Meta-Analysis for Quantifying Carbon Sequestration and Greenhouse Gas Emission in Biochar-Amended Paddy Soil after One-year of Application

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Abstract: Incorporation of biochar into soil has been recognized as a promising method to combat climate change. However, the full carbon reduction potential of biochar in paddy soil 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) emission respectively by 13.6 and 1.41% but having insignificant differences with no biochar amendment; and reduced nitrous oxide (N_2O) emission by 25.1%. Soil total carbon increase was mainly related to biochar rate, whereas CH_4 emission was related to 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 soil in 2020 ranged from 0.0066 to 2.0 Pg C within biochar incorporation rate from 2 to 40 t ha^{-1}. This study suggests that biochar application has a high potential to reduce carbon emissions 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

Supplementary information

Table S1. References for meta-analysis

Number	Main authours	Title	Journal	Year	References
1.	Shihong Yang, Ya'nan Xiao	Biochar improved rice yield and mitigated CH_4 and N_2O emissions from paddy field under controlled irrigation in the Taihu Lake Region of China	Atmospheric Environment	2019	[1]
2.	Afeng Zhang, Rongjun Bian	Enhanced rice production but greatly reduced carbon emission following biochar amendment in a metal-polluted rice paddy.	Environmental Science and Pollution Research	2015	[2]
3.	Jinyang Wang, Xiaojian Pan	Effects of biochar amendment in two soils on greenhouse gas emissions and crop production.	Plant and Soil	2012	[3]
4.	Yanghui Sui, Jiping Gao	Interactive effects of straw-derived biochar and N fertilization on soil C storage and rice productivity in rice paddies of Northeast China.	Science of the Total Environment	2016	[4]
5.	Yanan Xiao, Shihong Yang	Effect of Biochar Amendment on Methane Emissions from Paddy Field under Water-Saving Irrigation.	Sustainability	2018	[5]
6.	Liying Sun, Junyin Deng	Combined effects of nitrogen fertilizer and biochar on greenhouse gas emissions and net ecosystem economic budget from a coastal saline rice field in southeastern China.	Environmental Science and Pollution Research	2020	[6]
7.	Yuefeng Cui, Jun Meng	Effects of straw and biochar addition on soil nitrogen, carbon, and super rice yield in cold waterlogged paddy soils of North China.	Journal of Integrative Agriculture	2017	[7]
8.	Qiong Nan, Cheng Wang	Mitigating methane emission via annual biochar amendment pyrolyzed with rice straw from the same paddy field.	Science of the Total Environment	2020	[8]
9.	Shuwei Wang, Shutan Ma	A 2-year study on the effect of biochar on methane and nitrous oxide emissions in an intensive	Biochar	2019	[9]

		rice–wheat cropping system.			
10.	Jianlin Shen, Hong Tang	Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems.	Agriculture, Ecosystems & Environment	2014	[10]
11.	Afeng Zhang, Rongjun Bian	Change in net global warming potential of a rice–wheat cropping system with biochar soil amendment in a rice paddy from China.	Agriculture, Ecosystems and Environment	2013	[11]
12.	Afeng Zhang, Rongjun Bian	Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles.	Field Crops Research	2012	[12]
13.	Afeng Zhang, Liqiang Cui	Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain	Agriculture, Ecosystems and Environment	2010	[13]
14.	Zhen Wu, Xi Zhang	Biochar amendment reduced greenhouse gas intensities in the rice-wheat rotation system: six-year field observation and meta-analysis.	Agricultural and Forest Meteorology	2019	[14]
15.	Shihong Yang, Zewei Jiang	Effects of Biochar Amendment on CO_2 Emissions from Paddy Fields under Water-Saving Irrigation.	International Journal of Environmental Research and Public Health	2018	[15]

Table S2. Prediction of soil total carbon content in paddy field with different biochar incorporation rate

BC amount	LCI	UCI	Pred
1.78	1.0278	1.2019	1.1115
2	1.0299	1.2029	1.113
10	1.1057	1.2425	1.1721
14.8	1.1508	1.2702	1.209
20	1.1969	1.3061	1.2503
25	1.2362	1.349	1.2913
29.6	1.2674	1.3963	1.3303
40	1.3268	1.5257	1.4227

Note: LCI for bottom of 95% confidence interval; UCI for ceiling of 95% confidence interval; Pred stands for soil total carbon content ratio treatment group to control group. Same to the following tables

Table S3. Effect size of CO_2 emission with biochar amendment strategy under temperate continental monsoon climate

Climate	Estimate	Se	pval	LCI	UCI	Significance
Temperate continental monsoon climate	0.1129	0.0565	0.0456	0.0022	0.2236	*

Table S4. Key environmental factors affecting carbon emission

Items	Environment factor types	pval	Significance
Yield	soil	0.00747	**
	N	0.0478	*
CH_4	N	0.00414	**
	soil	<2e-16	***
N_2O	soil	3.58E-12	***
CO_2	soil	0.000211	***
	climate	8.31E-06	***

Table S5. Default value of carbon emission factors

Carbon emission items	Environment factors	Default	Se
Soil total carbon (g kg^{-1})	Stagnic Anthrosols	22.75	±3.74
	Hydragric Anthrosols	12.08	±0.164
	Chloridic Solonchaks	10.95	±1.45
	Gleyic Luvisols	12.49	±0.42
	Gleyic Stagnic Anthrosols	26.50	±0.9
	Eutric Cambisols	6.375	±0.9
Yield (t ha^{-1})	Ultisol	10.30	±0.23
	Stagnic Anthrosols	6.99	±2.89
	Chloridic Solonchaks	7.45	±1.89
	Hydragric Anthrosols	6.91	±1.54
	Gleyic Stagnic Anthrosols	10.22	±0.94
	Gleyic Luvisols	8.32	±0.13
	Eutric Cambisols	7.82	±1.79
CO_2 (kg ha^{-1} d^{-1})	Subtropical monsoon climate	11.31	±8.89
	Temperate continental monsoon climate	88.33	±32.06
CH_4 (kg ha^{-1} d^{-1})	Stagnic Anthrosols	0.32	±0.24
	Chloridic Solonchaks	1.25	±0.90
	Hydragric Anthrosols	0.72	±0.38
	Gleyic Stagnic Anthrosols	0.28	±0.035
	Gleyic Luvisols	3.32	±0.32
	Eutric Cambisols	0.34	±0.1052
N_2O (kg ha^{-1} d^{-1})	Gleyic Luvisols	0.0060	±0.0009
	Gleyic Stagnic Anthrosols	0.0014	±0.0002
	Hydragric Anthrosols	0.0203	±0.0257
	Chloridic Solonchaks	0.0032	±0.0021
	Stagnic Anthrosols	0.0086	±0.0086

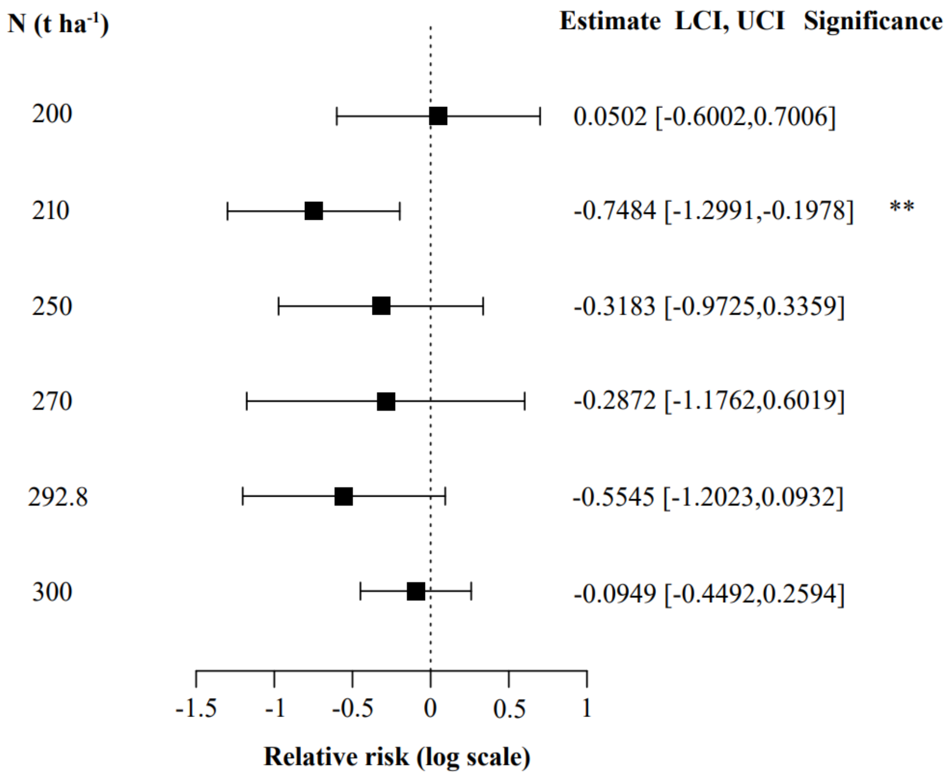

Figure S1. Effect size of CH_4 emission with nitrogen fertilizer under biochar amendment strategy

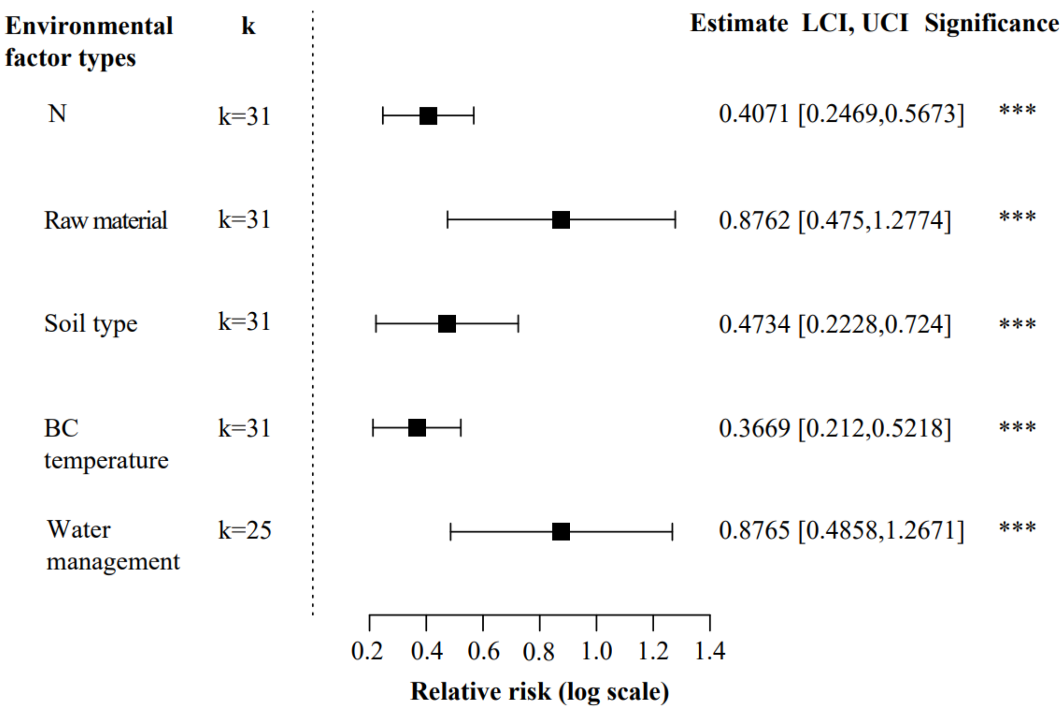

Figure S2. Effect size of CH_4 stimulation with nitrogen fertilizer under biochar amendment strategy

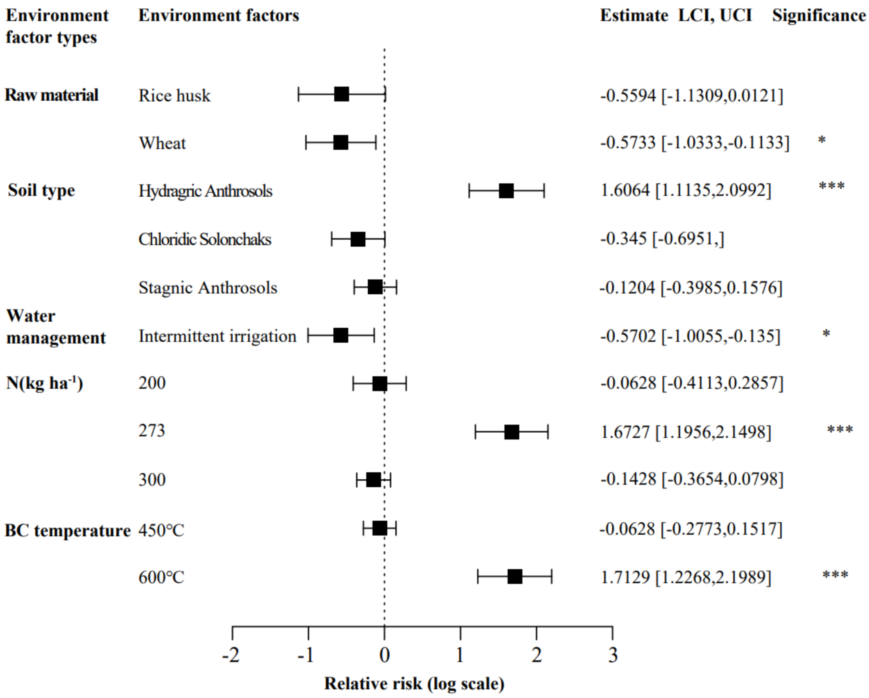

Figure S3. CH_4 emission promotion factor exploration

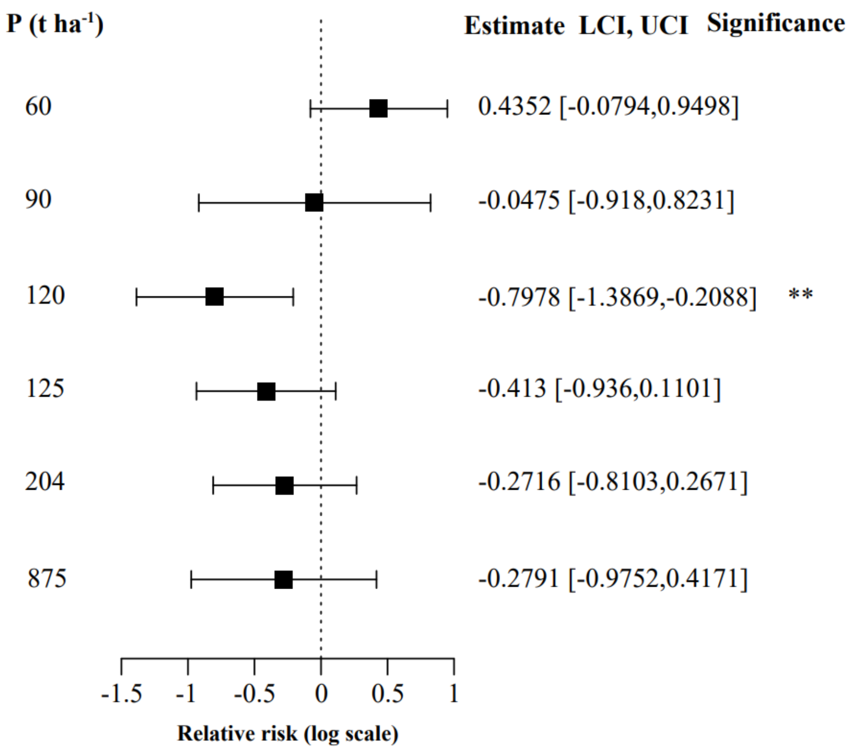

Figure S4. Effect size of N_2O emission with phosphate fertilizer under biochar amendment strategy

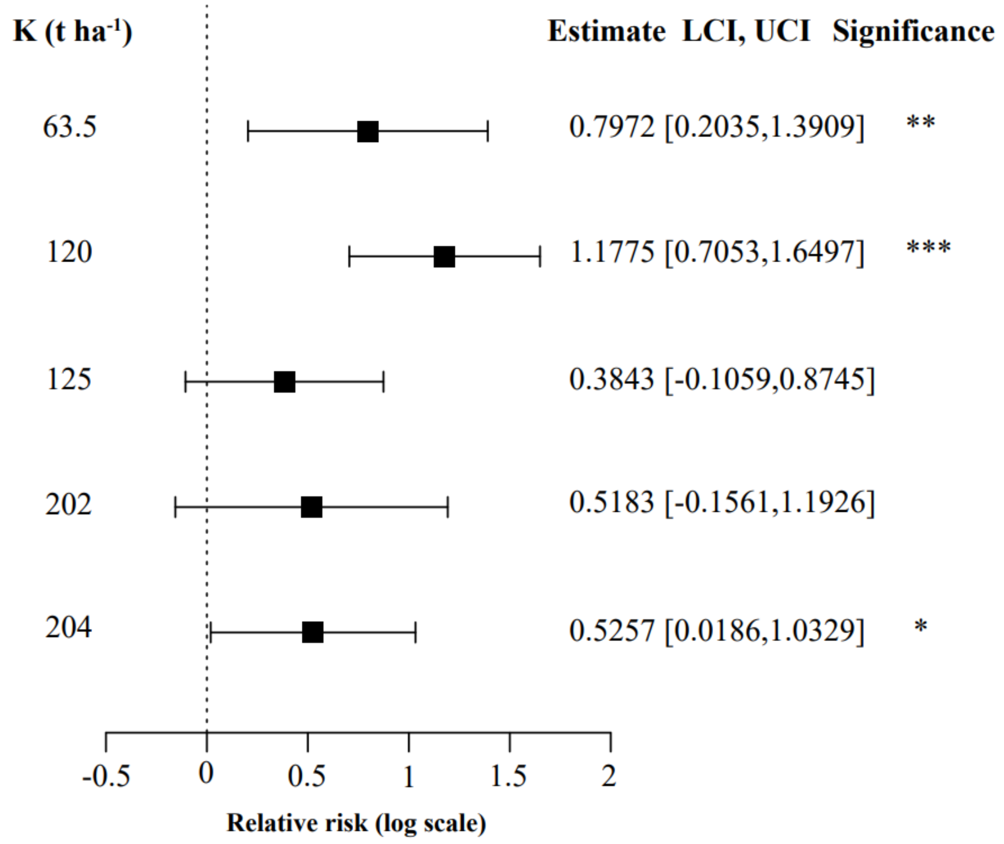

Figure S5. Effect size of N_2O emission with potassium fertilizer under biochar amendment strategy

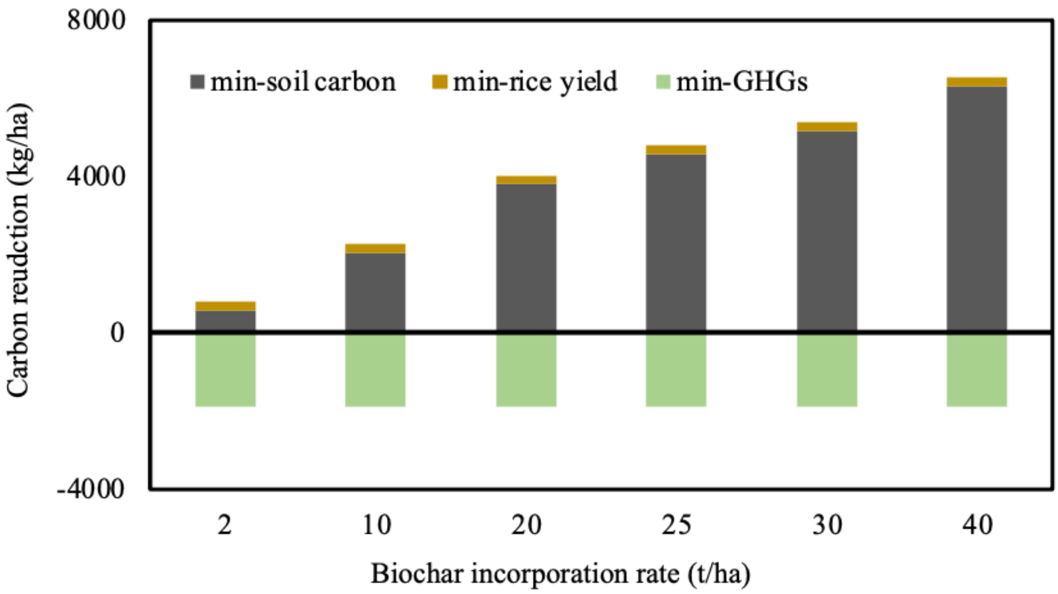

Figure S6. The minimal carbon potential with biochar incorporation into paddy soil

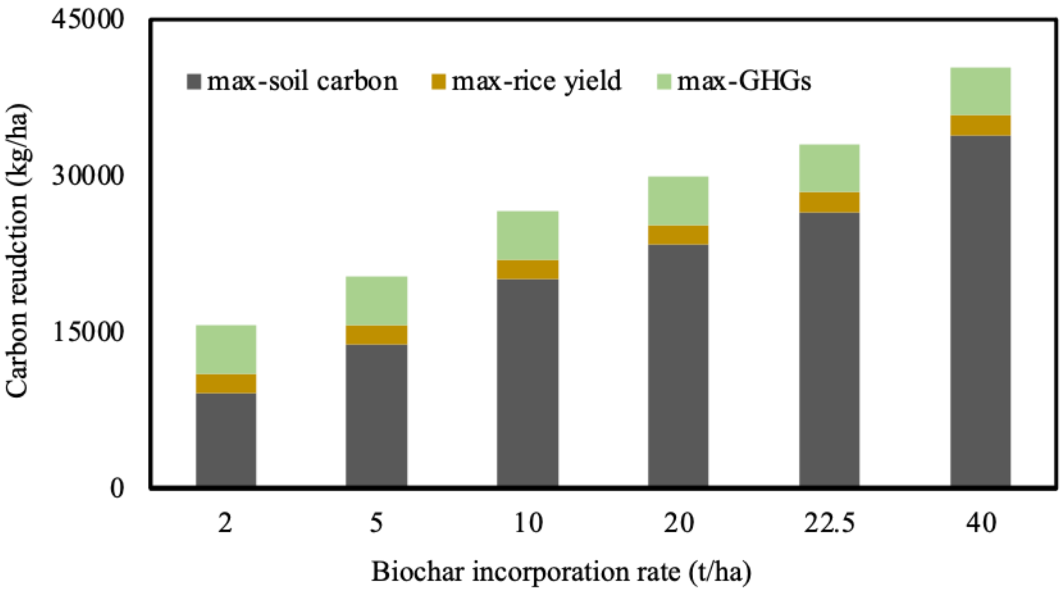

Figure S7. The maximal carbon potential with biochar incorporation into paddy soil

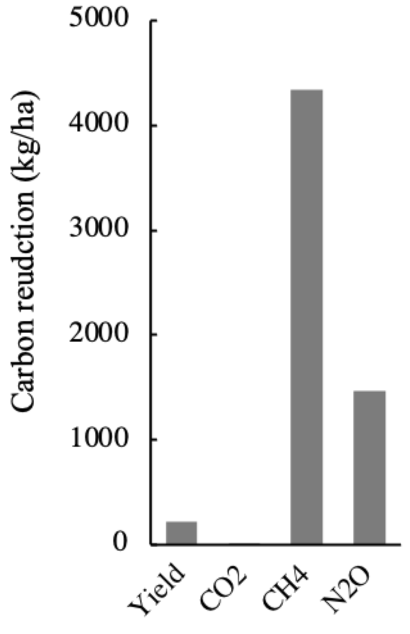

Figure S8. The minimal carbon reduction induced by rice yield promotion and carbon emission from GHGs with biochar incorporation in paddy field.

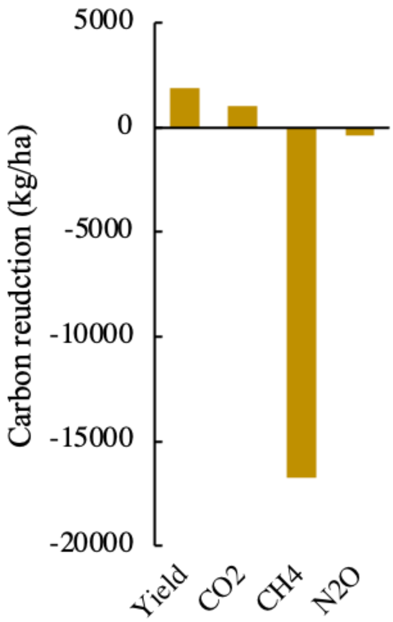

Figure S9. The maximal carbon reduction induced by rice yield promotion and GHGs mitigation with biochar incorporation in paddy field.

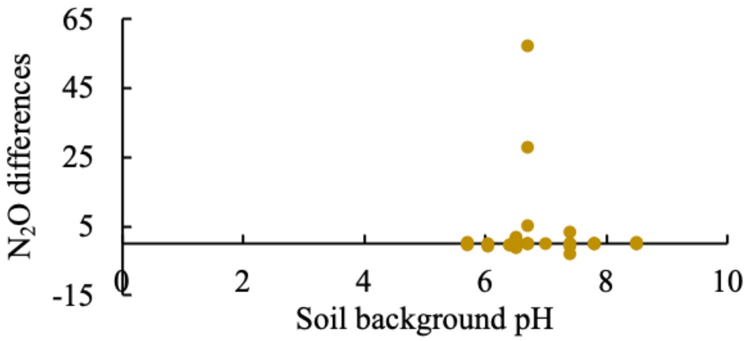

Figure S10. The relationship of soil background pH and N_2O difference with biochar amendment. Positive values represent for N_2O stimulation and negative values represent for N_2O reduction after biochar was incorporated.

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