

ORIGINAL RESEARCH

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# Maximizing nitrous oxide mitigation potential of straw-derived biochar in China with optimal application strategies

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## Abstract

Agricultural soils are a significant source of nitrous oxide (N<sub>2</sub>O) emissions. The application of biochar to soil offers a synergistic approach to establishing stable organic carbon (C) storage while reducing greenhouse gas (GHG) emissions, particularly through effective reductions in N<sub>2</sub>O emissions. However, current biochar application strategies often lack consideration of locally tailored application rates and biochar properties, limiting its N<sub>2</sub>O mitigation potential. Here, we conduct a spatially explicit analysis to investigate the N<sub>2</sub>O mitigation potential of straw-derived biochar in China's croplands, exploring optimal application strategies under both ideal and realistic conditions. The key drivers that influence the spatial patterns of straw-derived biochar's mitigation potential and application strategies are also revealed. We find that applying biochar with optimal strategies could avoid approximately 50% and 36% of nationwide cropland N<sub>2</sub>O emissions under ideal and realistic conditions, respectively. The optimal biochar application rate and properties required to achieve the maximum N<sub>2</sub>O reduction potential exhibit significant spatial variability, differing among biochar types. Key factors determining the optimal biochar application rate in various regions include N fertilizer application rates and soil organic carbon (SOC) content, while water input—including precipitation and irrigation water input—is the primary factor determining the optimal biochar properties. These findings may inform the development of site-specific biochar application strategies aimed at enhancing the N<sub>2</sub>O mitigation efficacy in croplands across China.

## Highlights

- Key drivers and the underlying mechanisms influencing straw-derived biochar's agricultural N<sub>2</sub>O mitigation potential were revealed.
- The spatial pattern of straw-derived biochar's N<sub>2</sub>O mitigation potential in China's croplands was depicted.
- The optimal application strategies of straw-derived biochar to maximize its N<sub>2</sub>O mitigation potential were demonstrated.
- Nearly half of the N<sub>2</sub>O emissions from croplands in China could be avoided with optimal biochar application strategies.

**Keywords** Biochar, Nitrous oxide, Cropland, Optimization, Mitigation potential

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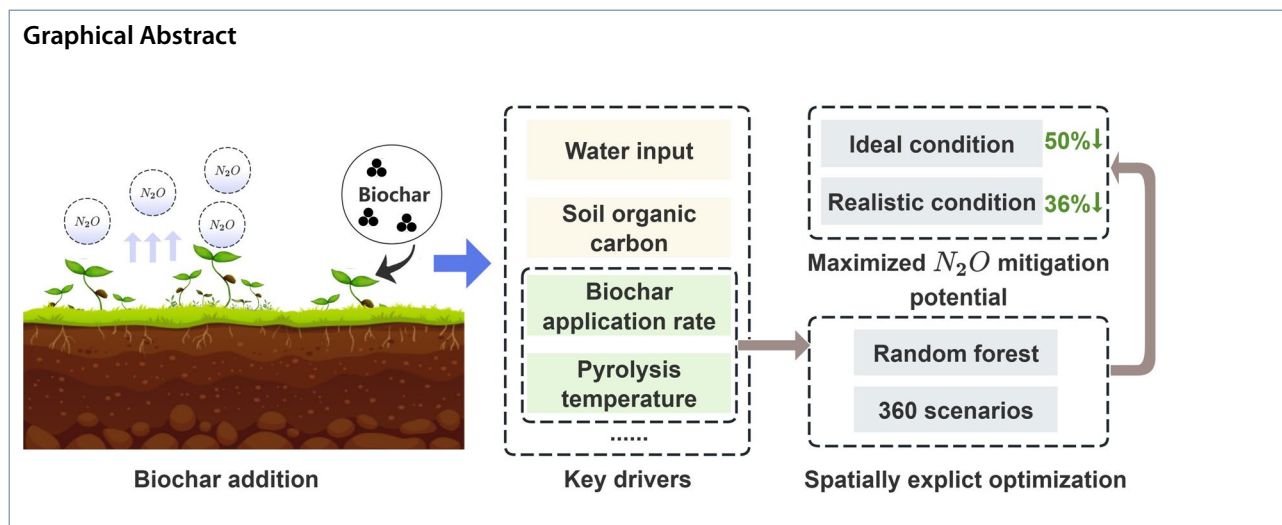
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## 1 Introduction

Biochar stands out as one of the most promising carbon dioxide removal (CDR) technologies for achieving the 1.5 °C climate target (Smith 2016; Xia et al. 2023a; Chen et al. 2019). It is currently the most widely deployed CDR technology responsible for more than 80% of removals by modern CDR technologies, and at a much lower cost (volume-weighted average price per carbon credit at 131 US dollar in 2023) than other relevant technologies, such as bioenergy with carbon capture and storage (BECCS) (300 US dollar) and direct air carbon capture and storage (DACCS) (715 US dollar) (Deng et al. 2024; Vaughan, et al. 2024). Another aspect that sets biochar apart from other CDR technologies is the fact that, beside carbon (C) sequestration, incorporating biochar into agricultural soils can improve their properties with benefits such as the reduction of greenhouse gas (GHG) emissions—particularly nitrous oxide (N<sub>2</sub>O) (Sohi 2012; Castaldi et al. 2011; Wang et al. 2023; Han et al. 2022; Yang et al. 2020). Therefore, deployment of biochar as a CDR technology can impact climate in more than one way, i.e., atmospheric carbon removal and storage and mitigation of soil GHG emissions, which are otherwise difficult to eliminate.

Although exploring the negative emission potential of biochar has received widespread attention in recent years, most studies have predominantly focused on its C sequestration capacity, often simplifying the consideration of biochar's GHG mitigation potential, particularly N<sub>2</sub>O. For example, Xia et al. (2023b) explored the climate mitigation potential of sustainable biochar production in China from a life cycle perspective. However, an average value of 35.5% was used to evaluate the N<sub>2</sub>O mitigation potential of biochar (Xia et al. 2023b). Deng et al. assessed the

negative emission potential of biochar in China by considering both its C sequestration capacity and its avoided GHG emissions from cropland soils (Deng et al. 2024). Although a proportion formula was employed—rather than a fixed value—to estimate the mitigation potential for GHG emissions, the influences of environmental factors and the physicochemical properties of biochar on its GHG mitigation efficacy were ignored. Such simplifications overlooked the spatial heterogeneity of biochar's mitigation potential for N<sub>2</sub>O emissions from agricultural soils, thereby resulting in inaccurate assessments of biochar's full negative emission potential (Wu et al. 2023; Gabetto et al. 2024; Bo et al. 2023).

To elucidate the spatial variability in the mitigation potential of biochar for N<sub>2</sub>O emissions from agricultural soils, several studies have sought to identify the key drivers and underlying mechanisms influencing its effectiveness. Although biochar application can simultaneously affect both nitrification and denitrification processes (Bo et al. 2023; Yang et al. 2022), its capacity to reduce N<sub>2</sub>O emissions is primarily attributed to the enhanced conversion of N<sub>2</sub>O to N<sub>2</sub> during denitrification (Xu et al. 2014a). Subsequent studies have revealed that this effect is largely driven by biochar-induced increases in soil pH, which in turn promote the abundance of *nosZ* genes and enhance denitrification enzyme activity (Zhong et al. 2025; Parasara and Agarwala 2025). Given the variability in biochar production conditions and application rates, several studies have explored how these factors influence its N<sub>2</sub>O mitigation potential. For instance, (Cayuela et al. 2014) identified biochar feedstock, pyrolysis conditions, and the C/N ratio as critical factors affecting its impact on N<sub>2</sub>O emissions from agricultural soils. Kaur et al. further highlighted the importance of experiment duration as a

determinant of biochar's effectiveness (Kaur et al. 2023). Regarding application rate, Liu et al. (2023a) reported that N<sub>2</sub>O emission reduction can be enhanced from 34% to 67% when biochar application rate increases from 10 to 20 t ha<sup>-1</sup> year<sup>-1</sup>.

Moreover, with the development of machine learning algorithms, the N<sub>2</sub>O mitigation potential of biochar applied in different regions with various climate and soil conditions has been assessed. For example, Liu et al. utilized the random forest algorithm to project changes in soil N<sub>2</sub>O emissions following biochar application at the global scale (Liu et al. 2019). He et al. leveraged a GA-BPNN-based approach to evaluate the mitigation potential of biochar on N<sub>2</sub>O emissions from global cropland soils (He et al. 2024). In recent years, increasing attention has been directed toward optimizing biochar production or application strategies to enhance both environmental and economic outcomes. Liu et al. proposed an optimal biochar application strategy that incorporates both biochar type and application rate, offering valuable insights for biochar use in agricultural soils (Liu et al. 2019). Adhikari et al. identified optimal biochar production sites in New Mexico using a multi-criteria decision analysis framework (Adhikari et al. 2024). He et al. developed a global biochar application strategy to maximize GHG emission reduction from croplands and to maximize crop yield (He et al. 2024).

However, comprehensive optimization of biochar application strategies—encompassing application rate and pyrolysis temperature for different biochar types and with diverse environmental conditions—to our knowledge remains absent. This limitation leads to an unknown pattern about the optimal deployment of biochar, hindering the maximization of its N<sub>2</sub>O mitigation potential. This research gap can be partially attributed to insufficient consideration of key drivers, such as nitrogen (N) fertilizer application rates and biochar properties, and the mechanisms through which they influence N<sub>2</sub>O reduction. Addressing these major gaps should improve our understanding of how natural and anthropogenic factors, alongside biochar's inherent properties, shape its N<sub>2</sub>O reduction capacity, thus supporting locally tailored

application strategies that maximize biochar's N<sub>2</sub>O mitigation potential.

In this study, we compiled a dataset on the effects of straw-derived biochar on N<sub>2</sub>O emissions from agricultural soils in China, employing machine learning algorithms and meta-analysis to elucidate the mechanisms by which environmental conditions and biochar's inherent properties influence its N<sub>2</sub>O mitigation potential. We then conducted a spatially explicit optimization under both ideal and realistic conditions to develop locally tailored biochar application strategies, aimed at maximizing biochar's potential for N<sub>2</sub>O mitigation.

## 2 Materials and methods

### 2.1 Data sources

A literature search was performed through Web of Science, Google Scholar, and China Knowledge Resource Integrated (CNKI) databases using the keywords including "Biochar", "Nitrous oxide", "N<sub>2</sub>O", "GHGs", "straw", and "soil" (see full search query in Supplementary Note a). Literature on the effects of biochar amendment on N<sub>2</sub>O emissions from Chinese agricultural soils, published between January 2010 and December 2023, was searched and screened. The searched papers were further filtered to meet the following criteria: (1) the studies included control treatments, with each treatment replicated three times or more; (2) the studies were conducted on agricultural soils in China; (3) the type of biochar feedstock was crop residue (rice-, wheat-, and maize-straw); and (4) the location, time, and basic properties of both the soil and the biochar were clarified. Based on the above criteria, 71 articles were chosen, comprising 392 sets of observational data on N<sub>2</sub>O emissions from agricultural soils treated with biochar addition (Figure S1). Among these data, more than 80% reported a mitigating effect of biochar on N<sub>2</sub>O emissions, whereas the remaining cases indicated an enhancement in N<sub>2</sub>O emissions. Since the selected papers may not have included all the necessary variables (e.g., soil properties, climate conditions, and management measures), we supplemented the missing information with additional datasets (Table 1).

**Table 1** Sources and description of the used datasets

Category	Data item	Source	Resolution	Year
Soil property	Soil organic carbon content	Harmonized World Soil Database 2.0 (Food and Agriculture Organization of the United Nations Website 2025)	1 km	/
	Soil bulk density			
Climate condition	Temperature	China Meteorological Forcing Dataset (Plateau et al. 2024)	~10 km	2009–2018 mean
	Precipitation			
Management measure	N fertilizer application	(Yu et al. 2022)	5 km	2016
	Irrigation water use	(Zhang et al. 2022)	~25 km	2011–2018 mean

## 2.2 Random forest model and relative importance analysis

The random forest (RF) model is an ensemble learning algorithm based on multiple decision trees (Breiman 2001). It can effectively reduce overfitting and has better generalization capabilities, making it suitable for representing complex nonlinear relationships between dependent and independent variables. The RF model was trained using 80% of the dataset and validated with the remaining 20%. The model's performance was assessed using the coefficient of determination ( $R^2$ ) and the root-mean-square error (RMSE).

The relative importance of each independent variable was measured based on the decrease in impurity at each split node during statistical analysis, and a larger difference indicates a greater importance of that variable. In this study, an importance threshold of 0.02 was used to filter the most important variables to train the RF model.

## 2.3 Spatial extrapolation and optimization

The trained RF model was used to extrapolate biochar's  $N_2O$  mitigation potential to China's croplands based on the spatial data of the identified most important environmental factors, including N fertilizer application rate, water input (sum of precipitation and irrigation water use), mean annual temperature (MAT), soil organic carbon (SOC), and soil bulk density (Table S1).

Among all the important drivers influencing biochar's  $N_2O$  mitigation potential, biochar's application rate, pH, carbon (C) content, and nitrogen (N) content are optimizable. Given that biochar's pH, C content and N content are determined by the pyrolysis temperature simultaneously (Li et al. 2022), we selected biochar's application rate and pyrolysis temperature as the optimization objects in this study to maximize the  $N_2O$  mitigation potential of straw-derived biochar in China's croplands. A total of 360 scenarios combining different biochar application rates (2–80 t/ha with an interval of 2 t/ha) and pyrolysis temperatures (300–700 °C with an interval of 50 °C) were established to explore the optimal application strategies to maximize biochar's  $N_2O$  mitigation potential at a 0.05° resolution under the ideal condition, which did not account for realistic straw resource limitation.

Moreover, we also evaluated the  $N_2O$  mitigation potential of biochar under the realistic condition, which considered real-world straw resource constraints. First, we estimated the province-level availability of straw by multiplying crop yield data from statistical yearbooks by straw-to-grain ratios (Zhang et al. 2021a). The available straw in each province was then assumed to be evenly distributed across croplands within the province to calculate the annual biochar application rates under

various pyrolysis temperatures (ranging from 300 to 700 °C, in 50 °C increments). Using these application rates, we evaluated the  $N_2O$  mitigation potential of biochar under realistic conditions and identified the optimal pyrolysis temperature for maximizing mitigation potential over a continuous 30-year application period.

## 2.4 Calculation of $N_2O$ emission intensity in China's croplands

The updated spatially-referenced nonlinear model (SRNM) was utilized to estimate the  $N_2O$  emission intensity in China's croplands at a spatial resolution of 0.05° (Shang et al. 2019). The SRNM model was developed based on field observations of  $N_2O$  emissions, with spatially-variable inputs including climate conditions, soil properties and crop management practices. The  $N_2O$  emissions of the updated SRNM model can be described as:

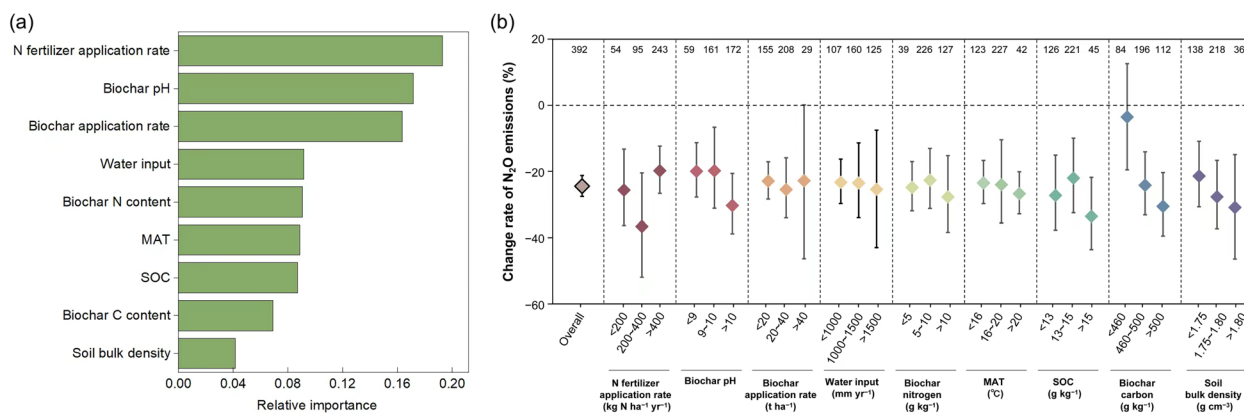
$$E_{ijk} = \alpha_{ij}R_{ijk}^2 + \beta_{ij}R_{ijk} + \gamma_{ij} + \varepsilon_{ijk} \quad (1)$$

where  $E_{ijk}$  denotes the predicted  $N_2O$  emission rate (kg N ha<sup>-1</sup> year<sup>-1</sup>) for crop type  $j$  in region  $i$  during year  $k$ .  $R_{ijk}$  is the N fertilizer application rate (kg N ha<sup>-1</sup> year<sup>-1</sup>).  $\alpha R^2 + \beta R$  represents emissions caused by fertilizer input.  $\gamma$  represents the intercept for background emissions, and  $\varepsilon$  denotes the residual term. More details can be found in the original paper (Shang et al. 2019).

## 3 Results

### 3.1 Key drivers and mechanisms affecting biochar's $N_2O$ mitigation potential

We leveraged a RF model to capture the nonlinear relationship between straw-derived biochar's  $N_2O$  mitigation potential and 25 environmental drivers, including biochar application rate and properties, soil physicochemical properties, climate conditions, and management measures (Table S1). The RF model performed well on both the training and testing datasets, achieving an  $R^2$  of 0.75 for the training set and 0.53 for the testing set, with RMSE values of 9.30 and 12.38, respectively (Figure S2). Through importance analysis (see Methods), 9 out of all the 25 initially selected environmental drivers were identified as the dominant drivers influencing biochar's  $N_2O$  mitigation potential in agricultural soils (Table S1). Among these, N fertilizer application rate emerged as the most influential variable, with a high relative importance score of 0.19, followed by biochar pH and application rate, both with relative importance values surpassing 0.16. Additional drivers, including water input, biochar N content, MAT, SOC, biochar C content, and soil bulk density, also played a certain role in affecting biochar's  $N_2O$  mitigation potential (Fig. 1a).



**Fig. 1** Key drivers influencing the mitigation potential of biochar. Relative importance values of different drivers **(a)**, and biochar-induced relative changes in N<sub>2</sub>O emissions based on a meta-analysis **(b)**. MAT—mean annual temperature, SOC—soil organic carbon. The numbers at the top of Figure b represent the number of samples in the corresponding categories

Leveraging a meta-analysis approach (see Methods and Supplementary Method a), we investigated the mechanisms through which these key drivers influence biochar's impact on N<sub>2</sub>O emissions from agricultural soils. Our results revealed that the N<sub>2</sub>O mitigation ratio following biochar amendment initially increases and then declines as N fertilizer application rates rise (Fig. 1b). Under typical soil conditions, both nitrification and denitrification occur concurrently, with their interactions contributing to overall N<sub>2</sub>O emissions (Li et al. 2018; Wang et al. 2018). When low levels of N fertilizer are applied, biochar's impact on reducing soil N<sub>2</sub>O emissions remains limited; this may be because, at low N levels, soil N<sub>2</sub>O emissions are largely due to nitrification (Wrage-Mönnig et al. 2018; Zhou et al. 2016), whereas biochar's mitigation effects are more pronounced during denitrification (Li et al. 2024a; Liang et al. 2020). By contrast, high N fertilizer application significantly raises soil NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N levels, particularly NO<sub>3</sub><sup>-</sup>-N concentrations that exceed biochar's adsorption capacity, which inhibits N<sub>2</sub>O reductase activity during denitrification and ultimately leads to increased N<sub>2</sub>O emissions (Liu et al. 2020).

In terms of biochar application rate, the mean N<sub>2</sub>O mitigation potential of biochar initially increases but subsequently declines as the application rate rises, with substantial uncertainties observed at high application rates (>40 t ha<sup>-1</sup>) (Ducey et al. 2013; Zhang et al. 2012). Adding larger quantities of biochar may lead to increased adsorption of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in soil, thereby altering soil redox potential and electron acceptors in ways that can reduce soil nitrification and denitrification (Singh et al. 2010; Xu et al. 2014b). However, since both N<sub>2</sub>O emission and biochar's N<sub>2</sub>O mitigation potential are influenced by the complex interactions among multiple drivers, the effect of biochar amendment on

N<sub>2</sub>O emission can vary considerably—even at the same application rate. This variability is especially pronounced at higher application rates, where significant alterations in soil physicochemical properties may amplify the influence of other environmental factors on biochar's N<sub>2</sub>O mitigation potential (Chi et al. 2024; Li et al. 2024b).

Regarding biochar properties, soil N<sub>2</sub>O emissions significantly decreased ( $-30.47 \pm 9.61\%$ ) when biochar's pH exceeds 10 (Fig. 1b). The pH of biochar can influence soil acidity and alkalinity, with high-pH biochar potentially exerting a "liming effect" that raises soil pH, promotes ammonia volatilization, reduces microbial N sources (Antoniou et al. 1990; Šimek et al. 2002), and facilitates complete denitrification to convert N<sub>2</sub>O to N<sub>2</sub> (Castaldi et al. 2011), thereby reducing soil N<sub>2</sub>O emissions. In terms of biochar's C and N content, biochar amendment is associated with apparent reductions in soil N<sub>2</sub>O emissions of  $27.89 \pm 10.56\%$  and  $30.71 \pm 8.83\%$  when biochar contained more than 10 g kg<sup>-1</sup> N and 500 g kg<sup>-1</sup> C, respectively (Fig. 1b). Biochar with a high C/N ratio is particularly effective in reducing soil N<sub>2</sub>O emissions (Case et al. 2012; Borchard et al. 2014). When such biochar is applied, it provides ample C sources for microbial activity, thereby intensifying soil microbial metabolic processes (Sombroek, et al. 2003). At the same time, due to its relatively low N content, high C/N biochar cannot provide sufficient N for soil nitrification and denitrification. This scarcity intensifies competition among microorganisms, leading to reduced soil N mineralization and constrained denitrification (Wang et al. 2016), thereby maximizing biochar's N<sub>2</sub>O mitigation potential.

Biochar significantly reduced soil N<sub>2</sub>O emissions by  $33.69 \pm 9.93\%$  and  $31.03 \pm 15.40\%$  when added into soils with SOC levels above 15 g kg<sup>-1</sup> and bulk density greater

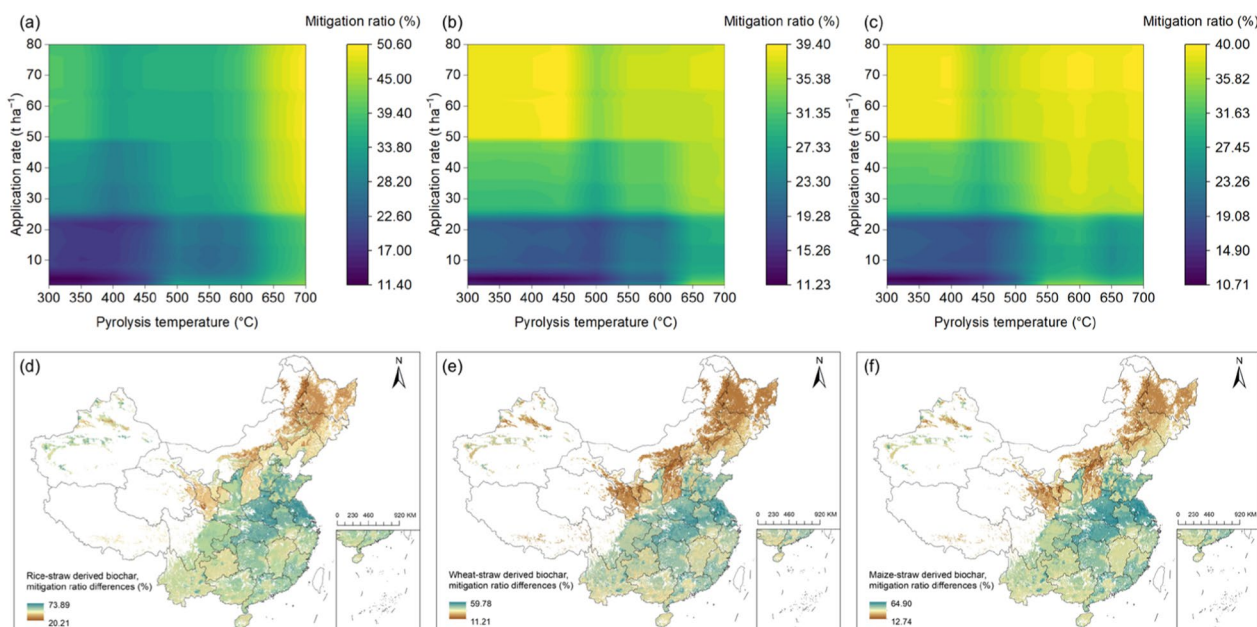
than  $1.80 \text{ g cm}^{-3}$ , respectively (Fig. 1b). SOC acts as a primary electron donor for energy and a precursor for cellular components, making its bioavailability essential in regulating soil microbial denitrification rates (Finn et al. 2017). In soils with low SOC, biochar is less effective in reducing  $\text{N}_2\text{O}$  emissions due to the limited availability of C sources as heterotrophic electron donors, which are insufficient to support complete denitrification (Bouwman et al. 1993). By contrast, in soils with high SOC, biochar can enhance  $\text{N}_2\text{O}$  reductase activity, effectively inhibiting  $\text{N}_2\text{O}$  emissions (Xia et al. 2023a). With respect to soil bulk density, biochar can effectively increase soil porosity owing to its high specific surface area and loose porous structure (Liao et al. 2021), which is particularly impactful in soils with high bulk density. This increased porosity fosters a more aerobic environment, inhibiting denitrification and thereby reducing  $\text{N}_2\text{O}$  emissions (Hossain et al. 2020; Wang et al. 2022).

In terms of climate conditions, biochar amendment significantly reduced soil  $\text{N}_2\text{O}$  emissions under higher MAT ( $>20^\circ\text{C}$ ) and increased water input ( $>1500 \text{ mm year}^{-1}$ ), achieving mitigation ratios of  $26.92 \pm 6.02\%$  and  $25.52 \pm 17.45\%$ , respectively (Fig. 1b). MAT directly influences soil microbial activity, affecting soil  $\text{O}_2$  pressure and available N content, thereby modulating  $\text{N}_2\text{O}$  emissions (Maag and Vinther 1996; Butterbach-Bahl and Dannenmann 2011). Under elevated MAT, the abundance of  $\text{N}_2\text{O}$ -reducing denitrifying bacteria (nosZ gene)

typically decreases, inhibiting the conversion of  $\text{N}_2\text{O}$  to  $\text{N}_2$  (Liao et al. 2022). However, biochar addition stimulates the growth of these bacteria, enhancing denitrification processes that convert  $\text{N}_2\text{O}$  to  $\text{N}_2$  (Liao et al. 2021). Regarding water input, varying amounts in agricultural fields alter soil moisture content, which in turn affects soil aeration and the occurrence of nitrification and denitrification (Hu et al. 2015). Nitrification predominates as the primary pathway of  $\text{N}_2\text{O}$  production under low water input, whereas denitrification takes precedence when water input is high. Since biochar's  $\text{N}_2\text{O}$  mitigation potential is primarily activated during denitrification (Cayuela et al. 2013), its effectiveness is particularly pronounced in conditions of increased water input.

### 3.2 Biochar's $\text{N}_2\text{O}$ mitigation potential under different application scenarios

The trained RF model was applied to estimate biochar's  $\text{N}_2\text{O}$  mitigation potential across all croplands in China at a spatial resolution of  $0.05^\circ$ , utilizing spatial data for the 9 key drivers. A total of 360 scenarios were developed, combining various biochar application rates and pyrolysis temperatures for three biochar types (rice-, wheat-, and maize-straw-derived biochar) to assess  $\text{N}_2\text{O}$  mitigation potential under different application strategies (see Methods).

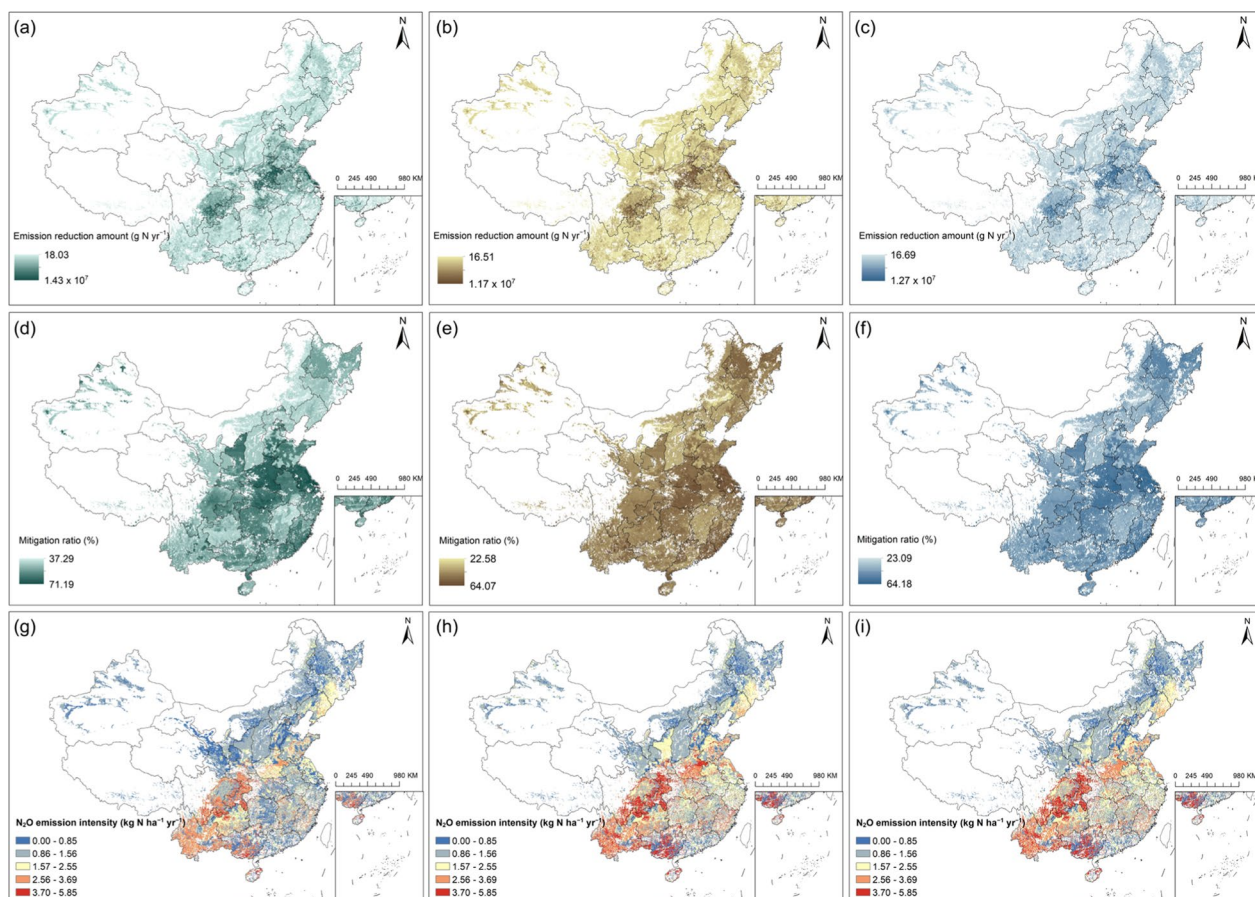


**Fig. 2**  $\text{N}_2\text{O}$  emission mitigation ratios of straw-derived biochar under different biochar application strategies. Nationwide average mitigation ratios of rice-(a), wheat-(b), and maize-straw-derived biochar (c), and the spatial pattern of differences in mitigation ratio between the optimal and the worst-case scenarios of rice-(d), wheat-(e), and maize-straw-derived biochar (f)

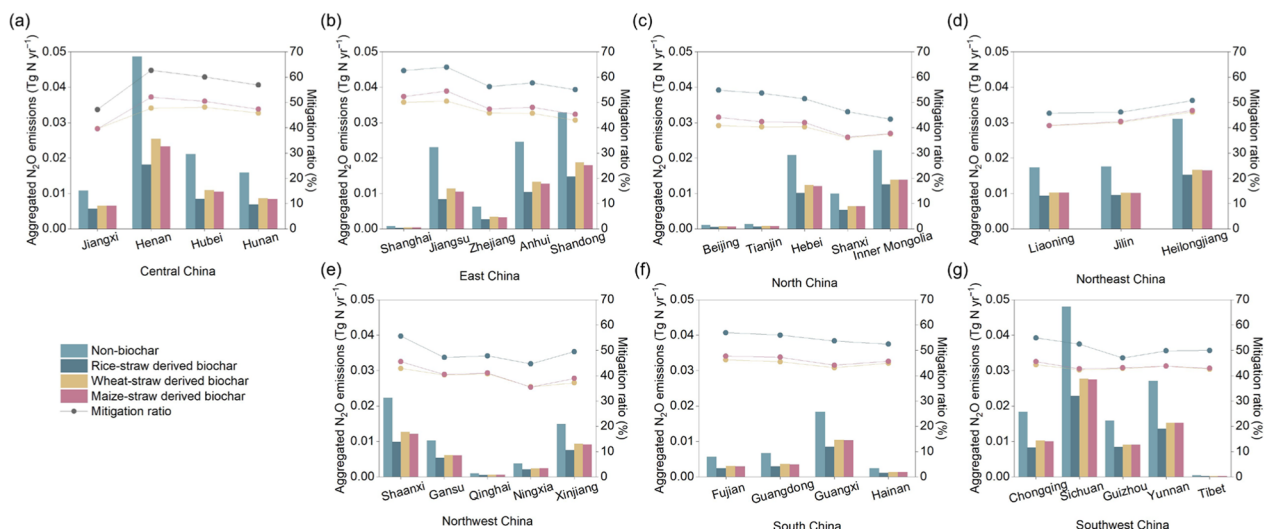
The results indicated that biochar produced at different pyrolysis temperatures and applied at varying rates significantly influenced its mitigation potential. Specifically, mitigation ratios ranged from 11.40% to 50.60% for rice-straw-derived biochar, 11.23% to 39.40% for wheat-straw-derived biochar, and 10.71% to 40.00% for maize-straw-derived biochar. When pyrolysis temperature exceeded 650 °C and the application rate surpassed 24 t ha<sup>-1</sup>, rice-straw-derived biochar achieved mitigation ratios above 40% (Fig. 2a). By contrast, wheat-straw-derived biochar demonstrated higher mitigation potential at lower pyrolysis temperatures, exceeding 38% when pyrolysis temperatures ranged from 300 to 450 °C with application rates above 50 t ha<sup>-1</sup> (Fig. 2b). Maize-straw-derived biochar exhibited notable mitigation potential under two conditions: at low pyrolysis temperatures with high application rates (300–400 °C and 50–80 t ha<sup>-1</sup>) or at high pyrolysis temperatures with moderate application rates (550–700 °C and > 26 t ha<sup>-1</sup>) (Fig. 2c).

Spatially, the maximum difference in N<sub>2</sub>O mitigation ratio reached 73.89%, 59.78%, and 64.90% for rice-, wheat-, and maize-straw-derived biochar, respectively when comparing optimal and worst-case scenarios (Fig. 2d–f). Central and East China displayed the largest disparities, particularly in Jiangsu and Henan provinces, underscoring the importance of optimal biochar application strategies in these regions to avoid substantial mitigation losses.

To further assess the maximum N<sub>2</sub>O mitigation potential of straw-derived biochar in China’s croplands under ideal condition (excluding constraints on straw resource availability), we identified the spatial pattern of optimal biochar application strategies—including pyrolysis temperature and application rate—at a spatial resolution of 0.05°. We analyzed the potential in two aspects: actual emission reduction amount and mitigation ratio, providing insights into how well biochar’s mitigation potential aligns with N<sub>2</sub>O emission intensities. The nationwide N<sub>2</sub>O emission reduction amount under optimal



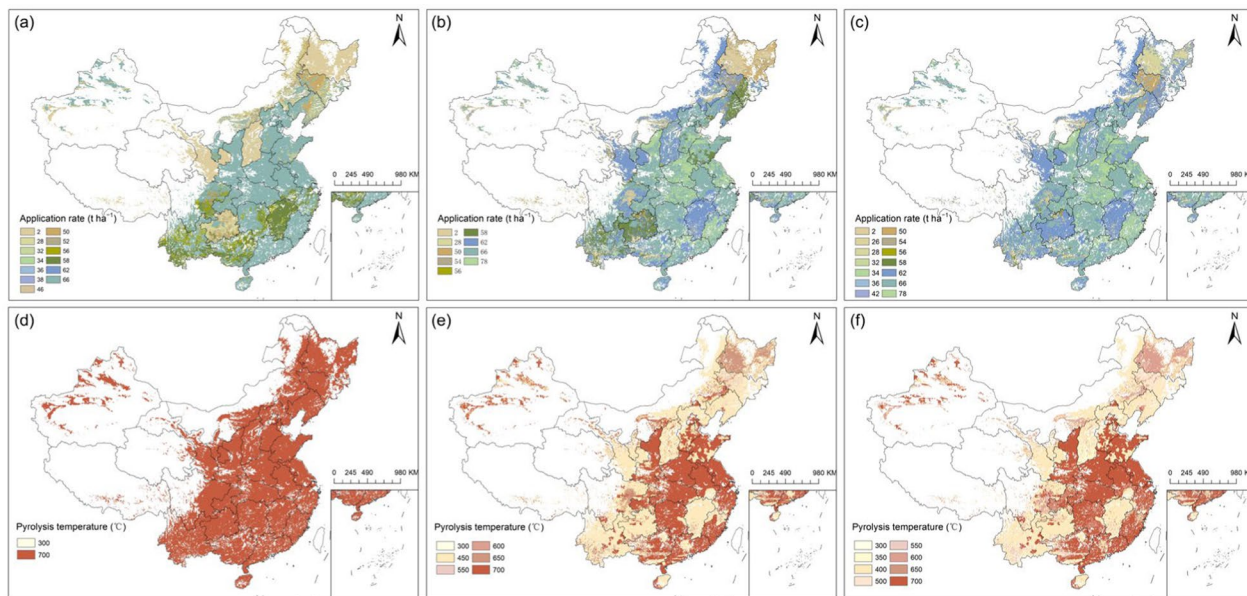
**Fig. 3** Spatial pattern of biochar’s N<sub>2</sub>O mitigation potential under the optimal application strategies. N<sub>2</sub>O emission reduction amount applying rice- (a), wheat- (b), and maize-straw-derived biochar (c). N<sub>2</sub>O mitigation ratio of rice- (d), wheat- (e), and maize-straw-derived biochar (f). N<sub>2</sub>O emission intensity following rice- (g), wheat- (h), and maize-straw-derived biochar application (i)



**Fig. 4** Province level aggregated mitigation potential of rice-, wheat-, and maize-straw-derived biochar under the optimal application scenario. Central China (a), East China (b), North China (c), Northeast China (d), Northwest China (e), South China (f), and Southwest China (g). Hongkong, Macau, and Taiwan were excluded from the analysis

application strategies was estimated to be 0.27, 0.22, and 0.23 Tg N year<sup>-1</sup> for rice-, wheat-, and maize-straw-derived biochar, respectively (Fig. 3a–c). Given that China’s average annual cropland N<sub>2</sub>O emissions from 2009 to 2018 were ~0.50 Tg N year<sup>-1</sup> (Supplementary Discussion a), optimal biochar application could potentially halve national cropland N<sub>2</sub>O emissions (Fig. 3g–i).

In terms of mitigation ratio, rice-straw-derived biochar exhibited the greatest potential, with a nationwide average of 52.68%, followed by maize-straw-derived biochar at 44.33% and wheat-straw-derived biochar at 43.01% (Fig. 3d–f). The superior mitigation capacity of rice-straw-derived biochar was likely due to its relatively higher pH value at the same pyrolysis temperature, despite its lower C content (Figure S3). Prior analyses



**Fig. 5** Optimal application strategies for straw-derived biochar under the ideal condition. The optimal application rates for rice- (a), wheat- (b), and maize-straw-derived biochar (c). Optimal pyrolysis temperature for rice- (d), wheat- (e), and maize-straw-derived biochar (f)

indicated that the pH value of biochar exerted a more pronounced effect on its N<sub>2</sub>O mitigation capacity compared to its C content.

Spatially, Jiangsu province exhibited the highest average N<sub>2</sub>O mitigation ratio at 56.33% across the three straw-derived biochar types, followed by Shanghai (54.99%) and Henan (54.18%). By contrast, Ningxia had the lowest average mitigation ratio, at only 38.58% (Fig. 4). The spatial variation in biochar's mitigation potential can be partially explained by the higher N fertilizer application rates in East China, Central China, and eastern Sichuan (Figure S4), where biochar can effectively reduce nitrogen loss and improve N use efficiency, thereby reducing N<sub>2</sub>O emissions. These areas also have higher MAT, water input, and soil bulk density (Figures S5 and S6), which further enhance the mitigation potential of biochar.

### 3.3 Optimal application rate of biochar under ideal condition

The optimal biochar application rate for maximizing N<sub>2</sub>O reduction potential varied significantly across regions and among different biochar types (Fig. 5). For rice-straw-derived biochar, optimal application rates were 2 t ha<sup>-1</sup> in Shanxi and Gansu, while croplands in Guizhou, Jilin, and Jiangxi predominantly showed optimal rates at 28 t ha<sup>-1</sup>, 50 t ha<sup>-1</sup>, and 58 t ha<sup>-1</sup>, respectively. In other regions, optimal rates reached up to 66 t ha<sup>-1</sup> (Fig. 5a). For wheat- and maize-straw-derived biochar, optimal application rates were relatively high in North, Central, East, and South China, exceeding 62 t ha<sup>-1</sup>, while in other regions, rates varied between 2 and 58 t ha<sup>-1</sup> (Fig. 5b, c). Overall, the optimal application rates of straw-derived biochar were lower in Northeast China, especially in Heilongjiang, where recommended rates ranged from 2 to 28 t ha<sup>-1</sup>.

Spatial variations in optimal biochar application rates were primarily influenced by variations in N fertilizer application rates and SOC content. Higher biochar application rates typically corresponded to areas with high N fertilizer application rates and substantial N<sub>2</sub>O emissions (Figures S4 and S7). In areas with low N fertilizer application rates, excessive use of nitrogen-containing biochar would result in an overabundance of soil nitrogen, which may enhance the denitrification process and, consequently, diminish biochar's effectiveness in reducing N<sub>2</sub>O emissions. Moreover, regions with higher optimal biochar application rates generally had lower SOC content (Figure S6). Denitrification is less important in soils with low SOC, which limits biochar's effectiveness in reducing soil N<sub>2</sub>O emissions (Zhang et al. 2021b). Therefore, more biochar is needed to increase the C sources in the soil (Chen et al. 2024), thereby realizing maximum reduction. By contrast,

soils with high SOC already contain sufficient C sources to support denitrification, and excessive application of biochar may alter soil physicochemical properties, potentially diminishing its mitigation potential.

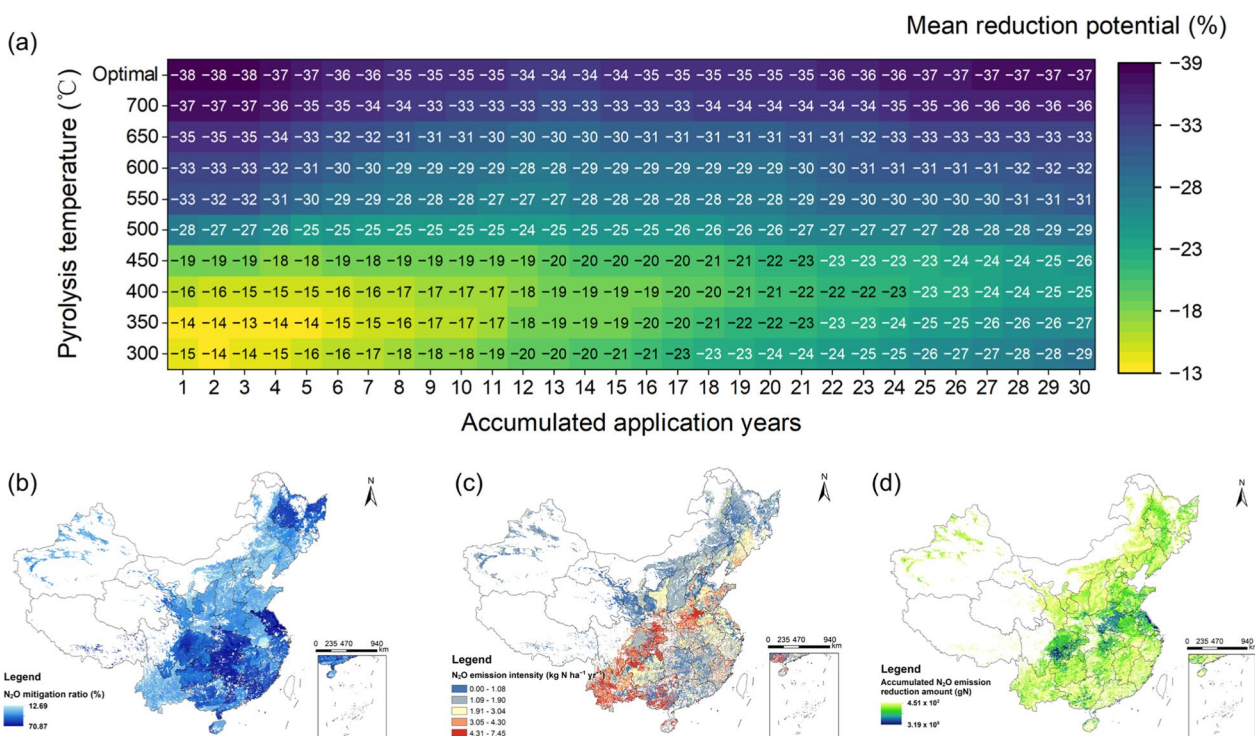
### 3.4 Optimal pyrolysis temperature of biochar under ideal condition

For rice-straw-derived biochar, the optimal pyrolysis temperature was 700 °C in most regions, with a few areas requiring 300 °C (Fig. 5d). By contrast, optimal pyrolysis temperature for wheat- and maize-straw-derived biochar ranged from 400 to 500 °C in most regions (Fig. 5e and f). This can be explained by differences in the C content response to pyrolysis temperatures among biochar types. The C content of rice-straw-derived biochar increases more slowly with pyrolysis temperature than that of wheat- and maize-straw-derived biochar (Figure S3). Previous mechanism analyses indicated that higher C content enhances mitigation potential; thus, higher pyrolysis temperatures are essential for rice-straw-derived biochar to reach its full potential.

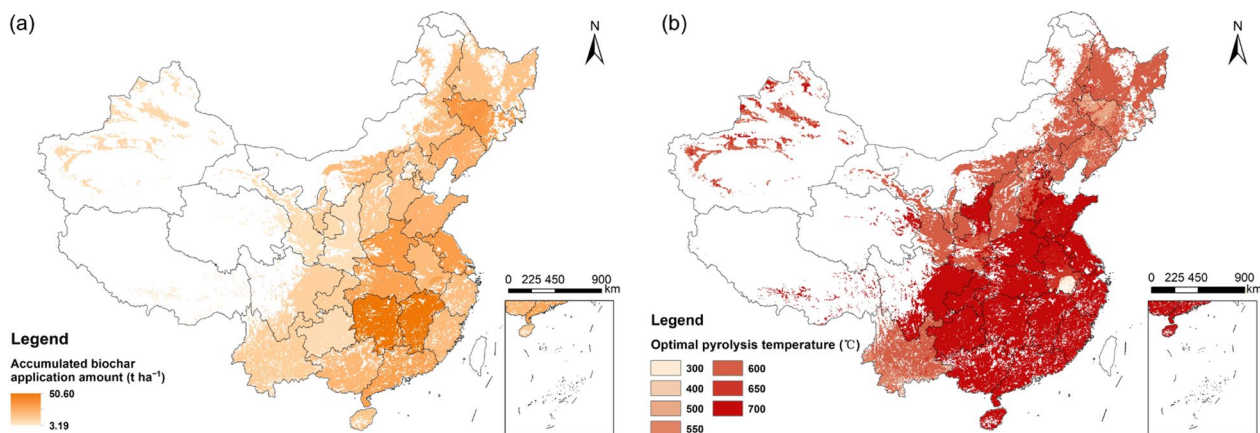
Water input was the main driver of spatial differences in optimal pyrolysis temperatures. Regions with higher water input generally required higher pyrolysis temperatures (Figure S5), as increased water accelerates soil percolation and leaching, intensifying soil acidification, and consequently increasing N<sub>2</sub>O emissions (Qiu et al. 2024). Therefore, biochar with higher pH values, achieved through higher pyrolysis temperatures, is necessary in these regions to balance soil pH and mitigate N<sub>2</sub>O emissions effectively.

### 3.5 N<sub>2</sub>O mitigation potential of biochar under real situation

Given that straw resources in China are currently inadequate to meet the raw material demands for achieving optimal biochar application rates nationwide (Supplementary Discussion b), we further investigated the N<sub>2</sub>O mitigation potential of biochar under real-world conditions where straw resources are constrained. The estimated average N<sub>2</sub>O mitigation ratio over 30 years of continuous biochar application demonstrated substantial variability across pyrolysis temperature scenarios, with values ranging from 19.51% to 34.49% (Fig. 6a). Under the optimal pyrolysis temperature scenario, this ratio could reach as high as 35.80%. Notably, the mitigation ratio was relatively low during the first 15 years when biochar was produced at lower pyrolysis temperature, particularly below 500 °C. However, with higher pyrolysis temperature, the mitigation ratio remained relatively stable over the 30-year period. Spatially, under the optimal pyrolysis temperature scenario, Hunan ranked higher owing to the greater availability of straw resources, which enabled a higher biochar application rate



**Fig. 6** N<sub>2</sub>O mitigation potential of biochar under the realistic condition. The mitigation potential for different accumulated biochar application years under various pyrolysis temperature scenarios (a). Spatial pattern of biochar’s N<sub>2</sub>O mitigation ratio under the optimal pyrolysis temperature scenario (b). Spatial pattern of average N<sub>2</sub>O emission intensity under the optimal pyrolysis temperature scenario (c). Spatial pattern of accumulated N<sub>2</sub>O emission reductions in 30 years with biochar application (d). The realistic condition considered straw resource constraint in each province used to produce biochar



**Fig. 7** Spatial pattern of accumulated biochar application amount and the optimal pyrolysis temperature under the realistic condition. Accumulated biochar application amount in 30 years (a). Optimal pyrolysis temperature (b). The realistic condition considered straw resource constraint in each province used to produce biochar

(Fig. 6b, c). By contrast, Henan ranked lower, as wheat, used as the feedstock for biochar production, exhibited a lower mitigation potential compared to rice straw-derived biochar. In terms of cumulative N<sub>2</sub>O emission reductions, 30 years of biochar application was estimated to reduce

N<sub>2</sub>O emissions from croplands in China by 5.46 Tg N (~0.18 Tg N year<sup>-1</sup>) (Fig. 6d).

Over a 30-year period, cumulative biochar application rates among provinces ranged from 3.19 to 50.60 t/ha, with the highest rate observed in Jiangxi (Fig. 7a). In terms of

optimal pyrolysis temperature, most croplands in East and Central China showed a preference for biochar produced at higher temperatures, while those in North and North-east China favored biochar produced at relatively lower temperatures (Fig. 7b). This regional variation was primarily attributed to the dominance of rice straw as a feedstock in East, Central, South, and Southwest China, where high-temperature pyrolysis was estimated to maximize biochar's N<sub>2</sub>O mitigation potential. By contrast, wheat and maize straws, which are the predominant biochar feedstocks in other regions of China, were found to achieve optimal N<sub>2</sub>O mitigation potential when pyrolyzed at lower temperatures.

## 4 Discussion

### 4.1 Uncertainty in identifying key drivers and underlying mechanisms

Biochar can influence N<sub>2</sub>O emissions from agricultural soils by affecting both nitrification and denitrification processes (Parasar and Agarwala 2025; Liu et al. 2023b). Previous studies have shown that the primary mechanisms underlying its N<sub>2</sub>O mitigation potential involve the increase of soil pH, which promotes the abundance of *nosZ* genes and enhances denitrification enzyme activity (Cayuela et al. 2024). Our findings further support this mechanism, revealing that biochar with a higher pH is associated with a greater potential to mitigate N<sub>2</sub>O emissions. However, some studies have reported that biochar addition may increase soil permeability and oxygen content, thereby stimulating nitrification and potentially leading to elevated N<sub>2</sub>O emissions (Zhong et al. 2025). Moreover, we found that higher pyrolysis temperatures were generally associated with greater N<sub>2</sub>O mitigation potential across most regions in China, likely due to the resulting increase in biochar pH. Conversely, a recent meta-analysis suggested that low-temperature pyrolysis favors the formation of oxygen-containing functional groups, which may play a more critical role in reducing N<sub>2</sub>O emissions (Zhong et al. 2025). These conflicting findings highlight the complexity of the interactions among biochar properties, soil characteristics, and ambient environment. Therefore, further research is needed to elucidate the underlying mechanisms governing the N<sub>2</sub>O mitigation effects of biochar under varying environmental and management conditions.

Moreover, although the importance analysis identified nine factors as the primary drivers influencing the N<sub>2</sub>O mitigation potential of straw-derived biochar (Table S1), other variables—such as the specific cropping systems in which biochar is applied—may also exert substantial influence. The relatively limited sample size, especially when compared with meta-analyses in other research domains, may obscure the effects of these additional factors. Therefore, as more data become available in the

future, the set of key drivers may be revised, and more robust and generalizable conclusions can be drawn.

### 4.2 Mismatch between mitigation ratio and amount

We observed a mismatch between the N<sub>2</sub>O mitigation ratio and mitigation amount following biochar application, with regions exhibiting high N<sub>2</sub>O mitigation ratios not always having correspondingly high emission reductions. This mismatch is due to the asymmetry in spatial patterns between N<sub>2</sub>O emissions and biochar's mitigation capacity. For example, while Shanghai, Beijing, Tianjin, and Qinghai provinces showed high mitigation potential, their relatively low N<sub>2</sub>O emissions resulted in small emission reductions. Overall, Central and East China demonstrated both high N<sub>2</sub>O mitigation ratios and substantial emission reductions, making these regions—particularly Henan and Jiangsu provinces—ideal candidates for pilot biochar application projects.

Background N<sub>2</sub>O emissions are primarily driven by N fertilizer application rates, with higher inputs generally resulting in increased emissions. By contrast, the N<sub>2</sub>O mitigation effect of biochar is influenced not only by N fertilizer application rate, but also by its physicochemical properties and the prevailing soil conditions. For example, acidic soils with moderate N inputs may exhibit a disproportionately high response to biochar due to improvements in pH and denitrification completeness, even if their baseline emissions are modest.

### 4.3 Effect of biochar application on crop yield

Following the biomass yield response formula proposed by Woolf et al. (Woolf et al. 2010), our recommended optimal biochar application rates are unlikely to reduce crop yield. Instead, under the optimal biochar application scenario, national average crop yields were estimated to increase by 59%, 82%, and 82% for rice-, wheat-, and maize-straw-derived biochar, respectively (Supplementary Discussion c). Therefore, if the role of biochar in improving crop yield is considered, even more N<sub>2</sub>O emission reduction may be achieved by substituting biochar for the excessive N fertilizer inputs. Our results also suggest that reducing N fertilizer inputs could lower the biochar application rate needed to achieve its maximum N<sub>2</sub>O mitigation potential.

### 4.4 Limitations and future outlook

Although this study revealed the key drivers and underlying mechanisms influencing the N<sub>2</sub>O mitigation potential of straw-derived biochar, as well as the optimal application strategies to maximize its effectiveness, uncertainties and complexities still remain. First, our study focused solely on N<sub>2</sub>O emissions, excluding other

GHGs such as carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>). As a result, the estimated optimal biochar application strategy may not maximize reductions in CO<sub>2</sub> and CH<sub>4</sub> emissions. Further research is needed to develop biochar application strategies that consider its mitigation potential across all major GHGs. Second, the potential impact of biochar aging on its mitigation capacity was not accounted for Mašek et al. (2013), attributed to a lack of comprehensive understanding of how aging affects biochar's N<sub>2</sub>O mitigation potential. This knowledge gap adds complexity and may lead to an overestimation of biochar's long-term effectiveness in reducing N<sub>2</sub>O emissions.

## 5 Conclusions

In this study, we conducted the first national scale assessment of straw-derived biochar's optimal application strategies to maximize its mitigation potential for N<sub>2</sub>O from agricultural soils in China at a spatial resolution of 0.05°, under both ideal and realistic conditions. The key drivers and mechanisms influencing biochar's optimal application strategies and associated N<sub>2</sub>O mitigation potential were revealed. We found that different application strategies of biochar can result in significant variations in its mitigation potential, particularly for rice-straw-derived biochar. N fertilizer application rate and SOC content dominated biochar's optimal application rate selection, while water input was the most significant factor determining biochar's optimal pyrolysis temperature. By applying the optimal application strategy of biochar, nationwide N<sub>2</sub>O emission reductions were estimated to offset approximately 50% and 36% of N<sub>2</sub>O emissions in China's croplands under the ideal and realistic conditions, respectively. Stakeholders and policymakers can utilize our results to achieve a more efficient application strategy to maximize the N<sub>2</sub>O mitigation potential of straw-derived biochar in China. The method proposed in our study can be used in other countries or even at a global scale to further investigate biochar's maximum N<sub>2</sub>O mitigation potential in global croplands and its contribution to the achievement of climate targets.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s42773-025-00544-1>.

Additional file 1.

## Acknowledgements

The computation is completed in the HPC Platform of Huazhong University of Science and Technology.

## Author contributions

Qingrui Wang, Qing Yang, and Ondřej Mašek designed the study. Qingrui Wang, Dunxue Yao, Xinyi Tang, Danchen Zhu, Yunqi Sun, and Han Zhang collected the data. Qingrui Wang, Dunxue Yao, Xinyi Tang, Haiping Yang, and Hanping Chen performed data analysis and wrote the manuscript with substantial contributions from all co-authors.

## Funding

This work was financially supported by the National Natural Science Foundation of China (grant no. 42201315 and 52076099), China Postdoctoral Science Foundation (grant no. 2023M731191), Hubei Natural Science Foundation Joint Fund Project of China (grant no. 2023AFD191), the Fundamental Research Funds for the Central Universities (HUST: YCJJ20230105), and the China Huaneng Group Science and Technology Research Project (grant no. HNKJ22-H137).

## Availability of data and materials

The soil property dataset HWSO v2.0 used in this study can be obtained at <https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v20/en>. The precipitation and temperature data used in this study are available at <https://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49>. The N fertilizer application rate data can be obtained at <https://doi.org/10.6084/m9.figshare.21371469.v1>. The irrigation water use data are available at <https://cstr.cn/18406.11.Hydro.tpdc.271220>. The compiled Meta-analysis data, biochar's N<sub>2</sub>O mitigation potential data under different scenarios and the relevant data are available from the corresponding author on reasonable request.

## Declarations

### Competing interests

Haiping Yang and Ondřej Mašek are EBMs of the journal *Biochar*, and they were not involved in the peer review or handling of the manuscript. The authors declare no competing interests.

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Received: 8 March 2025 Revised: 26 October 2025 Accepted: 29 October 2025

Published online: 03 January 2026

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