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Integrated biochar solutions can achieve carbon-neutral staple crop production

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Supplementary Note 1: GHG emissions from staple food production in China in 2018 (BAU)

Life cycle assessment (LCA) was used to evaluate GHG emissions from different scenarios. (1) Goal and scope: LCA was used in this study to evaluate life-inventory GHG emissions (carbon footprint, CF) from staple food (rice, wheat and corn) production in China and how different mitigation measures can reduce the CFs and achieve carbon neutrality; (2) functional unit: we adopted an area-based functional unit in the LCA, i.e., how much GHG is emitted from production of staple food per hectare (kg CO_2-eq ha^{-1}) under BAU and the mitigation scenarios; (3) life-cycle inventory: GHG emissions from production of various agricultural inputs, crop field cultivation and straw biomass burning and straw pyrolysis were included in this study; (4) life-cycle impact assessment: we aimed to evaluate the global warming potentials (GWPs) associated with GHG emissions under BAU and how mitigation scenarios can reduce the GWPs and achieve carbon neutrality.

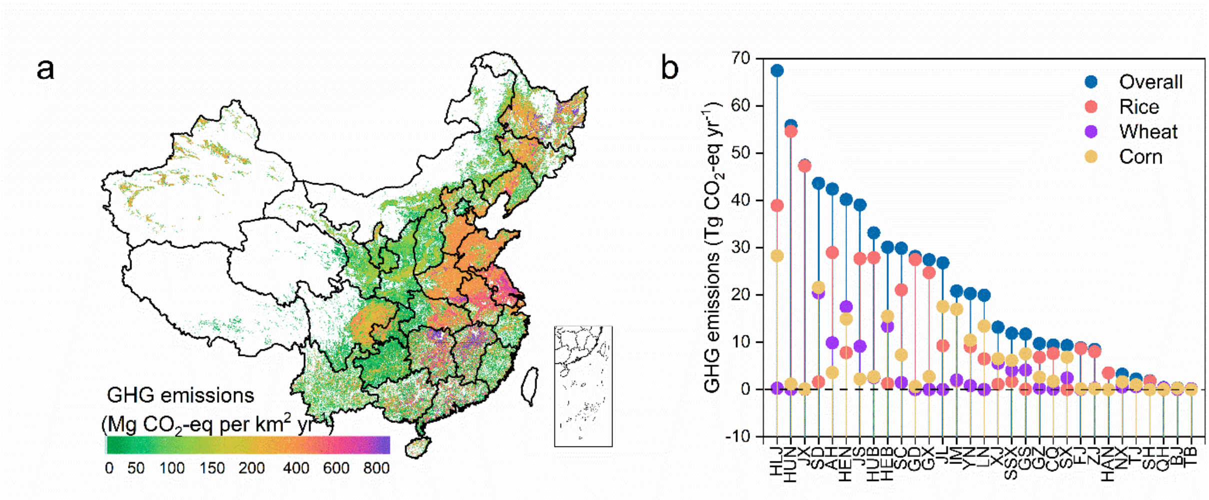
The system boundary of quantifying GHG emissions from life-cycle production of rice (*Oryza sativa*), wheat (*Triticum aestivum*) and corn (*Zea mays*) was set from production of agricultural inputs to harvesting of crop grains in BAU in 2018. Our assessment on quantification of GHG balance is on a territorial basis using the life-cycle perspective. The carbon (C) footprint (kg CO_2-eq ha^{-1}) was calculated using the following equation:

$$\text{Carbon footprint} = \sum_{i=1}^{m} AI_{CO_2} + \sum_{j=1}^{n} FO_{CO_2} + \sum_{g=1}^{k} BB_{CO_2}$$

where, AI_{CO_2} denotes GHG emissions associated with agricultural inputs (AI) production and transportation, including fertilizers, diesel oil, plastic film and pesticides. They were calculated by multiplying their application quantities by their individual GHG emission factors (Supplementary Table 1). We determined the synthetic and organic N application rates for each crop following the approach developed by Huang et al.[1] (Supplementary Table 2). We used production coefficients, i.e. the required amount of diesel oils or pesticides per units of crop grain, to estimate the average rate of diesel oils and pesticides for each staple crop[2]. FO_{CO_2} denotes the emissions from farm operation sector (FO), such as soil emissions of CH_4 and N_2O and soil organic carbon (SOC) stock change, and GHG emissions from irrigation activities. We used the Tier 1 method reported in the 2006 Intergovernmental Panel on Climate Change (IPCC) to estimate CH_4 emissions from paddy fields (Supplementary Table 3)[3]. For CH_4 emissions from wheat and corn cultivation, we assumed that 1 kg CH_4-C was absorbed per hectare per year[2]. The SOC change rates were extracted from Zhao et al.[4], which were evaluated through an extensive review of soil analyses that were related to SOC changes in the topsoil (0−20 cm) of cropland in China from 1980 to 2011 (Supplementary Table 4). We used the empirical models established by Chen et al.[5] based on the response of reactive N (Nr) losses to soil N surplus to evaluate N_2O emissions from field staple crop cultivation:

$$
N_2O \text{ emissions} = \begin{cases} 0.74\times\exp(0.011\times N_{surplus}) \text{ for rice cultivation } (p<0.01,\ R^2=0.46) \\ 0.54\times\exp(0.0063\times N_{surplus}) \text{ for wheat cultivation } (p<0.01,\ R^2=0.44) \\ 1.13\times\exp(0.0071\times N_{surplus}) \text{ for corn cultivation } (p<0.01,\ R^2=0.50) \end{cases}
$$

where $N_{surplus}$ denotes N surplus, defined as N application rate minus the amount of N taken up by aboveground crop biomass. The above-ground N uptake was calculated using the approach by Yan et al.[6]. The N_2O emissions induced by organic fertilizer (human and livestock manure) application were estimated by multiplying the application rate by the same emission factor (EF=1.0%)[2]. BB_{CO_2} denotes GHG (CH_4 and N_2O) emissions from domestic and open burning of crop straw biomass, which were estimated by multiplying the burning amounts by the GHG emission factors (Supplementary Tables 5 and 6). Previous study reported that, on average, approximately 44%, 18% and 38% of collected crop residues was retained in the field, used as feed for livestock and being burned, respectively, in China in 2018[7,8]. With improved economic situations and wide use of commercial energy in the countryside, crop straws (~2%) are rarely used as domestic fuels for cooking since 2010s. Moreover, burning straw for household energy has a very low energy conversion efficiency[7]. Therefore, the negligible household energy generated through domestic burning of crop straws was not considered in BAU. Staple straw biomass amount was extracted from previous studies[7,8]. See Supplementary Figure 1 for GHG emissions from staple food production in China in 2018.



Supplementary Figure 1. GHG emissions from staple food (rice, wheat and corn) production in China in 2018 (BAU scenario). HLJ, Heilongjiang; HUN, Hunan; JX, Jiangxi; AH, Anhui; JS, Jiangsu; SD, Shandong; HUB, Hubei; HEN, Henan; GD, Guangdong; GX, Guangxi; SC, Sichuan; HEB, Hebei; JL, Jilin; YN, Yunnan; LN, Liaoning; IM, Inner Mongolia; XJ, Xinjiang; SSX, Shaanxi; GS, Gansu; GZ, Guizhou; FJ, Fujian; CQ, Chongqing; ZJ, Zhejiang; SX, Shanxi; HAN, Hainan; NX, Ningxia; TJ, Tianjin; SH, Shanghai; QH, Qinghai; BJ, Beijing; TB, Tibet.

Supplementary Table 1 Emission factors of GHG and Nr from production and transportation of agricultural inputs

Agricultural inputs	Unit	GHGs emissions kg CO_2 eq unit^{-1} input	N_2O emissions g N unit^{-1} input	NO_X emissions g N unit^{-1} input	References
N fertilizer	kg N	8.3	0.09	13.47	9,10
P fertilizer	kg P_2O_5	1.5	0.013	2.16	9
K fertilizer	kg K_2O	0.98	0.017	2.9	9
Pesticides	kg	18	0.18	14.3	9
Electricity	kWh	0.95	0.0064	1.3	9
Diesel oil	kg	3.94	0.09	3.07	11,12
Organic fertilizer	kg N	11.3	0.11	8.96	11,12
Plastic film	kg	19	0.19	15.1	11,12

Supplementary Table 2 The synthetic N fertilizer and organic fertilizer (human and animal manure) application rates for rice, wheat and corn cultivation in different provinces in 2018

Province	Rice (kg N ha^{-1})		Wheat (kg N ha^{-1})		Corn (kg N ha^{-1})	
	Synthetic fertilizer	Organic fertilizer[a]	Synthetic fertilizer	Organic fertilizer	Synthetic fertilizer	Organic fertilizer
Beijing	209	110	222	117	222	117
Tianjin	253	113	220	98	200	89
Hebei	272	72	242	64	206	54
Shanxi	184	45	203	49	183	44
Inner Mongolia	214	58	197	53	220	60
Liaoning	222	93	206	86	139	87
Jilin	163	43	166	44	156	42
Heilongjiang	126	27	80	17	176	38
Shanghai	307	72	243	57	249	58
Jiangsu	242	53	253	55	248	54
Zhejiang	188	45	201	48	222	53
Anhui	182	59	206	66	172	56
Fujian	142	79	244	68	270	75
Jiangxi	168	70	123	77	119	74
Shandong	254	97	190	109	210	121
Henan	160	28	173	30	208	36
Hubei	148	36	136	33	184	45
Hunan	141	45	151	49	161	52
Guangdong	177	83	215	101	241	113
Guangxi	185	85	105	48	217	100

Hainan[b]	165	67	--	--	--	--
Chongqing	205	58	187	53	196	55
Sichuan	152	69	107	49	169	77
Guizhou	171	63	118	44	208	77
Yunan	180	51	147	42	285	80
Tibet	89	52	217	85	83	48
Shaanxi	283	25	220	19	274	24
Gansu	255	98	222	85	324	83
Qinghai[b]	--	--	122	83	179	49
Ningxia	287	61	252	54	257	55
Xinjiang	246	46	274	52	290	55

[a] "Organic fertilizer" includes human and livestock manure. [b] No rice is cultivated in Qinghai and no wheat and corn are cultivated in Hainan.

Supplementary Table 3 CH_4 emissions from rice paddies under BAU and different scenarios in different provinces (Straw-CH_4-N (S1), Biochar-CH_4-N (S2) and IPEG-CH_4-N (S3))

Province	CH_4 emission (kg CH_4 ha^{-1})			
	BAU	S1	S2	S3
Beijing	257	297	105	137
Tianjin	256	308	76	114
Hebei	249	295	87	128
Shanxi	206	261	65	116
Inner Mongolia	216	272	71	140
Liaoning	207	303	79	128
Jilin	188	285	68	140
Heilongjiang	174	272	59	113
Shanghai	275	335	95	98
Jiangsu	219	262	70	91
Zhejiang	242	300	79	87
Anhui	220	263	73	97
Fujian	300	366	109	114
Jiangxi	296	360	109	114
Shandong	221	276	49	107
Henan	267	314	94	162
Hubei	229	285	71	104
Hunan	298	360	112	114
Guangdong	330	398	124	128
Guangxi	291	378	126	128
Hainan	305	371	113	118
Chongqing	207	273	86	90
Sichuan	207	273	85	106
Guizhou	180	245	70	76
Yunan	191	257	75	87
Tibet	235	304	103	166

Shaanxi	252	301	102	105
Gansu	206	258	70	77
Qinghai[a]	--	--	--	--
Ningxia	214	270	67	136
Xinjiang	232	288	80	190

[a] No rice is cultivated in Qinghai.

Supplementary Table 4 Topsoil (0−20cm) SOC change rates of croplands under BAU and different scenarios in different provinces (kg C ha^{-1} yr^{-1}) (Straw-CH_4-N (S1), Biochar-CH_4-N (S2) and IPEG-CH_4-N (S3))

Province	BAU[a]	Rice			Wheat			Corn		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Beijing	166	243	452	365	366	749	605	346	902	711
Tianjin	166	348	885	722	352	705	601	328	827	695
Hebei	166	267	552	438	375	778	627	307	738	587
Shanxi	166	284	561	436	303	530	429	317	693	541
Inner Mongolia	166	289	576	404	281	466	351	381	933	632
Liaoning	-14	239	635	478	261	638	493	264	715	554
Jilin	-14	211	559	370	4	-32	-12	285	774	528
Heilongjiang	-14	192	507	378	137	329	248	324	881	681
Shanghai	268	481	1,019	1,056	514	955	995	478	1,030	1096
Jiangsu	268	426	889	778	465	841	756	409	839	754
Zhejiang	268	433	841	815	441	742	728	390	699	694
Anhui	268	391	743	650	455	809	721	400	800	712
Fujian	268	394	697	730	489	883	934	392	705	757
Jiangxi	268	398	712	746	362	509	530	419	806	868
Shandong	268	407	808	658	481	890	744	416	865	715
Henan	215	336	683	483	423	823	599	357	788	554
Hubei	215	408	894	753	389	693	606	358	726	632
Hunan	215	360	716	754	382	672	710	395	865	939
Guangdong	215	347	666	702	432	819	868	343	670	723
Guangxi	215	366	623	693	295	391	425	389	703	804
Hainan	215	331	609	640	--	--	--	--	--	--
Chongqing	176	351	655	625	331	546	529	419	868	848
Sichuan	176	377	730	634	353	606	539	416	861	760
Guizhou	176	343	630	611	289	438	431	359	691	687
Yunan	176	363	690	631	280	415	391	396	802	750
Tibet	176	322	569	407	470	910	640	455	977	668
Shaanxi	91	218	516	480	228	455	431	231	579	555
Gansu	91	197	441	529	206	392	464	248	641	798
Qinghai[a]	91	--[b]	--	--	218	426	341	271	725	564
Ningxia	91	235	578	463	195	358	301	312	879	716
Xinjiang	91	237	584	470	283	615	510	314	887	727

[a] The data were from Zhao et al.[4]. [b] No crop cultivation

Supplementary Table 5 The amounts of staple crop residue biomass used for field retention, livestock feed and burning in different provinces in 2018 (unit: Gg yr^{-1})

Province	Biomass retention			Biomass feeding			Biomass burning		
	Rice	Wheat	Corn	Rice	Wheat	Corn	Rice	Wheat	Corn
Beijing	0.4	29	180	0.1	10	63	0.2	17	102
Tianjin	192	306	758	67	106	264	109	174	430
Hebei	210	7,340	12,156	73	2,552	4,226	119	4,167	6,900
Shanxi	2	933	4,883	1	682	3,569	1	704	3,684
Inner Mongolia	363	833	14,915	266	609	10,902	274	628	11,253
Liaoning	971	4	5,507	601	2	3,409	1,802	7	10,215
Jilin	1,484	1	9,257	919	0.3	5,730	2,752	1	17,170
Heilongjiang	6,107	96	15,617	3,781	60	9,668	11,328	179	28,969
Shanghai	456	66	7	93	13	1	328	47	5
Jiangsu	9,263	7,027	1,819	3,220	2,443	632	5,258	3,989	1,033
Zhejiang	2,214	186	117	451	38	24	1,593	134	84
Anhui	8,276	7,964	3,759	2,877	2,769	1,307	4,698	4,521	2,134
Fujian	1,604	1	69	327	0.1	14	1,154	0.4	50
Jiangxi	9,183	17	102	1,872	3	21	6,609	12	74
Shandong	417	12,832	14,484	145	4,461	5,035	237	7,284	8,222
Henan	1,992	17,772	13,875	692	6,178	4,823	1,131	10,088	7,876
Hubei	9,548	2,422	2,178	1,947	494	444	6,872	1,743	1,567
Hunan	12,002	49	1,256	2,447	10	256	8,638	35	904
Guangdong	4,858	1	300	991	0.2	61	3,496	1	216
Guangxi	2,865	2	1,031	1,329	1	478	3,868	2	1,392
Hainan	589	--[a]	--	120	--	--	424	--	--
Chongqing	1,247	29	1,087	578	14	504	1,683	40	1,467
Sichuan	4,080	865	4,515	1,892	401	2,093	5,508	1,168	6,094
Guizhou	1,213	123	1,117	563	57	518	1,638	166	1,508
Yunan	1,724	272	3,987	800	126	1,849	2,328	367	5,382
Tibet	1	72	15	1	33	7	2	97	20
Shaanxi	263	1,607	3,063	192	1,175	2,239	198	1,212	2,311
Gansu	8	1,083	2,943	6	792	2,151	6	817	2,220
Qinghai[a]	--	172	61	--	126	45	--	130	46
Ningxia	221	162	1,272	162	118	930	167	122	959
Xinjiang	225	2,404	4,269	165	1,757	3,120	170	1,814	3,221

[a] No crop cultivation. The data were from Zhuang et al.[8].

Supplementary Table 6 Crop residue biomass burning induced GHG and air pollutants emissions (unit: kg Mg^{-1} biomass)

Straw type	CH_4	N_2O	NO_x	NH_3	BC[a]	SO_2	$PM_{2.5}$
Rice	1.20	0.03	0.99	0.17	0.50	0.64	9.39
Wheat	1.28	0.03	1.09	0.12	0.47	0.74	7.13
Corn	1.66	0.05	1.29	0.21	0.56	0.45	11.3

[a] BC means black carbon. References: Liu et al.[7] and Yang et al.[14].

Supplementary Note 2: GHG emissions from the scenario Straw-CH_4-N

The Straw-CH_4-N scenario comprises an increase in crop residues retention in croplands coupled with CH_4 mitigation and a reduction in fertilizer N use. On average, 44% of national staple crops residues were retained in the field under BAU, while 20% were used for producing feed for livestock and the remaining part was burned domestically or in the fields. We assumed that all the provincial staple crop residues (82%) were retained in the fields (except for those used as livestock feed) under Straw-CH_4-N. Since no-tillage and straw mulching is not a common practice in China, we assumed that farmers will not adopt no-tillage at large scale in future. Crop straw was therefore incorporated into the soil instead of being retained on the field surface in the Straw-CH_4-N scenario. Besides enhancing crop residue retention, intermittent irrigation regime (at least one drainage) was assumed to be expanded from current 75% to 100% to reduce CH_4 emissions from continuously flooded rice paddies under Straw-CH_4-N. In addition, N application rate in Straw-CH_4-N was reduced by 15% from that in BAU, considering the overuse of N fertilizer in China's croplands[5].

Increasing crop residue application will affect GHG emissions, crop yield and SOC sequestration, which were evaluated based on our meta-analysis results (Figure 2a). We established an empirical model based on the response of N_2O emissions under straw application (y) to straw N input (x):

$$y = e^{(0.008x - 0.1968)} \times N_2O_{without\text{-}straw} \ (p<0.05, R^2=0.14).$$

Here, $N_2O_{without\text{-}straw}$ denotes N_2O emissions without straw application, which was calculated based on straw application rate under BAU. Increasing straw application under Straw-CH_4-N will stimulate CH_4 emissions from paddy fields[3], which were evaluated using the Tier 1 method described in the 2006 IPCC guidelines (Supplementary Table 3). The straw application induced SOC sequestration rate was estimated through an empirical model established based on the meta-analysis dataset[4] (Figure 3b).

In the Straw-CH_4-N scenario, we assumed that all flooded paddy fields adopted intermittent irrigation. On average, intermittent irrigation reduced CH_4 emissions by 52% and increased N_2O emissions by 132% compared to flooded paddy fields[3,13]. Thus, switching the 25% of paddy fields that are currently under continuously flooded management to intermittent irrigation will reduce total CH_4 emissions by 13%, and increase N_2O emission by 33%. In addition, N application rates for staple crop cultivation in China are generally excessive with the consequences of low nitrogen use efficiency and high reactive N (Nr) losses, and consequently causing a cascade of environmental problems[5,6]. Numerous studies indicate that with additional knowledge-based N management (e.g., splitting N application), fertilizer N rate can be reduced by 15−20% without impairing crop yields[5,15]. Therefore, fertilizer N application rate in Straw-CH_4-N was reduced by 15% from that in BAU, coupled with an additional splitting application of N fertilizer to maintain staple crop yields[2]. Additional energy (e.g., diesel) and labor costs were needed for increasing straw incorporation and performing an additional N splitting application compared to BAU, which were also considered in our calculations as descried in Xia et al.[2]. Straw application largely increased CH_4 emissions from paddy fields, which will offset the climate benefit of SOC accrual[2]. Thus, we also calculated the mitigation potential of applying staple straw to upland fields instead of rice paddies. We found that applying all staple straw to wheat and corn fields will reduce GHG emissions approximately by 68 Tg CO_2-eq yr^{-1}. This means that the associated total GHG emissions from staple food production will be 492 Tg CO_2-eq yr^{-1}, which is still far away from carbon neutrality.

We used the meta-analysis approach to calculate the effects of straw (Straw-CH_4-N) and biochar application (Biochar-CH_4-N and IPEG-CH_4-N) on GHG emissions, Nr losses and crop yield (Figure 2a and Supplementary Dataset 1). The database regarding the effects of straw application on CH_4 emissions from paddy field were derived from Liu et al.[16]. The descriptions about the meta-analysis can be found in the Methods section.

Supplementary Note 3: GHG emissions from the scenario Biochar-CH_4-N

In the Biochar-CH_4-N scenario, we assumed that all provincial staple crop residues (except for those used as livestock feed) (82%) were converted into biochar through pyrolysis under 500°C before being applied to the fields (Supplementary Table 7), coupled with CH_4 mitigation through intermittent irrigation and a 15% reduction in fertilizer N use under Biochar-CH_4-N. In this study, we assumed that the pyrolysis process in the Biochar-CH_4-N and IPEG-CH_4-N is the same, except that the fate of bio-gas and bio-oil was not considered in the Biochar-CH_4-N. Supplementary Figures 2–3 and Supplementary Table 12 show the details of the pyrolysis processes and the char recoveries, energy requirements and operating emissions. Under the pyrolysis temperature of 500°C, 1 Mg crop residue of rice, wheat and corn will produce 0.281 Mg, 0.284 Mg and 0.289 Mg biochar, with the biochar-C content of 53% (rice), 62% (wheat) and 58% (corn) (see Supplementary Note 4 for details).

The effects of biochar application on GHG emissions, Nr losses and crop yield were calculated based on our meta-analysis results (Figure 2a). Overall, the effects of biochar application reported in our meta-analysis on crop yield (+11% vs. +10% in Ye et al.[17]), SOC contents (+35% vs. +39% in Bai et al.[18]) and N_2O emissions (-23% vs. -28% in He et al.[19]) are comparable to published regional or global meta-analyses. Biochar application induced SOC sequestration rate was estimated through an empirical model established based on the meta-analysis dataset (Figure 3a).

We also established an empirical model based on the response of N_2O emissions under biochar application (y, kg N ha^{-1} yr^{-1}) to biochar application rate (x, Mg C ha^{-1} yr^{-1}):

$$y = e^{(-0.0121x - 0.1019)} \times N_2O_{without\text{-}biochar} \ (p<0.05, R^2=0.25).$$

Here, $N_2O_{without\text{-}biochar}$ denotes N_2O emissions without biochar application. Since the effects of biochar application on CH_4 emissions from paddy fields were not affected by biochar application rate ($p>0.05$), we used the average reduction effect (26.4%) in the calculations. Changes in GHG emissions associated with intermittent irrigation and a 15% reduction in fertilizer N use in Biochar-CH_4-N were calculated using the same method as in Straw-CH_4-N.

Additional energy (e.g., diesel) and labor costs were needed for transporting crop straw and biochar and applying biochar to the field compared to BAU. In China, majority of agricultural products are distributed or transported through land transportation using diesel vehicles, with an average transportation distance of 70 km[2,20]. Here, we used the parameter published in Yuan et al.[20], the diesel consumed factor for road-transportation-used truck which had a carrying capacity of 28 Mg being 4.4 L Mg^{-1} cargo per 70 km, to calculate the total amounts of diesel oil consumed for crop straw and biochar transportation and distribution. We used the parameter of 4.4 L Mg^{-1} biochar to calculate the consumption of diesel oil for applying biochar to the soil (0−10 cm)[2]. Overall, these additional GHG emissions were negligible compared to biochar-induced GHG mitigation potentials (Figure 1).

Supplementary Table 7 The amounts of biochar produced from staple crop residues in different provinces in 2018 (unit: Gg yr^{-1}) (Biochar-CH_4-N (S2) and IPEG-CH_4-N (S3))

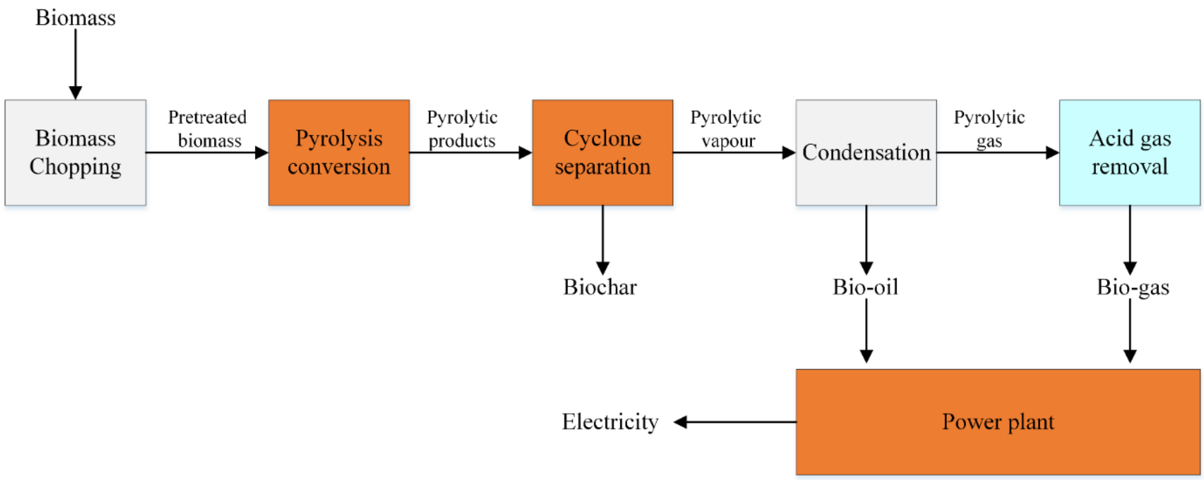
Province	Rice		Wheat		Corn	
	S2	S3	S2	S3	S2	S3
Beijing	0.2	0.1	14	9	85	59
Tianjin	90	68	144	110	356	277
Hebei	99	67	3,444	2,370	5,704	3,984
Shanxi	1	1	490	314	2,564	1,667
Inner Mongolia	191	94	437	217	7,832	3,943
Liaoning	830	559	3	2	4,705	3,246
Jilin	1,268	677	0.1	0.1	7,910	4,326
Heilongjiang	5,218	3,485	82	56	13,345	9,135
Shanghai	235	242	34	35	4	4
Jiangsu	4,346	3,582	3,297	2,744	854	721
Zhejiang	1,139	1,104	96	94	60	60
Anhui	3,883	3,127	3,737	3,039	1,764	1,456
Fujian	825	868	0.3	0.3	36	38
Jiangxi	4,727	4,972	9	9	53	57
Shandong	196	136	6,021	4,231	6,796	4,848
Henan	935	468	8,338	4,220	6,510	3,344
Hubei	4,914	3,799	1,247	973	1,121	888
Hunan	6,178	6,499	25	27	646	697
Guangdong	2,500	2,630	1	1	154	166
Guangxi	2,015	2,269	1	1	725	837
Hainan	303	319	--[a]	--	--	--
Chongqing	877	837	21	20	764	747
Sichuan	2,870	2,287	609	490	3,175	2,594
Guizhou	853	828	87	85	785	781
Yunan	1,213	1,078	191	171	2,804	2,554
Tibet	1	0.4	50	23	10	5
Shaanxi	138	130	844	804	1,608	1,555
Gansu	4	5	569	668	1,545	1,843
Qinghai	--	--	90	62	32	22

Ningxia	116	85	85	63	668	503
Xinjiang	118	88	1,262	947	2,242	1,706

[a] No crop cultivation.

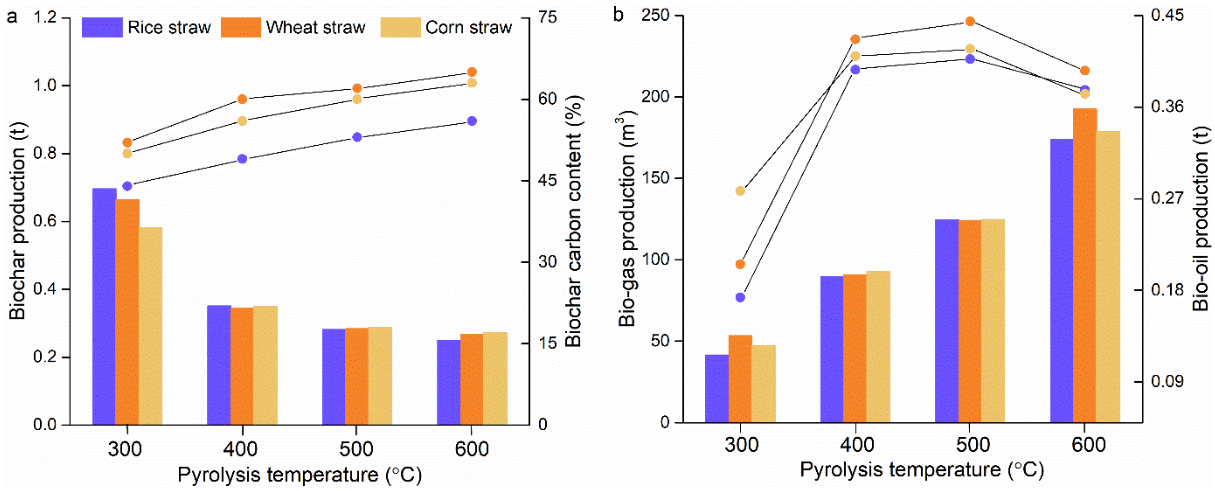
Supplementary Note 4: GHG emissions from the scenario IPEG-CH_4-N

Bio-gas and bio-oil produced during biochar production can be used to generate electric power through an integrated biomass pyrolysis and electricity (IPEG) system[14,21]. This can result in an indirect mitigation of GHG through substitution effects, since the energy (electricity) generated from the IPEG can replace traditional emissions sources, such as coal burning for electricity production (0.95 CO_2-eq kWh^{-1})[2]. Therefore, besides the direct mitigation potentials of biochar application as shown in the Biochar-CH_4-N, the indirect mitigation effects from energy substitution were also considered in IPEG-CH_4-N (Supplementary Figure 2). Also, the (IPEG) system was coupled with widely applied CH_4 (intermittent irrigation) and nitrogen (N) mitigation (a 15% reduction in fertilizer N use) measures (IPEG-CH_4-N).



Supplementary Figure 2. Process flow diagram of the integrated biomass pyrolysis and electricity (IPEG) system.

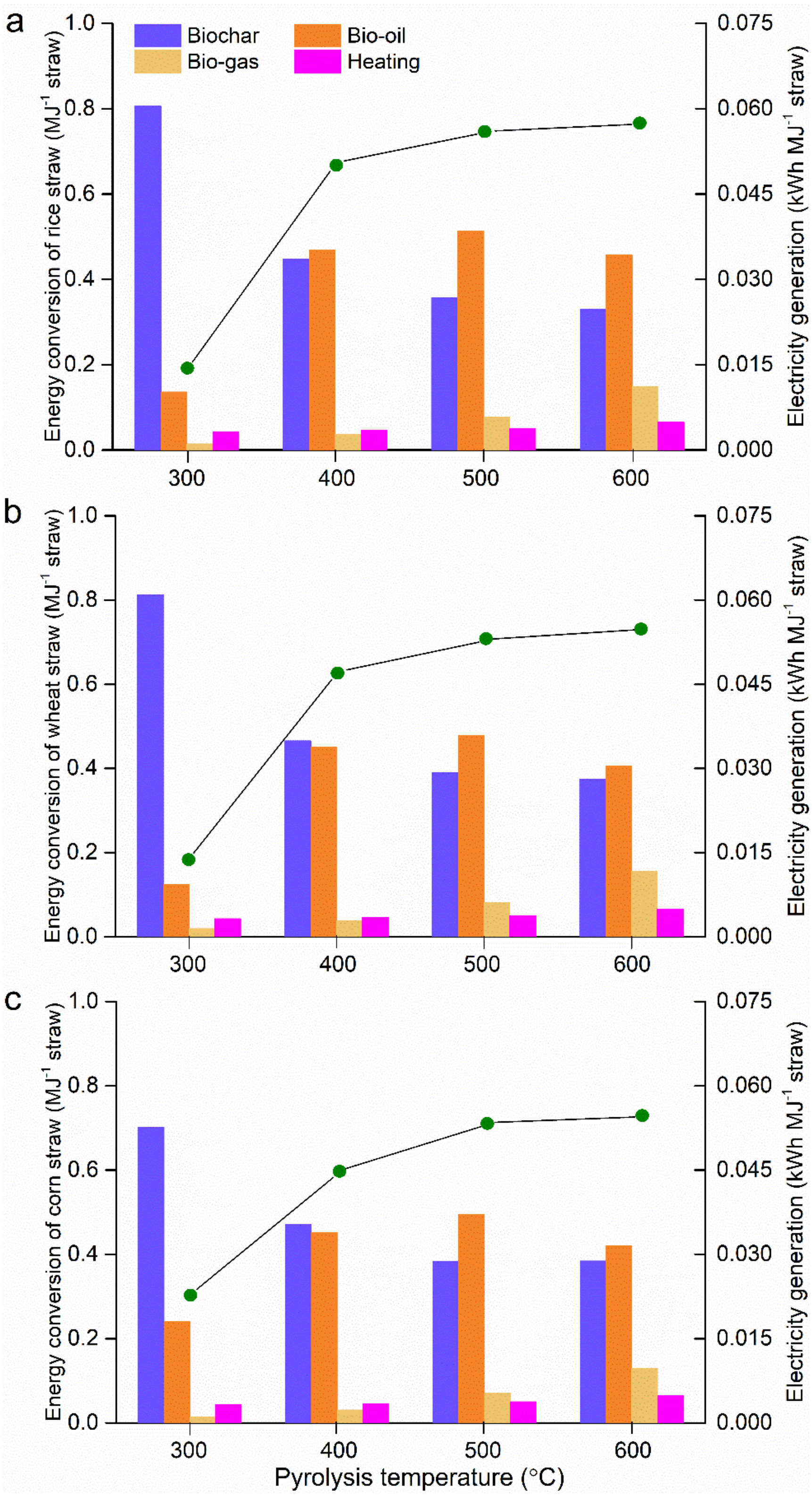
The processes of IPEG system are described in the Methods section (see descriptions of the IPEG system for details). It is well known that pyrolysis temperature greatly affects biochar production as well as ratio of bio-oil and bio-gas generation. In this study, IPEG system is operated pyrolysis at relatively low to medium temperatures (300−600°C), resulting in a higher yield of pyrolysis oil than syngas. As shown in Supplementary Figure 3, biochar production (varying between 0.25−0.69 Mg Mg^{-1} straw) and its carbon content (varying between 44−65%) decreased with the increase in pyrolysis temperature from 300 to 600°C. In contrast, bio-gas production increased clearly with pyrolysis temperature whereas bio-oil production increased with pyrolysis temperature from 300 to 500°C and then decreased if pyrolysis temperature further increased to 600°C. Yields of the main pyrolysis products (biochar and its carbon content, biogas and bio-oil) under different pyrolysis temperatures are comparable with the results derived from both pyrolysis experiment[21] and Aspen Plus stimulation study[14].



Supplementary Figure 3. Yield of the main pyrolysis products (biochar and its carbon content, bio-gas and bio-oil) at different pyrolysis temperatures with 1 Mg feedstock straw biomass[22-25]. The bar plot in the left (a) and right panel (b) represent the production of biochar and bio-gas, respectively; the lines represent biochar carbon content (a) and bio-oil production (b).

Majority of the straw energy was converted to biochar and bio-oil regardless of pyrolysis temperature (Supplementary Figure 4) and part of the straw energy was used for heating to sustain the IPEG system running. Every 1MJ rice straw will produce the electricity amount of 0.014 (300°C), 0.048 (400°C), 0.056 (500°C) and 0.058 (600°C) kWh. For wheat straw, the produced amounts of electricity are 0.014 (300°C), 0.046 (400°C), 0.053 (500°C) and 0.054 (600°C) kWh MJ^{-1} straw. For corn straw, the produced amounts of electricity are 0.024 (300°C), 0.046 (400°C), 0.054 (500°C) and 0.054 (600°C) kWh MJ^{-1} straw. Converting these values to per-weight basis (Supplementary Table 8), 1 kg rice straw will produce electricity with the amount of 0.22 (300°C), 0.73 (400°C), 0.85 (500°C) and 0.88 (600°C) kWh; 1 kg wheat straw will produce 0.23 (300°C), 0.78 (400°C), 0.89 (500°C) and 0.90 (600°C) kWh; and 1 kg corn straw will produce 0.40 (300°C), 0.76 (400°C), 0.89 (500°C) and 0.90 (600°C) kWh. Taking into consideration the amounts of biochar and electricity, a pyrolysis temperature of 500°C will produce the largest GHG mitigation potentials. Therefore, we operate the IPEG system under 500°C to evaluate its GHG mitigation potentials in the IPEG-CH_4-N. On average, 1 Mg staple crop straw biomass will produce 879 kWh of electricity (Supplementary Tables 9 and 10), and will lead to a fossil fuel offset (energy substitution effects) of 0.84 Mg CO_2-eq Mg^{-1} straw, which is consistent with the result (0.88 Mg CO_2-eq Mg^{-1} straw) of a recent study based on an Aspen Plus stimulation[14]. In this study, we have taken into account the bio-oil upgrading from a biomass pyrolytic polygeneration system. In this system, the condensed bio-oil was cooled and captured by a sprayed coolant containing sufficient water. The bio-oil was then upgraded by removing the water via gravity separation before being used. The energy (electricity) consumption for the bio-oil upgrading process was considered into the analysis (Supplementary Table 12). The electricity generation efficiencies of bio-gas and bio-oil listed in

Supplementary Table 10 are based on simple instead of complex upgrading process. Electricity generation in power plants normally does not require bio-oil and bio-gas to go through a complex upgrading process before combustion. Yang et al.[39] have suggested that the addition of bio-energy has no significant impact on the electricity generation efficiency of the power plants when the share of bioenergy is moderate (<15%). In our study, because there is not a huge amount of bio-oil and bio-gas produced from biomass, they will not, and were also implicitly assumed not to, exceed 15% of the fuels in power plants. Overall, our calculation of electricity production is based on the energy balance, and the electricity generation efficiencies are taken from related references that are based on the similar upgrading process as in this study.



Supplementary Figure 4. Energy balance and electricity production of the IPEG system at different pyrolysis temperatures with 1 MJ staple crop straw biomass. The dots indicate the electricity generation with 1 MJ staple crop straw.

Supplementary Table 8 Ultimate and proximate analyses % by weight (dry basis) of staple crop straw[a]

Type of Biomass	Wheat straw	Corn Straw	Rice straw
HHV (MJ kg^{-1}, dry basis)	16.8	16.6	15.12
Ultimate analysis			
Carbon (C)	43.0	43.3	40.1
Hydrogen (H)	5.64	5.92	5.47
Oxygen (O)	40.5	39.3	40.2
Nitrogen (N)	0.76	1.96	0.69
Sulphur (S)	0.78	0.66	0.48
Proximate analysis			
Fixed carbon (FC)	9.93	21.6	10.1
Volatile matter (VM)	80.7	82.2	76.9
Ash	9.37	8.86	13.1

[a] References: He et al.[23] and Ansari et al.[25]. HHV, higher heating value.

Supplementary Table 9 The bio-gas, bio-oil and electricity production of the IPEG system under pyrolysis temperature of 500°C with 1 Mg feedstock straw biomass

Bio-gas production	HHV (MJ Nm^{-3})	Bio-gas generation (Nm^3 Mg^{-1} biomass)	Energy generation (HHV, MJ Mg^{-1} biomass)	Electricity generation[a] (kWh Mg^{-1} biomass)
Rice	9.5	124	1,182	118
Wheat	11	124	1,366	137
Corn	9.5	125	1,185	119
Bio-oil production	**HHV (MJ kg^{-1})**	**Bio-oil generation (Mg Mg^{-1} biomass)**	**Energy generation (HHV, MJ Mg^{-1} biomass)**	**Electricity generation (kWh Mg^{-1} biomass)**
Rice	19.1	0.41	7,772	734
Wheat	18.0	0.44	8,003	756
Corn	19.6	0.42	8,185	773
Sum	**Electricity generation (kWh Mg^{-1} biomass)**			
Rice	852			
Wheat	893			
Corn	892			

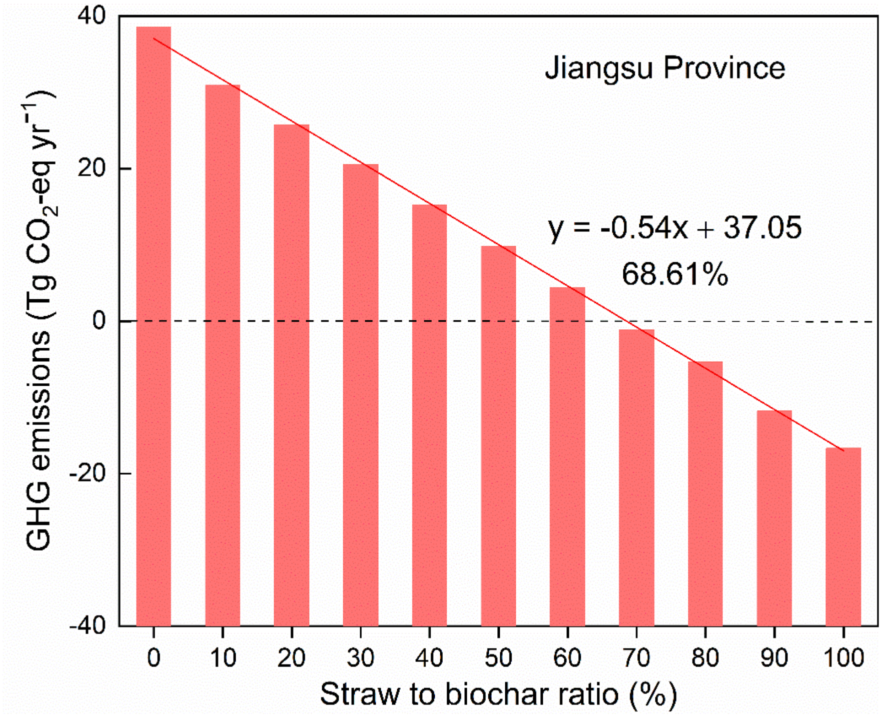
[a] The electricity generations from bio-gas and bio-oil were calculated by multiplying the "Energy generation" by the energy conversion efficiency factors (36%, biogas; 34%, bio-oil) as shown in Supplementary Table 10.

Supplementary Table 10 Electricity generation efficiencies from typical power plants with bio-gas and bio-oil

Type	Plant description	Electricity generation efficiency (%)[a]	References
Bio-gas	Combined heat and power plants (5 MW)	36.1	26

	Combined heat and power plants (364 kW)	38	27
	Thermal power plant (>100 MW)	36.1	26
	Solid oxide fuel cell (SOFC) generator (50 kW)	38.6	28
	Pyrolysis gas combustion power system (250 kW)	32.5	14
	Average	**36**	
Bio-oil	Fossil fuels power plants (20 MW)	30.4	29
	Gas turbine combined cycle (GTCC) power plant (10 MW)	38.7	29
	Diesel generator system (20 MW)	31.3	29
	Integrated gasification combined cycle (IGCC) Power plant (60 MW)	33.9	30
	Combined heat and power plants (675 MW)	35.7	31
	Average	**34**	

[a] The average electricity generation efficiencies of biogas (36%) and bio-oil (34%) in current typical power plants were used for estimating electricity generation in the IPEG system. The electricity generation efficiencies were calculated on the basis of HHV. The conversion ratio from LHV (lower heating value) to HHV was 0.9018 for bio-gas and 0.9213 for bio-oil.



Supplementary Figure 5. Net GHG emissions from staple crop production in Jiangsu province under different straw to biochar ratios.

Supplementary Table 11 The calculated straw-to-biochar ratios for achieving carbon neutrality for staple food production in different provinces in China

Province	Zero emissions$_{straw\text{-}to\text{-}biochar\text{-}ratio}$ [a]	Zero emissions$_{straw\text{-}to\text{-}biochar\text{-}ratio\text{-}corrected}$ [b]	Livestock feed	Direct straw application[c]
	%	%	%	%
Beijing	56.3	59.3	18.2	22.5
Tianjin	63.1	66.1	18.1	15.8
Hebei	56.3	59.3	18.2	22.5
Shanxi	44.6	47.6	29.4	23.0

Inner Mongolia	33.9	36.9	29.4	33.7
Liaoning	55.8	58.8	17.8	23.4
Jilin	43.6	46.6	17.8	35.6
Heilongjiang	55.4	58.4	17.8	23.8
Shanghai	95.4	98.4	11.6	0.00
Jiangsu	68.6	71.6	18.2	10.1
Zhejiang	89.1	92.1	10.6	0.00
Anhui	67.1	70.1	18.1	11.8
Fujian	111.5	100	10.6	0.00
Jiangxi	109.0	100	10.6	0.00
Shandong	57.6	60.6	18.1	21.3
Henan	40.6	43.6	18.2	38.2
Hubei	70.5	73.5	10.6	15.9
Hunan	101.2	100	10.6	0.00
Guangdong	114.4	100	10.6	0.00
Guangxi	112.9	100	16.5	0.00
Hainan	117.7	100	10.6	0.00
Chongqing	81.7	84.7	16.5	0.00
Sichuan	67.8	70.8	16.5	12.7
Guizhou	83.1	86.1	16.5	0.00
Yunan	75.9	78.9	16.5	4.6
Tibet	36.8	39.8	16.5	43.8
Shaanxi	67.8	70.8	29.4	0.00
Gansu	84.4	87.4	29.4	0.00
Qinghai[a]	47.8	50.8	29.4	19.8
Ningxia	52.2	55.2	29.4	15.4
Xinjiang	52.8	55.8	29.4	14.8

[a] The calculated theoretical straw to biochar ratios for achieving carbon neutrality for staple food production in China. The ratios in Fujian (FJ), Jiangxi (JX), Hunan (HN), Guangdong (GD), Guangxi (GX), and Hainan (HAN) Province are above 100%, which means that even if all of the provincial staple crop residues were used by the IPEG system, these provinces cannot become carbon neutral.

[b]To offset the emissions from FJ, JX, HN, GD, GX and HAN Province, additional 3% of staple crop residues in other provinces was assumed to be used in the IPEG system, and the proportion of straw in these six provinces was set to 100%.

We used the method described in the Methods section to calculate the proportion of staple crop residues required to support the IPEG system to achieve carbon-neutral staple food production in each province (see "Zero $\text{emissions}_{\text{straw-to-biochar-ratio}}$" in Supplementary Table 11). Taking Jiangsu Province as an example, theoretically feeding the IPEG system with 68.6% of staple crop residue can achieve carbon-neutral staple food production. We found that the theoretical proportion of staple crop residues was above 100% in 6 provinces (Hainan, Guangdong, Guangxi, Jiangxi, Fujian and Hunan). This denotes that even if all of the staple crop residues in these provinces were used in the IPEG system, these provinces could not become carbon neutral due to high CH_4 emissions from paddy fields

(Supplementary Table 3). Therefore, to offset the emissions from these provinces, additional 3% of staple crop residues in other provinces was assumed to be used in the IPEG system, and the proportion of straw in these six provinces was set to 100% (see "Zero $\text{emissions}_{\text{straw-to-biochar-ratio-corrected}}$" values in Supplementary Table 11). On average, 72% of staple crop residues would be required to feed the IPEG system to achieve carbon neutrality for staple food production in 2018 (Supplementary Table 11). Under this situation, cumulative GHG emissions from staple crop production could be reduced from the current 666 Tg CO_2-eq yr^{-1} to a net GHG reduction of 37.9 Tg CO_2-eq yr^{-1} (Figure 2b). We treat this result as "carbon neutrality" in this study partly because the achievement of precise carbon neutrality (zero emissions) is difficult in practice and partly to buffer the uncertainty around the estimate ($\pm$14 Tg CO_2-eq yr^{-1}).

To estimate GHG mitigation potentials under IPEG-CH_4-N, based on the proportions of "zero $\text{emissions}_{\text{straw-to-biochar-ratio-corrected}}$" and "direct straw application", we calculated the GHG emissions from specific staple crop cultivation in each province through considering the effects of biochar field application and energy substitution. For the majority of the provinces, part of the straw was used for biochar and energy production while part was directly retained in the field. The effects of combined application of biochar and straw on field GHG emissions and SOC sequestration were evaluated separately based on their respective application amount, before the effects were summed up ($\text{Effect}_{\text{straw-biochar}} = \text{Effect}_{\text{straw}} + \text{Effect}_{\text{biochar}}$) using the methods under Straw-CH_4-N and Biochar-CH_4-N. As shown in a recent meta-analysis by Shang et al.[34], the interactive effects between different agricultural managements on SOC sequestration and GHG emissions are commonly additive, and the additive effects were widely adopted in previous studies[2,3,34]. Therefore, we assumed that the effects of straw and biochar are additive in this study. Based on the capacity of the IPEG plant under pyrolysis temperature of 500 °C (31591 Mg biomass yr^{-1}) and available amounts of straw biomass (Supplementary Table 13), we have calculated the numbers of potential IPEG plants needed to be constructed in each province to achieve carbon neutrality for staple food production in China. The amounts of biochar and electricity produced under IPEG-CH_4-N in different provinces in 2018 were shown in Supplementary Table 13. Additional GHG emissions were produced under IPEG-CH_4-N due to transportation of crop residues, and production and application of biochar which were also included into the analysis (see Supplementary Note 3). GHG emissions from operation of the IPEG plants were from electricity consumption (Supplementary Table 12). However, these additional GHG emissions are negligible compared to the reductions induced by IPEG-CH_4-N (Figure 1). We did not consider GHG emissions from pyrolysis plant construction and equipment because they are insignificant. As shown in a recent study by Yang et al.[36], total GHG emissions from plant construction (582 t CO_2-eq) and equipment (270 t CO_2-eq) are estimated to be 852 t CO_2-eq, which are 42.6 t CO_2-eq yr^{-1} considering an operation duration of a pyrolysis plant for 20 years. Total GHG emissions from pyrolysis plant construction and equipment in IPEG-CH_4-N (0.5 Tg CO_2-eq yr^{-1}) only account for 0.15% of the fossils fuel offset (326 Tg CO_2-eq yr^{-1}). Therefore, GHG emissions from pyrolysis plant construction and equipment in IPEG-CH_4-N were not taken into account in our calculation.

Supplementary Table 12 The construction and maintenance cost for IPEG plant[a]

	Pyrolysis 300 °C	Pyrolysis 400 °C	Pyrolysis 500 °C	Pyrolysis 600 °C
Initial capital plant cost (×10^4 US\$ plant^{-1})	836	1163	1,618	2,250
Feedstock for pyrolysis (Mg yr^{-1})	30,000	30,000	30,000	30,000
Feedstock for heating (Mg yr^{-1})	1,361	1,441	1,591	2,094
Price of feedstock (US\$ Mg^{-1})	51.1	51.1	51.1	51.1
Electricity consumption (×10^4 kWh yr^{-1})	52.0	61.0	67.4	75.2
Operation emissions (kg CO_2-eq Mg straw^{-1})	16.5	19.3	21.3	23.8
Electricity price (US$/kWh)	0.113	0.113	0.113	0.113
Water Consumption (×10^4 Mg)	3.6	3.6	3.6	3.6
Price of water (US\$ yr^{-1})	0.756	0.756	0.756	0.756
Salary (US\$ yr^{-1})	453,787	45,3787	45,3787	45,3787
Discount rate (%)	7	7	7	7
Operation year	20	20	20	20
Equipment depreciation (×10^4 US\$ yr^{-1})	69.33	96.44	134.14	186.58
Price of gas (US\$ m^{-3})	0.12	0.14	0.22	0.28
Price of oil (US\$ Mg^{-1})	106.56	157.84	166.38	158.81

[a] References: He et al.[23], Xia et al.[32] and Liu et al.[33]. GHG emissions from operation of the IPEG plants were from electricity consumption. The start-up fuel is used to kick off the first pyrolysis unit and then the process heat generated from it will be used to fuel the next unit, and so forth. When large amounts of biochar are produced by continuously running pyrolysis units, the amount of start-up fuel is negligible and often omitted in techno-economic and LCA analyses[37, 38.]

Supplementary Table 13 The amounts of staple crop straw biomass used for biochar and electricity production, and the corresponding IPEG plant numbers and amounts of electricity generation in China in 2018

Province	Feedingstock biomass (Gg province^{-1})	IPEG plant number (province)	Electricity generation (×10^4 kWh)		
			Rice	Wheat	Corn
Beijing	205	8	39	2,885	17,828
Tianjin	1,380	51	20,197	33,772	83,508
Hebei	19,223	709	19,853	726,341	1,201,548
Shanxi	5,927	218	184	96,154	502,646
Inner Mongolia	12,800	468	27,675	66,472	1,189,266
Liaoning	11,527	420	164,884	687	978,955
Jilin	15,165	551	199,722	22	1,304,838
Heilongjiang	39,087	1,401	1,028,816	17,041	2,755,223
Shanghai	905	32	71,582	10,845	1,205
Jiangsu	22,022	788	1,057,279	840,880	217,443
Zhejiang	4,056	142	325,783	28,679	18,037
Anhui	23,778	850	923,123	931,329	439,028
Fujian	3,219	102	256,325	93	11,608
Jiangxi	17,895	567	1,467,851	2,870	17,128
Shandong	27,663	1,019	40,222	1,296,847	1,462,215
Henan	24,309	890	138,265	1,293,433	1,008,689
Hubei	17,894	633	1,121,365	298,222	267,860
Hunan	24,008	811	1,918,438	8,253	210,215
Guangdong	9,923	315	776,464	183	50,208

Guangxi	10,967	348	669,862	452	252,399
Hainan	1,134	36	94,196	--	--
Chongqing	5,037	179	246,970	6,111	225,378
Sichuan	16,684	597	675,279	150,150	782,432
Guizhou	5,310	189	244,346	25,982	235,545
Yunan	11,699	421	318,092	52,542	770,244
Tibet	84	4	132	6,970	1,429
Shaanxi	7,504	275	38,465	246,321	469,001
Gansu	7,547	278	1,433	204,846	556,011
Qinghai	253	10	--	18,874	6,742
Ningxia	1,979	72	25,221	19,315	151,725
Xinjiang	205	303	25,910	290,177	514,696

The adding amount of bio-energy was assumed to be 10−15% of the total feeding fuels in power plants to avoid a significant effect on the electricity generation efficiency of the power plants[39].

Supplementary Note 5: Cost-benefit analysis

The effects of mitigation scenarios on crop yields, Nr losses, air pollutants (SO_2, $PM_{2.5}$, NO_X and black carbon (BC)) emissions, and net environmental and economic benefits (NEEB) were evaluated. We established empirical models based on the response of crop yields under straw (biochar) application to straw N input rate (biochar input rate) to calculate staple crop yields under different scenarios (Supplementary Table 14). For Nr losses under BAU, we used the following models for calculation[5]: NH_3 emissions (y), $y = 2.97 + 0.16\times N_{rate}$ ($p<0.01$, $R^2=0.46$, rice), $y = -4.95 + 0.17\times N_{rate}$ ($p<0.01$, $R^2=0.71$, wheat), $y = 1.45 + 0.24\times N_{rate}$ ($p<0.01$, $R^2=0.75$, corn), N_{rate} denotes total N application rate; N leaching (y), $y = 6.03\times e^{(0.0048\times Nsurplus)}$ ($p<0.01$, $R^2=0.31$, rice), $y = 13.59\times e^{(0.009\times Nsurplus)}$ ($p<0.01$, $R^2=0.38$, wheat), $y = 25.31\times e^{(0.0065\times Nsurplus)}$ ($p<0.01$, $R^2=0.55$, corn), $N_{surplus}$ denotes N surplus that is defined as total N application rate minus the amount of N taken up by crop aboveground biomass; N runoff (y), $y = 8.69\times e^{(0.0077\times Nsurplus)}$ ($p<0.01$, $R^2=0.45$, rice), $y = 0.0336\times N_{rate} + 9.3264$ ($p<0.01$, $R^2=0.30$, wheat and corn); NO emissions (y), $y = 0.0013\times N_{rate} + 0.57$ ($p<0.05$, $R^2=0.22$, rice), $y = 0.0066\times N_{rate} + 0.57$ ($p<0.01$, $R^2=0.36$, wheat and corn). For Nr losses under straw application (Straw-CH_4-N), we used the following models based on our meta-analysis results for estimations: NH_3 emissions (y), $y = e^{(0.0023x + 0.0529)} \times NH_{3without\text{-}straw}$ ($p<0.01$, $R^2=0.06$); N leaching (y), $y = e^{(0.0007x - 0.0784)} \times Nleaching_{without\text{-}straw}$ ($p<0.05$, $R^2=0.16$) (x denotes straw N input rate, kg N ha^{-1} yr^{-1}). For Nr losses under biochar application (Straw-CH_4-N), we used the models based on our meta-analysis results for estimations: NH_3 emissions (y), $y = e^{(0.011x + 0.0915)} \times NH_{3without\text{-}biochar}$ ($p<0.05$, $R^2=0.21$); N leaching (y), $y = e^{(-0.0149x - 0.1044)} \times Nleaching_{without\text{-}biochar}$ ($p<0.01$, $R^2=0.59$); N runoff (y), $y = e^{(-0.0131x - 0.1142)} \times Nrunoff_{without\text{-}biochar}$ ($p<0.01$, $R^2=0.85$) (x denotes biochar application rate, Mg C ha^{-1} yr^{-1}). Staple crop production in majority of the provinces under IPEG-CH_4-N receives both straw and biochar application. The effects of combined application of biochar and straw on Nr losses were evaluated separately based on their respective application amount (using the calculation method in Straw-CH_4-N and Biochar-CH_4-N), before the effects were summed up ($Effect_{straw\text{-}biochar} = Effect_{straw} + Effect_{biochar}$). See Supplementary Tables 15−18 for the estimated Nr losses under different scenarios. Biomass burning induced air pollutants (SO_2, $PM_{2.5}$, NO_X and BC) emissions under BAU were estimated by multiplying the burning amounts by the emission factors (Supplementary Tables 5 and 6).

For cost-benefit analysis, we calculated net environmental and economic benefits (NEEB) under different scenarios using the equation: NEEB = NYB + NPB – GHG cost – Nr cost. Here, NYB represents net yield benefits from staple grain production[2], and NPB denotes net pyrolysis benefits which were calculated by subtracting the construction and maintenance cost for IPEG plant (Supplementary Table 12) from the gross economic incomes of selling biochar and energy (Supplementary Figure 6). GHG and Nr cost represents damage costs of GHG emissions and Nr losses to the environment and human health. NYB was calculated by subtracting agricultural input costs (agricultural inputs and labors) from the gross economic incomes of selling staple grains (Supplementary Table 18). Information concerning agricultural inputs and labor cost, and price of various food products can be find in the website of National Bureau of Statistic of the People's Republic of China (http://www.stats.gov.cn/) and National Product Cost Survey (http://www.npcs.gov.cn/). NPB was calculated by subtracting the maintaining costs (e.g., initial capital plant cost, water and electricity consumption costs and staff salary) from the obtained economic benefits of selling biochar production and energy source (Supplementary Table 12). The substantial increase in NEEB for corn under IPEG-CH_4-N (Figure 6) was due to the large pyrolysis benefits and reductions in GHG and Nr cost attributed to much higher amount of corn straw for pyrolysis and energy/biochar production compared to rice and wheat (Supplementary Tables 5, 7 and 12).

Damage costs of GHG and Nr refer to the damage to ecosystem and human health and the stimulation effect on climate warming. Damage costs to ecosystem denote soil acidification and water eutrophication caused by NH_3 and NO_X emissions, and water eutrophication caused by N leaching and runoff, which were derived from Xia and Yan[40]. Human health costs incurred by NH_3, and NO_X and N_2O emissions were derived from Gu et al.[41]. Since no studies have evaluated the health costs caused by N leaching and runoff in China, we assumed the costs were only sixth of that in European N assessment (about 1.41 \$ kg^{-1} N) after considering the difference of people's willingness to pay in China and Europe[27]. Damage costs of climate warming incurred by GHG emissions were extracted from van Grinsven et al.[42]. Overall, damage costs of GHG emissions and Nr losses are as follows[2]: CO_2 emissions, 26.6 US\$ Mg^{-1} CO_2-eq; NH_3 emissions, 5.72 US\$ kg^{-1} N; NOx emissions, 4.53 US\$ kg^{-1} N; N leaching and runoff, 1.41 US\$ kg^{-1} N.

Our results show that the current high price of biochar (270 US\$ t^{-1}) exceeds its economic benefits associated with crop yield enhancement, leading to a reduction in crop yield revenue by 15.7 billion US\$ yr^{-1}. If considering the total amount of biochar under IPEG-CH_4-N, we can backward calculate that only when the price of biochar drops below 156 \$ t^{-1} will its application produce positive economic returns for farmers. Therefore, national subsidy programs should be considered to provide an incentive for farmers to apply biochar and promote the deployment of the IPEG technology at large scales.

Supplementary Table 14 Staple crop straw yields (Mg ha^{-1}) under different scenarios in each province in China (Straw-CH_4-N (S1), Biochar-CH_4-N (S2) and IPEG-CH_4-N (S3))

Province	Rice				Wheat				Corn			
	BAU	S1	S2	S3[a]	BAU	S1	S2	S3	BAU	S1	S2	S3
Beijing	5.00	5.01	5.32	5.16	5.41	5.42	5.55	5.49	6.76	6.79	7.80	7.80
Tianjin	9.37	9.40	9.89	9.64	5.15	5.16	5.29	5.23	5.92	5.95	6.85	6.85
Hebei	6.70	6.71	7.11	6.91	6.15	6.17	6.32	6.24	5.65	5.67	6.56	6.56
Shanxi	7.50	7.51	7.97	7.74	4.08	4.09	4.20	4.14	5.62	5.64	6.55	6.55
Inner Mongolia	8.11	8.12	8.61	8.36	3.39	3.39	3.49	3.44	7.22	7.26	8.33	8.33
Liaoning	8.56	8.59	9.08	8.83	5.83	5.86	6.00	5.93	6.13	6.17	7.13	7.13
Jilin	7.70	7.72	8.17	7.95	0.33	0.33	0.34	0.33	6.62	6.67	7.69	7.69
Heilongjiang	7.10	7.12	7.54	7.33	3.31	3.32	3.41	3.36	6.30	6.36	7.30	7.30
Shanghai	8.49	8.52	8.97	8.74	6.10	6.12	6.26	6.19	7.22	7.26	8.34	8.34
Jiangsu	8.84	8.86	9.35	9.10	5.36	5.37	5.50	5.44	5.82	5.84	6.76	6.76
Zhejiang	7.33	7.35	7.76	7.56	4.19	4.20	4.31	4.26	4.18	4.19	4.89	4.89
Anhui	6.61	6.62	7.00	6.81	5.59	5.60	5.74	5.67	5.23	5.25	6.08	6.08
Fujian	6.43	6.44	6.83	6.63	5.00	5.01	5.13	5.07	4.38	4.39	5.11	5.11
Jiangxi	6.09	6.10	6.46	6.28	2.19	2.19	2.26	2.23	4.49	4.50	5.22	5.22
Shandong	8.66	8.68	9.17	8.93	6.09	6.10	6.25	6.18	6.63	6.65	7.69	7.69
Henan	8.08	8.10	8.57	8.33	6.28	6.29	6.44	6.37	5.00	5.02	5.81	5.81
Hubei	8.22	8.24	8.69	8.47	3.71	3.72	3.82	3.77	4.14	4.16	4.83	4.83
Hunan	6.67	6.68	7.07	6.88	3.42	3.43	3.52	3.47	5.65	5.67	6.55	6.55
Guangdong	5.77	5.78	6.13	5.96	5.00	5.01	5.13	5.07	4.54	4.55	5.30	5.30
Guangxi	5.80	5.81	6.17	5.99	1.67	1.67	1.72	1.69	4.68	4.70	5.48	5.48
Hainan	5.31	5.32	5.64	5.48	--	--	--	--	--	--	--	--
Chongqing	7.42	7.44	7.88	7.66	3.31	3.31	3.41	3.36	5.68	5.72	6.61	6.61
Sichuan	7.89	7.91	8.37	8.14	3.89	3.90	4.01	3.96	5.75	5.78	6.68	6.68
Guizhou	6.26	6.28	6.66	6.47	2.34	2.35	2.42	2.38	4.30	4.32	5.03	5.03
Yunan	6.21	6.23	6.60	6.41	2.19	2.19	2.26	2.23	5.19	5.22	6.04	6.04
Tibet	5.56	5.57	5.91	5.74	6.15	6.18	6.32	6.25	6.54	6.58	7.58	7.58
Shaanxi	7.66	7.67	8.13	7.90	4.15	4.16	4.27	4.21	4.95	4.97	5.78	5.78
Gansu	6.58	6.59	7.00	6.79	3.62	3.62	3.72	3.67	5.83	5.85	6.78	6.78
Qinghai	--	--	--	--	3.82	3.82	3.93	3.88	6.22	6.24	7.22	7.22
Ningxia	8.54	8.56	9.06	8.81	3.23	3.24	3.33	3.29	7.55	7.59	8.71	8.71
Xinjiang	9.27	9.29	9.84	9.56	5.54	5.56	5.70	5.63	8.01	8.06	9.24	9.24

[a] Staple crop production in majority of the provinces under IPEG-CH_4-N receives both straw and biochar application. Here, the effects of combined application of biochar and straw on crop yields were evaluated separately based on their respective application amount (using the calculation method under Straw-CH_4-N and Biochar-CH_4-N) before the effects were summed up ($Effect_{straw\text{-}biochar} = Effect_{straw} + Effect_{biochar}$).

Supplementary Table 15 Total N losses from staple crop production (Gg N province^{-1}) under BAU in each province in China

Province	NH_3 emissions	N_2O emissions	NOx emissions	N leaching	N runoff
Beijing	4.3	0.2	0.6	2.5	1.4
Tianjin	24.2	0.9	4.0	13.3	7.8
Hebei	378.8	14.2	67.0	241.9	123.9
Shanxi	131.9	5.0	23.1	90.0	41.7
Inner Mongolia	323.5	11.9	52.1	183.5	99.2
Liaoning	193.4	7.4	40.0	86.7	56.3
Jilin	266.5	9.2	59.6	120.8	78.2
Heilongjiang	505.2	17.1	119.7	236.9	142.2
Shanghai	9.8	0.4	1.7	2.0	3.8
Jiangsu	318.8	9.7	54.8	138.6	103.1
Zhejiang	41.4	1.2	7.5	12.0	12.5
Anhui	343.4	11.1	60.2	139.1	119.0
Fujian	34.0	0.8	5.6	9.0	9.4
Jiangxi	182.1	5.1	29.6	33.9	55.9
Shandong	575.9	22.6	98.6	293.5	189.4
Henan	485.8	17.5	93.0	310.8	180.4
Hubei	185.0	5.5	39.0	81.8	57.5
Hunan	193.6	4.9	37.7	43.7	56.2
Guangdong	112.8	3.6	17.2	29.8	35.6
Guangxi	149.0	5.1	23.0	61.5	42.4
Hainan	12.5	0.4	2.0	2.4	4.1
Chongqing	68.5	2.2	12.0	27.8	18.9
Sichuan	232.6	7.4	44.9	98.0	66.3
Guizhou	83.7	3.1	13.6	52.6	23.4
Yunan	226.0	10.1	34.8	225.4	58.3
Tibet	1.9	0.1	0.4	0.9	0.7
Shaanxi	140.6	6.0	23.6	155.9	41.5
Gansu	151.8	7.2	22.4	178.8	40.5
Qinghai[a]	5.1	0.2	1.0	3.0	2.1
Ningxia	39.4	1.4	6.1	24.9	11.8
Xinjiang	163.0	5.6	27.7	107.1	48.6

Supplementary Table 16 Total N losses from staple crop production (kg N province^{-1}) under Straw-CH_4-N in each province in China

Province	NH_3 emissions	N_2O emissions	NOx emissions	N leaching	N runoff
Beijing	4.5	0.2	0.4	2.5	1.7
Tianjin	25.0	0.9	3.0	13.4	9.6
Hebei	388.6	12.5	50.4	243.8	147.3
Shanxi	135.3	4.4	16.4	90.7	50.2
Inner Mongolia	337.5	10.8	33.1	185.4	131.4
Liaoning	203.5	7.2	21.7	88.2	82.1
Jilin	280.0	8.6	29.2	122.8	116.7
Heilongjiang	532.1	16.6	60.0	241.3	217.1
Shanghai	10.3	0.4	1.2	2.1	5.1
Jiangsu	327.2	8.9	41.5	139.5	122.5

Zhejiang	42.6	1.2	5.2	12.2	15.4
Anhui	350.5	10.5	45.2	140.0	138.2
Fujian	34.7	0.9	4.2	9.1	11.1
Jiangxi	186.5	5.5	21.5	34.3	67.1
Shandong	591.8	20.4	75.6	295.9	225.5
Henan	496.4	15.3	65.8	313.3	212.3
Hubei	189.8	5.3	26.0	82.6	70.6
Hunan	198.2	5.3	25.8	44.1	69.0
Guangdong	115.8	3.8	12.6	30.1	42.8
Guangxi	153.8	5.2	16.1	62.2	52.8
Hainan	12.8	0.4	1.5	2.4	4.9
Chongqing	71.2	2.1	7.6	28.2	24.9
Sichuan	241.8	7.3	27.1	99.4	88.2
Guizhou	86.5	3.0	9.1	53.2	29.4
Yunan	236.2	9.3	23.0	228.3	76.8
Tibet	2.0	0.1	0.3	0.9	0.9
Shaanxi	144.1	5.0	18.1	157.1	48.6
Gansu	156.4	6.0	17.8	180.3	48.1
Qinghai[a]	5.2	0.2	0.7	3.0	2.4
Ningxia	41.0	1.3	4.2	25.1	15.2
Xinjiang	169.4	4.9	20.0	108.0	61.6

Supplementary Table 17 Total N losses from staple crop production (Gg N province^{-1}) under Biochar-CH_4-N in each province in China

Province	NH_3 emissions	N_2O emissions	NOx emissions	N leaching	N runoff
Beijing	4.0	0.1	0.4	1.9	1.0
Tianjin	22.0	0.7	2.6	10.3	5.8
Hebei	349.2	9.9	44.2	185.1	97.8
Shanxi	126.0	3.7	14.3	70.1	35.7
Inner Mongolia	306.9	7.9	28.4	139.2	74.9
Liaoning	186.4	5.6	18.9	70.7	49.2
Jilin	256.3	6.6	25.5	94.5	68.2
Heilongjiang	477.0	13.7	54.0	186.9	120.1
Shanghai	8.2	0.2	1.1	1.5	2.1
Jiangsu	272.1	7.3	37.3	100.2	73.2
Zhejiang	35.5	1.1	5.1	9.6	8.5
Anhui	297.8	8.8	40.3	107.0	90.7
Fujian	29.5	0.9	4.0	7.5	6.8
Jiangxi	155.5	4.7	20.1	28.0	38.9
Shandong	526.9	16.3	65.8	228.9	148.4
Henan	438.5	11.5	57.3	204.5	144.6
Hubei	161.5	5.5	24.4	66.9	43.7
Hunan	167.1	5.5	25.2	36.0	39.5
Guangdong	97.6	2.9	12.0	24.5	24.8
Guangxi	135.5	4.2	14.9	50.5	34.1
Hainan	10.8	0.3	1.5	2.0	3.0
Chongqing	62.7	1.8	6.9	22.2	14.9
Sichuan	214.4	6.6	24.6	79.5	55.5

Guizhou	78.4	2.7	8.2	43.6	20.1
Yunan	217.4	8.0	20.1	180.2	50.1
Tibet	1.7	0.0	0.2	0.6	0.6
Shaanxi	132.4	4.5	15.9	121.1	36.0
Gansu	143.9	5.4	15.4	137.1	35.0
Qinghai[a]	4.4	0.2	0.6	2.4	1.9
Ningxia	36.5	0.9	3.7	18.2	8.9
Xinjiang	149.1	3.7	17.3	75.7	38.0

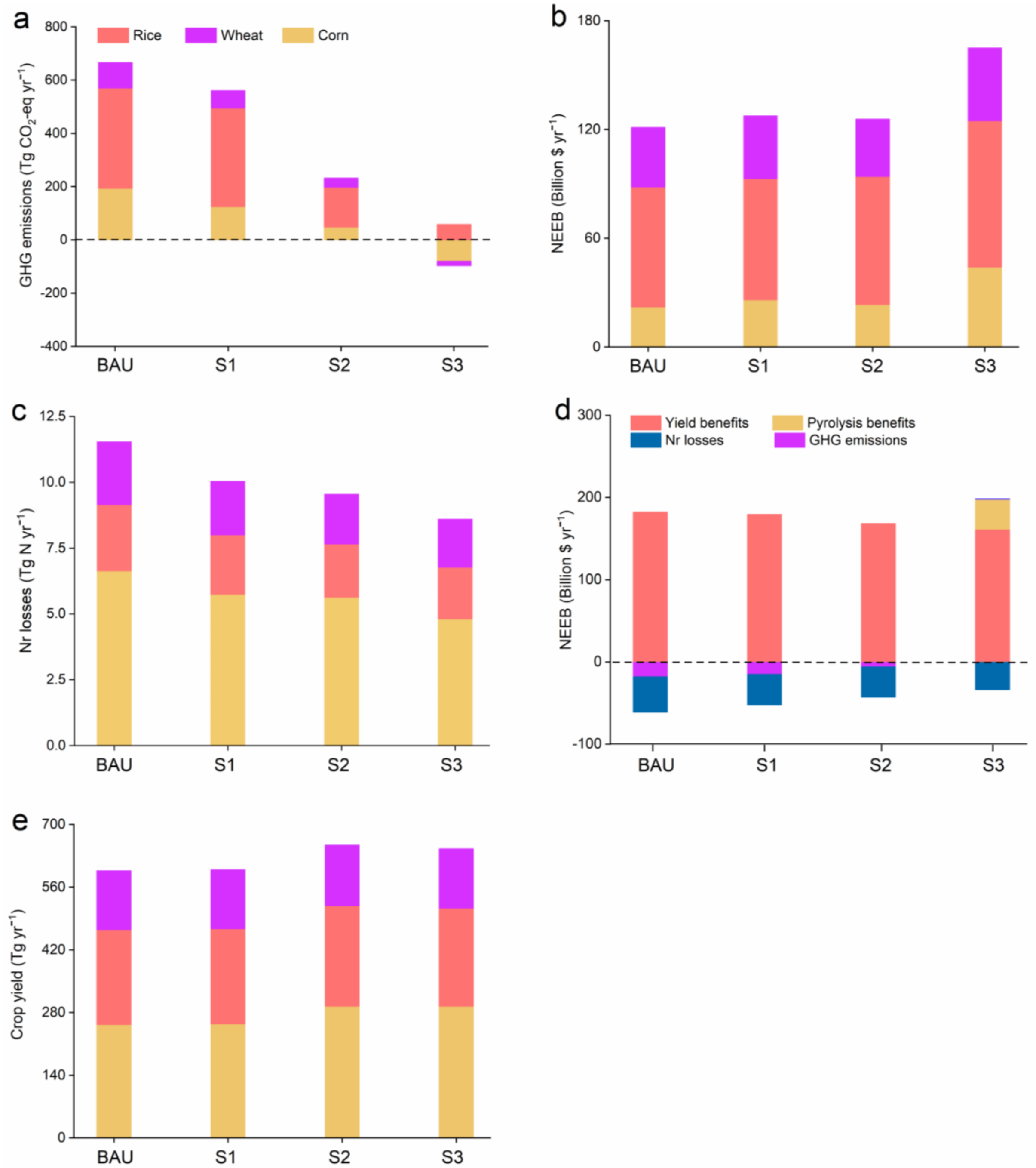
Supplementary Table 18 Total N losses from staple crop production (Gg N province^{-1}) under IPEG-CH_4-N in each province in China

Province	NH_3 emissions	N_2O emissions	NOx emissions	N leaching	N runoff
Beijing	3.8	0.1	0.3	1.5	0.8
Tianjin	21.3	0.5	1.9	8.4	4.7
Hebei	336.6	8.1	33.7	149.6	82.8
Shanxi	118.6	3.0	11.1	57.2	30.3
Inner Mongolia	293.1	7.1	21.7	111.1	76.2
Liaoning	175.6	4.5	12.6	59.1	42.7
Jilin	244.5	5.6	17.3	79.3	67.0
Heilongjiang	457.3	9.9	32.4	153.4	109.0
Shanghai	8.5	0.2	0.6	1.4	1.6
Jiangsu	281.0	5.4	25.5	87.7	59.9
Zhejiang	36.6	0.7	2.9	8.3	6.7
Anhui	304.3	6.8	27.6	94.4	73.7
Fujian	29.1	0.5	2.5	6.8	6.9
Jiangxi	155.5	3.3	11.3	28.2	39.6
Shandong	510.8	13.3	50.9	189.2	124.5
Henan	435.0	10.9	44.5	197.3	136.3
Hubei	163.9	3.2	14.8	56.4	36.9
Hunan	171.8	3.0	12.7	32.4	31.0
Guangdong	96.2	2.3	7.2	22.7	25.1
Guangxi	128.8	3.3	9.6	44.0	33.6
Hainan	10.8	0.3	0.9	2.0	3.0
Chongqing	61.2	1.2	4.2	18.0	11.2
Sichuan	208.7	4.4	15.6	66.5	44.9
Guizhou	75.2	1.9	5.3	33.9	14.9
Yunan	202.2	5.4	13.8	126.4	37.1
Tibet	1.8	0.0	0.2	0.6	0.6
Shaanxi	124.2	3.1	11.7	88.1	26.1
Gansu	134.5	3.6	11.3	95.8	24.9
Qinghai[a]	4.5	0.1	0.5	2.2	1.6
Ningxia	34.9	0.8	2.6	14.5	7.4
Xinjiang	144.2	2.9	12.8	59.6	31.4

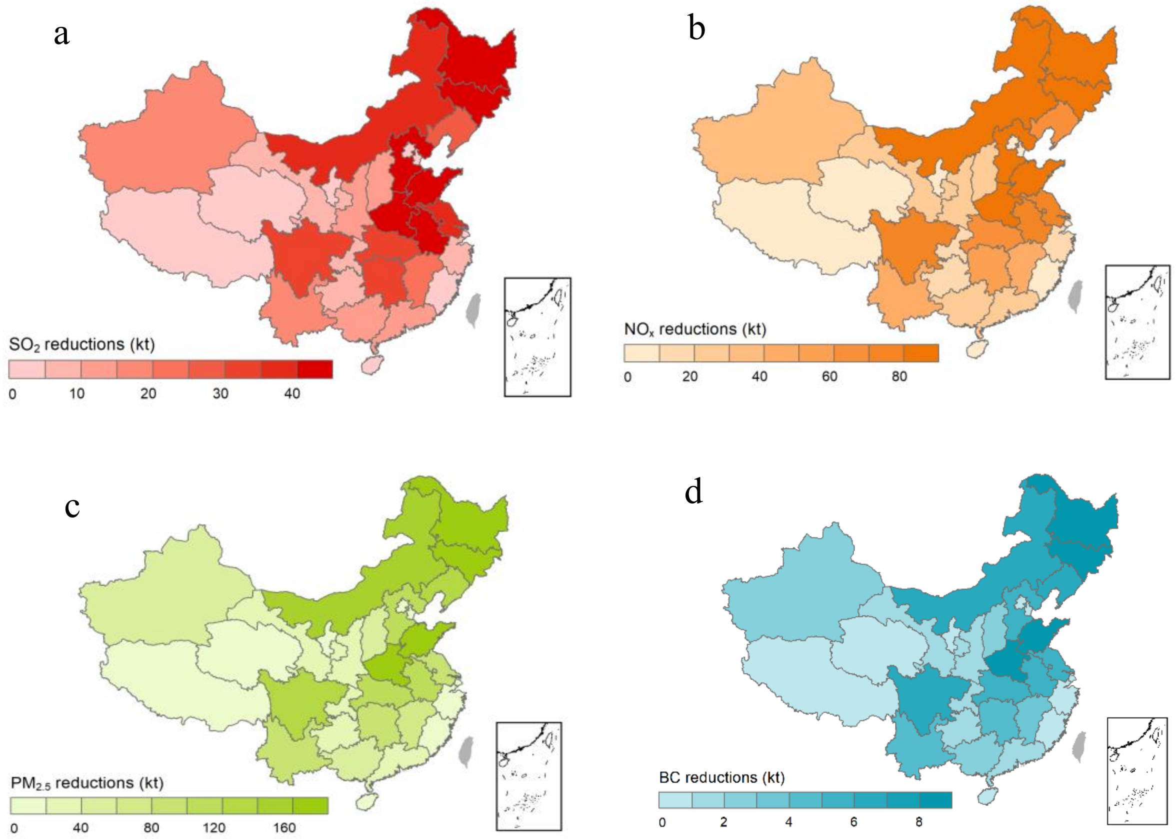
Supplementary Table 19 Price of food products and various agricultural economic inputs

Category	Cost or price
N fertilizer	0.55 US$ kg^{-1} N
P fertilizer	0.44 US$ kg^{-1} P_2O_5
K fertilizer	0.58 US$ kg^{-1} K_2O
Organic fertilizer	0.29 US$ kg^{-1} N
Diesel oil	0.91 US$ kg^{-1}
Pesticides	3.81 US$ kg^{-1}
Plastic film	1.48 US$ kg^{-1}
Electricity	0.08 US$ kWh^{-1}
Biochar	270 US$ t^{-1}
Rice labor	0.09 US$ kg^{-1} rice
Flour labor	0.08 US$ kg^{-1} wheat
Fodder labor	0.07 US$ kg^{-1} corn
Labor costs for biochar application	15.2 US$ t^{-1} ha^{-1}
Rice price	0.53 US$ kg^{-1}
Wheat price	0.47 US$ kg^{-1}
Corn price	0.32 US$ kg^{-1}

The data regarding agricultural inputs and labor cost and price of various food products was obtained from the website of National Bureau of Statistic of the People's Republic of China (http://www.stats.gov.cn/) and National Product Cost Survey (http://www.npcs.gov.cn/).



Supplementary Figure 6. Total GHG emissions, Nr losses, crop yield and net environmental and economic benefits (NEEB) from staple crop production under different scenarios in China. Straw-CH_4-N (S1), Biochar-CH_4-N (S2) and IPEG-CH_4-N (S3).



Supplementary Figure 7. The reductions in air pollutants (SO_2, $PM_{2.5}$, NO_X and BC) emissions induced by IPEG-CH_4-N.

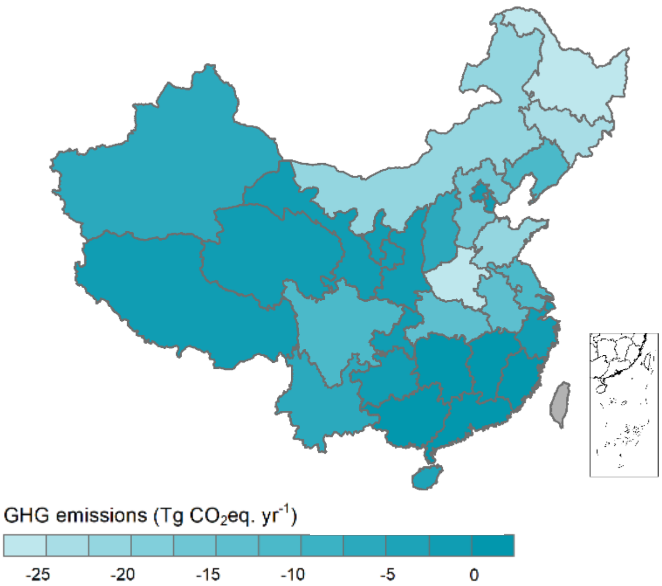
Supplementary Note 6: Maximum GHG mitigation potential under IPEG-CH_4-N

On average, 72% of provincial staple crop straw was required to feed the IPEG system to achieve carbon neutrality for staple food production in 2018 under IPEG-CH_4-N (Supplementary Table 11). Here, we further calculated the maximum GHG mitigation potentials by assuming that all the staple crop residues (except for those used for livestock feed) (82%) were used in accordance with the IPEG-CH_4-N. We found that total GHG emissions would be reduced from current 666 to a net GHG reduction of 236 Tg CO_2-eq yr^{-1} and the total reductions (902 Tg CO_2-eq yr^{-1}) can offset 8.5% of the total national emissions (Supplementary Table 20 and Supplementary Figure 8), together with higher crop yields and environmental benefits. Therefore, as the bioenergy with carbon capture and storage (BECCS) systems continue to develop, the implementation of IPEG-CH_4-N at large scales could result in a more prompt reduction in GHG emissions from agricultural production in China with better environmental and economic benefits.

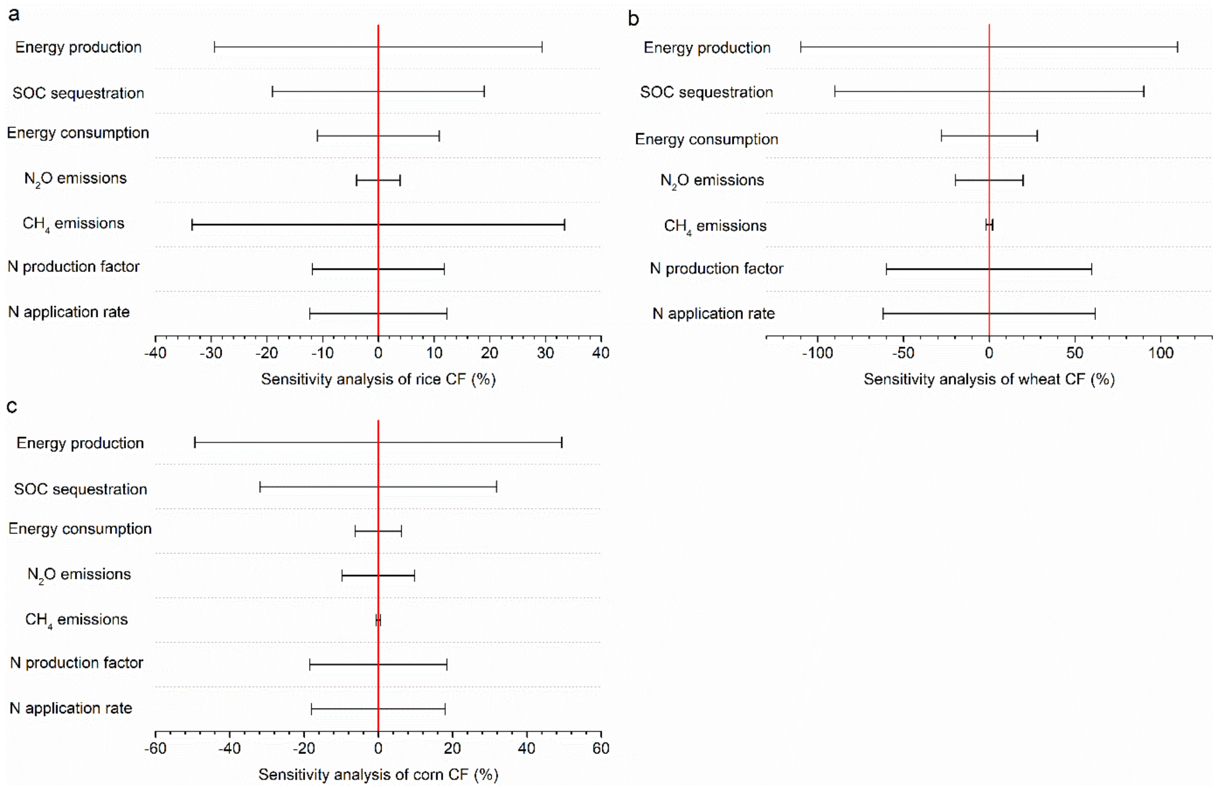
Supplementary Table 20 The maximum mitigation potentials of IPEG-CH_4-N on staple crop production in China

Scenarios	GHG emissions ($Tg\ CO_2\ yr^{-1}$)	Nr losses ($Tg\ N\ yr^{-1}$)	Crop yield ($Tg\ yr^{-1}$)	NEEB (billion US\$ yr^{-1})
BAU	666.5	11.5	596.8	121.3
Straw-CH_4-N	560.9	10.0	599.0	127.6
Biochar-CH_4-N	232.7	9.6	653.9	125.9
IPEG-CH_4-N	-38.0[a]	8.6	646.1	165.1
IPEG-CH_4-N (Maximum potential)	-236.1[a]	8.3	652.5	188.1

[a]Negative values denote the net GHG reduction effect attributed to the IPEG-CH_4-N.



Supplementary Figure 8. Maximum mitigation potential of IPEG-CH_4-N on net GHG emissions from staple food production in China.



Supplementary Figure 9. Sensitivity analysis of carbon footprint (CF) of staple food production in China under the scenario of IPEG-CH_4-N. Error bars indicate 95% confidence interval (CI) generated through Monte Carlo simulations, and data are presented as mean values +/- 95% CI. For sensitivity analysis, we assumed a CV of 30% for the 7 key components to individually evaluate how CF of staple food production in China responses to the changes in the single key component based on a Monte Carlo simulation. We found that CH_4 emissions from paddy fields and energy production from IPEG system are the two most sensitive factors determining rice CF. In contrast, energy production from IPEG system and SOC sequestration associated with biochar application are the two most sensitive factors determining wheat and corn CF.

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