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Sustained benefits of long-term biochar application for food security and climate change mitigation

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Biochar application offers significant potential to enhance food security and mitigate climate change. However, most evidence stems from short-term field experiments (≤3 y), leaving uncertainty about the long-term sustainability of these benefits, especially with annual biochar additions to soils. To address this knowledge gap, we analyzed a global dataset from 438 studies (3,229 observations) and found that long-term annual biochar application (≥4 y) not only sustains but often enhances its benefits. These include improved crop yields (+10.8%), reductions in CH_4 (–13.5%) and N_2O (–21.4%) emissions, and increased soil organic carbon content (+52.5%). In contrast, these benefits tend to diminish over time with single biochar applications due to the aging effect of biochar. Results from 29 global long-term experiments (4 to 12 y) confirm these sustained benefits for crop yield and greenhouse gas mitigation, although the magnitude of effects varies with soil properties, climate, and management practices. To maximize biochar's long-term benefits for global food security and climate change mitigation, it is essential to develop viable strategies, such as applying biochar at intervals of several years while tailoring practices to local soil, climate, and cropping conditions.

Significance

Biochar application is proposed as a promising strategy to improve food security and mitigate climate change. Whether these agronomic and environmental benefits are sustained under long-term biochar application remains unknown, especially considering the potential adverse effects of its continuous application in the soil environment. We analyzed an expansive global dataset and results from 29 global long-term field experiments (4 to 12 y) and found that long-term annual applications sustain and even enhance the benefits on crop yields, GHG mitigation, and SOC sequestration. In contrast, those benefits diminish over time under single applications. Future research should focus on optimizing the application strategies across diverse soil and climate conditions to maximize biochar's contributions to global food security and climate change mitigation.

biochar application | long-term benefits | food security | climate change mitigation | soil organic carbon

Ensuring food security and combating climate change are two of the greatest challenges of the 21st century (1). Biochar application is considered a promising management practice to address these issues (2). Short-term field experiments (≤3 y) have demonstrated its potential to improve soil fertility and crop yields, reduce greenhouse gas (GHG) emissions (e.g., CH_4 and N_2O), and increase soil organic carbon (SOC) sequestration across various agricultural systems (3, 4). For example, Xia et al. (4) have demonstrated that an integrated biochar approach can achieve carbon-neutral staple crop production with higher grain yields and lower environmental pollution. However, the long-term sustainability of these agronomic and environmental benefits under annual biochar application remains uncertain. Repeated applications may lead to unintended adverse effects, such as increased soil pH, reduced agrochemical efficacy, and potential inhibition of soil biota (5). For example, the high porosity and specific surface area of biochar can decrease the effectiveness of insecticides and herbicides, necessitating higher pesticide use to maintain yields, which may in turn harm soil biota and further impact crop productivity (6). Furthermore, excessive biochar application may cause lower water availability in clay soils, potentially decreasing grain crop yields (7). Understanding these dynamics is critical to optimizing biochar use for long-term agricultural and environmental benefits.

Compared to annual applications, a single biochar application, typically involving a large initial dose with no subsequent additions, may reduce potential adverse effects and lower economic costs. However, the positive effects of biochar application may decrease over time due to its gradual decomposition and erosion. For example, studies have shown that the stimulation of crop yields following a single biochar application is often limited to the first and second years (8, 9), suggesting that enhanced soil fertility decreases over time without repeated applications (10). Similarly, Awad et al. (11) reported that while high-rate biochar applications (>10 t ha^{-1}) significantly reduce CH_4 emissions from paddy fields during the first year, these effects are not sustained in the following 3 y, likely due to the declining impact of biochar on methanogenic activity. Despite these insights, no study has comprehensively evaluated the long-term effects of different biochar application regimes (that is, single versus annually repeated applications). This knowledge gap in research hinders the development of effective biochar strategies to maximize its long-term benefits for global food security and climate change mitigation.

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The effects of biochar application on crop yields and GHG mitigation are influenced not only by application regimes but also by management practices and soil properties. For instance, greater improvements in crop yields and SOC accumulation are typically observed when biochar is applied to nutrient-poor soils with poor structure (e.g., sandy soils), where it enhances soil macroaggregation and water and nutrient retention (12, 13). These benefits may diminish with long-term annual biochar application due to an imbalanced carbon-to-nitrogen (C/N) ratio, unless adequate N fertilizer is coapplied (14, 15). However, the optimal N rate for maximizing yields and SOC accrual under annual biochar applications remains unclear. In upland soils, repeated applications of biochar and high N fertilizer rates may initially suppress nitrous oxide (N_2O) emissions but later stimulate them due to increased N availability and enhanced bacterial ammonia oxidizer activity. In contrast, in paddy soils, anaerobic conditions may allow excess N to be fully denitrified to N_2 if biochar provides sufficient dissolved organic carbon (DOC). However, these processes are not yet well understood (16, 17).

Changes in soil pH due to biochar and N fertilizer application also influence CH_4 emissions by regulating methanogenic and methanotrophic microbial communities, measured by *mcr*A (methanogens) and *pmo*A (methanotrophs) gene copy numbers. For example, Wang et al. (18) reported that a single biochar application in acidic paddy soils reduced CH_4 emissions by decreasing the *mcr*A/*pmo*A ratio, but whether this holds in alkaline soils is not clear. Additionally, climatic factors and biochar production conditions (e.g., pyrolysis temperature) further affect CH_4 and N_2O emissions by influencing biochar's stability and interactions with soil microbes.

Despite these complexities, the intertwined effects of biochar application regimes, soil properties, management practices, and climate conditions on crop yield, GHG emissions, and SOC accrual remain insufficiently understood. To address these knowledge gaps, we synthesized the results of 438 studies with 3,229 observations, including 29 long-term field experiments (4 to 12 y) covering the major grain crops such as rice, wheat, and maize. Our findings reveal that long-term annual biochar application sustains or even enhances benefits, including increased crop yields, SOC stocks, and reduced CH_4 and N_2O emissions across varying conditions. In contrast, the benefits of single biochar applications tend to decline over time due to biochar aging.

Results and Discussion

A total of 438 peer-reviewed publications, comprising 3,229 paired observations (1,449 from annual applications and 1,780 from single applications) across global croplands (*SI Appendix*, Fig. S1), were included in the meta-analysis. The dataset also includes 29 long-term field experiments (4 to 12 y) that provide continuous measurements of crop yield, GHG emissions, or SOC content. These experiments were used to assess temporal trends in effects of annual (11 experiments) and single (18 experiments) biochar applications, while accounting for variations due to climate conditions, soil properties, and management practices at different sites (*SI Appendix*, Table S6).

Sustained Benefits on Food Security Under Long-Term Annual Biochar Application. On average, annual biochar application increases crop yields by 10.8%, with this effect persisting over time: <1 y (+11.6%), 1 to 3 y (+7.6%), 3 to 5 y (+7.9%), and ≥5 y (+10.7%) (Fig. 1*A* and *SI Appendix*, Tables S1 and S4). These sustained yield increases are observed across a broad range of soil properties, management practices, and climatic conditions (Figs. 1*A* and 2*A* and *SI Appendix*, Figs. S3–S7). Soil texture plays a key role, with sandy soils showing larger yield increases compared to clay and loamy soils (Fig. 1*A* and *SI Appendix*, Fig. S5*A*). This is likely due to biochar-improved soil structure and nutrient retention in sandy soils (19). Furthermore, yield increases in sandy soils grow from 11.4% in the first year to 42.1% after ≥5 y, suggesting that short-term studies tend to underestimate the long-term benefits of biochar in these soils. This is further evidenced by the significant yield increase over time in the long-term field study site with sandy soils (YX) (*SI Appendix*, Fig. S5*A*). Soil pH also influences biochar's impact. While annual biochar additions can raise soil pH, which may stress crops in alkaline soils (5), our findings show that long-term annual biochar application (3 to 5 y and ≥5 y) to alkaline soils (pH > 7.5) still results in greater yield increases (10.2 to 11.0%) compared to short-term applications (5.6 to 9.5%) (Fig. 1*A*). This suggests that the long-term benefits outweigh potential negative effects from increased pH. Additionally, long-term annual biochar applications (≥5 y) stimulate soil biota activity, as evidenced by increased microbial biomass carbon (*SI Appendix*, Figs. S2 and S8), which supports crop growth by improving nutrient availability and stress adaptation in both alkaline and acidic soils. Furthermore, yield benefits in strong acidic soils (pH ≤ 5.5) increased over time (*SI Appendix*, Fig. S10), likely reflecting the positive effects of a gradual increase in soil pH such as the alleviation of nutrient stress (20) and higher cation exchange capacity (CEC) values (21).

Apart from soil properties, management practices (e.g., N and biochar application rates) also play a critical role in regulating the response of crop yields to annual biochar application. Crop and microbial growth require balanced nutrient stoichiometry, and annual application of biochar with a high C/N ratio can lead to N deficiencies in the plant-microbe-soil system (14). Consistent with this, we found greater and more stable yield increases (12.2 to 14.9%) under high N fertilizer rates (≥240 kg N ha^{-1}) compared to lower rates (e.g., 150 to 240 kg N ha^{-1}, 3.4 to 9.9%) over time (Fig. 2*A*). Moreover, yield benefits increase significantly with higher N fertilization and cumulative biochar application rates (Fig. 3 and *SI Appendix*, Fig. S9), emphasizing the importance of optimizing N fertilization based on biochar application rates to sustain its long-term yield benefits. Crop type also influences biochar's effectiveness, with greater yield improvement observed in upland crops (7 to 13%) compared to rice (3 to 8%) across different experimental durations (Figs. 1*A* and 2*A*). This is likely because frequent irrigation in paddy fields reduces biochar's role in forming soil aggregates (22), which lessens its benefits on nutrient retention and SOC accumulation. This is evident in the lower SOC increases and yield responses observed in paddy fields compared to upland crops (Fig. 2*D*). However, incorporating biochar into soil, rather than surface application, may enhance rice yield benefits by reducing microbial decomposition and mitigating biochar aging effects through protection by soil minerals (23). No significant effects are observed among upland crops and N-fixation and non-N-fixation crops (*SI Appendix*, Fig. S9 and Table S3). Environmental factors, such as climate, also affect biochar's performance. Biochar has relatively small yield benefits in regions with high mean annual temperature (MAT > 16 °C) and precipitation (MAP > 1,200 mm) (Fig. 1*A* and *SI Appendix*, Fig. S3*A*), likely because these conditions stimulate biochar degradation (24). The sustained benefits of annual biochar application on crop yield under various conditions are supported by time series data from 11 long-term experimental site (5 to 12 y) (Fig. 4*A*). Biochar-induced yield benefits increase with application duration (i.e., a positive regression slope, S > 0) in 10 of these sites, with only one site showing a decline. This trend holds true for different crop types, biochar and N application rates, soil textures, and climate

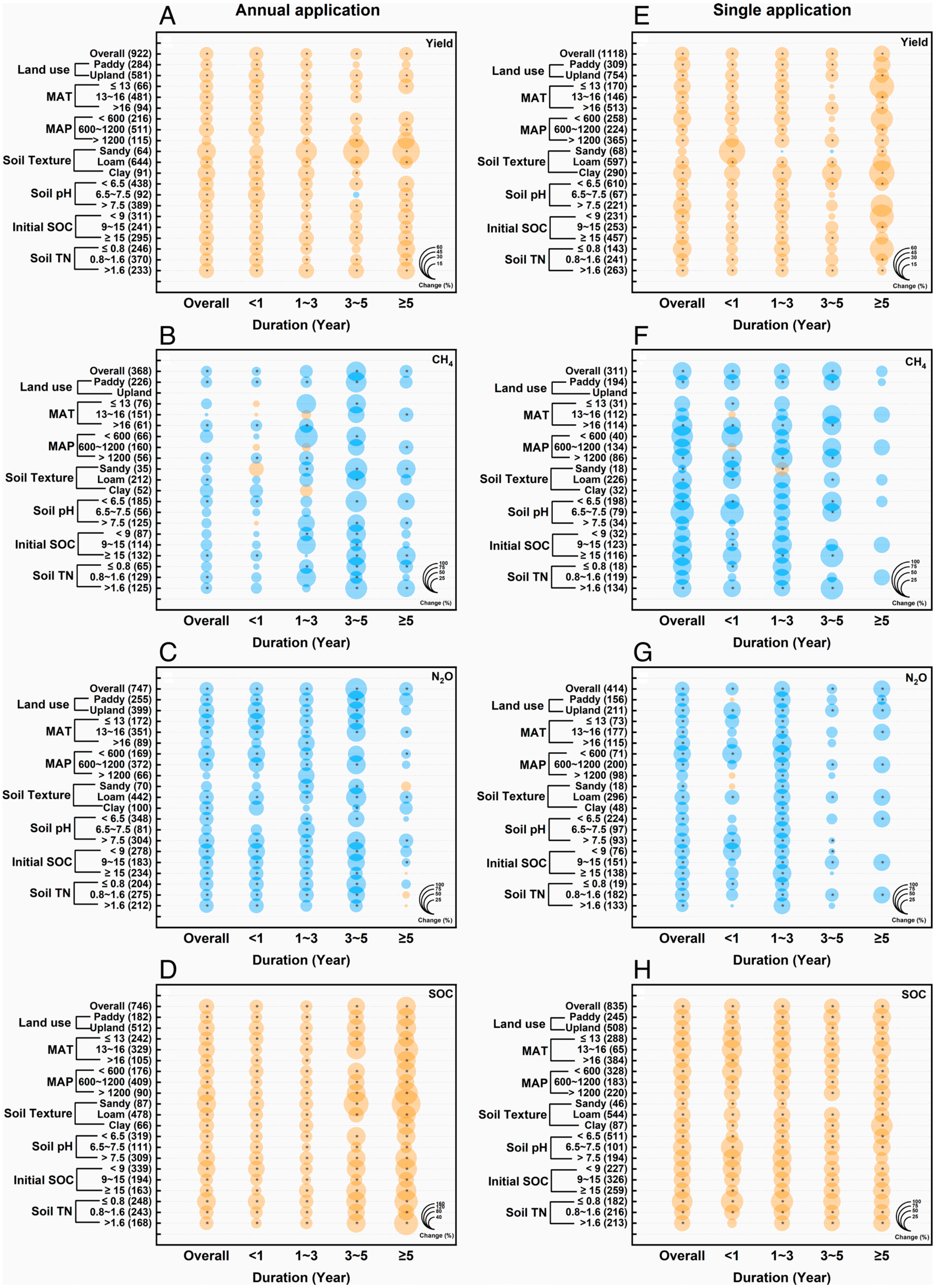

Fig. 1. Responses of crop yield, GHG emissions, and SOC content to annual (*A*–*D*) and single (*E*–*H*) applications of biochar over time, as affected by land use type, climate, and soil properties. Circle size represents the percentage change in each variable due to biochar application. Blue circles represent negative effects while orange circles represent positive effects. "*" denotes significant effects ($P < 0.05$). The total number of experimental observations is given in parentheses. Units: MAT: °C; MAP: mm; Initial SOC content: g kg^{-1}; Soil TN content: g kg^{-1}.

zones (*SI Appendix*, Figs. S3–S7), with the yield responses consistent with the meta-analysis findings (Figs. 1 and 2).

In contrast to annual application, the positive effects of single biochar applications on crop yields, an overall increase by 9.5%, tend to weaken over time for several crop types, soil properties, and climatic zones (Figs. 1*E* and 2*E*). While single applications provide similar benefits in the short term (<3 y), these benefits often become insignificant after 5 y in almost half (18 of 41) of the experimental categories listed in Figs. 1 and 2. Soils with low SOC (<9 g kg^{-1}), TN (<0.8 g kg^{-1}), or receiving low N fertilization rates (<150 kg

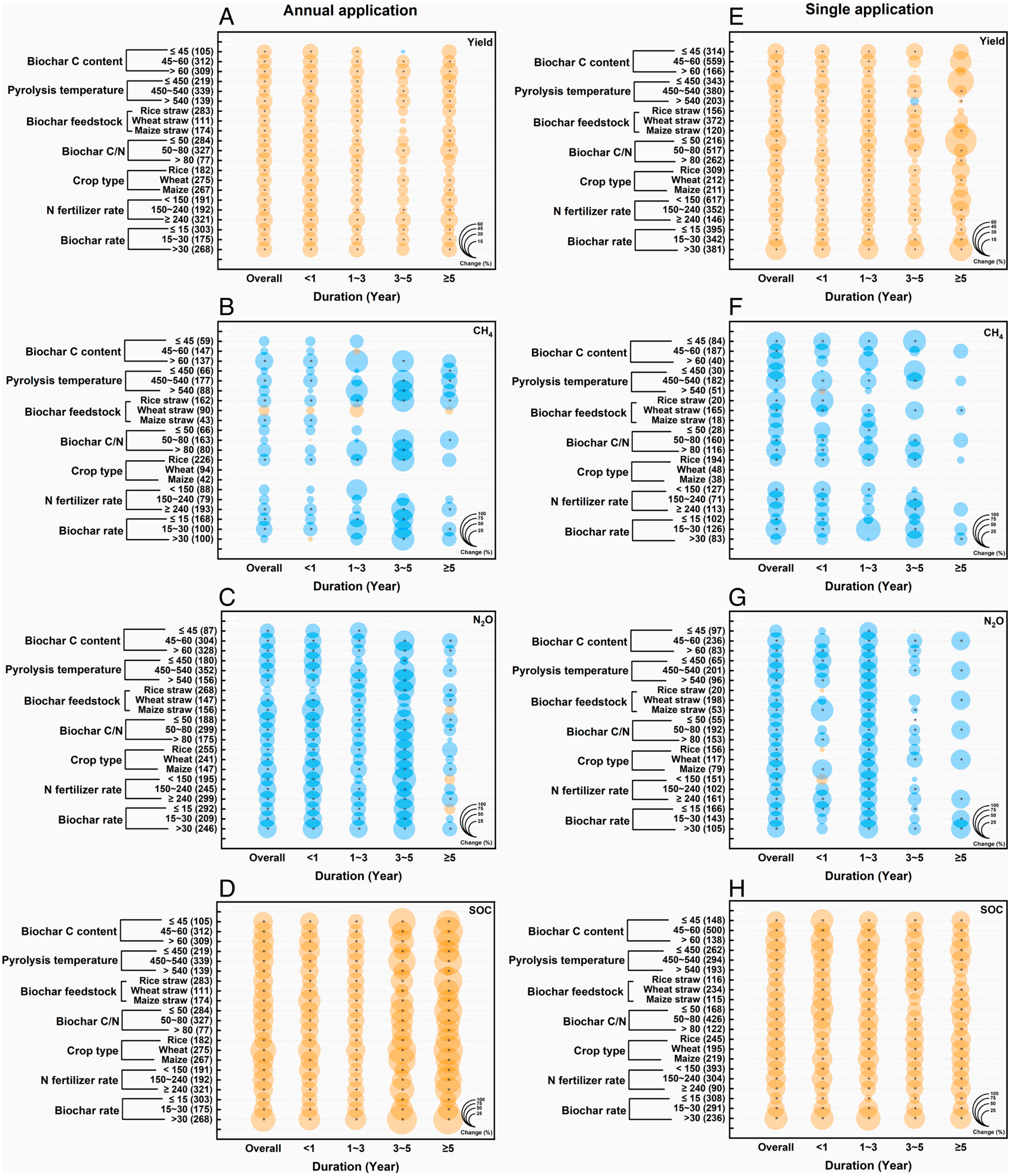

Fig. 2. Responses of crop yield, GHG emissions, and SOC content to annual (*A-D*) and single (*E-H*) applications of biochar over time, as affected by management practices and biochar properties. Circle size represents the percentage change in each variable due to biochar application. Blue circles represent negative effects while orange circles represent positive effects. "*" denotes significant effects ($P < 0.05$). The total number of experimental observations is given in parentheses. Units: Biochar C content: %; Pyrolysis temperature: °C; N fertilizer rate: kg N ha^{-1} $season^{-1}$; Biochar rate: t ha^{-1} $season^{-1}$.

N ha^{-1}) are particularly prone to fading benefits, suggesting the decline is partly linked to low nutrient availability. The diminished effects of single biochar application likely stem from its aging process (25). Over time, carbon mineralization and aromatic C degradation reduce biochar's C content and functionality. Without replenishment, this leads to declining nutrients, a waning liming effect (26, 27), and ultimately impacts crop growth and yields. This trend is corroborated by data from 14 long-term experiments (5 to 10 y), 10 of which show declining yield benefits over time ($S < 0$), with significant declines at three sites (Fig. 4*E*). These

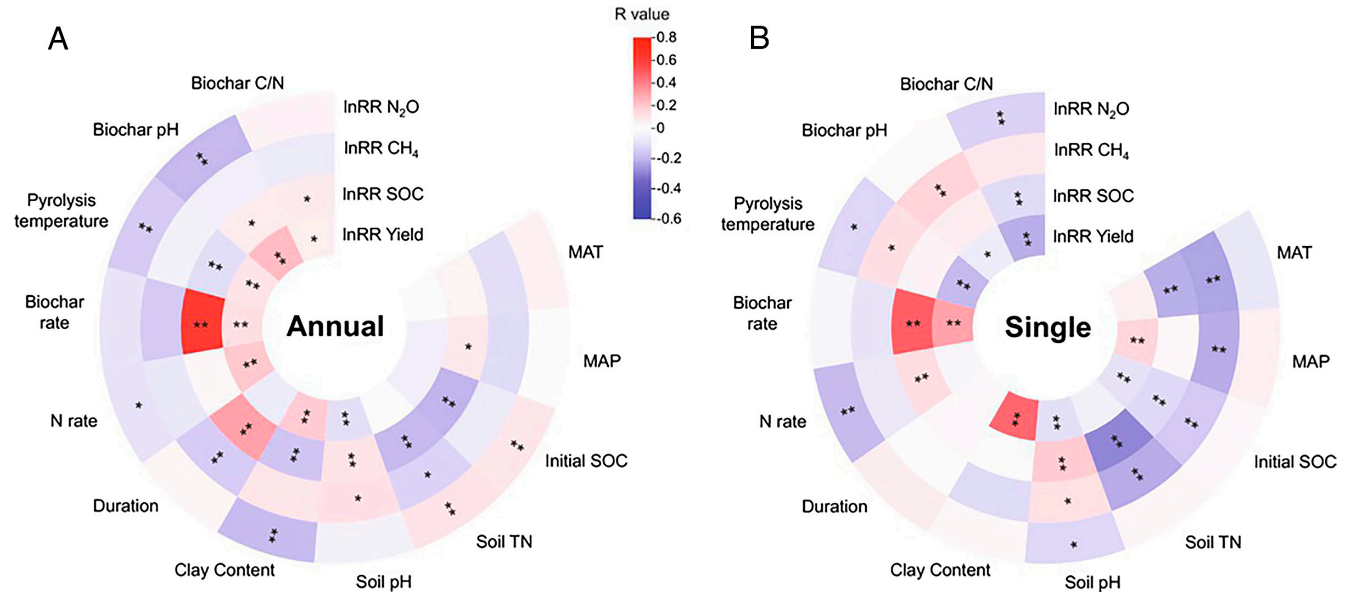

Fig. 3. Correlations between environmental and experimental factors and the response ratios of crop yields, GHG emissions, and SOC content for annual (*A*) and single (*B*) biochar applications. *, ** denote significant effects at $P < 0.05$ and $P < 0.01$, respectively. Soil TN, soil pH, and clay content refer to the initial soil properties before biochar application. The N and biochar rates refer to the application rates during the crop-growing season.

findings emphasize that annual biochar applications are more effective than single applications in maintaining long-term yield benefits in diverse agricultural systems.

GHG Emissions Under Long-Term Biochar Application.

CH_4 emissions. Overall, annual biochar application has no impact on CH_4 emissions from upland fields, but significantly reduces the emissions from paddy fields by 13.5% (Fig. 1*B*), and the reductions increase significantly over time ($P < 0.01$) (Fig. 3). This reduction is attributed to the increased methanotrophic activity and suppressed growth of methanogens due to improved soil aeration (28), as evidenced by changes in the gene abundance of *pmo*A (+17.1%) and *mcr*A (–18.5%) (*SI Appendix*, Fig. S9). Compared to annual applications, single biochar applications at high rates show more pronounced reductions in the first few years (–26.5%). However, these effects diminish and become insignificant after 5 y (Fig. 1*F*), likely due to decreased labile carbon availability and the weakening of biochar's influence on methanogenic and methanotrophic microbes as it ages (25). Biochar significantly reduces CH_4 emissions in acidic paddy soils but not in neutral and alkaline soils, regardless of the application regime (Fig. 1 *B* and *F*). This can be attributed to aluminum toxicity in acidic soils, inhibiting the growth or activities of methanogens and methanotrophs (29). Biochar alleviates this stress, favoring methanotrophs, which are more sensitive to pH changes. As a result, the methanogen/methanotroph ratio decreases, enhancing CH_4 reduction (30). In low-fertility paddy soils (SOC < 9 g kg^{-1}; TN < 0.8 g kg^{-1}), where methanogenic activity is substrate-limited (31), biochar-imported DOC can stimulate CH_4 production, thereby reducing its mitigation efficiency. In contrast, high-fertility paddy soils (SOC > 15 g kg^{-1}; TN > 1.6 g kg^{-1}) show significant CH_4 reductions due to biochar's stronger stimulation of methanotrophic activity and suppression of methanogens.

Management practices, such as biochar application rate, also influence CH_4 emissions. With annual applications, higher per-year biochar application rates result in significantly greater CH_4 reductions ($P < 0.01$) (Fig. 3*A*). However, this effect is not observed with single applications (Fig. 3*B*), likely because of aging effects, during which process the oxidation of biochar's aromatic carbon skeleton alters its surface chemistry, diminishing its capacity to adsorb or electron-shuttle with methanogenic/methanotrophic communities (25). Regardless of application frequency, CH_4 emissions consistently decrease across application rates (Fig. 2 *B* and *F*). Moreover, the reduction effects tend to increase with cumulative biochar application rates (*SI Appendix*, Fig. S9*B*). N application rates also modify biochar's effects on CH_4 emissions. Under annual biochar application, greater CH_4 reductions occur at higher N rates (>240 kg N ha^{-1}), whereas under single applications, reductions are more pronounced at lower N rates (<150 kg N ha^{-1}) (Fig. 2 *B* and *F*), which is further supported by the results from GH long-term field experiment (*SI Appendix*, Fig. S7*D*). These contrasting patterns may stem from biochar-N fertilizer interactions affecting the methanogen/methanotroph ratio, a topic requiring further study. Warm and wet climates show greater CH_4 reductions with biochar application (Fig. 1 *B* and *F*). Moreover, long-term experiments in these climate regions (e.g., SH and YX for annual applications, GH, NJ, and GD for single applications) reveal that CH_4 reduction effects tend to increase over time (Fig. 4 *B* and *F*). This is likely because high temperatures and precipitation in these regions enhance microbial activity and chemical reactions on biochar surfaces, and amplify CH_4 reduction effects (32, 33). Biochar production conditions, such as feedstock type and pyrolysis temperature, also influence CH_4 emissions by affecting biochar quality and its interactions with soil methanogens and methanotrophs. These factors are discussed in greater detail in *SI Appendix*.

N_2O emissions. On average, N_2O emissions are significantly reduced by 21.4% under annually repeated biochar applications and by 23.3% under single applications (Fig. 1 *C* and *G*). These reductions can be attributed to biochar-stimulated microbial N immobilization, supported by the sustained increase in microbial biomass N content (*SI Appendix*, Figs. S2 and S8). Additionally, biochar enhances the expression of N_2O reductase genes in denitrifying microbes, promoting the reduction of N_2O to dinitrogen (N_2) (17). Biochar enhances PsN_2OR's structural stability, boosting its catalytic efficiency in converting N_2O to N_2 during the final stage of biological denitrification. In solution, it stabilizes the enzyme through hydrophobic, π–π

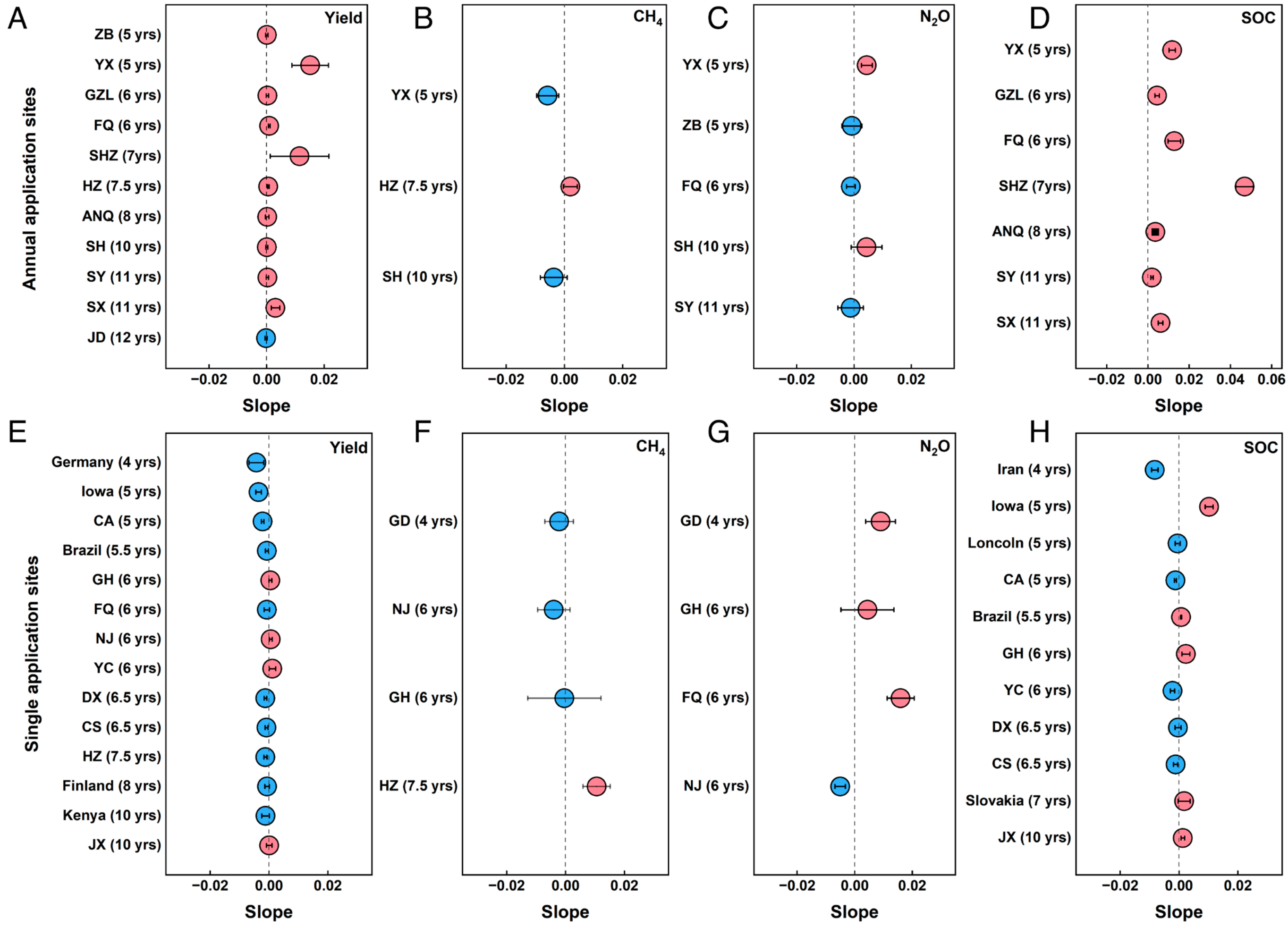

Fig. 4. Slopes of linear regression for response ratios of crop yields, GHG emissions, and SOC content over time for annually repeated (*A*–*D*) and single (*E*–*H*) biochar applications at 29 long-term field study sites. Error bars are SD, and if the error bars do not overlap with zero, the slopes are significantly different from zero. Red dots denote positive slopes (S > 0), while blue dots indicate negative slopes (S < 0). These long-term experiments contribute to the overall dataset for meta-analysis. Negative slopes (S < 0) do not necessarily imply negative biochar effects, and positive slopes (S > 0) do not necessarily imply positive effects. Indeed, overall biochar effects are positive for yield and SOC, but negative for CH_4 and N_2O. Biochar-induced enhancements in yield and SOC, or reductions in CH_4 and N_2O, may weaken annually yet remain significant, which means yield and SOC continue to increase, and CH_4 and N_2O continue to decrease, albeit at a lower rate compared to the previous year.

stacking, and hydrophilic interactions, adsorbs N_2O, delivers it to the enzyme's active site, accelerates the reaction, and retains N_2O near the enzyme surface (34, 35). In three of five long-term experiments (ZB, FQ, and SY) with annual applications, N_2O reductions increased over time, as indicated by negative regression slopes (S < 0) (Fig. 4*C*). Conversely, in two of three long-term experiments (GH and FQ) with single applications, N_2O reductions diminished over time (S > 0) (Fig. 4*G*), indicating a gradual decline in mitigation effects under single applications.

Under annual biochar application, N_2O reductions increase significantly with higher N fertilizer rates (Fig. 3 *A* and *B*), which is also observed in the long-term field sites (ZB, SH, and FQ) (*SI Appendix*, Fig. S7). This effect is likely due to the combined application of biochar and high N application, resulting in a synergic effect on the stimulation of crop productivity and root exudates (30, 36). Greater crop productivity improves N uptake and fertilizer use efficiency, reducing the amount of available N for N_2O production (30). Moreover, enhanced root exudates resulting from higher crop productivity stimulate microbial activity, likely promoting the conversion of N_2O to N_2 (37) than the combination of biochar and low N rate. In addition, the reduction effects remain stable with total biochar rates under two application regimes (*SI Appendix*, Fig. S9*C*).

In theory, the increase in C availability resulting from biochar additions should enhance the conversion of N_2O to N_2 in flooded paddy fields more effectively than in upland soils, given the anaerobic conditions in paddy fields (38). However, biochar reduced N_2O emissions more strongly in upland soils (25 to 27%) than in paddy soils (18 to 21%), and the reduction effects are increasing over time in five of eight long-term upland field experiments (*SI Appendix*, Fig. S4*E*). This discrepancy is likely due to the higher mobility of biochar particles and reduced mixing with soil in rice paddies, caused by frequent irrigation. These conditions limit biochar's interaction with soil microbes, thereby diminishing its potential to facilitate N_2O reductions (39).

The effect of biochar on N_2O emissions is also strongly influenced by soil texture (Figs. 1 *C* and *G* and 3 *A* and *B*). In clay soils, poor aeration and anaerobic conditions promote denitrification, favoring the reduction of N_2O to N_2 (40). Biochar enhances this process, as evidenced by the increased N_2O reductions with higher clay content under annual application (Fig. 3*A* and *SI Appendix*, Fig. S5*E*). However, over time, biochar application leads to significant and sustained reductions in N_2O emissions in loam soils under both application regimes (Fig. 1 *C* and *G* and *SI Appendix*, Fig. S5 *E* and *F*), while effects are less consistent in sandy and clay soils. This is likely because long-term biochar application in loam soils promotes aggregate formation, stimulating microbial growth, N immobilization, and soil N retention. Moreover, high nutrient availability and well-aerated conditions in loam soils allow biochar to significantly stimulate crop root growth and the release of root exudates, which serve as substrate for soil denitrifiers (41). Together, these mechanisms contribute to the long-term sustained reduction effects on N_2O emissions in loam soils.

Biochar-induced reductions in N_2O emissions increase with soil pH (Fig. 3 *A* and *B*), with significant reductions in alkaline soils that persist over time (Fig. 1 *C* and *G*). This effect is primarily attributed to the greater simulation in soil denitrifiers than nitrifiers under higher soil pH conditions (42). The effectiveness of biochar in reducing N_2O emissions also varies with precipitation and temperature gradients. Regions with high mean annual temperature (MAT > 16 °C) and mean annual precipitation (MAP > 1,200 mm) experience lower and less stable reductions. These results can be attributed to the accelerated microbial decomposition of biochar particles in warm, wet environments (24), and this decomposition will be strengthened during the aging process. In addition, frequent wet-dry cycles caused by heavy rainfall promote soil nitrification–denitrification processes, leading to pulsed N_2O emissions (39, 43). Under these conditions, biochar struggles to mitigate these rapid emission spikes.

SOC Content Under Long-Term Biochar Application. Biochar application significantly increases SOC contents, regardless of application frequency, environmental conditions, or soil properties (Figs. 1 *D* and *H* and 2 *D* and *H*). On average, annual application of biochar boosts SOC content by 52.5%, with these effects becoming more pronounced over time—rising to 69.0% after 3 to 5 y and 83.5% after more than 5 y ($P < 0.05$). While average SOC increases are smaller with a single biochar application (+30.5%), they remain consistently significant over time (26.9% after 3 to 5 y and 27.4% after more than 5 y). Biochar increases SOC stocks through multiple mechanisms. First, it contains a high concentration of stable organic C, which becomes part of the SOC pool after biochar application (30, 44). In addition, biochar application increases soil C input by stimulating plant growth (Fig. 1 *A* and *E*) and promotes retention of rhizodeposits and microbial necromass in soil microaggregates (45), thereby enhancing the formation of mineral-associated organic matter and long-term soil C sequestration. The SOC accrual induced by biochar is further amplified by higher application rates under both annual and single-application regimes ($P < 0.01$, Fig. 3 *A* and *B*). SOC content increased markedly with progressive biochar accumulation in soil—independent of application method (*SI Appendix*, Fig. S9*D*)—indicating that higher total biochar loads drive more substantial SOC gains. Evidence from long-term experiments reinforces these benefits. At all seven long-term sites (5 to 11 y) subjected to annual biochar application, its effect on SOC content increased over time, with six sites showing significant trends (Fig. 4*D*). In contrast, out of 11 long-term sites with a single biochar application (4 to 10 y), its effect on SOC increased over time at only five sites, and only two sites showed significant increases (Fig. 4*H*). At the remaining six sites, while the positive influence of biochar on SOC gradually diminished over time, presumably as a result of biochar aging, when aromatic carbon is prone to oxidative degradation, leading to a decrease in inert organic carbon in biochar, the SOC content continued to rise, albeit at a slower pace.

Biochar-induced SOC gains also vary by climate and soil type. Subtropical and tropical regions (MAT > 16 °C) show lower SOC accrual compared to temperate regions (Fig. 1 *D* and *H*), as higher microbial activity in warmer climates accelerates biochar decomposition (46). Sandy and infertile soils exhibit greater SOC improvements compared to clay-rich or high-SOC soils (e.g., paddy soils) (Fig. 1*D* and *SI Appendix*, Fig. S5*G*), as evidenced by significant negative correlations between SOC increments and initial SOC levels (Fig. 3). Soils with lower initial SOC have a greater C saturation deficit, leading to higher initial sequestration rates and a longer time to reach a new C equilibrium (47).

Management practices further influence SOC gains. Both meta-analysis and long-term field experiments show that higher N application rates enhance SOC accrual with biochar additions (Fig. 3 and *SI Appendix*, Fig. S7*G*), particularly under single-application regimes. This is because combined application of biochar and high N rate results in a synergic effect on plant growth, driving additional C inputs from root litter and exudates (30). Biochar quality also matters, particularly its C/N ratio. SOC increments positively correlate with biochar C/N ratios under annual applications ($P < 0.01$) but negatively correlate under single applications ($P < 0.01$) (Fig. 3 *A* and *B*). This pattern may be due to priming effects: Single applications of high-C/N biochar can induce positive priming, increasing the mineralization of native SOC, which can persist for years and reduce net SOC gains (47–49). In contrast, long-term annual applications of high-C/N biochar also induce priming but provide enough carbon inputs to offset native soil C losses, due to its lower N availability and microbial C mineralization rates, ultimately increasing SOC levels (50, 51). Additionally, the pyrolysis temperature of biochar plays a regulatory role in SOC accrual by altering aromatic C structures and available C fractions, as discussed in *SI Appendix*.

Net GHG Mitigation Effect and Biochar Application Strategies. The net exchange of CO_2, CH_4, and N_2O between soils and the atmosphere, expressed in CO_2 equivalents, constitutes the net global warming potential (nGWP) of a cropping system. However, given the growing global food demand and limited agricultural land, it is more meaningful to assess nGWP per unit of yield—known as GHG intensity (GHGI) (52). Our findings demonstrate that long-term biochar application effectively increases crop yields, enhances SOC sequestration, and reduces GHG emissions. However, the net GHG mitigation effect of biochar application at site and regional scales remains uncertain. To address this, we assessed the long-term effects of biochar on nGWP and GHGI, using data from five sites with simultaneous measurements of key components. As expected, long-term annual and single biochar application decrease both nGWP and GHGI, and the magnitude of these reductions sustains or even increases over time (*SI Appendix*, Fig. S12 *A* and *B*). The greatest reductions are found under annual biochar applications.

To estimate the global potential of biochar applications, we extrapolated the results from overall treatment effects from the meta-analysis (see Methods). We estimate that converting 40% of globally produced straw to biochar annually instead of returning it directly to croplands (S1) could increase global grain yields by 0.12 Pg y^{-1} and carbon dioxide removal (CDR) potential by 1.29 Pg CO_2-eq y^{-1} (*SI Appendix*, Fig. S12*C*). Increasing this conversion to 70% of straw—the maximum amount feasible for biochar production (S2)—could further enhance these benefits to approximately 0.19 Pg y^{-1} for grain yields and 2.01 Pg CO_2-eq y^{-1} for CDR potential (*SI Appendix*, Fig. S12*C*). This yield increase is roughly equivalent to 32% of the United States' annual grain production, based on the 2018 to 2021 average (53). Even the GHG emissions associated with biochar production, transport, and application were considered (0.25 t CO_2 t^{-1} biochar) (4), the CDR potential of S2 is 1.84 Pg CO_2-eq y^{-1}, equivalent to offsetting about 4.6% of global fossil fuel CO_2 emissions. These results position biochar as a critical climate mitigation tool. This GHG mitigation potential might increase even further when bioenergy generated during biochar production is used to displace fossil fuels (4). A comprehensive life-cycle assessment is therefore essential to evaluate the impacts of biochar production and application on global CDR potential.

Over the timescale of studies in our dataset, annually repeated biochar applications can offset the gradual decline in benefits—such as crop yield increases and GHG mitigation—seen with single applications due to biochar aging (Fig. 5). However, as biochar accumulates in soil over time, potentially negative effects might develop over longer timescales. For instance, prolonged biochar additions could raise soil pH to levels harmful to plant growth, reduce the effectiveness of agrochemicals, and inhibit soil biota (10). It remains unclear whether there is a threshold beyond which repeated applications outweigh their benefits. To address this, extending ongoing field experiments and conducting paired annual and single-application trials across diverse soil, climate, and cropping conditions are crucial for optimizing biochar application strategies, particularly in determining the ideal frequencies and rates.

The importance of application frequency and rate is reflected in biochar application guidelines and protocols from various countries. For example, the guidelines from ICAR-Indian Institute of Soil Science (54) and the University of Nottingham (55) suggest that a single biochar application can provide beneficial effects over multiple growing seasons, and that there is no need for additional application. In contrast, guidelines from the International Biochar Initiative (56) and the US Biochar Initiative (57) indicate that biochar amendments can be applied repeatedly, depending on the target application rate, biochar availability, and soil management practices. Our analysis indicates that the benefits of single biochar applications for crop yield, GHG mitigation, and SOC improvement gradually diminish over time due to biochar aging (e.g., pore collapse, blockage, and decrease in specific surface area). Thus, periodic reapplications are necessary to sustain biochar's long-term benefits, although annual applications may not be required. We propose that by strategically applying biochar at multiyear intervals or incorporating tailored break periods between annual applications, its long-term benefits can be sustained in a cost-effective manner while minimizing potential risks (Fig. 5). For instance, in high-rainfall tropical regions, higher application frequency paired with lower biochar application rates is recommended. The humid and warm conditions in these areas accelerate biochar degradation, necessitating more frequent replenishment. Conversely, in arid temperate regions, longer application intervals with higher biochar application rates may be optimal, as slower degradation rates reduce the need for frequent reapplication. Future research should focus on optimizing the application strategies across diverse soil and climate conditions to maximize biochar's contributions to global food security and climate change mitigation.

While periodic biochar application adapted to local soil and climate conditions can help reduce costs and sustain long-term benefits, the initial economic burden may remain considerable—especially for risk-averse farmers hesitant to adopt unfamiliar agricultural practices (58). Our cost–benefit analysis (*SI Appendix*) shows that the net economic and environmental benefit (NEEB), primarily driven by increased crop yields and reductions in GHG emissions, can offset approximately 81% of the biochar procurement costs. This offset could be even greater if the mitigation of reactive nitrogen losses is also considered (4). To facilitate broader adoption, government-supported subsidy programs—such as Australia's Carbon Farming Initiative—are essential for encouraging farmers to gradually incorporate biochar into their land management practices (57, 59). Since many farmers are unlikely

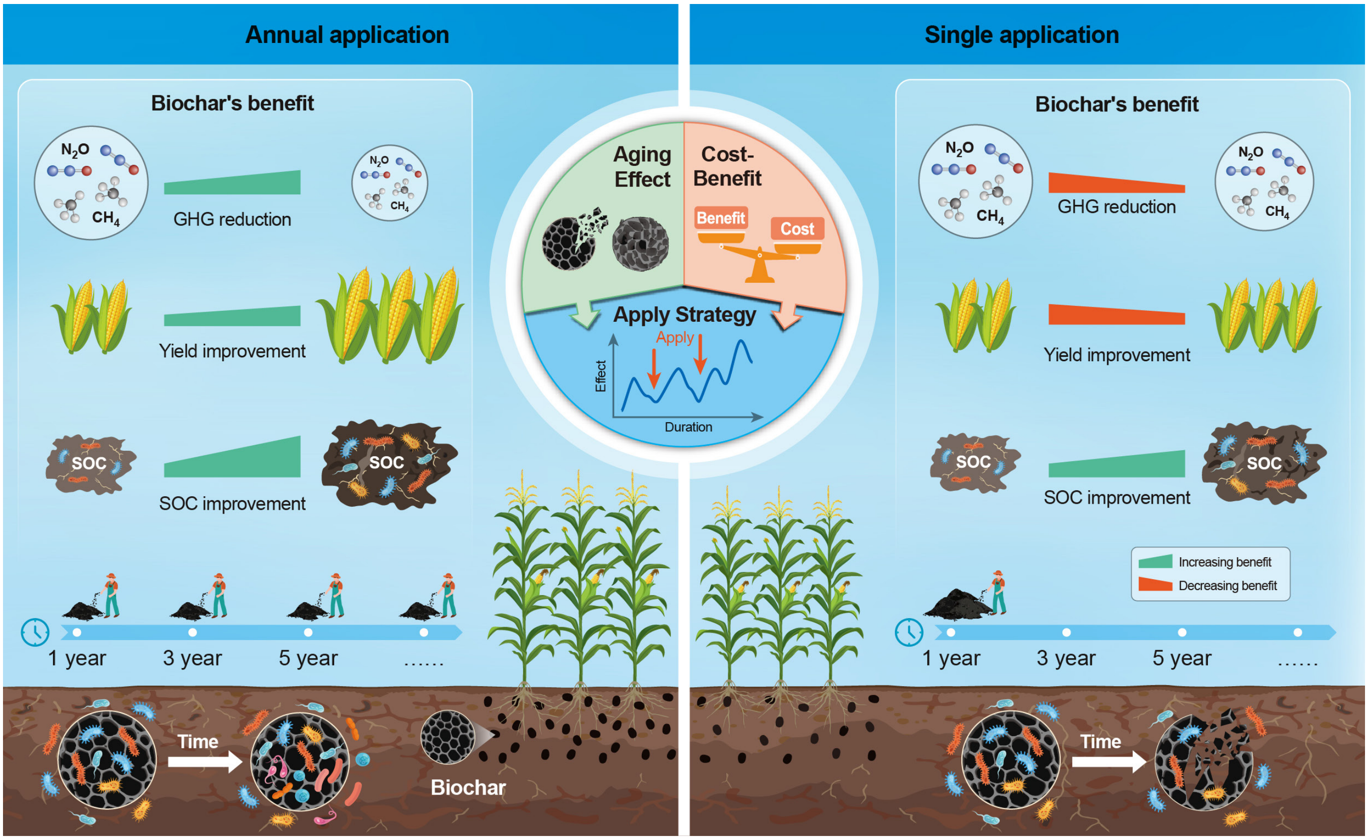

Fig. 5. Conceptual diagram illustrating sustained benefits of long-term biochar application on food security and climate change mitigation.

to increase input costs without compelling evidence of effectiveness, large-scale demonstration trials in key grain-producing regions (e.g., the North China Plain and the US Corn Belt) are critical to establishing the economic and environmental credibility of biochar application. In summary, as a scalable and sustainable solution, biochar holds significant promise in addressing the dual challenges of agricultural productivity and environmental sustainability.

Materials and Methods

This study investigates the effects of long-term biochar application on crop yields, GHG emissions, and SOC content to assess its potential as a sustainable agricultural practice. To do so, we collected peer-reviewed studies published before February 2025 that reported biochar's effect on crop yield, CH_4 and N_2O emissions, and SOC content. Data were sourced from databases such as Web of Science, Scopus, Google Scholar, China National Knowledge Infrastructure Database (CNKI), and China Wanfang Database. The search keywords included "biochar", "cropland or farmland or agriculture", "CH_4 or methane or N_2O or nitrous oxide or GHG or greenhouse gas", "grain yield or crop yield", "SOC", "soil pH", and "microbial biomass C and N (MBC and MBN)". To be included in our dataset, studies had to meet the following criteria: a) at least one of the target variables was reported for both the control (without biochar application) and treatment (with application of biochar produced from crop straws) plots; b) experimental duration was reported and studies included at least covered a full crop-growing season; and c) the biochar application frequency was reported (annually repeated application or a single application in the first year). For each study, mean values for both control and treatment plots were recorded or calculated when necessary. Pot experiments were included, while lab incubation studies were not included. SD was used as the measure of variance and was either recorded directly or calculated from the reported measures of variance in each study, and the missing SD was estimated based on the mean values of the variable and the average coefficient of variation (CV) across the dataset. In total, 438 peer-reviewed publications (encompassing 255 sites and 3,229 observations) reporting results from global croplands were included (*SI Appendix*, Fig. S1).

We evaluated the effects of biochar on crop yield and GHG mitigation under two respective application regimens, i.e., annually repeated application, and one-time application, usually involving a high amount in the first year and no additions thereafter. The natural log-transformed response ratio (lnRR) was used to quantify the effects of biochar application on the variables via the following equation:

$$\ln RR = \ln(X_t/X_c), \quad \textbf{[1]}$$

where Xt and Xc represent the means of the treatment (with biochar application) and control (without biochar application) groups for variable X, respectively.

Effect sizes were weighted by the inverse of the variance instead of replications for better data representativeness, and missing variances were estimated using the average CV across the dataset (60). The meta-analysis was conducted in R using the "rma.mv" function of the "metafor" package, which is designed for multivariate/multilevel meta-analysis and empowers the modeling of complex dependency structures in meta-analytic data. To account for nonindependence of observations derived from the same study, we included study ID as a random effect (61). The means of the categorical variables were considered significantly different from each other if their 95% CI did not overlap. For ease of interpretation, results were backtransformed and presented as the percentage of changes [(RR − 1) × 100] in the variables under biochar application. A positive percentage change denotes an increase due to biochar application, whereas a negative value indicates a decrease in the respective variable.

Across the dataset, 172 out of 258 biochar experiments were conducted in China, and 86 experiments were conducted in other countries. We investigated the differences in the effect of biochar application between Chinese and non-Chinese experiments (*SI Appendix*, Table S2). The results show that biochar application exhibits consistent trends on enhancing food security and GHG mitigation in both Chinese and non-Chinese experiments, although the response ratios vary between these two groups. These results suggest that the potential bias stemming from the difference of observation numbers in China and other countries is negligible. Besides, the publication bias was assessed using Egger's test, which showed no bias ($P \geq 0.05$) (*SI Appendix*, Table S4).

We calculated the GWP and GHGI with the data from four long-term field experiments (three received annual application and two received single application) which simultaneously reported CH_4 emission, N_2O emission, and SOC content with and without biochar application for at least 5 y (*SI Appendix*, Fig. S12 *A* and *B*). This allowed to assess the long-term impact of biochar application on the net GHG mitigation under similar environmental and climate conditions. Over a 100-y time horizon, the warming effects induced by the CH_4 and N_2O are 25 and 298 times that of CO_2, respectively (46, 61). Thus, we used the following equations to calculate the GWP (kg CO_2-eq ha^{-1}) and its response to biochar application:

$$GWP = CH_4 \times 25 + N_2O \times 298, \quad \textbf{[2]}$$

$$\Delta GWP = GWP_{BC} - GWP_{CK}, \quad \textbf{[3]}$$

where CH_4 and N_2O represent the cumulative emissions (kg ha^{-1}) of CH_4 and N_2O, respectively, and GWP_{BC} and GWP_{CK} represent the GWP with and without biochar application, respectively.

Under the dual pressures of climate warming and food security, GHGI (kg CO_2-eq t^{-1}) serves as an effective composite evaluation index, which simultaneously considers the responses of both GHG emissions and crop yields to biochar input:

$$GHGI = GWP/Yield, \quad \textbf{[4]}$$

$$\Delta GHGI = GHGI_{BC} - GHGI_{CK}, \quad \textbf{[5]}$$

where yield refers to the crop yield (t ha^{-1}), and $GHGI_{BC}$ and $GHGI_{CK}$ represent the GHGI with and without biochar application, respectively.

We further extrapolated our results on crop yields and GHG emissions under annually repeated biochar application to global croplands with all data in the dataset (*SI Appendix*, Fig. S12 *C* and *D*), which was calculated by multiplying the average biochar-induced average effects (area-scaled metrics) with the corresponding biochar application amounts and the corresponding total land area. Three scenarios were set based on current straw and biochar managements and the potential feedstock amounts: business as usual (BAU), currently on average 40% of crop straws was retained in croplands (62); biochar application scenario: 40% of crop straws was assumed to be produced into biochar before its application to the field (S1) (63); and 70% of crop straws was assumed to be produced into biochar before its application to the field (S2) (63). The S2 scenario reflects the maximum feasible biochar application amount accounting for competing uses of crop straw, such as straw fuel and animal feed.

Biochar-induced changes in CH_4 emissions (ΔCH_4, kg C ha^{-1} y^{-1} per t C ha^{-1} y^{-1}) and N_2O emissions (ΔN_2O, kg N ha^{-1} y^{-1} per t C ha^{-1} y^{-1}) were calculated by the following equations:

$$\Delta CH_4 = \frac{CH_4 - C_{BC} - CH_4 - C_{CK}}{\text{Biochar C}}, \quad \textbf{[6]}$$

$$\Delta N_2O = \frac{(N_2O - N_{BC}) - (N_2O - N_{CK})}{\text{Biochar C}}, \quad \textbf{[7]}$$

where CH_4-C_{CK}, CH_4-C_{BC}, N_2O-N_{CK}, and N_2O-N_{BC} refer to the emissions of CH_4 and N_2O without and with biochar application, respectively. Biochar C refers to the total C input through biochar application (t C ha^{-1} y^{-1}).

The SOC density (SOCD, kg C ha^{-1}), the SOC sequestration rate (SOCSR, kg C ha^{-1} y^{-1}), and biochar-induced change in SOCSR (ΔSOCSR, kg C ha^{-1} y^{-1} per t C ha^{-1} y^{-1}) were calculated using the following equations:

$$SOCD = SOC \times BD \times H \times 10, \quad \textbf{[8]}$$

$$SOCSR_{CK} = \frac{SOCD_{CK} - SOCD_{IN}}{T}, \quad \textbf{[9]}$$

$$SOCSR_{BC} = \frac{SOCD_{BC} - SOCD_{IN}}{T}, \quad \textbf{[10]}$$

$$\Delta \mathrm{SOCSR} = \frac{(\mathrm{SOCSR}_{BC} - \mathrm{SOCSR}_{CK}) \times 1000}{\mathrm{Biochar\ C/T}}, \qquad [11]$$

where SOC refers to the SOC content (g kg^{-1}) of the plow horizon, BD is the soil bulk density (g cm^{-3}), and H is the depth of the plow horizon (0.2 m). $SOCD_{IN}$, $SOCD_{CK}$, and $SOCD_{BC}$ refer to the initial SOCD before biochar application, and SOCD without and with biochar treatment, respectively. $SOCSR_{CK}$ and $SOCSR_{BC}$ refer to SOCSR without and with biochar treatments when experiments ended, respectively. We estimated the initial BD for paddy fields (64) and uplands (65) for the studies where the initial BD was missing but the SOC content was provided. The weighted averages and 95% CI of ΔCH_4, ΔN_2O, and ΔSOCSR were calculated using the rma.mv function in the R package metafor, and this package defaults to using the inverse-variance weighting method. Due to data deficiency, we only focus on the changes of SOC and its stock of the top soil layer (0 to 20 cm).

We estimated biochar-induced yield increments ΔYield (Pg y^{-1}) using the following equation:

$$\Delta \mathrm{Yield} = \sum_{j=1}^{m} E_{ij} \times \mathrm{Yield}_{CRj}, \qquad [12]$$

where E_{ij} represents the effect of biochar on yield (%) under duration i (overall; <1 y; 1 to 3 y; 3 to 5 y; ≥5 y) for crop j (e.g., rice, wheat, maize), and Yield_{CRj} represents the current global yield (Pg y^{-1}) for crop j. We used the average effect of rice, wheat, and maize to represent the effect of biochar on yield of other crops.

We used the following equations to calculate the biochar-induced and straw-induced net per-area GHG balance (GHGA) (kg CO_2-eq ha^{-1} y^{-1} per kg C ha^{-1} y^{-1}) and overall GHG balance (GHGO) (Pg CO_2-eq y^{-1}):

$$\mathrm{GHG_A} = \Delta CH_4 \times 25 \times \frac{16}{12} + \Delta N_2O \times 298 \times \frac{44}{28} - \Delta \mathrm{SOCSR} \times \frac{44}{12}, \qquad [13]$$

$$\mathrm{GHG_O} = \sum_{j} \mathrm{GHG}_{Aij} \times A_i \times BC_i \times 10^{-9}, \qquad [14]$$

where GHGAij refers to the GHGA under duration i for land use type j; Ai refers to the harvest area of paddy or upland [163 million ha of paddy field, and 430 million ha of upland (cereal grain crop harvest area)] (53); and BCi is the amount of biochar C (Pg y^{-1}) applied to paddy or upland fields. The biochar-induced net C balance is calculated as the difference in C balance between the BAU and the S1 or S2 scenario.

Data, Materials, and Software Availability. The meta-analysis dataset generated during this study can be found in Dataset S1 in the online version. All other data are included in the manuscript and/or supporting information.

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