C content (> 20 g kg^{-1}) than in soils with lower C content. This trend may be because the high amount of available C supports heterotrophic processes with the completion of denitrification from nitrate to N_2 [85]. Biochar's effectiveness in reducing N_2O emissions can last three years in the field. However, the long-term responses remain uncertain and need further investigation.

Biochar addition significantly decreased soil CH_4 emissions from field trials by 14.8% in this meta-analysis. Previous meta-analyses have shown neutral [32] and negative [34,86] responses of CH_4 emissions, suggesting that more evidence from field studies is emerging to support that biochar suppresses CH_4 emissions. Methane flux is regulated by the balance between the activities of methanogens and methanotrophs, which are responsible for CH_4 production and consumption, respectively. The effect of biochar on CH_4 fluxes may include the following mechanisms: (1) biochar increases soil porosity and aeration, which may increase oxidation of CH_4 and/or suppress CH_4 production [80]; (2) biochar may increase the abundance of methanotrophs and/or change the structure of methanotrophic community [87,88]. Jeffery et al. [34] reported that the reduction in CH_4 emissions was more pronounced in acidic soils, possibly because methanotrophs benefited more from biochar's liming effect. The results from laboratory experiments agreed with this interpretation (Fig. S5). However, the results from field experiments showed a different trend—a greater reduction in CH_4 emissions in alkaline soils (Fig. 3)—which needs further investigation.

4.2.3. GWP and GHGI

Biochar showed great potential in reducing GWP, especially GHGI, which agreed with previous findings [35,89], suggesting that biochar amendment to soils can be an effective tool for mitigating climate change and enhancing food security. The non-significant responses of GWP in laboratory experiments were due to the combination of incubation and pot studies. The studies in this meta-analysis showed that biochar addition increased and reduced GWP in incubation (17.9%, n = 78) and pot (−10.9%, n = 26) experiments, respectively. The increased GWP in incubation studies was largely due to a positive response of CO_2 emissions (34.3%, n = 78) from biochar-amended soils. Some possible reasons explaining the increased CO_2 emissions under laboratory conditions have been discussed previously in 4.2.1. Additionally, the compiled data for analyzing GWP showed that the application rates of biochar in the incubation trials were greater than those in the field and pot trials, with a median of 60 Mg ha^{-1}, 20 Mg ha^{-1}, and 23 Mg ha^{-1}, respectively (Fig. S37). Biochar-derived respiration can linearly increase with increasing biochar addition rate [90]. The increased GWP in incubation studies could be attributed to biochar-derived CO_2 emissions. Nevertheless, studies suggested that the actual soil-derived CO_2 may not be altered after the correction for the biochar-derived CO_2 [90,91].

Field trials showed great potential for decreasing the GHGI of croplands with biochar amendment in different climate zones, although simultaneous assessments of GHG emissions and crop yield are relatively limited. Course-textured soils and soils with medium-high SOC content (10–20 g kg^{-1}) benefited the most from biochar addition in terms of reduction in GWP and GHGI. Butnan et al. [92] reported that biochar affected coarse-textured soils more than high-clay soils, possibly because it is easier to incorporate biochar into coarse-textured that fine-textured soils, leading to better soil aeration [31]. A recent meta-analysis indicated that soil pH was the most important factor explaining the GWP variations under biochar treatment [89]. Results herein showed that soil pH significantly affected the responses of CH_4 emissions and crop yield to biochar amendment but not GWP or GHGI. The differences could be due to the various data sources and the limited quantity of data for some land-management categories.

The GWP and GHGI benefits of biochar addition were significant in the short term, consistent with Xu et al. [89]. They suggested that biochar reduced GWP and increased crop yield in the early experimental stage, but the effect size would become weaker with a longer experimental duration. Nevertheless, long-term benefits could be expected, considering the longevity of biochar in soils [5]. More long-term studies are needed to verify this inference. The decrease in GWP and GHGI and the increase in SOC were more pronounced at biochar application rates of 40–80 Mg ha^{-1}, implying a greater climate change mitigation potential with high rates of biochar application. However, 40–80 Mg ha^{-1} may be unrealistic and not practical for croplands under active production. It might not be economically beneficial for producers to implement such high biochar usage rates [66]. Among all the data pairs compiled from field trials in this study, more than 95% were conducted with application rates of less than 40 Mg ha^{-1} (~64%, 18%, and 14% for the groups of ≤ 10, 10–20, and 20–40 Mg ha^{-1}, respectively). Lower biochar application rates tend to cause less significant changes in soil physical and chemical properties than higher rates [93]. Singh et al. [93] found that increased crop yield due to biochar amendment correlated with decreased bulk density and increased soil porosity. Therefore, a compromise of the biochar application rate must be reached considering the trade-offs among biochar's C credits, yield benefit, mitigation potential, and economic returns.

4.3. Biochar effects on soil resilience

Apart from the increase in SOC, this meta-analysis showed that biochar amendment increased soil TIN and NO_3^- contents in the field. However, previous meta-analyses observed that biochar amendment significantly decreased soil NO_3^- (−12% to −10%) and NH_4^+ (−11% to −6%) [19,94], or had no effect on soil NO_3^- [27]. The contradictory results could be the confounding effect between field and laboratory experiments (including pot and incubation) and the duration of these experiments. For example, in Nguyen et al.'s database, 83% of field trials lasted more than one month, while 69% of pot trials lasted less than one month [94]. This study showed that reductions in soil TIN and NH_4^+ contents in laboratory experiments were largely attributed to incubation studies. Biochar may accelerate soil N transformation in the short term, including increased soil inorganic N assimilation [19] and immobilization [95], raised soil NH_3 volatilization (Fig. 1b), and stimulated nitrification [95,96]. Zheng et al. [97] suggested that the enhanced N immobilization could create a temporary organic N reservoir, which would be slowly mineralized in the long term. The short-term incubations may not catch this long-term effect. The higher application rate of biochar in laboratory conditions than in field experiments was another possible reason for the different soil NH_4^+ responses between experiment scales (Fig. S38). In addition, the co-application of biochar and N fertilizer could increase soil inorganic N content [94]. In this meta-analysis database, ~90% of the field trials and ~60% of the laboratory experiments received N fertilizer application. Biochar addition significantly increased NO_3^- and TIN with N fertilization but had no effect without N fertilization in field trials (Figs. S20–21). Soil NO_3^- increased in the long-term (>5 years) after biochar addition, possibly due to the decrease in denitrification rates [98].

This study showed reductions in inorganic N leaching in both field and laboratory studies, which agreed with previous reports [19,27]. Some possible mechanisms for this response include: (1) biochar has adsorption capacity for NH_4^+ and NO_3^- due to its negatively charged surface and large surface area [99]; (2) biochar has a porous structure, making it possible for NO_3^- to become entrapped within these structures [100,101]; and (3) biochar can increase soil water holding capacity, thereby reducing the amount of water available for percolation [13].

5. Conclusions and prospects

This study offered the first attempt to systematically compare biochar effects on multiple variables (i.e., crop yield, SOC, soil GHG emissions, and soil inorganic N dynamics) in field and laboratory experiments and highlighted the importance of data derived at field scale. Both experiments proved that biochar can be an effective CSA management for abating climate change and simultaneously enhancing food security by decreasing soil GHG emissions and GHGI and increasing crop yield and SOC. However, there exist contrasting effects of biochar on CO_2 emissions and soil inorganic N content under laboratory conditions and under field settings, underscoring the need for caution when projecting laboratory results to field-scale situations. Unrealistically high rates of biochar (e.g., >80 Mg ha^{-1}) in the laboratory experiments could lead to these discrepancies and may overestimate biochar's benefit on soil C sequestration and/or underestimate its climate change mitigation potential. Such high rates are impractical in field conditions because of the high cost of feedstock, transportation, and pyrolysis.

It should be noted that most studies that reported SOC changes included biochar-C in their SOC measurement; however, it is more important to consider the net priming effect caused by biochar and the SOC dynamic, excluding the biochar-C fraction [102]. Although biochar addition is an effective way to sequester C, the production and transportation could emit a certain amount of C [103], which may offset some of the climate change mitigation benefits of biochar. Such trade-offs should be further considered in a full Life Cycle Assessment.

Biochar can remain in the soil for a long time due to its slow decomposition rate [9]. The stability of biochar would be gradually altered, and its interactions with soil biotic and abiotic factors may profoundly affect how biochar could influence soil properties, crop yield, and GWP in the long-term. However, the legacy effects of biochar amendment remain uncertain and an under-investigated aspect of biochar research. Current laboratory experiments usually last days, weeks, or months, and field experiments often span less than five years. More long-term field experiments are essential for examining biochar effects on agroecosystems.

Quantifying biochar effects on agroecosystems at large scales (e.g., from regional to global scales) is urgently needed and requires knowledge of the underlying mechanisms and data support from field experiments and/or *in-situ* observations. Modeling, including process-based modeling [104] and machine-leaching methods [66], provides an effective tool to predict biochar effects under multiple scenarios. However, modeling biochar effects remains in its early stage. With more reliable data from field measurements, future research may integrate process-based modeling and machine learning toward realistic predictions of biochar effects on food security and climate mitigation at large scales.

Credit author statement

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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