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Review

Meta-Analysis for Quantifying Carbon Sequestration and Greenhouse Gas Emission in Paddy Soils One Year after Biochar Application

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Abstract: The incorporation of biochar into soils has been recognized as a promising method to combat climate change. However, the full carbon reduction potential of biochar in paddy soils is still unclear. To give an overview of the quantified carbon reduction, a meta-analysis model of different carbon emission factors was established, and the life cycle-based carbon reduction of biochar was estimated. After one year of incorporation, biochar significantly increased the total soil carbon (by 27.2%) and rice production (by 11.3%); stimulated methane (CH_4) and carbon dioxide (CO_2) emissions by 13.6% and 1.41%, respectively, but having insignificant differences with no biochar amendment; and reduced nitrous oxide (N_2O) emissions by 25.1%. The soil total carbon increase was mainly related to the biochar rate, whereas CH_4 emissions were related to the nitrogen fertilizer application rate. Biochar pyrolysis temperature, soil type, and climate were the main factors to influence the rice yield. The total carbon reduction potential of biochar incorporation in Chinese paddy soils in 2020 ranged from 0.0066 to 2.0 Pg C using a biochar incorporation rate from 2 to 40 t ha^{-1}. This study suggests that biochar application has high potential to reduce carbon emissions, thereby contributing to the carbon neutrality goal, but needs field-scale long-term trials to validate the predictions.

Keywords: carbon reduction; soil organic carbon; carbon emission; climate change

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1. Introduction

To combat climate change, reaching carbon neutrality at an early date is the goal of the whole world. Different countries have worked together to curb the global temperature increase to less than 1.5 °C above the pre-industrial era in the Paris Agreement in 2015 [1]. China has accordingly set a 2060 carbon neutrality goal [2]. To achieve the goal, carbon dioxide (CO_2) would be the first target greenhouse gas (GHG) to be removed from the atmosphere and likely to be stored in the soil and ocean. Furthermore, non-CO_2 GHG reduction (e.g., methane (CH_4) and nitrous oxide (N_2O) have 86 and 300 times more global warming potential (GWP20) than CO_2, respectively) is important for reaching carbon neutrality [3]. Hence, the reduction and storage of CO_2, combined with CH_4 and N_2O mitigation are matters of great scientific interest worldwide. Accordingly, a number of negative carbon emission technologies (NCETs) have been conceived, including direct air capture, bioenergy with carbon capture and storage, afforestation, enhanced rock weathering, biomass pyrolysis (biochar production), and soil carbon sequestration [4].

Rice is the main staple food in China and several other Asian countries. In China alone, the rice planting area covered more than 30 million ha in 2020, according to FAOSTAT [5]. However, paddy (rice) soil is an important source of GHG emissions [6–8]. Paddy soils could contain a vast carbon stock, but also emit a significant amount of GHGs during rice growth stages if not properly managed [9]. Of the many NCETs, biochar incorporation into paddy soils has become increasingly popular for both soil carbon sequestration and GHGs reduction [10–15]. Biochar is a black carbon-rich product obtained by biomass pyrolysis under limited (or no) oxygen conditions [16]. Biochar is a stable recalcitrant C source and is difficult for soil microorganisms to degrade, owing to the material's aromatic carbon structure [17]. Furthermore, biochar application has been shown to improve soil fertility and quality by increasing the nutrient supply to plants, neutralizing the soil reaction, enhancing microbiological activities, and improving soil structure and water retention ability [18], which consequently helps fix carbon from the atmosphere through the increased rate of photosynthesis and biomass production. If incorporated into paddy soils, biochar itself could lock up almost 40% of the carbon produced via photosynthesis [17,19], which would otherwise return to the atmosphere in the absence of biochar incorporation.

Biochar incorporation into paddy soils also holds great potential for CH_4 and N_2O mitigation. Nan et al. [20,21] reported that biochar incorporation both at low (2.8 t ha^{-1}) and high (22.5 t ha^{-1}) application rates significantly reduced CH_4 emissions from paddy soils, owing to biochar's positive effect on CH_4 oxidation capacity. A prominent N_2O mitigation effect was also achieved with biochar application due to biochar's ability to raise soil pH and lower the available dissolved organic nitrogen content in the soil [22,23]. Since biochar can benefit rice yield promotion [20,21], soil carbon sequestration, and GHG mitigation [24,25], it becomes an ideal material to achieve carbon neutrality in paddy cultivation systems. On the contrary, some reports suggested that biochar incorporation into paddy soils could increase CH_4 and N_2O emissions [26–29], which were attributed mainly to the biochar-induced redox conditions. The variation in GHG mitigation outcomes of biochar might result from various soil types, climatic conditions, farm management practices, and water management in paddy cultivation, as well as biochar feedstocks, preparation conditions, and incorporation rates. Such complexity creates difficulty in estimating the real carbon reduction potential of biochar under a paddy cultivation system.

The Intergovernmental Panel on Climate Change (IPCC) [19] suggested a standard method to evaluate the carbon stock in paddy soils and to calculate the newly added carbon stock via biochar amendment [19]. However, the carbon reduction calculations were based on a global scale, making it difficult to distinguish biochar's real potential for carbon reduction in paddy soils in different regions and countries. Although a standard method was suggested by IPCC, it also highlighted that a country-specific method for soil organic carbon stock calculation in tier 3 would be more desirable [19]. It is still hard to identify key factors for optimizing the carbon reduction potential in paddy soils with biochar amendment, warranting the development of specific and practical models to estimate biochar's carbon reduction potential.

Meta-analysis could be an effective way to evaluate the overall biochar effects on GHG reduction and rice production enhancement and to unravel the key factors contributing to biochar-induced benefits in climate change mitigation. Through meta-analysis, the relevant effects of biochar on GHG mitigation and rice production could be quantified in a comparative manner using statistical methods. Furthermore, heterogeneity exploration could unravel key factors that would influence biochar's effect on GHG reduction, rice yield increment, and soil carbon sequestration. However, to comprehensively understand biochar's practical potential for carbon emission reduction, a method for carbon emission calculation from 'cradle to grave' based on the whole life cycle analysis (LCA) is needed [30].To date, no report is available for the estimation of biochar performance concerning carbon reduction from Chinese paddy soils via a whole life cycle assessment of biochar using meta-analysis.

This research aims to establish a model to estimate carbon reduction potential under different biochar amendment scenarios using a whole life cycle analysis of biochar. To make a specific and practical estimation of the carbon reduction potential of biochar, field experimental data reporting soil total carbon (TC) increase, rice yield promotion, and GHG emissions were collected, and a meta-analysis was conducted. The default value of carbon emission factors and correction coefficients of management practices were utilized in the adapted method. The model would make carbon reduction potential estimation more realistic and less laborious than the existing models, especially under paddy soil conditions.

2. Materials and Methods

2.1. Data Collection and Meta-Analysis

For the meta-analysis, a literature search was performed using Web of Science with the search terms 'biochar' AND 'paddy' AND 'rice production' OR 'GHGs emission', retrieving 53 research articles published before 1 November 2021. Only studies conducted at field scale were retained to reflect a more realistic effect of biochar in soil than lab-based studies. For studies continuing over multiple years, only the relevant data reported in the first year of the study were adopted to infer the pristine biochar's effect on carbon reduction. After filtering the data mentioned above, 15 studies and 68 data points were available for the Supplementary Materials Table S1. Details about soil TC, rice yield, and GHG emissions were collected from these field studies. Environmental factors such as water management (e.g., continuous flooding and intermittent irrigation), climate, biochar incorporation rate, and fertilizer input were also recorded.

The natural log-transformed [31] ratio of the treatment and control values was used as the effect size (odds ratio) [32] by using the R software package (The R Project for Statistical Computing). A random-effects model was used to calculate the odds ratio. Before the meta-analysis, bias correction and normalization were performed to ensure the unbiased database. The effect size of biochar input on soil TC, rice yield, and GHG emissions was first evaluated as a basic quantified impact (categorical moderator ratio). Heterogeneity was calculated to find the key factors that would influence biochar-induced effect size on soil TC, rice yield, and GHG emissions. Categorical moderator variables were included in the model to explore the specific treatments that would lead to the heterogeneity and effect size ratio. As the biochar incorporation rate can be a continuous variable, the predication function in the metafor package was also used to calculate the effect size of the biochar incorporation rate on soil TC increase. The effect size of a specific treatment was used to calculate the correction coefficient based on the categorical moderator ratio of the specific treatment-induced heterogeneity. The function of correction coefficients was used to adjust the categorical moderator ratio to the effect size of the specific treatment that induced heterogeneity, making the evaluation of specific treatments more precise and accurate. Default values of the carbon emission factors (i.e., soil TC, rice yield and GHG emission) were calculated based on the average value, standard error, and sample quantity. The default values were classified by the categorical moderator variables which induced the heterogeneity most significantly. The default value and effect size ratio were then used for the carbon emission calculation.

2.2. Carbon Emission Calculation

The difference in carbon dynamics between paddy soils with and without biochar incorporation was calculated by considering five aspects: (1) increased carbon stock by rice yield increment (ΔC_{Yield}), (2) soil total carbon increase (ΔC_{soil}), (3) GHG mitigation after biochar incorporation (ΔC_{GHGs}), (4) GHG emission offset due to the avoided fossil fuel with biochar incorporation (C_{offset}), and (5) carbon emissions during the biochar production process ($C_{production}$). Carbon emissions from paddy soils following biochar amendment were calculated using Equation (1).

$$\Delta C_{paddy} = \Delta C_{Yield} + \Delta C_{soil} + \Delta C_{GHGs} + C_{offset} - C_{production} \quad (1)$$

where ΔC_{paddy} is the net carbon reduction amount (kg) during the rice growth cycle with biochar amendment, ΔC_{Yield} is the increased carbon (kg) through augmented rice yield with biochar amendment, ΔC_{GHGs} is the direct reduced CO_2 equivalent GHG carbon emissions with biochar amendment (kg), C_{offset} is the indirect carbon emission offset (kg) by renewable energy during biochar production process, and $C_{production}$ is off-farm carbon emissions (kg) during the biochar production process.

It has been acknowledged internationally that biochar incorporation into paddy soils benefits rice yield increase [20,21]. Hence, the increased carbon content by an augmented rice yield would be part of the carbon sequestration with biochar application, as ΔC_{Yield} in Equation (1). Accompanied by a rice yield increase, the rice straw biomass will also increase. In the current study, biochar incorporation was considered only in the first year, and treatments without both rice straw and biochar incorporation were considered as the control scenarios. According to IPCC-2019 [15], the carbon content from the increased rice straw biomass would be returned to the atmosphere in the short term (less than 1 year) and will not contribute to the net carbon reduction. The ΔC_{Yield} was estimated using Equation (2).

$$\Delta C_{Yield} = A_{harvest} * \Delta Y_{rice} * C_{rice} \tag{2}$$

where ΔC_{Yield} is the increased carbon (kg) through the augmented rice yield with biochar amendment, $A_{harvest}$ is the harvest area of a paddy (ha), ΔY_{rice} is the rice yield difference (dry biomass) between biochar and control scenarios (kg ha^{-1}), and C_{rice} is the carbon content of rice grain, the default being 0.4 kg kg^{-1} [19].

Biochar incorporation exerts a complex influence on the soil carbon cycle, including soil organic carbon increase brought by biochar carbon and negative priming effect [33]. Biochar carbon content could also experience a reduction due to the liable carbon mineralization [17]. Meanwhile, soil native carbon would be increased or decreased due to a negative or positive priming effect. Furthermore, the boosted root growth by nutrient supplements from biochar would also increase the soil organic carbon. Hence, the calculation of soil carbon change (ΔC_{soil}) from the total soil carbon difference after harvesting rice with or without biochar amendment would be a direct and accurate way. Hence, ΔC_{soil} was calculated according to Equation (3).

$$\Delta C_{soil} = (TC_{biochar} - TC_{ck}) * A_{harvest} \tag{3}$$

where ΔC_{soil} is the net soil TC (kg) with biochar incorporation into paddy soil, $TC_{biochar}$ is total carbon content (kg ha^{-1}) with biochar incorporation after rice was harvested, and TC_{ck} is total carbon content (kg ha^{-1}) in the control scenario after rice was harvested.

With the biochar incorporation scenario, three major GHGs were taken into consideration, i.e., CO_2, CH_4, and N_2O. The global warming potential of CH_4 and N_2O emissions were converted into CO_2-eq for a 20-year scenario (WGP20) by multiplying CH_4 by 86 and N_2O by 300. Changes in warming potential due to biochar addition were calculated as the difference from the control without biochar addition following Equation (4).

$$\Delta C_{GHGs} = (\Delta C_{CO_2} + 86 * \Delta C_{CH_4} + 300 * \Delta C_{N_2O}) * A_{harvest} * 12/44 \tag{4}$$

where ΔC_{GHGs} is the CO_2-eq carbon reduction (kg) with biochar incorporation during rice growth cycle, ΔC_{CO_2} is the carbon reduction (kg) from CO_2 mitigation with biochar incorporation, ΔC_{CH_4} is the carbon reduction (kg) from CH_4 mitigation with biochar incorporation, ΔC_{N_2O} is the carbon reduction (kg) from N_2O mitigation with biochar incorporation, and 12/44 is the molar fraction of carbon in CO_2.

During the pyrolysis of biomass (biochar production), biofuel is produced and connected to power generation equipment to generate electricity for operating the carbonization equipment. In this case, the generated electricity could be regarded as carbon offset emissions (C_{offset}). Biofuel in the biochar production process was calculated according to the report by Patrick [34] and the EBC method [35]. One ton of biochar could generate 682.2 L of biofuel (density of 1.2 g cm^{-3}). One kilogram of biofuel could produce

3.2 kg CO_2-eq. Accordingly, the production of 1 ton biochar would generate 669.8 kg C (i.e., 669.8 kg C t^{-1} biochar).

Carbon emissions during the biochar preparation process will offset part of its carbon sequestration effect. Carbon emissions during the biochar production process are mainly caused by equipment power consumption, liquefied petroleum gas combustion during equipment preheating, and pyrolytic gas incineration. Related gases including CO_2, CH_4, and N_2O are likely to be emitted during the process. Carbon emissions during the operation of biochar production equipment were calculated in accordance with the European Union's biochar standards [35]. During the production of each ton of biochar, the electricity consumption emits 45 kg CO_2-eq, the CH_4 content in the pyrolysis gas is 0.138 kg (11.9 kg CO_2-eq), and preheating the equipment produces 30 kg CO_2-eq t^{-1} biochar. In summary, the production of 1 t biochar would produce 86.9 kg of CO_2-eq or 23.7 kg of carbon ($C_{production}$ = 23.7 kg C t^{-1} BC).

2.3. Uncertainty Analysis

Sources of uncertainty in the adapted meta-analysis model include default values and unexplored environmental factors that could induce heterogeneity of carbon emission factors, correction coefficients of different carbon emission factors, and increased soil TC induced by different biochar incorporation rates. The error of different carbon emission factors is likely to propagate during the calculation of net carbon emission reduction.

3. Results

3.1. Impact of Biochar on Carbon Emission Factors

The categorical moderator ratios of different carbon emission factors with biochar incorporation into soil combined with confidence intervals and significance levels are shown in Figure 1. The categorical moderator ratio is expressed as the difference between the natural logarithm of the treatment group and the control group. The results showed that biochar incorporation increased soil carbon (27.2%), rice production (11.3%), CO_2 emissions (1.41%), and CH_4 emissions (13.6%), and reduced N_2O emissions from rice fields by 25.1%. The heterogeneity test showed that the various carbon emission factors with biochar amendment had a strong heterogeneity ($p < 0.0001$). Therefore, environmental factor variables and treatments were introduced to explain the heterogeneity of each carbon emission factor.

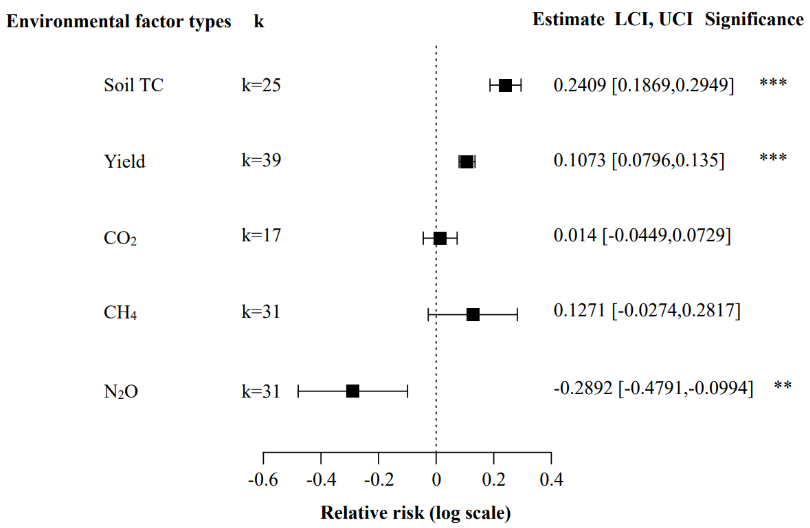

Figure 1. Analysis of the heterogeneity of carbon emission factors under the circumstances of applying biochar to paddy soils. Estimate stands for mean effect size; ** and *** indicate statistical significance levels at 0.01 and 0.001, respectively; k stands for number of samples; values in brackets mean LCI (the bottom of 95% confidence interval) and UCI (the ceiling of 95% confidence interval).

3.2. Heterogeneity Analysis for Rice Yield Variation

Environmental factors causing the heterogeneity in rice yield are shown in Table 1. The results showed that biochar pyrolysis temperature, soil type, climatic conditions, and water management methods were all important factors to cause the heterogeneity of rice yield ($p < 0.05$) after biochar amendment. The biochar incorporation rate and feedstock for biochar production had an insignificant ($p > 0.05$) impact on rice yield.

Table 1. Environmental factors affecting rice yield heterogeneity under biochar application scenarios.

Environmental Factor Types	QM	PQM	k
Biochar amount	3.2139	0.073	39
Biochar temperature	10.8249	**0.0286**	37
Biochar material	4.7397	0.0935	37
Soil type	47.8961	**<0.0001**	39
Climate	40.4763	**<0.0001**	37
Water management	7.1269	**0.0076**	35

Note: QM for heterogeneity of estimated moderator; PQM for significance test of QM; k for number of samples.

Further sub-group analysis of biochar and environmental factor types causing heterogeneity of rice yield was carried out to obtain the key factors causing heterogeneity under specific treatments. Heterogeneity analyses of the impact of water management conditions, climatic conditions, soil types, and biochar pyrolysis temperatures on rice yield are shown in Figure 2; the results show that rice yield was significantly increased when biochar was pyrolyzed at 300~350 °C (13.6%), 450 °C (11.3%), 500 °C (11.3%), and 600 °C (19.3%), respectively. In Hydragric Anthrosols, Chloridic Solonchaks, and Stagnic Anthrosols, rice yield was increased by 13.3%, 27.1%, and 8.95%, respectively, with biochar application. Intermittent water management and subtropical monsoon climate also significantly increased the rice yield by 8.49% and 12.4%, respectively.

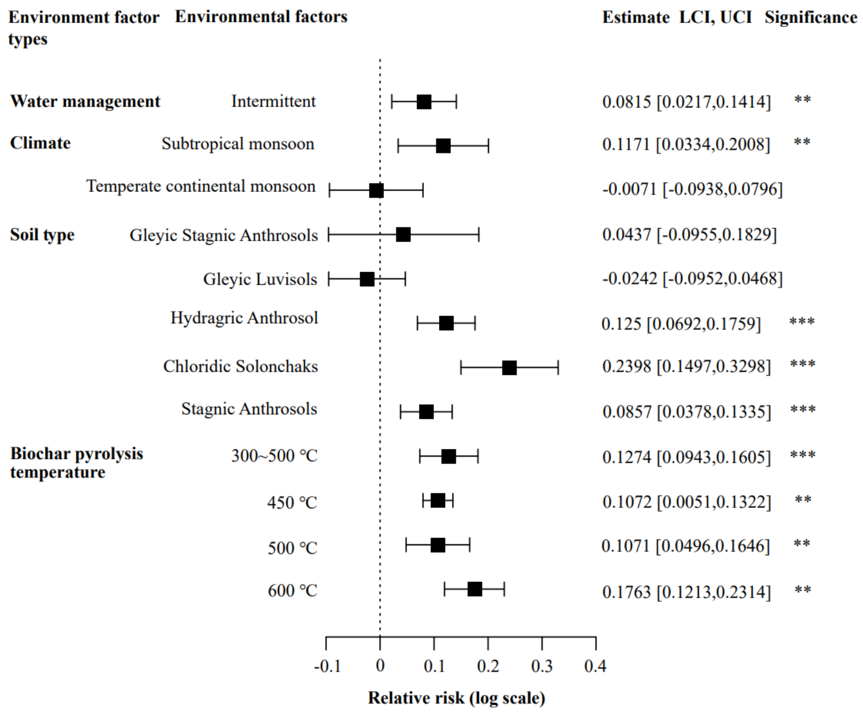

Figure 2. Estimated impact of key factors of heterogeneity on rice yield in biochar-amended soil. Estimate stands for mean effect size; ** and *** indicate statistical significance levels at 0.01 and 0.001, respectively, for the estimate; values in brackets mean LCI (the bottom of 95% confidence interval) and UCI (the ceiling of 95% confidence interval). Treatments explored but without appearance in this figure represent no effect size.

3.3. Heterogeneity Analysis of Soil Total Carbon Variation

Environmental factor types affecting the TC contents in paddy soils under biochar amendment are shown in Table 2. The results show that among the selected heterogeneity influencing factors, only the biochar incorporation rate caused a significant ($p < 0.05$) heterogeneity of the TC content in paddy soils. The feedstock for biochar production, biochar pyrolysis temperature, soil type, climate, and water management methods had no significant ($p > 0.05$) effect on soil TC. Furthermore, a predict function in the metafor package was used to predict soil TC increase when different biochar incorporation rates were used in paddy soils (Supplementary Materials Table S2).

Table 2. Factors affecting heterogeneity of soil TC in paddy soils amended with biochar.

Environmental Factor Types	QM	PQM	Significance	k
Biochar amount	16.1367	<0.0001	***	25
Raw material	4.41	0.1103		25
Biochar temperature	7.6371	0.1058		25
Soil type	7.4562	0.1889		25
Climate	0.6096	0.435		25
Water management	0.0048	0.9448		23

Note: QM for heterogeneity of estimated moderator; PQM for significance test of QM; *** indicates statistical significance levels at 0.001 for QM; k for number of samples.

3.4. Heterogeneity Analysis for CO_2 Emission

Biochar application showed no significant effect on soil CO_2 emissions (Table 3). It was found that climatic conditions rather significantly ($p < 0.05$) induced the heterogeneity of biochar performance on soil CO_2 emissions. Biochar incorporation increased CO_2 emissions significantly by 12.0% only in the temperate continental monsoon climate (Supplementary Materials Table S3).

Table 3. Factors affecting CO_2 emissions from paddy soils under biochar incorporation.

Environmental Factor Types	QM	PQM	k
Biochar amount	1.8279	0.1764	17
Raw material	5.379	0.0679	15
Soil type	4.0161	0.2597	17
Climate	3.997	**0.0456**	17
Water management	3.2422	0.0718	13

Note: QM for heterogeneity of estimated moderator; PQM for significance test of QM; k for number of samples.

3.5. Heterogeneity Analysis of CH_4 Emission

Based on the published data, biochar incorporation showed a 13.6% increase in CH_4 emissions, but with no significant difference with treatments without biochar application. However, heterogeneity analysis was still necessary to explore the key factors influencing paddy CH_4 emissions (Table 4). Among the selected factors of heterogeneity, N fertilizer was the main source of heterogeneity for CH_4 emissions from paddy soils ($p = 0.0212$). Although N fertilizer input at different levels was a key factor affecting CH_4 emissions, 210 kg ha^{-1} N fertilizer could significantly reduce CH_4 emissions from paddy soils. Except for 210 kg ha^{-1}, the effect size of other levels of N fertilizer caused a statistically insignificant reduction in CH_4 emissions (Supplementary Materials Figure S1). Therefore, in the subsequent calculation process, the effect value in Supplementary Materials Figure S1 was used for correction coefficient calculation with 210 kg ha^{-1} N fertilizer input. Other N fertilizer input levels were the overall effect size of CH_4 emissions under the biochar input scenario in Table 1. As a 13.6% increase in CH_4 emissions was not statistically significant, considering the 86-fold global warming potential of CH_4 on a 20-year scale, a subgroup analysis was also conducted to explore the key factors that contribute to CH_4 emissions. The analysis found that the phenomenon was mainly observed in Hydragric Anthrosols, with an N fertilizer level of 273 kg ha^{-1} and biochar prepared at 600 °C temperature (Supplementary Materials Figures S2 and S3).

Table 4. Factors affecting CH_4 emissions from paddy soils under biochar incorporation scenario.

Environmental Factor Types	QM	PQM	k
Biochar amount	0.1271	0.2817	31
Raw material	1.3656	0.5052	31
Soil type	7.3851	0.2867	31
Climate	3.1852	0.0743	31
Water management	0.3698	0.5431	25
N	18.0088	**0.0212**	31
P	12.3697	0.1355	31
K	12.7907	0.0774	31

Note: QM for heterogeneity of estimated moderator; PQM for significance test of QM; k for number of samples.

3.6. Heterogeneity Analysis of N_2O Emission

The effects of different environmental factor types on N_2O emissions in paddy soils after biochar application are shown in Table 5. The heterogeneity analysis showed that the inputs of phosphate (P) and potassium (K) fertilizer unexpectedly affected N_2O emissions from paddy soils (p <0.0001). P fertilizer application generally reduced N_2O emissions, while K fertilizer application generally promoted N_2O emissions from paddy soils. However, statistically, only 120 t ha^{-1} of P fertilizer input significantly reduced N_2O emissions by 55% (Supplementary Materials Figure S4), and 63.5, 120, and 204 t ha^{-1} of K fertilizer input significantly increased N_2O emissions by 121.9%, 224.6%, and 69.2%, respectively (Supplementary Materials Figure S5).

Table 5. Factors affecting N_2O emissions from paddy soils under biochar incorporation.

Environmental Factor Types	QM	PQM	k
Biochar amount	0.4801	0.4884	31
Raw material	5.0767	0.079	31
Climate	0.115	0.7346	31
Water management	0.8517	0.3561	25
N	2.3091	0.8892	31
P	33.027	< 0.0001	31
K	31.1186	< 0.0001	31

Note: QM for heterogeneity of estimated moderator; PQM for significance test of QM; k for number of samples.

3.7. Carbon Emission Correction Factors

Based on the above heterogeneity analysis outcomes, some heterogeneity-sensitive specific treatments were listed for categorical estimation in Table 6. The effect size of environmental factor types and specific treatments inducing the heterogeneity and categorial moderate coefficients were used to calculate the correction factors (Table 6). If no correction coefficient was needed, or in other words, if no heterogeneity was induced by a specific treatment, the correction coefficient was given as 1 [19].

Table 6. Environmental correction factors.

<table>
<tr><th>Items</th><th>Environmental Factor Types</th><th>Environmental Factors</th><th>Correction Coefficients</th></tr>
<tr><td rowspan="3">Yield</td><td>Water management</td><td>Intermittent</td><td>0.98</td></tr>
<tr><td rowspan="2">Climate</td><td>Subtropical monsoon</td><td>1.02</td></tr>
<tr><td>Temperate continental monsoon</td><td>1</td></tr>
</table>

Table 6. *Cont.*

Items	Environmental Factor Types	Environmental Factors	Correction Coefficients
	Soil type	Gleyic Stagnic Anthrosols	1
		Gleyic Luvisols	1
		Hydragric Anthrosols	1.02
		Chloridic Solonchaks	1.18
		Stagnic Anthrosols	0.98
	Biochar temperature (°C)	300~350	1.03
		450	1.01
		500	1.01
		600	1.09
CO_2	Climate	Temperate continental monsoon	1.09
CH_4	N (kg ha^{-1})	200	1
		210	0.42
		250	1
		270	1
		273	1
		292.8	1
		300	1
		456	1
N_2O	Soil type	Gleyic Stagnic Anthrosols	1
		Gleyic Luvisols	1
		Hydragric Anthrosols	1
		Chloridic Solonchaks	1
		Stagnic Anthrosols	1
	P (kg ha^{-1})	60	1
		90	1
		120	0.6
		125	1
		204	1
		875	1
	K (kg ha^{-1})	63.5	2.96
		120	4.33
		125	1
		202	1
		204	2.26

3.8. Calculation of Net Carbon Emissions from Biochar-Amended Paddy Soils

Variance and partial least square analyses were used to explore the key environmental variables that affected soil TC, rice yield, and GHG emissions, as impacted by Supplementary Materials Table S4. Then, the most significant difference induced by a specific environmental factor was selected to calculate the Supplementary Materials Table S5. The environmental variables that significantly affected the carbon emission factors are shown in Supplementary Materials Figure S1. The results showed that soil type was the main factor that induced most of the carbon emission factors impacted by biochar application (soil TC, rice yield, CH_4 and N_2O emissions). The climate was a key factor affecting CO_2 emissions from paddy soils. The default values of carbon emission factors are shown in Supplementary Materials Figure S2.

The calculation formulas for each carbon emission factor were updated in Equations (5)–(9), considering treatment-induced heterogeneity.

$$\Delta C_{Yield} = A_{harvest} * D_{rice} * (e^{MES} * F_{WM} * F_{ST} * F_C * F_{BT} - 1) * C_{rice} \quad (5)$$

where D_{rice} stands for default rice production under different scenarios, kg ha^{-1}. MES stands for log transformation for odds ratios. F_{WM}, F_{ST}, F_C, and F_{BT} stand for correction factors of water management, soil type, climate, and biochar pyrolysis temperature, respectively. C_{offset} = 132 kg C t^{-1} biochar. $C_{production}$ = 23.7 kg C t^{-1} biochar.

$$\Delta C_{GHGs} = (\Delta C_{CO_2} + 86 * \Delta C_{CH_4} + 300 * \Delta C_{N_2O}) * 12/44 \quad (6)$$

$$\Delta C_{CO_2} = A_{harvest} * D_{CO_2} * (e^{MES} * F_C - 1) * D \quad (7)$$

$$\Delta C_{CH_4} = A_{harvest} * D_{CH_4} * (e^{MES} * F_N - 1) * D \quad (8)$$

$$\Delta C_{N_2O} = A_{harvest} * D_{N_2O} * (e^{MES} * F_P * F_K - 1) * D \quad (9)$$

where D is the rice growth duration (days); the default of D is 112 days according to IPCC [19]. D_{CO_2}, D_{CH_4}, and D_{N_2O} stand for default CO_2, CH_4, and N_2O emissions under different scenarios, respectively, kg ha^{-1} d^{-1}. F_N, F_P, and F_K stand for correction factors of N fertilizer, P fertilizer, and K fertilizer, respectively.

The relative deviation from predicted and measured values for soil TC, rice yield, and GHG emissions was −3.7~52.5% (Figure 3). Obtaining an absolute rice harvest area was unrealistic according to the classification of environmental factor types (e.g., soil type, climate change, soil management, and biochar incorporation rate). Therefore, the potential of biochar for carbon reduction was calculated based on the whole life cycle (considering carbon emissions and byproduct offset during biochar production process) of biochar. As soil TC increase was significantly related to the biochar incorporation rate, carbon reduction potentials with a series of biochar carbon incorporation rates were calculated. The minimum carbon emission reduction potential with biochar incorporation rates of 2, 10, 20, 25, 30, and 40 t ha^{-1} ranged from 0.22 t C ha^{-1} to 30.51 t C ha^{-1}. The maximum carbon reduction potentials with biochar incorporation rates of 2, 10, 20, 25, 30, and 40 t ha^{-1} ranged from 16.92 t C ha^{-1} to 66.34 t C ha^{-1} (Figure 4). With higher biochar application rate, the carbon emission reduction effect would mainly come from biochar carbon storage in soil (Supplementary Materials Figures S6 and S7). The paddy harvest area in China was estimated to be 30.1 million ha in 2020, according to the National Bureau of Statistics of China [36]. Correspondingly, the total carbon reduction potential of biochar incorporation in Chinese paddy soilss ranged from 0.0066 to 2.0 Pg C with biochar incorporation rates from 2 to 40 t ha^{-1}.

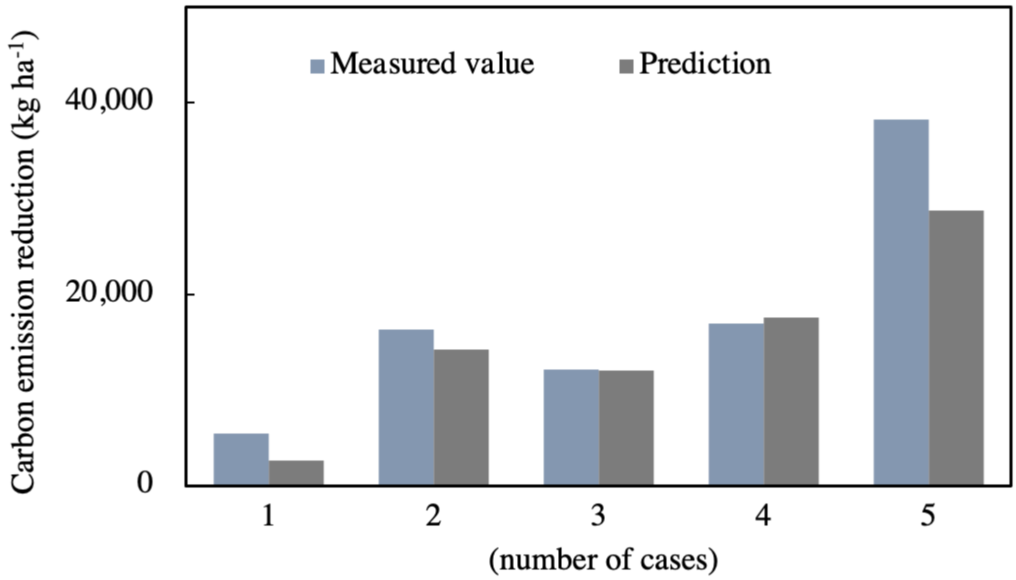

Figure 3. Measured and predicted values of carbon emission reduction from paddy soils under biochar incorporation.

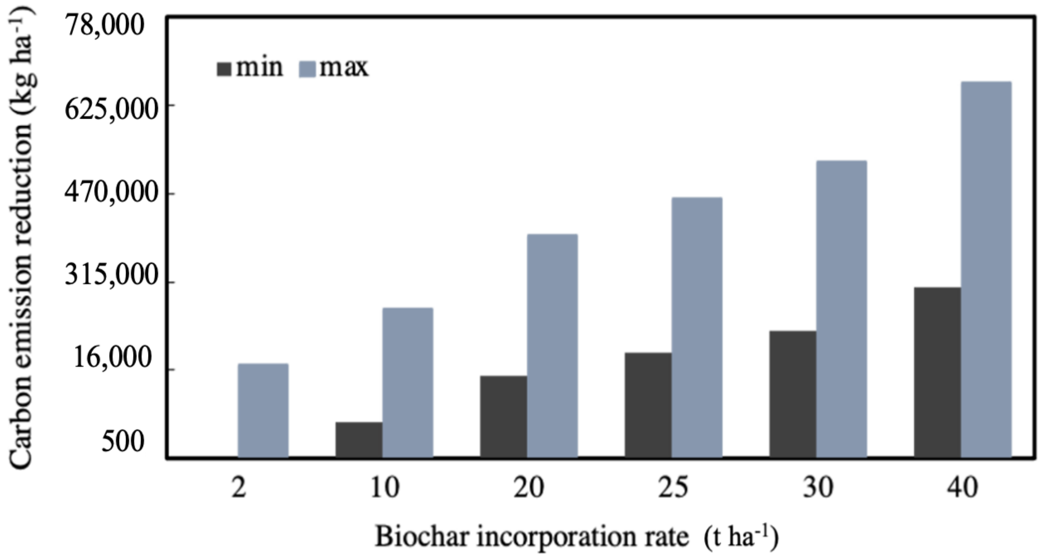

Figure 4. Carbon reduction potentials with biochar amendment in paddy soils.

4. Discussion

Biochar incorporation in paddy soils significantly increased soil TC by approximately 27.2%, being the main contributing factor to carbon emission reduction. The highly recalcitrant structure [20] makes it hard for soil microorganisms to metabolize biochar. According to Yi et al. [17], only 17% of the liable biochar carbon would be mineralized to CO_2 and released into the atmosphere after two years of biochar incorporation into the soil. In addition, biochar incorporation might increase the soil carbon content through a negative priming effect [37,38], owing to mineral organic protection. All these reasons make biochar a promising material for carbon sequestration in paddy fields. However, recent research found that biochar stability in paddy soils was much weaker than in environments with less human interference [17]. This phenomenon could be attributed to the oxygen secretion by rice roots, which would enhance the biochar oxidation rate, an effect similar to plowing [11]. This indicates that more research should be conducted to strengthen the understanding on biochar stability in the soil in order to maintain a suitable carbon sequestration performance.

The effect of biochar on rice yield was affected by several environmental factors. Biochar amendment significantly increased rice yield by 11.3%, which is close to 11.8% reported by Awad et al. [39]. Biochar pyrolysis temperature, soil type, climate, and water management induced the heterogeneity of rice yield as impacted by biochar application. Soil type and climatic variation had the greatest influence on rice yield. This was probably because different climatic conditions created different soil types, which led to different nutrient availabilities and root proliferation patterns [40], hence different rice yields. Notably, the biochar incorporation rate had no effect on rice yield increase, but the former was related to biochar pyrolysis temperature. These results suggest that even a small amount of biochar (i.e., 2 t ha^{-1}) could lead to an increase in rice yield. This result is consistent with the annual low-rate biochar incorporation concept (annual 2.8 t ha^{-1} biochar application) reported by Wu et al. [18,21]. The yield promotion effect of biochar prepared at 300~350 °C and 600 °C was better than that of biochar prepared at 500 °C. This is different from previous studies [41], and might be affected by climate and soil type variations. Therefore, the relationship between rice yield and biochar pyrolysis temperature under controlled environmental conditions warrants further investigations.

Biochar incorporation has almost no effect on soil CO_2 emissions based on the collected data. This phenomenon is reasonable in that biochar contains a small amount of labile carbon that could be mineralized to CO_2 within a relatively short period after soil incorporation. Nutrient elements carried with biochar would also increase the rate of microbial respiration for their growth [42], which could contribute to increased CO_2 emissions. Even carbon emission reduction in terms of CO_2 emissions was observed with biochar application; however, it should be noted that biochar incorporation would sequestrate a large amount of recalcitrant organic carbon in the soil and increase crop yield preserving more photosynthetic carbon. Furthermore, although the CO_2 emission increase was not significant in general with biochar application, CO_2 emissions would probably sustain a significant increase in a temperate continental monsoon climate.

Collected field data showed that biochar incorporation has no influence on CH_4 emissions in paddy soils due to the significant heterogeneity of different scenarios compared to treatments without biochar amendment. The heterogeneity test showed that the nitrogen application level was the key factor causing the difference in CH_4 emissions. Nitrogen plays an important role in CH_4 emissions, mainly because methanogens and methanotrophs require nitrogen to obtain energy [43]. On the other hand, different concentrations of various nitrogen forms (e.g., nitrate, ammonium) exerted different influences on CH_4 emissions [43–45]. A low concentration of ammonium nitrogen promoted CH_4 oxidation activity, whereas a high concentration of ammonium nitrogen would inhibit CH_4 oxidation due to a competitive mechanism [43–45]. Considering the small quantity of field data, the effect size evaluation under different N input levels was limited in this study. Nevertheless, to pursue a satisfactory CH_4 mitigation effect, N fertilizer type and application rate could be important breakthrough strategies.

Soil types and P and K fertilizers were the key factors affecting N_2O emissions from paddy soils. Soil type affecting N_2O emissions was a reasonable finding because varied pH values, nutrient status, and textures would influence N_2O emissions, and the K fertilizer application rate affected N utilization for the plant to grow, thus potentially changing the N_2O emission response to N fertilizer [14,46,47]. Neutral to slightly acidic soil pH favored N_2O emissions (Supplementary Materials Figure S10).Therefore, biochar might be more effective in mitigating N_2O emissions in acid soil. However, many studies reported that different nitrogen fertilizer types and application rates could affect N_2O emissions. The N fertilizer application rate could greatly affect nitrification and denitrification processes related to N_2O production. Yue et al. indicated that 100 kg N ha^{-1} incorporation gave minimum N_2O emissions of rice paddy in China [48]. However, in the present study, P and K fertilizers appeared to be the key factors that induced heterogeneity of N_2O emissions.

The effect of K fertilizer on GHG emissions was previously reported by Yang et al. [49]. The increase in N_2O emissions might have resulted from the fact that P and K fertilizer application rates affected N utilization for the plant to grow, and thus potentially changed the N_2O emission response to N fertilizer [50]. The relationship between N fertilizer and N_2O emissions could not be established in this study, likely due to the small size of available field data.

A large relative deviation (52.5%) of total carbon emissions in the form of soil TC, rice yield, and GHGs occurred when biochar performed low for carbon reduction. The significant difference between measured carbon reduction values and predicated values in case 1 (Figure 3) occurred due to the inaccuracy of CH_4 emission prediction. Therefore, a significant effect size ratio was not obtained. The model was more accurate in a high carbon reduction scenario. Xu et al. [51] reported a maximum of 12 t C reduction ha^{-1} when biochar was amended into paddy soil at a 20 t ha^{-1}, which had a 20% difference from the minimum carbon reduction (15 t C ha^{-1}) of the predicated one. These results are probably due to the soil carbon difference because they obtained soil SOC changes according to the 2006 IPCC guided method without considering biochar application. In this paper, a more practical soil TC change was used. Furthermore, it also should be noted that when calculating carbon reduction, GWP20 was used in this study rather GWP100 for CH_4 and N_2O calculations, which will also give a higher carbon reduction when CH_4 is reduced. However, greater carbon reduction with biochar addition into paddy soils should be recorded and calculated to enhance the carbon reduction model accuracy.

Biochar carbon storage and CH_4 mitigation contributed to the main reduction in carbon released into the atmosphere with biochar amendment in paddy soils. Biochar carbon storage increased with the biochar incorporation rate, while GHG mitigation and yield promotion were not related to the biochar incorporation rate. Generally, when the biochar incorporation rate was higher than 5 t ha^{-1}, biochar carbon storage would account for the entire carbon reduction performance (Supplementary Materials Figures S6 and S7). CH_4 mitigation performance was another important factor affecting the carbon reduction effect with biochar addition (Supplementary Materials Figures S8 and S9). Although CH_4 emissions were the second highest (CO_2 the highest and N_2O the lowest), the biggest carbon emission contribution difference in CH_4 emissions resulted from its 86-fold greater global warming potential than CO_2 on a 20-year scale. Moreover, although the GWP of N_2O is 300 times that of CO_2, the emission amount is lower compared with CO_2 and CH_4. Therefore, to obtain a more promising performance in carbon reduction by biochar application, efforts to reduce CH_4 emissions with biochar amendment are of great importance, as biochar carbon storage from recalcitrant composition is hard to increase but can be achieved by increasing the biochar incorporation rate. However, when considering economic feasibility, an optimum and practical biochar incorporation rate should be set to maximize carbon reduction potential.

5. Conclusions

A meta-analysis was conducted to calculate the carbon reduction potential of paddy soils with various biochar amendment scenarios one year after biochar application. The results showed that the effects of biochar on increasing the soil TC and rice yield and reducing GHG emissions were highly heterogenous. Soil type was the most influential environmental factor on the carbon emission factors. Rice yield increment was determined by multiple environmental factors such as soil type, climate, and biochar pyrolysis temperature. The N_2O emission reduction was related to phosphate and potassium fertilizer application rates. Although biochar application had no significant effect on paddy soil CO_2 emissions, climatic conditions did show a significant influence. The overall relative deviation of the predicted carbon reduction was −3.7~52.5% compared to the measured values. Only one-year carbon reduction performance under biochar amendment in paddy soils was considered in this study. The scarcity and inconsistency of long-term field experimental data make the long-term carbon reduction calculation with biochar application challenging. This should be further explored and calculated to give a clear understanding of the long-term carbon reduction potential of biochar when it is incorporated into paddy soils.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12123065/s1, Table S1: References for meta-analysis; Table S2: Prediction of soil total carbon content in paddy field with different biochar incorporation; Table S3: Effect size of CO_2 emission with biochar amendment strategy under temperate continental monsoon climate; Table S4: Key environmental factors affecting carbon emission; Table S5: Default value of carbon emission factors; Figure S1: Effect size of CH_4 emission with nitrogen fertilizer under biochar amendment strategy; Figure S2: Effect size of CH_4 stimulation with nitrogen fertilizer under biochar amendment strategy; Figure S3: CH_4 emission promotion factor exploration; Figure S4: Effect size of N_2O emission with phosphate fertilizer under biochar amendment strategy; Figure S5: Effect size of N_2O emission with potassium fertilizer under biochar amendment strategy; Figure S6: The minimal carbon potential with biochar incorporation into paddy soils; Figure S7: The maximal carbon potential with biochar incorporation into paddy soils; Figure S8: The minimal carbon reduction induced by rice yield promotion and carbon emission from GHGs with biochar incorporation in paddy field; Figure S9: The maximal carbon reduction induced by rice yield promotion and GHGs mitigation with biochar incorporation in paddy field; Figure S10: The relationship of soil background pH and N_2O difference with biochar amendment. Positive values represent for N_2O stimulation and negative values represent for N_2O reduction after biochar was incorporated.

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