Xu *et al. Biochar* (2026) 8:106
https://doi.org/10.1007/s42773-026-00628-6

Biochar

**REVIEW** **Open Access**

# Warming increases $CO_2$ emissions in biochar-amended cropland soil

Tongyu Xu[1†], Qiufeng Xu[2†], Yan Lei[3], Fei Li[1*], Amit Kumar[4], Dafeng Hui[5], Jianming Xue[6], Shengdao Shan[1], Yongfu Li[7], Hepeng Li[8] and Junjie Lin[1*]

## Abstract

Biochar application is recognized as a promising strategy for enhancing soil carbon (C) sequestration, yet its influence on carbon dioxide ($CO_2$) emissions under a warming climate remains inadequately understood. We conducted a global meta-analysis of 2079 paired observations from 32 peer-reviewed publications to quantify the responses of $CO_2$ emissions in biochar-amended soils to warming and to identify their key drivers. Overall, warming increased $CO_2$ emissions in biochar-amended soils by 77% on average, with a 117.5% increase in croplands and a 30.9% increase in forests. The effect was strongest for woody biochars, intermediate for crop-derived biochars, and weakest for grass-derived biochars. Increases in $CO_2$ emissions were positively associated with warming magnitude, biochar characteristics, and soil properties. Warming magnitude was the dominant driver, followed by biochar application rate, soil C/N ratio, and biochar C/N ratio. The relative importance of these secondary drivers varies across cropland and forest ecosystems. These findings indicate that the climate mitigation potential of biochar may be overestimated if warming-induced C losses are ignored in biochar-amended cropland soil. To enhance the resilience of biochar applications, context-specific strategies should prioritize non-woody feedstocks, lower pyrolysis temperatures, and moderate application rates, particularly in vulnerable cropland systems. It is necessary to integrate the warming effects into biochar life-cycle assessments and soil C management frameworks to ensure realistic projections of its role in climate mitigation and carbon sequestration, particularly in cropland ecosystems under warming conditions.

## Highlights

- Warming boosts $CO_2$ emissions from biochar-amended soils by 77% on average, with a higher increase in croplands than in forests.
- Warming magnitude is the top driver of emission changes, followed by biochar characteristics and soil properties.
- Woody biochars induce a stronger warming response than non-woody feedstocks.
- Biochar application needs to be optimized by integrating warming effects.

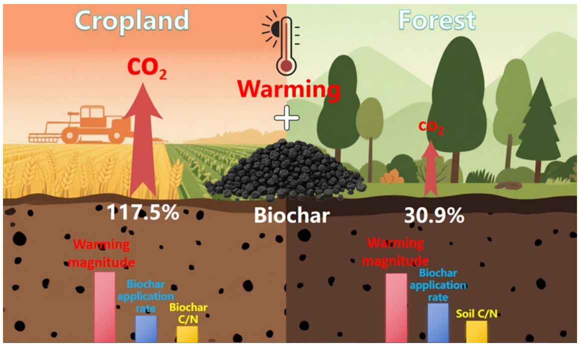
**Keywords** Greenhouse gas, Biochar amendment, Global warming, Soil organic matter, Climate change

---

[†]Tongyu Xu and Qiufeng Xu have contributed equally to this work.

*Correspondence:
Fei Li
flissrs@yeah.net
Junjie Lin
ybu_lin@126.com
Full list of author information is available at the end of the article

**Graphical Abstract**



## 1 Introduction

Soil is a primary terrestrial carbon (C) pool, playing a critical role in regulating climate feedbacks (Georgiou et al. 2022). Significant fluctuations in soil respiration are early indicators of shifts in the global C cycle (Possinger et al. 2025). Land ecosystems sequestrated an average of 1.3 Gt C $y^{-1}$ in nonliving organic matter pools (Bar-On et al. 2025). However, both warming and C inputs accelerate soil organic carbon (SOC) decomposition, reinforcing a positive feedback between the soil C cycle and rising temperature (Lin et al. 2023). A modest 10% change in the soil C pool would be equivalent to the total anthropogenic carbon dioxide ($CO_2$) emissions over the past 30 years (Kirschbaum 2000). Therefore, quantifying the response of soil $CO_2$ emissions to warming under increased C inputs is critical for predicting the stability of the soil C reservoir under climate change.

Biochar is produced through the anaerobic pyrolysis of plant and animal residues (Antonangelo et al. 2025). It is a promising strategy to incorporate biochar into soil for raising SOC storage and indirectly removing atmospheric $CO_2$ (Ghosh et al. 2025). Biochar application improves soil health via physical structure optimization, water and nutrient retention, and ecosystem resilience (Lin et al. 2025b; Zhou et al. 2026). Corn straw biochar reduces $CO_2$ emissions by 15–17% in agricultural and forest soils (Mohan et al. 2018; Zhou et al. 2024). Woody biochar decreases $CO_2$ emissions by 33% in a temperate *Miscanthus* plantation (Case et al. 2014). However, these studies did not account for warming effects, leading to a potential overestimation of biochar's carbon sequestration potential in a changing climate (Bamminger et al. 2017). Global warming is expected to intensify soil $CO_2$ emissions in terrestrial ecosystems (Chen et al. 2024; Hu et al. 2024). Soil heterotrophic respiration has already increased by 2% per decade, potentially rising 40% by 2100 under high-emission scenarios (Nissan et al. 2023). Tropical forest soils may lose over 13% of their C storage (65 Pg C) with a 4 °C temperature rise this century (Nottingham et al. 2020). Long-term field warming accelerated recalcitrant SOC decomposition in temperate grasslands (Feng et al. 2017). 1.5 years of experimental warming increased 38% of ecosystem respiration in high-latitude tundra (Xue et al. 2016). According to IPCC AR6, riparian zones were projected to have a 4–17% increase in $CO_2$ emissions by 2100 (Cheng et al. 2025). A 2 °C warming increases cropland soil $CO_2$ emissions by an average of 15% (Gao et al. 2022), highlighting the potential for a strong positive feedback between global warming and soil C pools.

Warming governed $CO_2$ emissions from biochar-treated soils. The warming effect was regulated by the feedstock type, pyrolysis temperature, application rate of biochar, and soil properties (Huang et al. 2022a; Jiang et al. 2025). The pyrolysis temperature of biochars stimulates microbial activity and accelerate $CO_2$ release in warmed soils due to higher preferential substrate utilization (Yang et al. 2022). Warming increases soil $CO_2$, $CH_4$, and $N_2O$ production rates by altering microbial community composition, enzymatic activities, and biochar–SOC interactions in a four-year spruce biochar-amended temperate forest soil (Cui et al. 2021). A 2.5 °C soil warming increased total $CO_2$ emissions by 28% under 2 years of 30 t $ha^{-1}$ *Miscanthus* biochar addition in cultivated temperate cropland soil (Bamminger et al. 2018). Similarly, 800 °C pyrolyzed bamboo biochar raises the relative abundance of recalcitrant soil C fractions and increases the temperature sensitivity of $CO_2$ emissions by 17.7–19.3% in a temperate *Populus nigra* plantation soil (Chen et al. 2023). The warming effects appear particularly pronounced in croplands, where biochar is often applied to enhance productivity. Nevertheless, the overall response of $CO_2$ emissions to warming remains poorly understood in biochar-amended soils.

Progress toward generalization has been hindered by inconsistencies in experimental design, biochar types, and warming magnitudes. Most existing studies are site-specific, short-term, or confined to narrow ranges of soil types and climatic conditions. Moreover, the relative importance of soil properties versus biochar characteristics in shaping $CO_2$ responses to warming remains uncertain. Critically, few studies have synthesized data across ecosystems to quantify the risk of a warming-induced positive feedback loop in biochar-amended soils. Despite extensive studies on biochar-induced soil carbon sequestration, there is a lack of comprehensive, cross-ecosystem analysis of $CO_2$ emission feedback from biochar-amended soils under warming conditions (Huang et al. 2023). The relative importance of warming magnitude, biochar characteristics, and soil properties in regulating such feedback remains unclear, which is a critical gap for accurately evaluating the climate mitigation potential of biochar. To address this gap, we conducted a global meta-analysis to (1) quantify the impact of warming on $CO_2$ emissions from biochar-amended soils across cropland and forest ecosystems, and (2) assess the relative importance of warming intensity, biochar characteristics, and soil properties in regulating these responses.

## 2 Materials and methods

### 2.1 Data collection and inclusion criteria

The literature screening followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement: (1) We searched peer-reviewed literature published up to October 28, 2025, in the Web of Science, Scopus, and CNKI databases, yielding 2261 peer-reviewed articles; (2) Title and abstract screening excluded studies irrelevant to biochar–soil–warming interactions, leaving 187 articles; (3) Full-text review against the inclusion criteria excluded 155 articles; (4) A total of 32 articles were finally included, from which 2079 paired observational data were extracted for each sampling date (Fig. S1). Keywords included “biochar OR black carbon OR charcoal”, “$Q_{10}$ OR warming OR temperature increase OR global change OR temperature sensitivity OR climate change”, and “soil carbon OR carbon sequestration OR carbon storage OR carbon stock”. Studies were selected according to the criteria: (i) the study must include concurrent high temperature (treatment) and low temperature (control) settings for evaluating $CO_2$ emissions, (ii) the experiment must be conducted on terrestrial soils (e.g., cropland, forest, or grassland), (iii) exact biochar application rates and pyrolysis temperatures must be clearly reported, (iv) key initial soil properties (e.g., pH, SOC) must be provided. Both laboratory incubations and field warming experiments were included if they met the above criteria.

Data extracted included $CO_2$ emission rates (mean, standard deviation, and replication number), biochar characteristics (feedstock origin, pyrolysis temperature, C/N ratio, application rate, and particle size), soil properties (SOC, TN, pH, and clay content), geographical coordinates (latitude and longitude), and the experimental incubation duration for each observation. Graphical data were digitized using Getdata Graph Digitizer v2.4. In total, 2079 observational data points were screened out from 32 publications through a rigorous screening process from an initial pool of 2261 peer-reviewed articles (Fig. 1, Table S1).

### 2.2 Standardization and classification

Biochar application rates were standardized to a common unit (%) from the original values in tons per hectare, accounting for soil bulk density (BD) and application depth. If no BD has been reported, the default value was set as 1.5 t $m^{-3}$ for sandy soil, 1.4 t $m^{-3}$ for sandy loam soil, 1.2 t $m^{-3}$ for loam soil, 1.1 t $m^{-3}$ for clay soil, and 0.8 t $m^{-3}$ for organic-rich soil from peer-reviewed reports. Biochar feedstock was classified into woody materials from thinning or pruning operations, crop residues (maize, rice, wheat, and mushrooms), and grass (*Miscanthus giganteus* or *Ageratum hirta*). Biochar particle size was categorized into > 1 mm and < 1 mm.

### 2.3 Statistical analyses

The warming effect on $CO_2$ emissions was assessed using the natural log of the response ratio (RR) in biochar-amended soils (Zhang et al. 2020). This metric was calculated as $\ln (X_t/X_c)$, where $X_t$ and $X_c$ denote the means of the higher (treatment group) and lower (control group) temperature datasets, respectively (Hedges et al. 1999). To enhance interpretability, the RR was further transformed into a percentage change using the formula $(e^{RR}-1) \times 100\%$ (Dong et al. 2021). The variance of the response ratio was computed following established statistical procedures, considering the standard deviations and sample sizes of both the treatment and control groups. If no standard deviation (SD) was reported, we used 1/10 of the mean value as the SD (Dong et al. 2024; Liu et al. 2013), which is a widely accepted method for imputing missing SD values in meta-analyses. If only the standard error was reported, the standard deviation was calculated using the formula $SD = SE \times \sqrt{n}$ (Zhang et al. 2020). To address the non-independence of multiple observations from a single study, the mean effect size was estimated using the random-effects model, with weighting

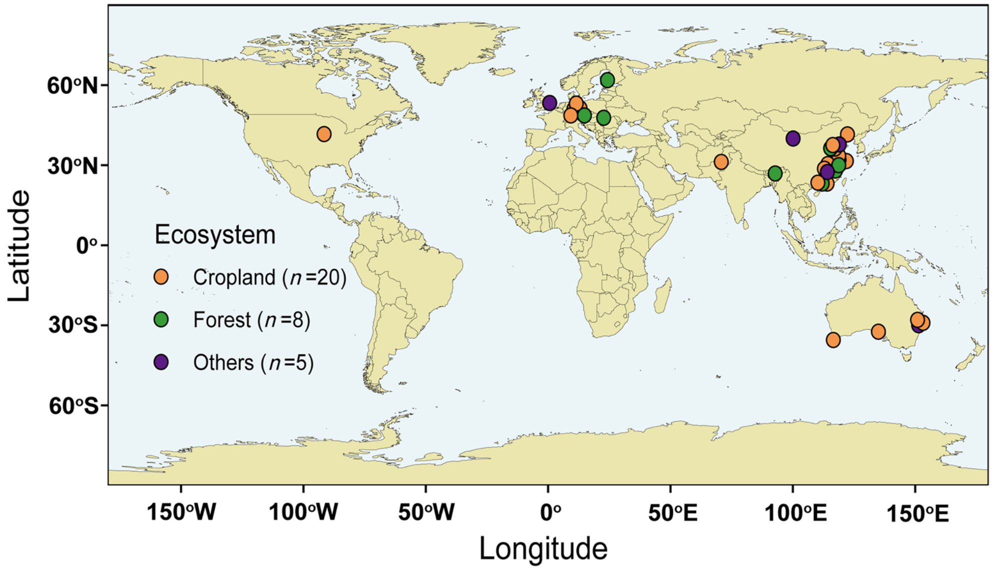


**Fig. 1** Global distribution of soil sampling sites ($n = 33$)

factors calculated based on the within-study variance and between-study variance (Dong et al. 2025; Koricheva et al. 2013), and the latter was determined via restricted maximum likelihood estimation for continuous data (Veroniki et al. 2016). The confidence interval (95%) was derived from 999 bootstrap iterations (Huo et al. 2017).

Publication bias was evaluated using Rosenthal's fail-safe number and the trim-and-fill method (Duval and Tweedie 2000; Rosenthal 1979). A weighted random forest model was used to identify the relative importance of various variables in influencing the warming effect (Han and Zhu 2020; Terrer et al. 2019). All analyses were performed in R (version 4.3.3), with the "metafor" for meta-analysis and "randomForest" packages to ensure the robustness and reliability of the results (Viechtbauer 2010).

## 3 Results

### 3.1 Warming effect on $CO_2$ emissions

Warming increased $CO_2$ emissions from biochar-amended soils across all ecosystems, with a mean effect size of 77.0% (95% CI: 73.3–80.4%, $p < 0.001$; Fig. 2). The warming effect varied across land uses, with croplands showing a 117.5% increase (95% CI: 111.5–123.9%)—3.8-fold higher than forests (30.9%, 95% CI: 26.1–35.7%; Fig. 2). The distinct warming effects indicate that land use-specific biochar application should be considered in soil carbon management practice. Woody biochar-amended soils showed a stronger warming response compared to crops or grass-derived biochar-amended soils in all ecosystems (Fig. 2). Biochar with smaller

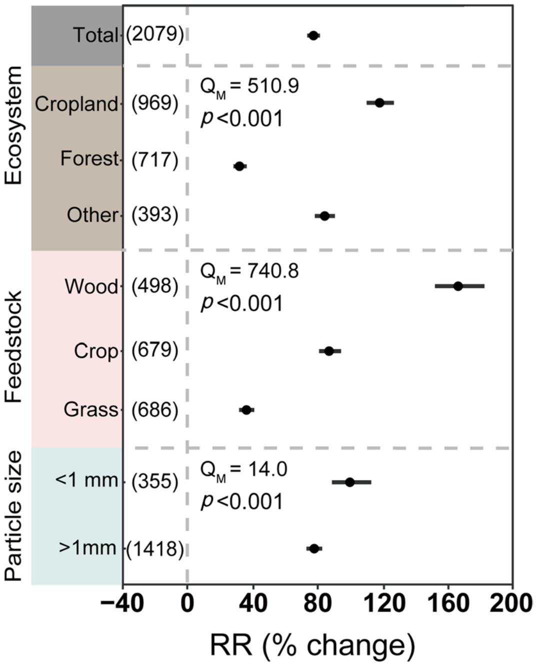


**Fig. 2** The average effect size percent change of warming on $CO_2$ emission after biochar amendment. The error bars represent 95% confidence intervals. If the 95% CIs do not overlap zero, the warming effects are considered significant at $p < 0.05$. The numbers in parentheses indicate sample sizes of observations. $Q_M$: heterogeneity in group cumulative effect sizes. RR, average effect size percent change (the formula $(e^{RR}-1) \times 100\%$ was used to convert the average effect size into a percentage change)

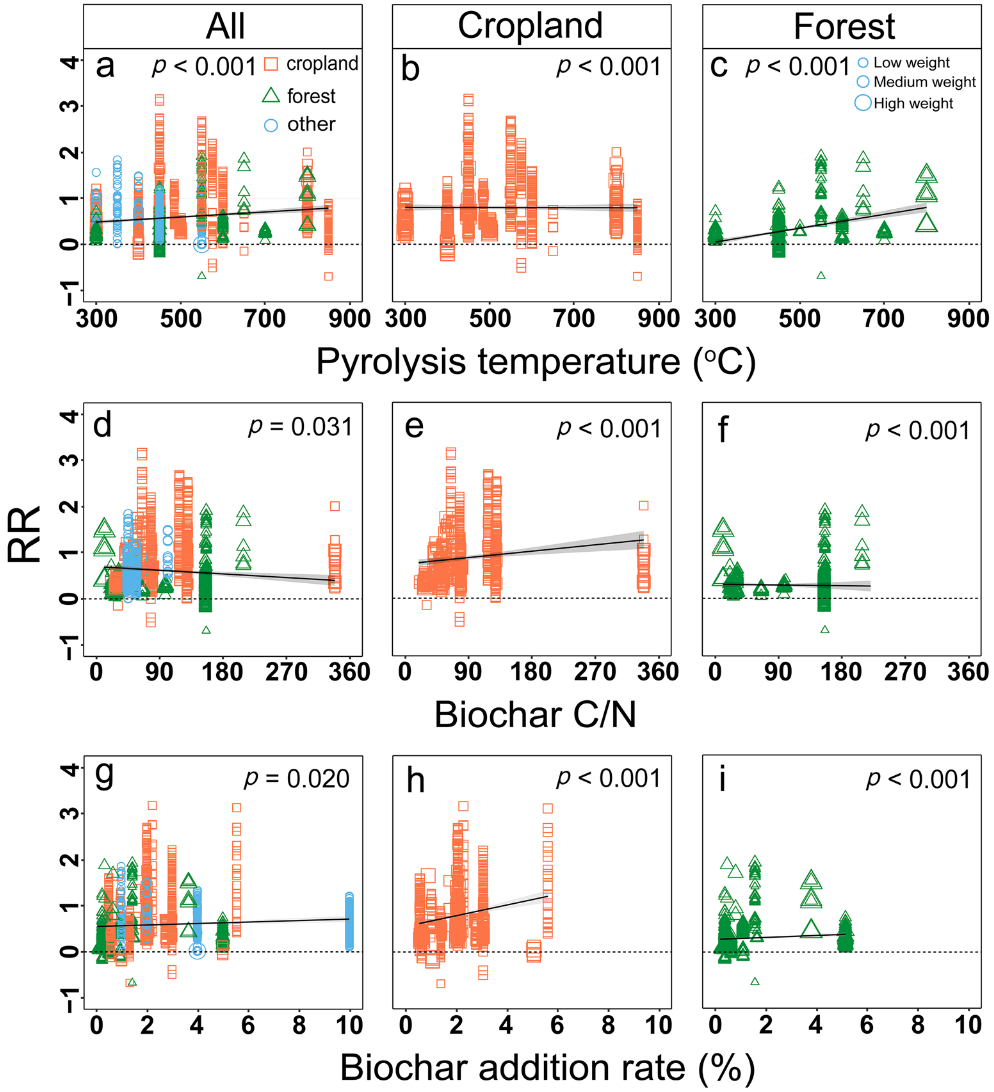


**Fig. 3** Relationships between the warming effect on $CO_2$ emission and biochar characteristics. The size of symbols (squares, triangles, circles) denotes the weight of the observation used in the meta-regression quantified as the inverse of the square root of the within-study variance, with larger sizes indicating greater weights. Biochar C/N, biochar carbon-to-nitrogen ratio

particles induced a larger increase in the warming effect compared to larger particles (Fig. 2).

### 3.2 Impacts of biochar characteristics on the warming effects

Biochar characteristics such as pyrolysis temperature, biochar C/N, and application rate modulated the warming-induced $CO_2$ emissions. Specifically, the warming effect was positively correlated with pyrolysis temperature and the application rate of biochar in both cropland and forest soils (Fig. 3a–c, g–i, Table 1). However, the warming-induced change in $CO_2$ emissions was positively correlated with the C/N ratio of biochar in croplands (Fig. 3e), while decreasing with the C/N ratio of biochar in forest soils (Fig. 3f).

### 3.3 Impacts of soil properties on the warming effects

The warming effect on $CO_2$ emissions increased with SOC, TN, soil C/N ratio, pH, and clay content across all ecosystems (Fig. 4a, d, g, j, m). In croplands, the warming effect was positively related to SOC, TN, pH, and clay content (Fig. 4b, e, k, n), yet had no relationship with soil C/N ratio (Fig. 4h, Table 1). In forest soils, the warming effect increased with soil C/N ratio, pH, and clay content, while not varying with SOC and TN (Fig. 4i, l, o, Table 1).

**Table 1** Relationships of the effect size (RR) with biochar characteristics and soil properties by meta-regression

| Variable | Total | | | | | Cropland | | | | | Forest | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *k* | $Q_T$ | $Q_M$ | $Q_E$ | *p* | *k* | $Q_T$ | $Q_M$ | $Q_E$ | *p* | *k* | $Q_T$ | $Q_M$ | $Q_E$ | *p* |
| ΔT | 2079 | 231,604 | 836.93 | 230,766 | **< 0.001** | 969 | 65,034 | 791.4 | 64,243 | **< 0.001** | 717 | 52,065 | 17.37 | 52,048 | **< 0.001** |
| Pyrolysis temperature | 1992 | 213,315 | 36.056 | 213,279 | **< 0.001** | 936 | 114,527 | 0.012 | 114,527 | > 0.05 | 663 | 35,010 | 99.76 | 36,910 | **< 0.001** |
| Biochar C/N | 1650 | 164,109 | 13.37 | 164,096 | **< 0.001** | 756 | 91,449 | 15.25 | 91,434 | **< 0.001** | 663 | 47,908 | 1.27 | 47,907 | > 0.05 |
| Biochar addition rate | 2079 | 231,148 | 13.67 | 231,134 | **< 0.01** | 969 | 123,358 | 43.64 | 123,314 | **< 0.001** | 717 | 59,170 | 13.33 | 59,157 | **< 0.001** |
| SOC | 1854 | 208,227 | 53.04 | 208,174 | **< 0.001** | 792 | 93,588 | 149.15 | 93,439 | **< 0.001** | 687 | 63,587 | 284.2 | 63,303 | **< 0.001** |
| Soil TN | 1620 | 188,666 | 44.12 | 188,622 | **< 0.001** | 612 | 71,397 | 74.05 | 71,323 | **< 0.001** | 633 | 60,692 | 243.4 | 60,449 | **< 0.001** |
| Soil C/N | 1638 | 181,454 | 33.35 | 181,421 | **< 0.001** | 612 | 82,177 | 7.28 | 82,170 | **< 0.01** | 633 | 61,368 | 66.19 | 61,302 | **< 0.001** |
| Soil pH | 1833 | 161,446 | 204.77 | 161,241 | **< 0.001** | 792 | 104,889 | 31.56 | 104,856 | **< 0.001** | 648 | 6932 | 4.94 | 6927 | **< 0.05** |
| Clay | 1443 | 158,115 | 3.63 | 158,111 | **< 0.05** | 726 | 114,340 | 28.90 | 114,311 | **< 0.001** | 498 | 4337 | 27.97 | 4309 | **< 0.001** |

k is the number of observations. The *p*-values in bold are statistically significant at $p < 0.05$

$Q_T$, total heterogeneity in effect sizes of all observations; $Q_M$, heterogeneity in group cumulative effect sizes; $Q_E$, residual errors; ΔT, the absolute temperature change; C/N, carbon-to-nitrogen ratio; SOC, soil organic carbon; TN, soil total nitrogen

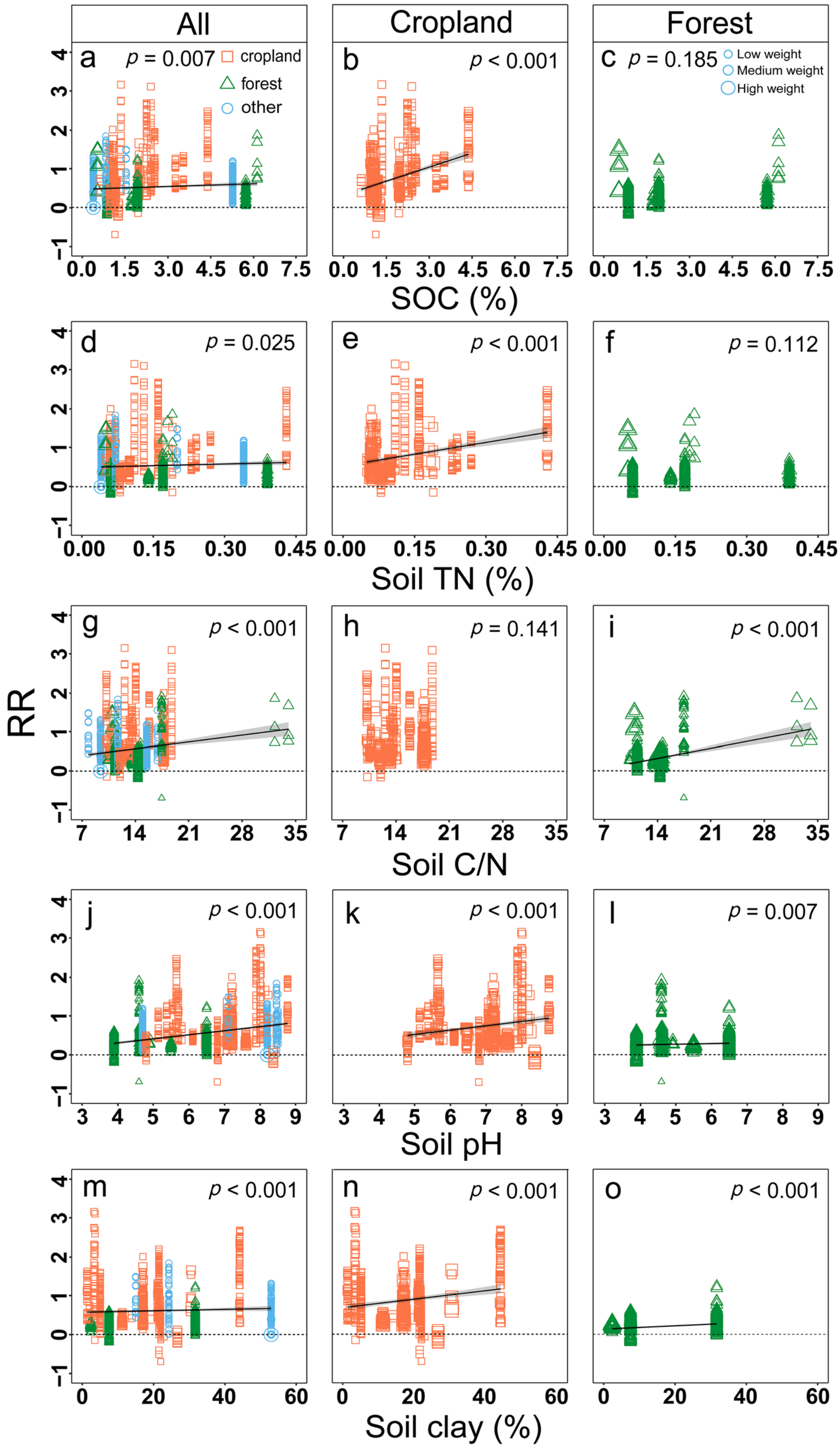


**Fig. 4** Relationships between the warming effect on $CO_2$ emission and soil properties in biochar-amended soil. The size of symbols (squares, triangles, circles) denotes the weight of the observation used in the meta-regression quantified as the inverse of the square root of the within-study variance, with larger sizes indicating greater weights. SOC, soil organic carbon content; TN, soil total nitrogen content; soil C/N, soil carbon-to-nitrogen ratio

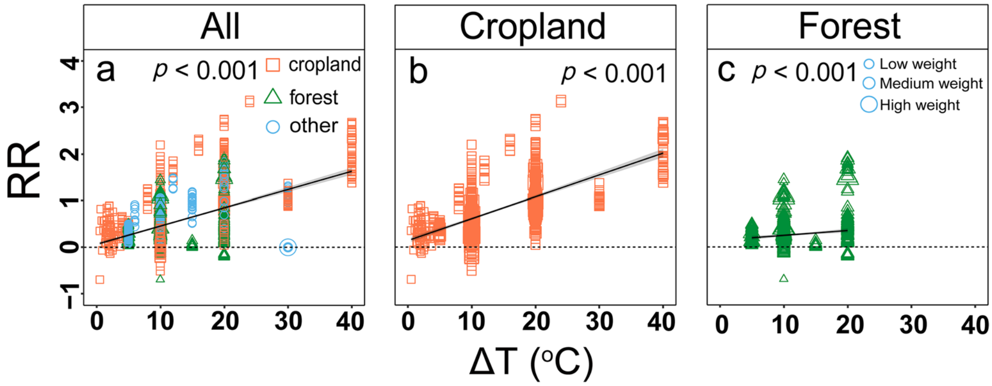


**Fig. 5** Relationships between the warming effect on $CO_2$ emission and warming magnitude in biochar-amended soil. The size of symbols (squares, triangles, circles) denotes the weight of the observation used in the meta-regression quantified as the inverse of the square root of the within-study variance, with larger sizes indicating greater weights. ΔT, the absolute temperature change

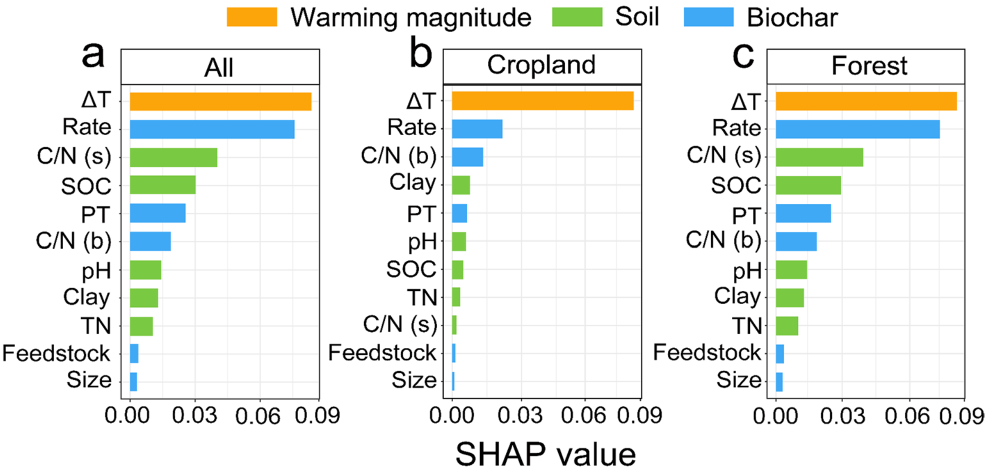


**Fig. 6** Importance of variables regulating the warming effect in biochar-amended soils. The larger SHAP values indicate a higher relative importance of the variables in governing the warming effect on $CO_2$ emission. SHAP, shapley additive explanations; ΔT, the absolute temperature change; pH, soil pH; Rate, biochar addition rate (%); SOC, soil organic carbon content; TN, soil total nitrogen content; C/N (s), soil carbon-to-nitrogen ratio; Clay, soil clay content (%); PT, pyrolysis temperature (°C); C/N (b), biochar carbon-to-nitrogen ratio; Size, biochar particle size

### 3.4 Impacts of warming magnitude on the warming effects

The experimental warming magnitude (ΔT, temperature difference, the absolute temperature change) increased the warming effect on $CO_2$ emission across all ecosystems (Fig. 5a–c, Table 1). The $CO_2$ emission in croplands responded much faster to warming than in forests with a greater slope (Fig. 5b, c). Experimental duration did not influence the warming effect on $CO_2$ emissions across all observations (Fig. S2).

### 3.5 Variables importance of key influencing factors

Warming magnitude was the most important predictor of the warming effect on $CO_2$ emissions, surpassing both soil properties and biochar characteristics across all ecosystems (Fig. 6). Specifically, the relative importance of the variables was ΔT > biochar application rate > biochar C/N > clay > pyrolysis temperature > soil pH > SOC in croplands (Fig. 6b), and ΔT > biochar application rate > soil C/N > SOC > pyrolysis temperature > biochar C/N in forests (Fig. 6c). Notably, the relative importance of biochar C/N is more critical in regulating the warming effect in croplands than in forest, while soil C/N plays a more dominant role in forests than in croplands (Fig. 6b, c).

### 3.6 Publication bias

The fail-safe number for the warming effect (represented as RR) was 142,911,954 (Table S2), indicating the statistical robustness of this result. The trim-and-fill model analysis indicated that the results remained robust against missing values of $CO_2$ emission rates, thereby ruling out the influence of publication bias (Table S2). Overall, these tests suggest that publication bias in the context of warming effects on $CO_2$ emissions did not pose a significant concern for this study.

## 4 Discussion

### 4.1 Warming effects on $CO_2$ emissions

The temperature-induced $CO_2$ loss can counteract the increased soil C sequestration from biochar application. Warming accelerated $CO_2$ emission by 30.9–117.5% in biochar-amended soils across ecosystems (Fig. 2). A 2.5 °C warming increased $CO_2$ release by 28% in biochar-free croplands over 2 years (Bamminger et al. 2018). Warming shortened turnover times of both active and inert C pools, driving $CO_2$ release under biochar amendment in saline soils (Sun et al. 2016). Elevated temperature shifted microbial species richness, community structure, and enzymatic diversity, altering the substrate accessibility to microbes in biochar-amended soils (Jiang et al. 2021). Warming-sensitive microbial phylotypes may be activated under warming stress, accelerating SOC decomposition and $CO_2$ emission (Oliverio et al. 2017). Initially, microbes consume the labile fractions of fresh biochar and SOC. However, as temperature rises and biochar ages, fungi may increase their degradation of more inert C in biochar and soil, leading to higher $CO_2$ release despite the long-term stability of biochar in agricultural soils (Bamminger et al. 2016). The aromaticity and humification degree of dissolved organic matter may be responsible for the variability of the warming effect (Zhao et al. 2023). Furthermore, the physicochemically protected SOC may be exposed to microbes with accelerated biochar aging under warming (Schindlbacher et al. 2015; Zhang et al. 2022).

### 4.2 Ecosystem-specific responses to warming

The warming-induced increase in $CO_2$ emissions was 3.8 times higher in croplands than in forests under biochar amendment (Fig. 2). The vulnerability of SOC is great in agricultural soils compared with natural forest ecosystems (Nogués et al. 2023). Warming accelerates SOC turnover and long-term soil C losses (Deng et al. 2016; Wei et al. 2014). Agricultural management practices, e.g., tillage and irrigation, may destroy soil aggregates, weaken the physical protection of SOC, increase the microbial accessibility of SOC, and exacerbate the temperature sensitivity of SOC decomposition (Khan et al. 2023; Zhou et al. 2023). The warming effect is much greater in farmland soils than in forest soils at comparable pH values, as evidenced by steeper regression slopes (Fig. 4k–l). Considering a positive correlation between the warming effect and soil pH (Fig. 4j–l), soil acidification may buffer warming-induced $CO_2$ emissions across ecosystems (Huang et al. 2022b). In addition to the physical protection effect, differences in substrate supply and microbial community structure are also key influencing factors (Abdalla et al. 2022). For instance, compared with the abundant recalcitrant lignin that dominates forest ecosystems, crop residues usually input a higher proportion of labile, readily decomposable carbon into soils (Bamel et al. 2025). Meanwhile, long-term and frequent fertilization in farmland can also elevate the relative abundance of copiotrophic bacteria (Li et al. 2024a). These bacteria display an extremely sensitive response to readily decomposable substrates under warming conditions, which further amplifies the temperature sensitivity of SOC decomposition (Su et al. 2023; Zheng et al. 2025). Thus, the expansion of agricultural land may exacerbate SOC loss and $CO_2$ emissions under warming, aggravating climate change feedbacks. The strategies of reforestation and other land-based C capture should be prioritized to optimize C sequestration in biochar-amended soils.

### 4.3 Impacts of biochar feedstock and pyrolysis temperature

Biochar characteristics regulate the warming effect on $CO_2$ emissions in biochar-amended soils. The related characteristics are biochar C content, aromaticity, volatile matter, and levels of easily oxidized C, metals, and phenolic substances, as well as surface properties (Cui et al. 2021). Chemical recalcitrance is stronger in wood biochar-amended soils with higher lignin, and thus responds more strongly to warming compared to crop- or grass-biochar amendment soils (Fig. 2). This finding supports the C quality–temperature hypothesis, which posits that more refractory components require higher activation energy and therefore have greater temperature sensitivity than labile components (Bird et al. 1999; Murtaza et al. 2024). When coexisting with such chemically resistant woody biochar, microbes may preferentially decompose native SOC under warming conditions, consistent with the preferential substrate utilization hypothesis (Lin et al. 2025a). Thus, the decomposability of biochar and its aging extent relative to SOC play a central role in microbial C utilization preferences.

The biochar characteristics are further modulated by pyrolysis temperature, biochar pH, mineral nutrients, and physical structure, particularly C components. The effect size of warming on $CO_2$ emissions increases with biochar pyrolysis temperature (Fig. 3a–c). High-temperature pyrolysis increases aromatic C sequestration and chemical stability (Saffari et al. 2020), but reduces structural stability of biochar (Crombie et al. 2015; Shrivastava et al. 2021; Suliman et al. 2016). In contrast, low-temperature pyrolysis retains more non-pyrolyzed organic residues and nutrients, such as low-molecular-weight volatiles in biochar (Murtaza et al. 2024; Wang et al. 2017; Zhu et al. 2017). Microbial response to biochar is highly dependent on pyrolysis temperatures and warming intensity (Huang et al. 2023). Therefore, adopting moderate or lower pyrolysis temperatures may help mitigate warming-induced $CO_2$ release while preserving biochar's soil improvement functions.

### 4.4 Impacts of particle size and application rate

Particle size shapes warming-induced $CO_2$ release from biochar-amended soils. Smaller particles create stronger responses due to larger surface area (Fig. 2), which offers more sites for microbial colonization (de Jesus Duarte et al. 2019; Jaafar et al. 2015). Increased exposure of reactive sites accelerates substrate hydrolysis and C mineralization (Meena et al. 2023). Smaller biochar particles act as more efficient "hotspots" to promote greater microbial growth and $CO_2$ production due to enhanced microbial access to both the biochar-associated C and SOC (Ameloot et al. 2013). Thus, the combination of increased specific surface area and enzymatic action is a key driver of the stronger warming-induced $CO_2$ emissions from biochar-amended soils.

Smaller-sized biochar can release more alkaline ions and increase soil pH (Sarfraz et al. 2020), and further promote $CO_2$ release under warming (Fig. 4j–l). Elevated alkalinity favors fungi growth, enabling decomposition of more recalcitrant SOC fractions (Qin et al. 2019). Fine-sized biochar ($< 0.05$ mm) increased $CO_2$ emissions by raising soil pH and fungi/bacteria (F/B) ratio (Chen et al. 2017). As soil pH increased, the relative abundance and diversity of bacteria and fungi disproportionally increased. Temperature sensitivity of SOC decomposition increased with an increase in the F/B ratio and activation energy ($E_a$) needed (Briones et al. 2014; Qin et al. 2019). The $E_a$ required for more recalcitrant or aged biochar-C decomposition increased exponentially at a high biochar application rate (Chen et al. 2019; Davidson and Janssens 2006; Luetzow and Koegel-Knabner 2009). Higher-straw biochar application rate induced stronger warming effects on $CO_2$ emission in cropland soils (Chen et al. 2019).

### 4.5 Dominant role of warming magnitude

The warming magnitude ($\Delta T$) is the dominant driver of the warming effect of $CO_2$ emissions in biochar-amended soils. The intrinsic microbial temperature sensitivity is a key determinant of soil organic carbon decomposition rates (Niu et al. 2024). The warming effect increased with the $\Delta T$ (Fig. 5). Warming alters organic matter composition and reduces the proportion of cold-preferring bacteria, resulting in an increase in carbohydrates and soil carbon losses (Li et al. 2024b). Microbial activity is intrinsically temperature-sensitive without acclimation to warming over weeks or decades, and intrinsic microbial temperature sensitivity together with substrate depletion dictates the temporary soil carbon loss induced by warming by regulating microbial biomass (Walker et al. 2018). Besides, $\Delta T$ was generally applied with greater methodological uniformity in short-term controlled experiments or long-term field warming. The robust gradients created by experimental warming across studies may amplify the influence of $\Delta T$ on $CO_2$ release.

### 4.6 Strategies to mitigate the warming effect

A smart application of biochar in combination with conservation agriculture practices can further stabilize soil C under climate warming. First, produce biochar at lower pyrolysis temperatures to reduce its reactivity and minimize the warming response of $CO_2$ release. Second, apply biochar at optimized rates to avoid overstimulating microbial activity. Third, utilize non-woody feedstocks (e.g., crop residues or grasses) to achieve a lower warming response. Fourth, to ensure effective carbon sequestration, stricter management practices are required in farmland ecosystems, such as optimizing the physicochemical properties of biochar. Importantly, site-specific guidelines need to be developed based on land use, soil type, and climate context. Finally, it will be critical to advance continued ongoing monitoring and soil–biochar–climate interaction models for refining sustainable biochar management strategies.

### 4.7 Data limitations

The data coverage is sparse in tropical and polar ecosystems, arid and semi-arid zones, and high-latitude tundra, although SOC decomposition may be highly sensitive to warming in these ecosystems. Further, the observations are predominantly concentrated in temperate regions of China and Europe, and such spatial sampling imbalance may reduce the universality and external validity of the research conclusions. Besides, data from highly acidic or saline soils are still lacking. These gaps limit the generalizability of our findings and highlight the need for expanded research across diverse biomes, regions, and soil conditions. Besides, most observations are from laboratory studies, and the magnitudes of experimental warming are usually extreme ($> 20$ °C), which is quite different from real conditions. Thus, future research should focus on field warming experiments with reasonable temperature gradients to further assess the responses of $CO_2$ emissions from biochar-amended soils to warming.

## 5 Conclusion

Warming increases $CO_2$ emissions from biochar-amended soils governed by warming intensity, biochar characteristics, and soil properties. Notably, croplands have stronger warming responses than forests. The warming effect increases with higher biochar pyrolysis temperature, application rate, and soil properties such as SOC, TN, soil C/N ratio, soil pH, and clay content. Warming intensity is the most critical regulator, underscoring the importance of incorporating global warming projections into life-cycle assessments of biochar projects. The climate mitigation potential of biochar may be overestimated if the warming effects are not considered. To strengthen the role of biochar in climate resilience, context-specific guidelines should be applied, such as favoring non-woody feedstocks, lower pyrolysis temperatures, moderate application rates, and tailored management in croplands where risks are greatest. Such targeted strategies will ensure that biochar use aligns with projected warming impacts, increasing its effectiveness as a tool for sustainable soil management and climate mitigation.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-026-00628-6.

Additional file 1.

Additional file 2.

### Author contributions

Tongyu Xu and Qiufeng Xu: Conceptualization, Methodology, Formal Analysis, Writing – original draft. Yan Lei, Fei Li, and Junjie Lin: Data Curation, Conceptualization, Supervision. Hepeng Li, Junjie Lin, Shengdao Shan: Supervision, Funding Acquisition. Amit Kumar, Dafeng Hui, Jianming Xue: Writing – review & editing. Yongfu Li, Hepeng Li, Junjie Lin: Writing – review & editing. All authors read and approved the final manuscript.

### Funding

This research was supported by the "Pioneer" and "Leading Goose" R&D Program of Zhejiang (2025C02097, 2024C02002), Zhejiang Provincial Natural Science Foundation (LZ25C030003, LQ21C030004), Zhejiang Forestry Science and Technology Project (2026F1065-2), and the Science and Technology Research Program of Chongqing Municipal Education Commission (KJZD-K202503502).

### Data availability

Data will be made available from the corresponding author on reasonable request.

## Declarations

### Competing interests

The authors declare that they have no known competing financial interests.

### Author details

[1]School of Environment and Natural Resources, Zhejiang University of Science and Technology, Hangzhou 310023, China. [2]Institute of Loess Plateau, Shanxi University, Taiyuan 030006, China. [3]School of Materials and Environmental Engineering, Chengdu Technological University, Chengdu 611730, China. [4]School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China. [5]Department of Biological Sciences, Tennessee State University, Nashville, TN 37209, USA. [6]Scion Group, New Zealand Institute of Bioeconomy Science, PO Box 29237, Riccarton, Christchurch 8440, New Zealand. [7]National Key Laboratory for Development and Utilization of Forest Food Resources, College of Environmental and Resource Sciences, Zhejiang A&F University, Hangzhou 311300, China. [8]Zhejiang Academy of Forestry, Hangzhou 310023, China.

**Received: 30 November 2025 Revised: 9 April 2026 Accepted: 26 April 2026**

### References

Abdalla K, Sun Y, Zarebanadkouki M, Gaiser T, Seidel S, Pausch J (2022) Long-term continuous farmyard manure application increases soil carbon when combined with mineral fertilizers due to lower priming effects. Geoderma 428:116216. https://doi.org/10.1016/j.geoderma.2022.116216

Ameloot N, Graber ER, Verheijen FGA, De Neve S (2013) Interactions between biochar stability and soil organisms: review and research needs. Eur J Soil Sci 64:379–390. https://doi.org/10.1111/ejss.12064

Antonangelo JA, Sun X, Eufrade-Junior HdJ (2025) Biochar impact on soil health and tree-based crops: a review. Biochar 7:51. https://doi.org/10.1007/s42773-025-00450-6

Bamel D, Dey A, Mondal BK, Bhattacharyya R, Das D, Das S, Das TK, Dash AK (2025) Non-abundance of cellulose and lignin in crop residue biomass increases decomposability and lowers temperature sensitivity of the process and helps in labile soil organic carbon build-up. J Soil Sci Plant Nutr 25:7710–7727. https://doi.org/10.1007/s42729-025-02625-3

Bamminger C, Poll C, Sixt C, Högy P, Wüst D, Kandeler E, Marhan S (2016) Short-term response of soil microorganisms to biochar addition in a temperate agroecosystem under soil warming. Agric Ecosyst Environ 233:308–317. https://doi.org/10.1016/j.agee.2016.09.016

Bamminger C, Poll C, Marhan S (2017) Offsetting global warming-induced elevated greenhouse gas emissions from an arable soil by biochar application. Global Change Biol. https://doi.org/10.1111/gcb.13871

Bamminger C, Poll C, Marhan S (2018) Offsetting global warming-induced elevated greenhouse gas emissions from an arable soil by biochar application. Glob Change Biol 24:e318–e334. https://doi.org/10.1111/gcb.13871

Bar-On YM, Li X, O'Sullivan M, Wigneron J-P, Sitch S, Ciais P, Frankenberg C, Fischer WW (2025) Recent gains in global terrestrial carbon stocks are mostly stored in nonliving pools. Science 387:1291–1295. https://doi.org/10.1126/science.adk1637

Bird MI, Moyo C, Veenendaal EM, Lloyd J, Frost P (1999) Stability of elemental carbon in a savanna soil. Glob Biogeochem Cycles 13:923–932. https://doi.org/10.1029/1999gb900067

Briones MJI, McNamara NP, Poskitt J, Crow SE, Ostle NJ (2014) Interactive biotic and abiotic regulators of soil carbon cycling: evidence from controlled climate experiments on peatland and boreal soils. Glob Change Biol 20:2971–2982. https://doi.org/10.1111/gcb.12585

Case SDC, McNamara NP, Reay DS, Whitaker J (2014) Can biochar reduce soil greenhouse gas emissions from a *Miscanthus* bioenergy crop? GCB Bioenergy 6:76–89. https://doi.org/10.1111/gcbb.12052

Chen J, Li S, Liang C, Xu Q, Li Y, Qin H, Fuhrmann JJ (2017) Response of microbial community structure and function to short-term biochar amendment in an intensively managed bamboo (*Phyllostachys praecox*) plantation soil: effect of particle size and addition rate. Sci Total Environ 574:24–33. https://doi.org/10.1016/j.scitotenv.2016.08.190

Chen J, Chen D, Xu Q, Fuhrmann JJ, Li L, Pan G, Li Y, Qin H, Liang C, Sun X (2019) Organic carbon quality, composition of main microbial groups, enzyme activities, and temperature sensitivity of soil respiration of an acid paddy soil treated with biochar. Biol Fertil Soils 55:185–197. https://doi.org/10.1007/s00374-018-1333-2

Chen Q, Tao B, Jiang Y, Wang J, Zhang B (2023) Combined effects of biochar addition with varied particle size and temperature on the decomposition of soil organic carbon in a temperate forest, China. Soil Sci Plant Nutr 69:45–53. https://doi.org/10.1080/00380768.2022.2129443

Chen Y, Qin W, Zhang Q, Wang X, Feng J, Han M, Hou Y, Zhao H, Zhang Z, He J-S, Torn MS, Zhu B (2024) Whole-soil warming leads to substantial soil carbon emission in an alpine grassland. Nat Commun 15:4489. https://doi.org/10.1038/s41467-024-48736-w

Cheng S, Kumar A, Lan G, Zhang W, Yu Z, Zhang S, Yu Z-G, Yao M, Lin J (2025) Thermal sensitivity and rising greenhouse gas emissions in riparian zone soils: implications for ecosystem carbon dynamics. J Environ Manag 381:125194. https://doi.org/10.1016/j.jenvman.2025.125194

Crombie K, Masek O, Cross A, Sohi S (2015) Biochar - synergies and tradeoffs between soil enhancing properties and C sequestration potential. GCB Bioenergy 7:1161–1175. https://doi.org/10.1111/gcbb.12213

Cui J, Glatzel S, Bruckman VJ, Wang B, Lai DYF (2021) Long-term effects of biochar application on greenhouse gas production and microbial community in temperate forest soils under increasing temperature. Sci Total Environ 767:145021. https://doi.org/10.1016/j.scitotenv.2021.145021

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173. https://doi.org/10.1038/nature04514

de Jesus Duarte S, Glaser B, Pellegrino Cerri CE (2019) Effect of biochar particle size on physical, hydrological and chemical properties of loamy and sandy tropical soils. Agronomy. https://doi.org/10.3390/agronomy9040165

Deng L, Zhu G-y, Tang Z-s, Shangguan Z-p (2016) Global patterns of the effects of land-use changes on soil carbon stocks. Glob Ecol Conserv 5:127–138. https://doi.org/10.1016/j.gecco.2015.12.004

Dong H, Zhang S, Lin J, Zhu B (2021) Responses of soil microbial biomass carbon and dissolved organic carbon to drying-rewetting cycles: a meta-analysis. CATENA 207:105610. https://doi.org/10.1016/j.catena.2021.105610

Dong H, Lin J, Lu J, Li L, Yu Z, Kumar A, Zhang Q, Liu D, Chen B (2024) Priming effects of surface soil organic carbon decreased with warming: a global meta-analysis. Plant Soil 500:233–242

Dong H, He P, Liu M, Kuzyakov Y, Li LJ (2025) Nitrogen availability governs priming effect induced by biodegradable microplastics through microbial life-strategies. Eur J Soil Sci. https://doi.org/10.1111/ejss.70170

Duval S, Tweedie R (2000) Trim and fill: a simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. Biometrics 56:455–463. https://doi.org/10.1111/j.0006-341X.2000.00455.x

Feng W, Liang J, Hale LE, Jung CG, Chen J, Zhou J, Xu M, Yuan M, Wu L, Bracho R, Pegoraro E, Schuur EAG, Luo Y (2017) Enhanced decomposition of stable soil organic carbon and microbial catabolic potentials by long-term field warming. Glob Change Biol 23:4765–4776. https://doi.org/10.1111/gcb.13755

Gao H, Tian H, Zhang Z, Xia X (2022) Warming-induced greenhouse gas fluxes from global croplands modified by agricultural practices: a meta-analysis. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2022.153288

Georgiou K, Jackson RB, Vindušková O, Abramoff RZ, Ahlström A, Feng W, Harden JW, Pellegrini AFA, Polley HW, Soong JL, Riley WJ, Torn MS (2022) Global stocks and capacity of mineral-associated soil organic carbon. Nat Commun 13:3797. https://doi.org/10.1038/s41467-022-31540-9

Ghosh D, Page-Dumroese DS, Han H-S, Anderson N (2025) Role of biochar made from low-value woody forest residues in ecological sustainability and carbon neutrality. Soil Sci Soc Am J 89:e20793. https://doi.org/10.1002/saj2.20793

Han M, Zhu B (2020) Changes in soil greenhouse gas fluxes by land use change from primary forest. Glob Change Biol 26:2656–2667. https://doi.org/10.1111/gcb.14993

Hedges LV, Gurevitch J, Curtis PS (1999) The meta-analysis of response ratios in experimental ecology. Ecology 80:1150–1156. https://doi.org/10.2307/177062

Hu H, Chen J, Zhou F, Nie M, Hou D, Liu H, Delgado-Baquerizo M, Ni H, Huang W, Zhou J, Song X, Cao X, Sun B, Zhang J, Crowther TW, Liang Y (2024) Relative increases in CH4 and CO2 emissions from wetlands under global warming dependent on soil carbon substrates. Nat Geosci 17:26–31. https://doi.org/10.1038/s41561-023-01345-6

Huang R, Wang Z, Xiao Y, Yu L, Gao X, Wang C, Li B, Tao Q, Xu Q, Gao M (2022a) Increases in temperature response to CO2 emissions in biochar-amended vegetable field soil. Environ Sci Pollut Res 29:50895–50905. https://doi.org/10.1007/s11356-022-19011-6

Huang X, Cui C, Hou E, Li F, Liu W, Jiang L, Luo Y, Xu X (2022b) Acidification of soil due to forestation at the global scale. For Ecol Manag. https://doi.org/10.1016/j.foreco.2021.119951

Huang S, Zhu X, Fang J, Zhang X, Zhang H, Zhang Z, Wu X, Zhu X (2023) Pyrolysis temperature dependent effects of biochar on shifting fluorescence spectrum characteristics of soil dissolved organic matter under warming. Sci Total Environ 892:164656. https://doi.org/10.1016/j.scitotenv.2023.164656

Huo C, Luo Y, Cheng W (2017) Rhizosphere priming effect: a meta-analysis. Soil Biol Biochem 111:78–84. https://doi.org/10.1016/j.soilbio.2017.04.003

Jaafar NM, Clode PL, Abbott LK (2015) Soil microbial responses to biochars varying in particle size, surface and pore properties. Pedosphere 25:770–780. https://doi.org/10.1016/S1002-0160(15)30058-8

Jiang RW, Galo M, Oelbermann M (2021) Soybean and soil responses to biochar amendment in controlled environments with elevated temperature and carbon dioxide. Can J Soil Sci 102:65–76. https://doi.org/10.1139/cjss-2020-0133

Jiang Z, Zhang S, Tang C, Xiao M, Zhou J, Luo Y, Ge T, Yu B, White JC, Li Y (2025) Divergent effects of straw and biochar on soil carbon priming are depth-dependent in subtropical Moso bamboo forests. Biol Fertil Soils. https://doi.org/10.1007/s00374-025-01927-z

Khan MZ, Chabbi A, Hicks Pries CE, Torn MS, Rumpel C (2023) Management impacts on whole soil warming responses of CO2 production and efflux in temperate climate. Geoderma 440:116725. https://doi.org/10.1016/j.geoderma.2023.116725

Kirschbaum MUF (2000) Will changes in soil organic carbon act as a positive or negative feedback on global warming? Biogeochemistry 48:21–51. https://doi.org/10.1023/a:1006238902976

Koricheva J, Gurevitch J, Mengersen K (2013) Handbook of meta-analysis in ecology and evolution. Princeton University Press

Li J, Zhao J, Liao X, Hu P, Wang W, Ling Q, Xie L, Xiao J, Zhang W, Wang K (2024a) Pathways of soil organic carbon accumulation are related to microbial life history strategies in fertilized agroecosystems. Sci Total Environ 927:172191. https://doi.org/10.1016/j.scitotenv.2024.172191

Li S, Delgado-Baquerizo M, Ding J, Hu H, Huang W, Sun Y, Ni H, Kuang Y, Yuan MM, Zhou J, Zhang J, Liang Y (2024b) Intrinsic microbial temperature sensitivity and soil organic carbon decomposition in response to climate change. Glob Change Biol 30:e17395. https://doi.org/10.1111/gcb.17395

Lin J, Hui D, Kumar A, Yu Z, Huang Y (2023) Editorial: Climate change and/or pollution on the carbon cycle in terrestrial ecosystems. Front Environ Sci. https://doi.org/10.3389/fenvs.2023.1253172

Lin J, Chen B, Dong H, Zhang W, Kumar A, Hui D, Zhang C, Shan S, Zhu B (2025a) Effects of soil moisture fluctuation and microplastics types on soil organic matter decomposition and carbon dynamics. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2025.109781

Lin J, Cheng Q, Kumar A, Zhang W, Yu Z, Hui D, Zhang C, Shan S (2025b) Effect of degradable microplastics, biochar and their coexistence on soil organic matter decomposition: a critical review. TrAC Trends Anal Chem 183:118082. https://doi.org/10.1016/j.trac.2024.118082

Liu X, Zhang A, Ji C, Joseph S, Bian R, Li L, Pan G, Paz-Ferreiro J (2013) Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. Plant Soil 373:583–594

Meena M, Yadav G, Sonigra P, Nagda A, Mehta T, Swapnil P, Harish MA, Kumar S (2023) Multifarious responses of forest soil microbial community toward climate change. Microb Ecol 86:49–74. https://doi.org/10.1007/s00248-022-02051-3

Mohan D, Abhishek K, Sarswat A, Patel M, Singh P, Pittman CU Jr. (2018) Biochar production and applications in soil fertility and carbon sequestration - a sustainable solution to crop-residue burning in India. RSC Adv 8:508–520. https://doi.org/10.1039/c7ra10353k

Murtaza G, Usman M, Iqbal J, Hyder S, Solangi F, Iqbal R, Okla MK, Al-Ghamdi AA, Elsalahy HH, Tariq W, Al-Elwany OAAI (2024) Liming potential and characteristics of biochar produced from woody and non-woody biomass at different pyrolysis temperatures. Sci Rep. https://doi.org/10.1038/s41598-024-61974-8

Nissan A, Alcolombri U, Peleg N, Galili N, Jimenez-Martinez J, Molnar P, Holzner M (2023) Global warming accelerates soil heterotrophic respiration. Nat Commun. https://doi.org/10.1038/s41467-023-38981-w

Niu S, Chen W, Liáng LL, Sierra CA, Xia J, Wang S, Heskel M, Patel KF, Bond-Lamberty B, Wang J, Yvon-Durocher G, Kirschbaum MUF, Atkin OK, Huang Y, Yu G, Luo Y (2024) Temperature responses of ecosystem respiration. Nat Rev Earth Environ 5:559–571. https://doi.org/10.1038/s43017-024-00569-3

Nogués I, Mazzurco Miritana V, Passatore L, Zacchini M, Peruzzi E, Carloni S, Pietrini F, Marabottini R, Chiti T, Massaccesi L, Marinari S (2023) Biochar soil amendment as carbon farming practice in a Mediterranean environment. Geoderma Reg 33:e00634. https://doi.org/10.1016/j.geodrs.2023.e00634

Nottingham AT, Meir P, Velasquez E, Turner BL (2020) Soil carbon loss by experimental warming in a tropical forest. Nature 584:234-#x0002B; https://doi.org/10.1038/s41586-020-2566-4

Oliverio AM, Bradford MA, Fierer N (2017) Identifying the microbial taxa that consistently respond to soil warming across time and space. Glob Change Biol 23:2117–2129. https://doi.org/10.1111/gcb.13557

Possinger AR, Driscoll CT, Green MB, Fahey TJ, Johnson CE, Koppers MMK, Martel LD, Morse JL, Templer PH, Uribe AM, Wilson GF, Groffman PM (2025) Increasing soil respiration in a northern hardwood forest indicates symptoms of a changing carbon cycle. Commun Earth Environ 6:418. https://doi.org/10.1038/s43247-025-02405-y

Qin S, Chen L, Fang K, Zhang Q, Wang J, Liu F, Yu J, Yang Y (2019) Temperature sensitivity of SOM decomposition governed by aggregate protection and microbial communities. Sci Adv. https://doi.org/10.1126/sciadv.aau1218

Rosenthal R (1979) The file drawer problem and tolerance for null results. Psychol Bull 86:638–641. https://doi.org/10.1037/0033-2909.86.3.638

Saffari N, Hajabbasi MA, Shirani H, Mosaddeghi MR, Mamedov AI (2020) Biochar type and pyrolysis temperature effects on soil quality indicators and structural stability. J Environ Manag 261:110190. https://doi.org/10.1016/j.jenvman.2020.110190

Sarfraz R, Yang W, Wang S, Zhou B, Xing S (2020) Short term effects of biochar with different particle sizes on phosphorous availability and microbial communities. Chemosphere. https://doi.org/10.1016/j.chemosphere.2020.126862

Schindlbacher A, Schnecker J, Takriti M, Borken W, Wanek W (2015) Microbial physiology and soil $CO_2$ efflux after 9 years of soil warming in a temperate forest - no indications for thermal adaptations. Glob Change Biol 21:4265–4277. https://doi.org/10.1111/gcb.12996

Shrivastava P, Kumar A, Tekasakul P, Lam SS, Palamanit A (2021) Comparative investigation of yield and quality of bio-oil and biochar from pyrolysis of woody and non-woody biomasses. Energies. https://doi.org/10.3390/en14041092

Su R, Wu X, Hu J, Li H, Xiao H, Zhao J, Hu R (2023) Warming promotes the decomposition of oligotrophic bacterial-driven organic matter in paddy soil. Soil Biol Biochem 186:109156. https://doi.org/10.1016/j.soilbio.2023.109156

Suliman W, Harsh JB, Abu-Lail NI, Fortuna A-M, Dallmeyer I, Garcia-Perez M (2016) Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. Biomass Bioenergy 84:37–48. https://doi.org/10.1016/j.biombioe.2015.11.010

Sun J, He F, Zhang Z, Shao H, Xu G (2016) Temperature and moisture responses to carbon mineralization in the biochar-amended saline soil. Sci Total Environ 569:390–394. https://doi.org/10.1016/j.scitotenv.2016.06.082

Terrer C, Jackson RB, Prentice IC, Keenan TF, Kaiser C, Vicca S, Fisher JB, Reich PB, Stocker BD, Hungate BA, Penuelas J, McCallum I, Soudzilovskaia NA, Cernusak LA, Talhelm AF, Van Sundert K, Piao S, Newton PCD, Hovenden MJ, Blumenthal DM, Liu YY, Mueller C, Winter K, Field CB, Viechtbauer W, Van Lissa CJ, Hoosbeek MR, Watanabe M, Koike T, Leshyk VO, Polley HW, Franklin O (2019) Nitrogen and phosphorus constrain the $CO_2$ fertilization of global plant biomass. Nat Clim Change 9:684. https://doi.org/10.1038/s41558-019-0545-2

Veroniki AA, Jackson D, Viechtbauer W, Bender R, Bowden J, Knapp G, Kuss O, Higgins JPT, Langan D, Salanti G (2016) Methods to estimate the between-study variance and its uncertainty in meta-analysis. Res Synth Methods 7:55–79. https://doi.org/10.1002/jrsm.1164

Viechtbauer W (2010) Conducting meta-analyses in R with the metafor package. J Stat Softw 36:1–48. https://doi.org/10.18637/jss.v036.i03

von Luetzow M, Koegel-Knabner I (2009) Temperature sensitivity of soil organic matter decomposition-what do we know? Biol Fertil Soils 46:1–15. https://doi.org/10.1007/s00374-009-0413-8

Walker TWN, Kaiser C, Strasser F, Herbold CW, Leblans NIW, Woebken D, Janssens IA, Sigurdsson BD, Richter A (2018) Microbial temperature sensitivity and biomass change explain soil carbon loss with warming. Nat Clim Chang 8:885–889. https://doi.org/10.1038/s41558-018-0259-x

Wang D, Fonte SJ, Parikh SJ, Six J, Scow KM (2017) Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. Geoderma 303:110–117. https://doi.org/10.1016/j.geoderma.2017.05.027

Wei X, Shao M, Gale W, Li L (2014) Global pattern of soil carbon losses due to the conversion of forests to agricultural land. Sci Rep 4:4062. https://doi.org/10.1038/srep04062

Xue K, Yuan MM, Shi ZJ, Qin Y, Deng Y, Cheng L, Wu L, He Z, Van Nostrand JD, Bracho R, Natali S, Schuur EAG, Luo C, Konstantinidis KT, Wang Q, Cole JR, Tiedje JM, Luo Y, Zhou J (2016) Tundra soil carbon is vulnerable to rapid microbial decomposition under climate warming. Nat Clim Change 6:595. https://doi.org/10.1038/nclimate2940

Yang Y, Sun K, Han L, Chen Y, Liu J, Xing B (2022) Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content. Soil Biol Biochem 169:108657. https://doi.org/10.1016/j.soilbio.2022.108657

Zhang S, Yu Z, Lin J, Zhu B (2020) Responses of soil carbon decomposition to drying-rewetting cycles: a meta-analysis. Geoderma. https://doi.org/10.1016/j.geoderma.2019.114069

Zhang X, Zhang Q, Zhan L, Xu X, Bi R, Xiong Z (2022) Biochar addition stabilized soil carbon sequestration by reducing temperature sensitivity of mineralization and altering the microbial community in a greenhouse vegetable field. J Environ Manag. https://doi.org/10.1016/j.jenvman.2022.114972

Zhao Y, Lin J, Cheng S, Wang K, Kumar A, Yu Z-G, Zhu B (2023) Linking soil dissolved organic matter characteristics and the temperature sensitivity of soil organic carbon decomposition in the riparian zone of the Three Gorges reservoir. Ecol Indic 154:110768. https://doi.org/10.1016/j.ecolind.2023.110768

Zheng J, van Groenigen KJ, Hartley IP, Xue R, Wang M, Zhang S, Sun T, Yu W, Ma B, Luo Y, Shi Z, Luo Z (2025) Temperature sensitivity of bacterial species-level preferences of soil carbon pools. Geoderma 456:117268. https://doi.org/10.1016/j.geoderma.2025.117268

Zhou M, Xiao Y, Zhang X, Sui Y, Xiao L, Lin J, Cruse RM, Ding G, Liu X (2023) Warming-dominated climate change impacts on soil organic carbon fractions and aggregate stability in Mollisols. Geoderma 438:116618. https://doi.org/10.1016/j.geoderma.2023.116618

Zhou J, Zhang S, Lv J, Tang C, Zhang H, Fang Y, Tavakkoli E, Ge T, Luo Y, Cai Y, Yu B, White JC, Li Y (2024) Maize straw increases while its biochar decreases native organic carbon mineralization in a subtropical forest soil. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2024.173606

Zhou J, Tang C, Vancov T, Fu S, Fang Y, Ge T, Dong Y, Luo Y, Yu B, Cai Y (2026) Biochar mitigates the suppressive effects of nitrogen deposition on soil methane uptake in a subtropical forest. Agric Ecosyst Environ 395:109951

Zhu X, Chen B, Zhu L, Xing B (2017) Effects and mechanisms of biochar-microbe interactions in soil improvement and pollution remediation: a review. Environ Pollut 227:98–115. https://doi.org/10.1016/j.envPol.2017.04.032