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Greenhouse gas intensity of three main crops and implications for low-carbon agriculture in China

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1 **Title Page**

2 **Title**

3 Greenhouse gas intensity of three main crops and implications for low-carbon agriculture in China

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17 **Abstract:**

18 China faces significant challenges in reconciling food security goals with the objective of becoming a
19 low-carbon economy. Agriculture accounts for approximately 11% of China's national greenhouse gas
20 (GHG) emissions with cereal production representing a large proportion (about 32%) of agricultural
21 emissions. Minimizing emissions per unit of product is a policy objective and we estimated the GHG
22 intensities (GHGI) of rice, wheat and maize production in China from 1985 to 2010. Results show
23 significant variations of GHGIs among Chinese provinces and regions. Relative to wheat and maize,
24 GHGI of rice production is much higher owing to CH₄ emissions, and is more closely related to yield
25 levels. In general, the south and central has been the most carbon intensive region in rice production
26 while the GHGI of wheat production is highest in north and northwest provinces. The southwest has
27 been characterized by the highest maize GHGI but the lowest rice GHGI. Compared to the baseline
28 scenario, a 2% annual reduction in N inputs, combined with improved water management in rice
29 paddies, will mitigate 17% of total GHG emissions from cereal production in 2020 while sustaining
30 the required yield increase to ensure food security. Better management practices will entail additional
31 gains in soil organic carbon further decreasing GHGI. To realize the full mitigation potential while
32 maximizing agriculture development, the design of appropriate policies should accommodate local
33 conditions.

34 **Key words:** food security, low-carbon agriculture, greenhouse gas intensity, China

35 **1. Introduction**

36 China has made substantial efforts to increase crop production to feed about 20% of the global
37 population with only 8% of the world's arable land (World Bank 2013). Looking towards 2020, the
38 government has set a target of increasing the national grain production capacity to over 545 Mt from
39 497 Mt in 2010 to meet the growing demand for higher animal protein diets and to
40 maintain the domestic food self-sufficiency rate at 95%. This implies that average grain yield must
41 grow by at least 0.9% annually in the period 2011-2020. However, Chinese agriculture is grappling
42 with related constraints in terms of limited arable land, declining water availability, an increasing
43 opportunity cost of rural labour and increasing vulnerability to climate change (Fan et al. 2011). The
44 sector is also a significant source of anthropogenic greenhouse gases (GHG) emissions emitting
45 approximately 820 Mt CO₂ equivalent (CO₂e) in 2005, or 11% of the national total (NCCC 2012).
46 Cropland N₂O emissions produced in soils through the microbial processes of nitrification and
47 denitrification was responsible for 25.3% of agriculture GHG emissions in 2005 and CH₄ emissions
48 from rice cultivation contributed 20%. Cereal production (rice, wheat and maize) accounted for about
49 47% of national N fertilizer consumption (Heffer 2009) and generated around 32% of GHG emissions
50 from agriculture.

51 Agriculture is also under increasing scrutiny to mitigate climate change through both emissions
52 reduction and carbon sequestration. The Ministry of Agriculture (MOA) has initiated programs to
53 improve fertilizer use efficiency by 3% and enhance irrigation water use efficiency by 6% by 2015
54 from 2010. The government also plans to bring an additional 11.3 Mha of croplands under
55 conservation tillage between 2009-2015 in north China (MOA 2009). The aim of integrating
56 mitigation into agriculture translates into a reduction in GHG intensity (GHGI), expressed as the
57 overall GHG emissions per unit of product (Chen et al. 2011; Venterea et al. 2011; Tubiello et al. 2012).
58 Applying this indicator can encourage better practices resulting in higher crop yields and reduced N
59 losses and GHG emissions, which is vital to pursue low carbon development in agriculture (Norse
60 2012).

61 FAO (Tubiello et al. 2014) reported that over the period 1961-2010 the world average GHGI of
62 rice decreased by 49% while that of wheat and maize increased by 45%, suggesting that effective
63 mitigation strategies are needed to achieve sustainable intensification; i.e. ensuring that efficiency
64 improvements can lead to reduced absolute emissions. Bonesmo et al. (2012) investigated the GHGI of

65 95 arable farms in Norway, showing that increased gross margins in grain and oilseed production
66 could be achieved with decreasing GHGI. The GHGIs of cereal production on experimental sites were
67 also quantified in China indicating that economic and climate benefits can be simultaneously achieved
68 by some improved management practices (Shang et al. 2011; Huang et al. 2013; Ma et al. 2013). But
69 to date there is no synthetic estimate of current and historical GHGI of cereal production on a national,
70 regional or provincial level in China. Such information is crucial for identifying efficient regional
71 mitigation strategies and actions tailored to local agricultural production systems and management
72 practices.

73 This paper estimates GHGI for rice, wheat and maize production using data for the national,
74 regional and provincial scale for 2006. Illustrating the trends and evolution of intensity we quantify
75 national and regional GHGI from 1985 to 2010 at 5-year intervals and analyze emission reduction and
76 carbon sequestration potentials from cereal production. The analysis informs potential national or
77 regional policies to foster sustainable intensification in rural China.

78 2. Materials and methods

79 2.1. Methodology

80 GHGI is calculated by dividing total Global Warming Potential (GWP)-weighted emissions from
81 cereal production by crop yield (Eqn (1)). N₂O emissions are accounted for quantifying GHGI of
82 wheat and maize production while both CH₄ and N₂O are considered for rice paddies. Carbon
83 sequestration is not directly included in the estimate due to large uncertainties in soil organic carbon
84 (SOC) content and limited data availability. Despite consensus on the average SOC increment in
85 China's cropland, discrepancies in annual intensity change rates have been reported using various
86 methods (Pan et al. 2010; Sun et al. 2010; Yan et al. 2011; Yu et al. 2012). Nevertheless, SOC change
87 patterns and interactions with GHGI will be analyzed in the discussion section. The analysis focuses
88 on emissions within the farm gate, i.e. they are not full life-cycle assessment (e.g. emissions related to
89 energy use and fertilizer manufacture and transportation).

90 We followed IPCC Guidelines (IPCC, 2006) to estimate direct N₂O emissions from the three
91 major N input sources - synthetic fertilizers, organic manure and crop residues. Although indirect N₂O
92 emissions via N deposition and nitrate leaching and runoff could be significant depending on the local
93 conditions (e.g. Venterea et al. 2011; Maharjan et al. 2014), especially in cases where there is a high rate
94 of N application, they were not taken into account into this study due to high uncertainty. Quantification
95 of CH₄ emissions from rice paddies was based on regional CH₄ flux.

$$\begin{aligned} GHGI &= I_{N_2O} + I_{CH_4} = \frac{Emissions_{N_2O} + Emissions_{CH_4}}{Yield} \\ Emissions_{N_2O} &= N_2O - N_{input} \cdot EF_1 \cdot \frac{44}{28} \cdot GWP_{N_2O} \\ Emissions_{CH_4} &= Flux_{CH_4} \cdot GWP_{CH_4} \\ N_2O - N_{input} &= F_{SN} + F_{AW} + F_{CR} \end{aligned} \quad (1)$$

97 Where: GHGI (kgCO₂e/t); I_{CH₄} is the intensity of CH₄ emissions in rice paddies and I_{N₂O} is the
98 intensity of N₂O emissions (kgCO₂e/t); Emissions_{N₂O} is the N₂O emissions from rice, wheat or maize
99 fields (kgCO₂e/ha); Emissions_{CH₄} represent the CH₄ emissions from rice paddies(kgCO₂e/ha); Yield
100 denotes the per hectare average production (t/ha); N₂O-N_{input} represents the total N inputs (kgN/ha);
101 EF₁ is the emission factor for N₂O emissions from N inputs (kg N₂O-N/kg N input); 44/28 is to
102 convert emissions from kg N₂O-N to kg N₂O; Flux_{CH₄} represents the CH₄ flux from rice paddies
103 (kgCH₄/ha); GWP_{N₂O} and GWP_{CH₄} denote the direct GWP of N₂O and CH₄ at the 100yr horizon, 298

104 and 25; F_{SN} , F_{AW} , F_{CR} represent N inputs from synthetic fertilizers, animal manure and crop residues,
105 respectively (kgN/ha).

106 Detailed equations for calculating N inputs from animal manure (F_{AW}) and crop residues (F_{CR}) are
107 presented in Annex A.

108 2.2. Data sources

109 Agriculture activity data were collected at the provincial level while emission factors and other
110 parameters (e.g. IPCC default factors) were average national values. In other words, data for
111 N_2O-N_{input} in Eqn (1) are province-specific and $Flux_{CH_4}$ are region-specific, while other factors were
112 held identical among provinces. Regions in China refer to northeast, north, northwest, east, south and
113 central, and southwest China, each of which includes 3-7 provinces/municipalities. Farming activity
114 data (cropping area, production, yield and total N fertilizer consumption) were extracted from the
115 China Rural Statistical Yearbooks (MOA 1986-2013). Per hectare N application rates for individual
116 crops were collected from the China Agricultural Products Cost-Benefit Yearbooks (NDRC
117 2001-2011), which are the sum of N fertilizer (pure nutrient) and 30% N fraction in compound and
118 mixed fertilizers. To calculate the national and provincial GHGI in 2006, we used the three-year
119 average of 2005-2007 to represent 2006 conditions to avoid large inter-annual variations.
120 China-specific emission factors for direct N_2O emissions from croplands were obtained from Gao et al.
121 (2011), which are 0.0105 and 0.0041 for upland and rice paddies, respectively. CH_4 fluxes of rice
122 paddies in each region were direct CH_4MOD modeled results from studies by Zhang et al. (2011a),
123 which were employed for compiling National GHG Emission Inventories.

124 For estimating N inputs from animal manure, livestock numbers and the fraction of grazing
125 animals were derived from the China Livestock Yearbooks (MOA 2001-2011) while other information
126 required was selected from relevant literature and IPCC default values corresponding to conditions in
127 China as displayed in Table S1. Estimation of N inputs from crop residues were mainly based on
128 values reported by Gao et al. (2011) summarized in Table S2. Detailed information for data selection is
129 provided in Annex B.

130 Regional level SOC data in 2010 were derived from Yu et al. (2013) to represent 2006 levels, and
131 historic SOC contents were derived from similar research by Yu et al. (2012).

132 2.3. Design of emission scenarios for future cereal production

133 To project total GHG emissions and investigate mitigation potential from cereal production in China to
134 2020, we designed four agricultural management scenarios based on historical trends and the increase
135 in expected future productivity. Total GHG emissions shall be affected by the GHGI and grain
136 production, or N input and CH₄ flux levels, yield and cultivated area of each crop.

137 To focus on the impacts of GHGI change on overall emissions, cultivated area of each crop were
138 assumed constant from 2010 to 2020. In all scenarios, 0.5%, 1% and 1.5% annual increase in yield
139 were assigned for rice, wheat and maize respectively, based on 2005-2013 yield data released by the
140 MOA (2006-2013). S0 is a conservative scenario that prescribes the same proportion of increase in N
141 input relative to yield improvement. Scenario S1 assumes that no further N input is required to sustain
142 equal productivity as in S0, while the N rate decreases by 1% per year under S2. Scenario S3 is an
143 optimal scenario incorporating best management practices to cut the overall N rates and improve the
144 irrigation regimes in rice paddies while achieving the yield requirements for safeguarding national
145 food self-sufficiency (annual N input decrease at 2% and CH₄ flux decrease at 1%). The annual rates
146 of change for these factors over 2010-2020 are summarized in Table 1.

147 **3. Results and discussions**

148 3.1. GHGI of rice production in 2006

149 GHGI of rice production in 2006 ranged from 730 kgCO₂e/t in Ningxia Province to 1,549 kgCO₂e/t in
150 Hainan Province, with a national average of 947 kgCO₂e/t (Fig. 1a). In general, CH₄ made up about
151 90% of the total GHG emissions and was therefore the dominant gas in determining the carbon
152 footprint of rice cultivation. Consequently, there was no obvious relationship between GHGI levels
153 and N application rates, the latter being the major source of N₂O emissions. For example, the Jiangsu
154 Province in east China received 51% higher N application than national average in rice production but
155 was moderate in GHGI (16% lower than national average). It is, however, evident that the estimated
156 GHGI for rice production was negatively correlated with yield levels. There was a large provincial
157 variation in GHGI (Fig. 2a) with the most carbon intensive provinces located in the southeast coastal
158 areas due to the highest regional CH₄ flux (250 kg/ha) because of higher temperature and greater level
159 of organic matter input (Zhang et al. 2011a). The low GHGI in the southwestern provinces (Sichuan,
160 Chongqing, Guizhou and Yunnan) can be attributed to lower CH₄ flux (200 kg/ha) relative to other
161 places (215-250 kg/ha) because of low levels of organic matter application and rice biomass
162 productivity. Among the six major rice producing provinces, which accounted for 55% of the national
163 production, Hunan and Jiangxi had higher GHGIs than the national average, while Hubei, Jiangsu,
164 Sichuan and Heilongjiang were below the national mean.

165 3.2. GHGI of wheat and maize production

166 The national average GHGI of wheat (Fig. 1b) and maize (Fig. 1b) for 2006 production were 265 and
167 230 kgCO₂e/t, respectively. Large spatial variability can be observed among provinces. For example,
168 producing one ton of wheat in Ningxia emitted 3 times more N₂O than in Heilongjiang, attributable to
169 significant differences in synthetic N input and wheat and maize yields between Chinese provinces. In
170 general, synthetic N fertilizer made up at least 70% of total emissions and was therefore the primary
171 emission contributor. Fig. 1(b, c) also shows that the trends of GHGI, which are affected by
172 place-specific yield levels, were not necessarily consistent with those of per hectare N application rates.
173 For instance, although the N application rate for maize in Ningxia (280 kgN/ha) was 30% higher than
174 in Guangxi (215 kgN/ha), a much higher yield in Ningxia (6.97t/ha) than in Guangxi (3.88 t/ha) results

175 in a lower maize GHGI in Ningxia. In contrast, a high N rate and low wheat productivity made
176 Ningxia the most carbon intensive province for wheat cultivation.

177 The geographic variations of GHGIs of wheat (Fig. 2b) and maize (Fig. 2c) show both similarities
178 and differences. In general, similar levels of GHGI can be observed for wheat and maize production
179 (except for Ningxia); e.g. Yunnan was one of the most carbon intensive areas for both wheat and maize
180 production in 2006. More N fertilizers were added to croplands in the northwest provinces to
181 compensate poor soil fertility, resulting in elevated regional GHGI of wheat and maize production. The
182 levels of maize GHGI converged to the range of 200-300 kgCO₂e/t, with obvious correlation with N
183 rates and yields. Provincial discrepancies were more evident for wheat GHGI, implying that farmers
184 were potentially more rational in determining the fertilizer amount for maize than for wheat. Among
185 the five major wheat producing areas - Henan, Shandong, Hebei, Anhui and Jiangsu, which
186 contributed about 73% of the national production, GHGI levels in Hebei and Jiangsu were superior to
187 the national average. Among the major maize producing areas, only Hebei had a higher GHGI than the
188 national mean, while Jilin, Shandong, Henan and Heilongjiang were lower.

189 GHGIs at the provincial level were further integrated to the regional scale for 2006 and compared
190 with yields and SOC contents (Fig. S1) to indicate regional GHGI reduction strategies (Annex C).

191 3.3. Historical trends of regional GHGI of cereal production

192 Fig. 3a shows that national GHGI of rice production evolved at a different way to those of wheat and
193 maize production, and the latter has always been the least carbon intensive of the three crops. Rice
194 GHGI saw little variation between 1985 and 2000, which can be explained by nearly the same rate of
195 growth in the CH₄ flux, yield (Fig. 3b) as well as the N rate over this period. However, when rice yield
196 reached a periodic peak in 1998 the CH₄ flux continued to climb, resulting in a sharp rise in GHGI in
197 the first decade of the 21st century. Wheat and maize GHGIs had been steadily increasing from 1985 to
198 2000 since the growth rate of N application exceeded the rate of yield improvement. The GHGI began
199 to stabilize or even decrease after 2000 as the combined effects of increasing yields, albeit at a lower
200 rate, and a stabilized synthetic N rate promoted by the national “Soil testing and fertilizer
201 recommendation program” (MOA 2005) initiated in 2005. At the national level, there was also a
202 positive correlation between SOC improvement and cereal productivity increase (Fig. 3b) (Pan et al.
203 2009).

204 Fig.4 illustrates that nearly all regional GHGI of rice, wheat and maize production reached a
205 higher level in 2010 relative to 1985. For rice production (Fig. 4a), south and central and east regions
206 have consistently been the most carbon intensive areas due to favorable climate conditions and greater
207 level of organic matter application (Zhang et al. 2011a). In parallel, rice paddies in eastern, southern
208 and central China are found to have experienced the greatest SOC increase (Zhang et al. 2007; Pan et
209 al. 2010). In contrast, a lower level of crop residues, farm manure and green manure application
210 enabled the southwest to emit least GHG in producing same amount of rice.

211 For wheat production (Fig. 4b), all regions except north China exhibited the same trend as the
212 national average. Consequently, reducing N rates should be advocated in northern provinces,
213 confirming the findings of other experimental and theoretical studies (Ju et al. 2009, 2011). Maize
214 GHGI evolution patterns (Fig. 4c) were more diverse between geographic regions, with northeast
215 China having the lowest GHGI . The northwest has been characterized with the highest GHGI in both
216 wheat and maize production.

217 3.4. Ways to improve GHGI of cereal production while safeguarding food security

218 Integrated soil-crop management systems and better nutrient management techniques are advocated to
219 address the key constraints to yield improvement and alleviate environmental impacts (Fan et al. 2012;
220 Zhang et al. 2012). Extensive overuse of synthetic N fertilizers is well documented in China (Cui et al.
221 2010; Chen et al. 2011), resulting in significant losses and serious environmental externalities (Guo et
222 al. 2010). Zhang et al. (2013) suggest a possible 42% cut in nationwide N fertilizer use applying the
223 balance concept to equalize N input and above ground N removal. In parallel to optimal quantity,
224 application time, right placement and appropriate product are also essential to better nutrient
225 management. Adjusting basal/topdressing ratio of N fertilizers and popularizing fertilizer deep
226 placement could improve crop N uptake and minimize N losses compared with conventional practices
227 of applying largest proportion of N fertilizers on the surface before seeding (Cui et al. 2008; Zhang et
228 al. 2011b). Replacing a proportion of ammonium-based fertilizers with nitrate-based fertilizers can
229 also help minimize N₂O emissions and ammonia losses (Zhang et al. 2013). Nitrogen use efficiency
230 (NUE) can also be improved by applying fertilizers added with nitrification and/or urease inhibitors
231 and slow- and controlled-released fertilizers (Akiyama et al. 2010).

232 Better recycling of organic manures including animal excreta, crop residues and green manure

233 enables further improvement in NUE, SOC content and land productivity. Adopting conservation
234 tillage is found to be conducive to accumulate SOC density, improve water availability and reduce
235 water and wind erosion, especially on land of poor productivity (Xu et al. 2007; He et al. 2010). Such
236 practices shall be extended to wider areas supported by the MOA. Finally, biochar addition can be
237 beneficial to soil quality and yield increase therefore offering substantial mitigation potential when it
238 becomes economically available (Wang et al. 2014). As to CH₄ emissions from rice paddies,
239 upgrading irrigation regimes from mid-season drainage, currently being practiced in most rice
240 cultivation regions, to intermittent irrigation or controlled irrigation, could avoid as much as 1.256
241 CO₂e per hectare according to nationwide meta-analysis results (Wang et al. 2014).

242 In addition to mitigating climate change, some of these measures could actually be cost saving,
243 simultaneously reducing input costs and/or enhancing productivity (Wreford et al. 2010; Wang et al.
244 2014). Further, in recent decades SOC content of cropland has increased along with improved crop
245 yields in most regions of China (Pan et al. 2010; Yan et al. 2011; Yu et al. 2012). These findings
246 highlight the important role of cropland in achieving emission reduction, safeguarding food security and
247 enhancing carbon sequestration.

248 3.5. Implication for mitigation potential from cereal production

249 Fig. 5 illustrates that total GHG emissions from rice, wheat and maize production have grown by 12%
250 from 2005 to 2010 caused by an 11% increase in cropping area and a 5% increase in average yield (Fig.
251 3b). In the S0 baseline scenario, although yields improve at the same rate of increase in N inputs,
252 resulting in constant GHGI, total GHG emissions will still go up because of higher production levels.
253 However, if no more N input is needed to enhance yields, emissions will stop increasing (scenario S1)
254 and GHGIs will decrease. In contrast, if better fertilization practices are promoted to suppress the
255 overuse of N fertilizers, total emissions will decline (scenario S2) by 8% compared to S0. Scenario S3
256 assumes substantial efforts are dedicated to minimizing the GHGI of cereal production by eradicating
257 N over-application, adopting better water management in rice paddies and improving yield levels. In
258 this case, I_{N2O} of rice, wheat and maize shall decline by 2.5%, 3% and 3.4% respectively, and I_{CH4} by
259 1.5% annually. Under this scenario, total GHG emissions are estimated to be 224MtCO₂e, a 17%
260 decrease relative to S0 enabled by an 18% decrease in N input, 0.5-1.5% improvement in yields and 1%
261 cut in average CH₄ flux. Such a mitigation scenario is feasible since the 18% cut in N use falls under

262 the lower range of suggested 30-60% reduction (Ju et al. 2012; Zhang et al. 2013) and the 546 Mt
263 cereal production meets the target for ensuring national food security.

264 Apart from the emission reduction potential, SOC density is projected to continue to increase at a
265 rate of 0.4-0.48 tC/ha/yr in paddy soils and 0.16-0.22 tC/ha/yr in upland soils in the 2010s (Yu et al.
266 2013). This implies that even the C inputs (including manure and crop residue) to Chinese croplands
267 remain unchanged with no improvement in tillage practices, aggregate national SOC stocks will still
268 increase over the period 2010-2020. If improved agricultural management practices are widely adopted,
269 as much as 70MtCO₂ could be sequestered in the cropland soils. Carbon sequestration is therefore
270 able to compensate 31% of GHG emissions under scenarios S3.

271 **4. Conclusions**

272 A low carbon development pathway implies minimization of emissions while increasing food
273 production and GHGI is an indicator combining both objectives. As such it is a central element of any
274 definition of sustainable intensification (Godfray and Garnett 2104). Our results on the GHGI of rice,
275 wheat and maize production show that the southeast was the most carbon- intensive region in rice
276 production in terms of CH₄ emissions, while GHGI of wheat and maize were both high in most north
277 and northwest provinces due to the typical farming practices of farming systems in China. GHGI was
278 low for all the three crops in the northeast area. The substantial heterogeneities of GHGI among
279 provinces/regions and the inconsistency between trends of GHGIs and N application rates indicate
280 considerable scope for improving carbon performance of cereal production and that actions and
281 policies aiming to promote sustainable food production should be tailored to local conditions. Under
282 the BAU scenarios where food production must grow to meet the demand of about 1.45 billion
283 population, total GHG emissions will continue to increase albeit with constant GHGIs. Controlling
284 GHG emissions from arable land thus requires additional mitigation efforts. Most abatement practices
285 that improve crop yields will not only enable emission reductions but also improve soil fertility via
286 carbon sequestration, therefore providing a triple win. Such findings can inform a broad range of
287 policy, practitioner and investment discussions on GHG mitigation strategies, and can also serve as
288 benchmark values for allocating quotas or as the baseline for generating carbon credits for any
289 market-based mechanism.

290 Despite positive synergies with yield and soil fertility, abatement measures have not been widely
291 adopted by farmers due to economic, political and social factors. Required capacity and infrastructure
292 must be improved and agricultural extension service upgraded to lower GHGI and realize the
293 mitigation potential and land productivity and fertility improvement potential that agricultural
294 production offers.

295

296

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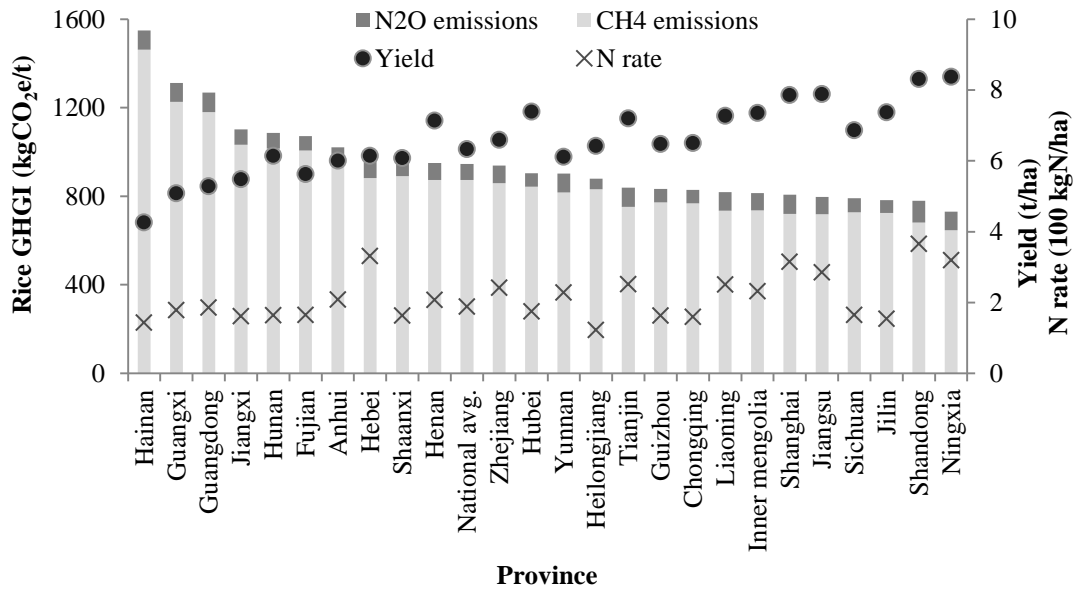
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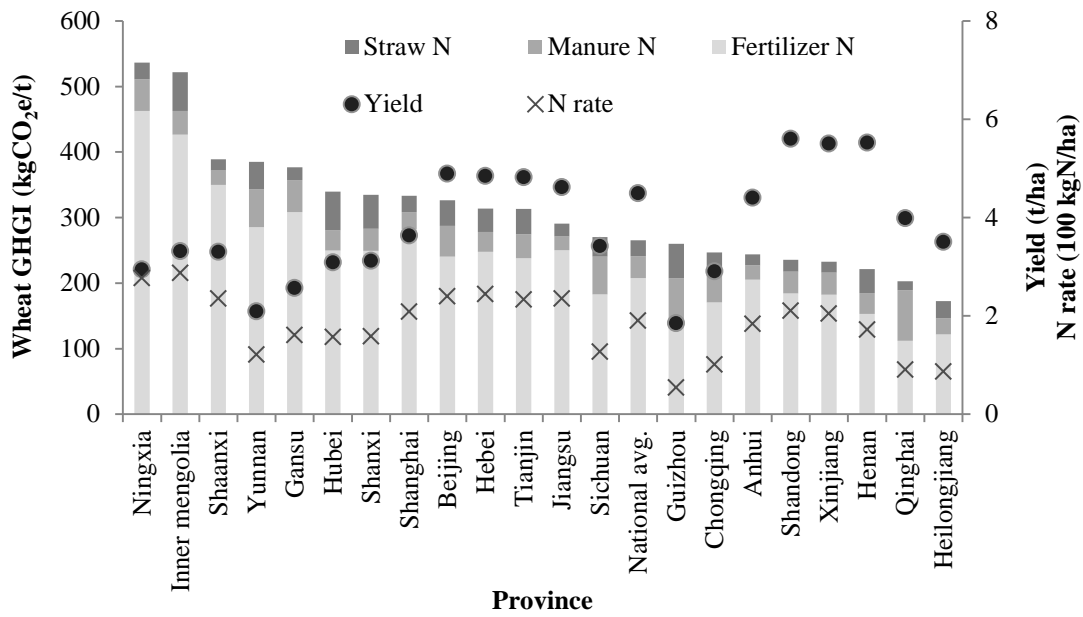
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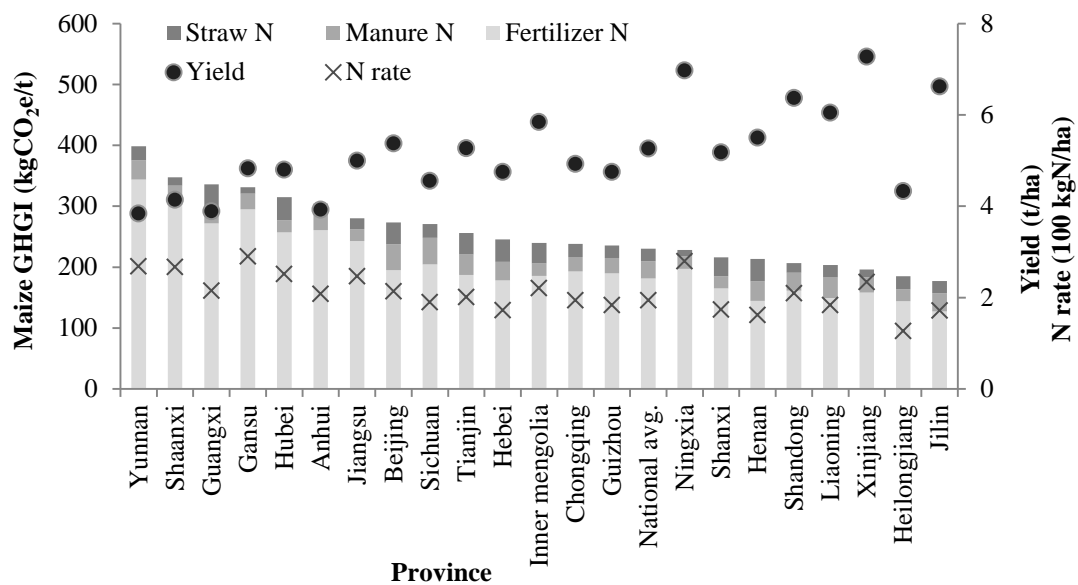
400 (a)



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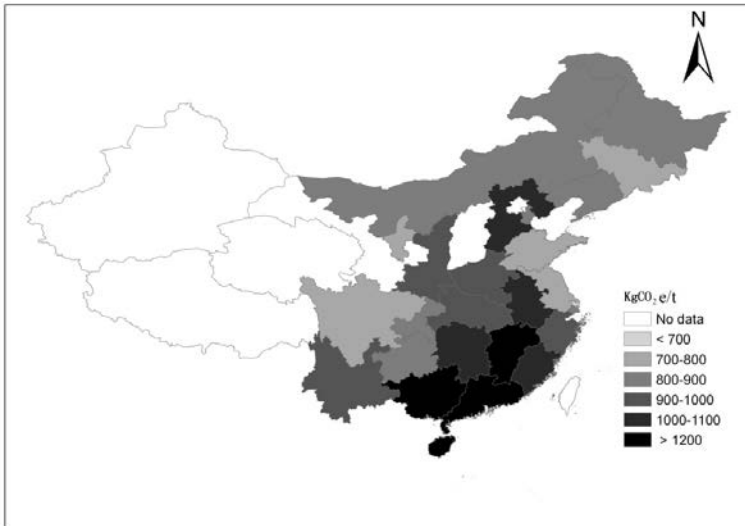


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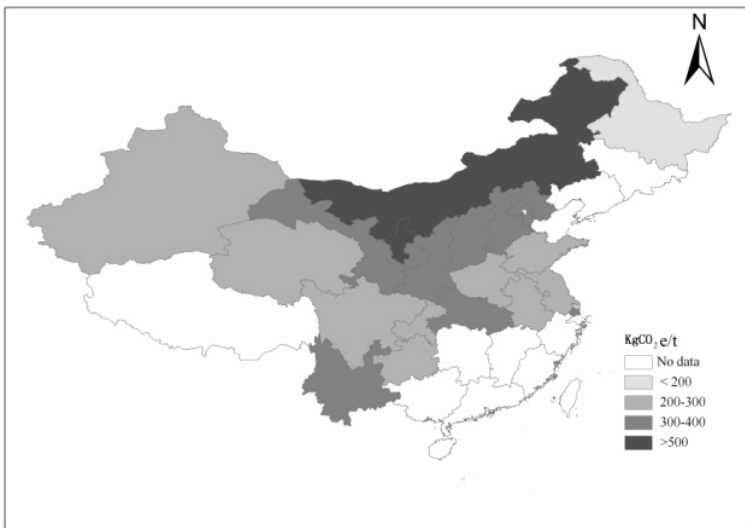
405 (c)

406 Fig.1 GHGI of rice (a), wheat (b) and maize (c) production in different provinces in 2006. The bars in
 407 (a) represent the contributions of N₂O and CH₄ to total GHGI; the bars in (b) and (c) represent the
 408 contributions of different N inputs to N₂O-derived GHGI.

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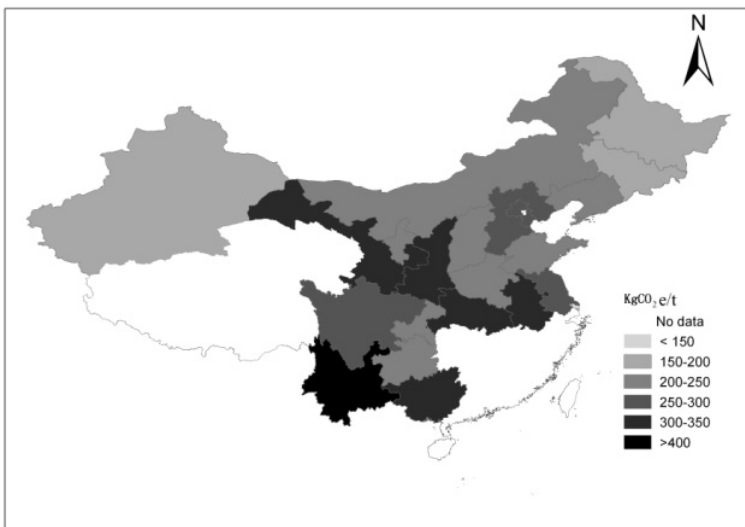


411 (a)



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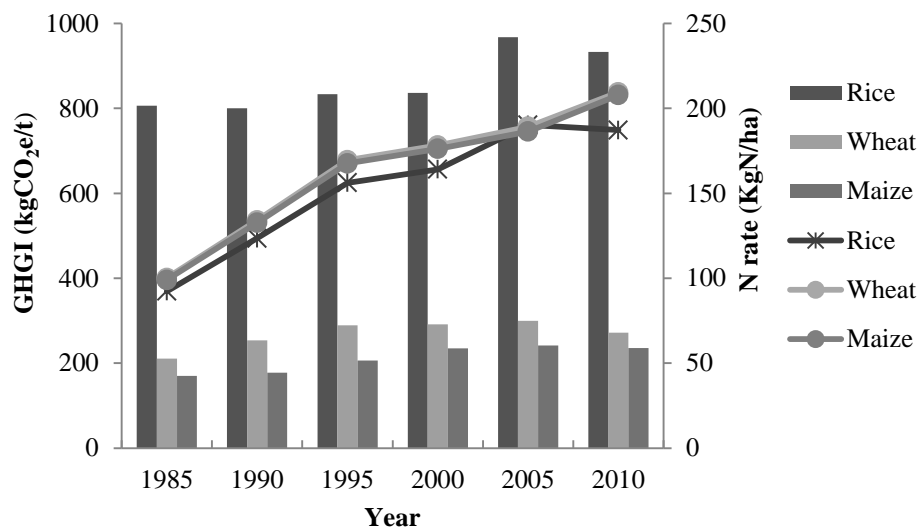


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415 (c)

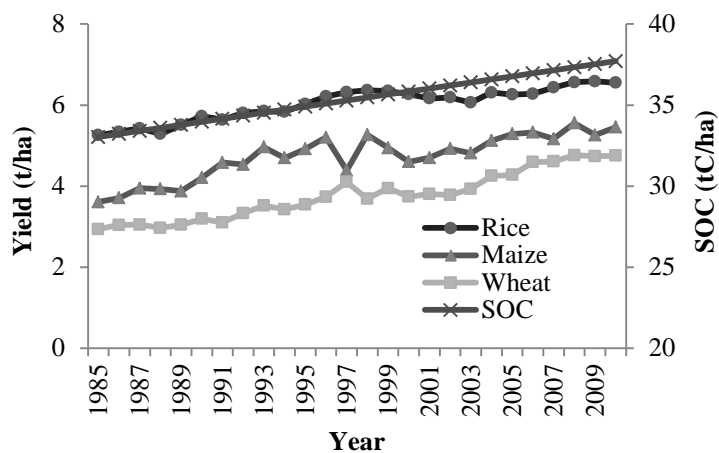
416 Fig.2 The provincial GHGI levels of rice (a), wheat (b) and maize (c) production for 2006

417



418

419 (a)



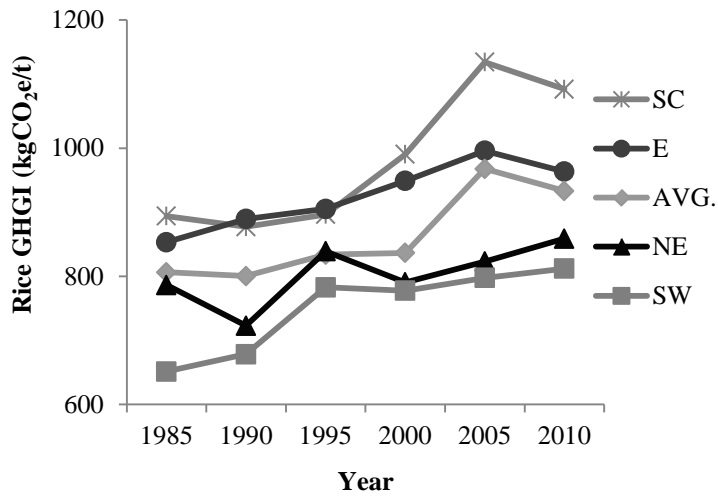
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421 (b)

422 Fig.3 Historical trends of national average GHGI (a) and yield (b) of rice, wheat and maize production

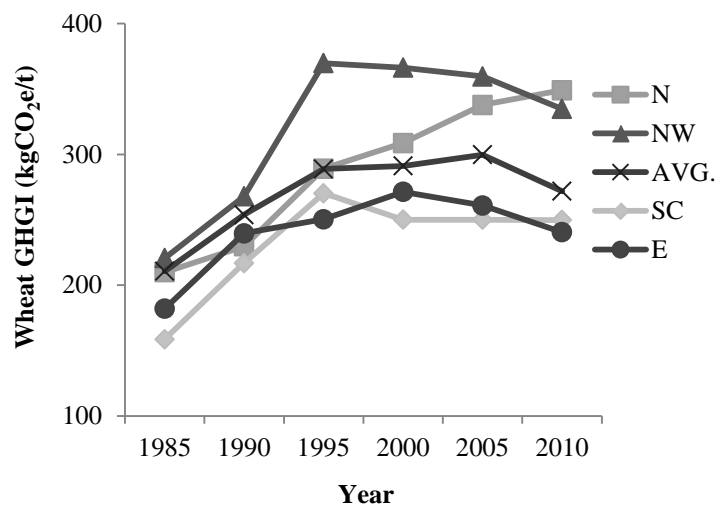
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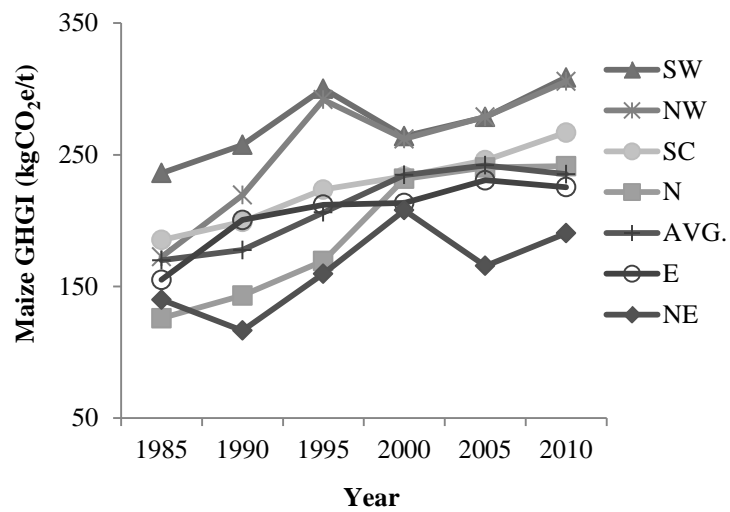
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426 (a)



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428 (b)



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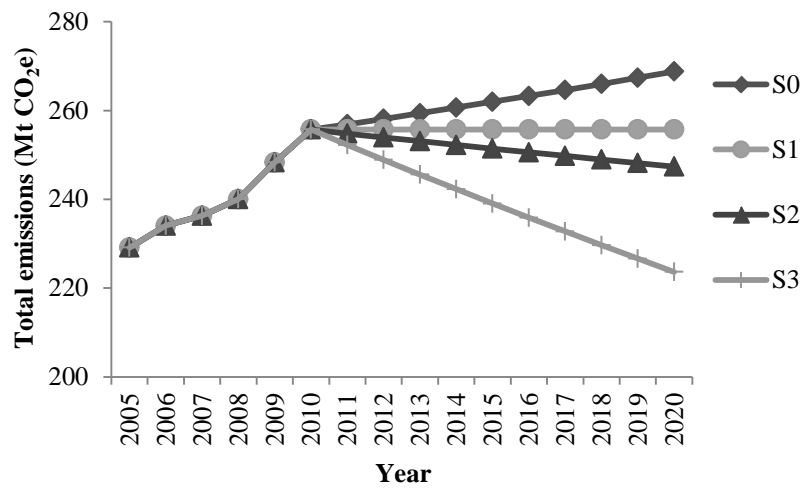
430 (c)

431

432 Fig.4 Historic evolution of regional GHGI of rice (a), wheat (b) and maize(c) production. NE, N, NW,
433 E, SC, SW and AVG refer to northeast, north, northwest, east, south and central, southwest China, and
434 national average, respectively.

435

436



437

438 Fig.5 Total GHG emission scenarios from rice, wheat and maize production to 2020 in China

439

440

441 Tables:

442 Table 1 Emission scenarios for cereal production (annual rates of change)

| Scenario | S0 | S1 | S2 | S3 |
|------------------|-------------|-------------|-------------|-------------|
| N_2O-N_{input} | rice +0.5% | Constant | rice -1% | rice -2% |
| | wheat +1% | | wheat -1% | wheat -2% |
| | maize +1.5% | | maize -1% | maize -2% |
| Yield | rice +0.5% | Same as S0 | Same as S0 | Same as S0 |
| | wheat +1% | | | |
| | maize +1.5% | | | |
| I_{N_2O} | Constant | rice -0.5% | rice -1.5% | rice -2.5% |
| | | wheat -1% | wheat -2.0% | wheat -3.0% |
| | | maize -1.5% | maize -2.5% | maize -3.4% |
| $Flux_{CH_4}$ | Constant | Constant | Constant | -1% |
| I_{CH_4} | -0.5% | -0.5% | -0.5% | -1.5% |
| Cropping area | Constant | Constant | Constant | Constant |

443

444 Note: changes in I_{N_2O} and I_{CH_4} are deduced from alterations in N_2O-N_{input} , $Flux_{CH_4}$ and Yield. According to
445 Eqn(1), I_{N_2O} and I_{CH_4} is proportional to N_2O-N_{input} and $Flux_{CH_4}$ respectively, and both are inversely proportional
446 to Yield.

Supplementary Material

Title: Greenhouse gas intensity of three main crops and implications for low-carbon agriculture in China

Journal: Climatic change

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Appendix A Estimation of N inputs from animal manure and crop residues

N inputs from animal manure (F_{AW}) was estimated following Eqn (S1).

$$F_{AW} = \frac{\sum_T N_T [(1 - \text{Frac}_{\text{Grazing}(T)}) \text{Nex}_T (1 - \text{Frac}_{\text{Loss}(T)})]}{CA_{eqv}} \quad (S1)$$
$$\text{Nex}_T = N_{\text{rate}(T)} \left[\frac{TAM_T}{1000} \right] \times 365$$
$$N_T = \text{Days_alive}_T \left[\frac{N_{S(T)}}{365} \right] \quad \text{if } \text{Days_alive}_T < 365$$
$$CA_{eqv} = a \times CA_{\text{veg}} + b \times CA_{\text{fruit}} + CA_{\text{other}}$$

N_T is the annual population of livestock T. T denotes livestock category. $\text{Frac}_{\text{Grazing}(T)}$ is the fraction of grazing population (%). Nex_T represents the annual N excretion (kgN/animal/yr). $\text{Frac}_{\text{Loss}(T)}$ represents the amount of managed manure N that is lost in the manure management system (%). CA_{eqv} denotes the equivalent cropping area (kha). $N_{\text{rate}(T)}$ denotes the default N excretion rate (kgN/(1000 kg animal mass/day)). TAM_T is the typical animal mass (kg/animal). Days_alive_T is the average breeding days before slaughter. $N_{S(T)}$ is the average number slaughtered (or use stock number if average breeding days exceed a complete year). CA_{veg} , CA_{fruit} and CA_{other} are the cropping areas of vegetables, fruits and other crops (total excluding vegetable and fruits), respectively (kha). a and b is the ratio of organic

manure received by respectively vegetable fields and fruits compared with other crop lands.

N inputs from animal manure crop residues (F_{CR}) was estimated following Eqn (S2).

$$F_{CR} = \frac{\sum_i F_{CR-AG(i)} + F_{CR-BG(i)}}{\sum_i CA_i} \quad (S2)$$

$$= \frac{\sum_i Pdt_i \cdot R_{ST-GR(i)} \cdot N_i \cdot (R_{SR(i)} + R_{BG-AG(i)})}{\sum_i CA_i}$$

$F_{CR-AG(i)}$ and $F_{CR-BG(i)}$ represent the N input from aboveground and belowground crop residues, respectively (kgN/ha). i denotes crop type (rice, wheat, maize). CA_i is the annual cropping area (kha). Pdt_i is the annual harvested product (kt). $R_{ST-GR(i)}$ is the ratio of straw to grain in terms of dry matter. N_i is the N content of crop i residue (g/kg). $R_{SR(i)}$ is the proportion of above-ground residue returned to land (%). $R_{BG-AG(i)}$ is the ratio of below-ground residue weight to above-ground plant weight.

Since N application rates for the three main cereals are only available for 2005 and 2010 at 5-year intervals, Eqn (S3) was formulated to estimate the N application rate in a given year.

$$F_{SN(i)j} = F_{SN(i)2005} \cdot \frac{F_{SNj}}{F_{SN2005}} = F_{SN(i)2005} \cdot \frac{TN_j}{TCA_j} \cdot \frac{TCA_{2005}}{TN_{2005}} \quad (S3)$$

$F_{SN(i)j}$ is the N application rate in year j in a province (kgN/ha). i denotes crop type and j denotes year. $F_{SN(i)2005}$ is the N rate of crop i in 2005(kgN/ha). F_{SNj} and F_{SN2005} denote the crop-wide average N rate in year j and 2005, respectively (kgN/ha). TN_j and TN_{2005} are the provincial total synthetic N consumption in year j and 2005(kt). TCA_j and TCA_{2005} represent the total cropping area in year j and 2005(kha).

Appendix B Data sources for estimation of N inputs from animal manure and crop residues

The annual number of livestock slaughtered was collected for pigs, hens, broiler chicken and rabbits with the average breeding days standing at 158, 65, 352 and 105, respectively (MOA 2001-2011). For other types of animals, annual stock numbers were used. The fraction of grazing cattle or sheep was the ratio of total grazing animals (the sum of livestock numbers in grazing areas and half-grazing areas) to the total stock number (MOA 2001-2011). a and b in Eqn (S1) were assigned 4 and 5 since survey results (Huang and Tang 2010; Zhang et al. 2013) reported that vegetable and fruit fields generally received respectively 4 and 5 times more organic manure than cereal cropping lands in the 2000s.

Other information required in Eqn (S1) was selected from relevant literature and IPCC default values corresponding to conditions in China as displayed in Table S1.

Table S1 Selected values for estimating N input to croplands from animal manure

| | Non-dairy cattle | Milk cows | Sheep (goats) | Horses | Asses | Mules | Pigs | Chicken | Rabbits |
|--------------------------------------|---------------------|--------------|------------------|--------|-------|-------|-----------------|---------|---------|
| Frac _{Grazing} ^a | 17% | | 35% | | | | | | |
| N _{rate} | 0.34 | 0.47 | 1.27 | 0.46 | 0.46 | 0.46 | 0.50 | 0.82 | |
| TAM | 319 | 350 | 29 | 238 | 130 | 130 | 50 ^b | 2 | |
| Nex | 39.6 | 60.0 | 13.4 | 40.0 | 21.8 | 21.8 | 9.1 | 0.5 | 8.1 |
| Frac _{Loss} | 40% | 40% | 67% | 50% | 50% | 50% | 35% | 50% | 50% |
| Days _{alive} ^c | | | | | | | 158 | 180 | 105 |

^aData in this table represents the national average.

^b IPCC default value for Asia is 28. Here we adopted 50 according to Chinese conditions.

^c Days_{alive} of chicken is the weighted number of broiler chicken (65 days) and hens (352 days), which account for 60% and 40% of chicken population, respectively.

Values for parameters in Eqn (S2) were mainly obtained from the research by Gao et al. (2011) and are summarized in Table S2. The proportion of above-ground straw residues returned to land in 2006 was derived from results reported by Gao et al. (2009). The nationwide ratio of straw returned to land was reported at 15.2% in 1999 (Han et al. 2002) and rose to 24.3% in 2006 (Gao et al. 2009), implying an annual growth rate of 6.93%. This rate was employed to estimate the percentage of straw recycled to farmland in target years.

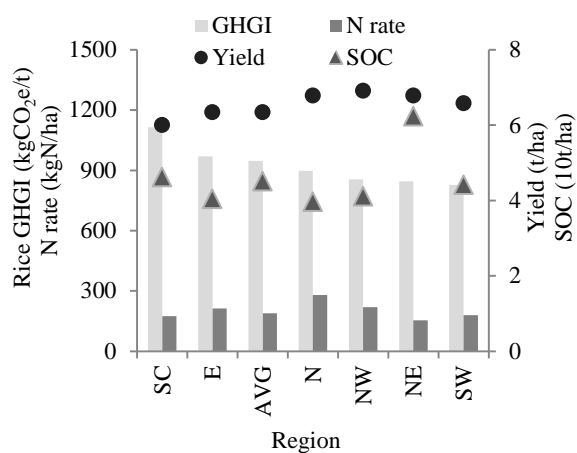
Table S2 Selected values for estimating N input to croplands from crop residues

| | Rice | Wheat | Maize |
|-------------------------------------|-------|-------|-------|
| R _{ST-GR} | 0.9 | 1.1 | 1.2 |
| N g/kg | 9.1 | 6.5 | 9.2 |
| R _{BG-AG} | 0.125 | 0.166 | 0.170 |
| North | 57.7% | 84.5% | 51.0% |
| Northeast | 25.0% | 36.6% | 22.1% |
| East | 19.4% | 28.5% | 17.2% |
| R _{SR(2006)} South Central | 58.9% | 86.3% | 52.0% |
| Southwest | 30.1% | 44.2% | 26.6% |
| Northwest | 14.8% | 21.6% | 13.0% |
| National average | 29.9% | 43.8% | 26.4% |

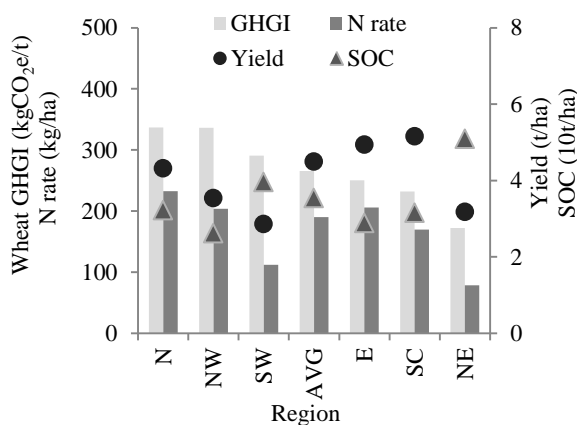
Note: North region includes Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia; Northeast region includes Heilongjiang, Liaoning and Jilin; East region includes Shanghai, Anhui, Fujian, Jiangsu, Jiangxi, Shandong and Zhejiang; South Central region includes Guangdong, Hainan, Henan, Hubei, Hunan and Guangxi; Southwest region includes Chongqing, Guizhou, Sichuan, Yunnan and Tibet; Northwest region includes Gansu, Qinghai, Shaanxi, Ningxia and Xinjiang.

Appendix C GHGI at regional level in 2006 and implications for mitigation strategies

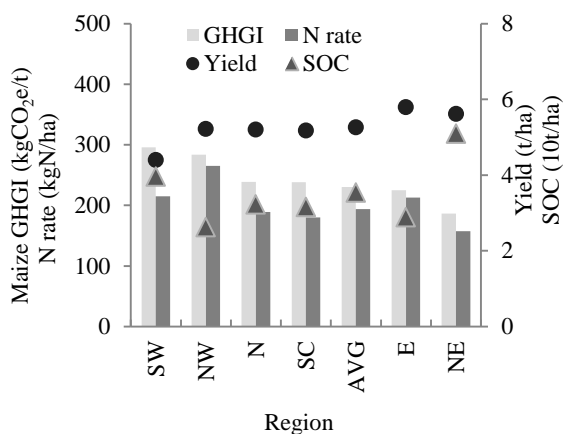
The GHGI, yield and synthetic N rate of rice, wheat and maize cultivation as well as the SOC content at the regional scale in 2006 are illustrated in Fig. S1. In general, the southwest had lowest cereal yields, albeit second highest SOC after the northeast. Conversely more N fertilizers were added to croplands in northwest provinces to compensate poor soil fertility, resulting in elevated regional GHGI of crop production. Fig. S1 reveals that yield levels do not necessarily correspond to local SOC status, since productivity is also influenced by climate, precipitation and other factors. In this regard, regional strategies to minimize GHGI and improve soil fertility should accommodate local climatic, soil and water conditions and management practices. For example, in the northwest measures improving SOC density (e.g. conservation tillage) should be favored to enhance soil fertility and land productivity. In intensive cropping systems in east and north China where over-fertilization is prominent, more efficient use of N fertilizer can allow N rates to be cut by 30 to 60% without sacrificing crop yields (Ju et al. 2009). Although the northeast was the least carbon intensive region in cereal production, this came at the expense of net carbon losses, especially in Heilongjiang Province (Pan et al. 2010; Yu et al. 2012), thus calling for better management practices to sustain soil fertility in this region.



(a)



(b)



(c)

Fig.S1 GHGIs of rice (a), wheat (b) and maize (c) production in different regions in 2006 and their relationship with yield, N rates and SOC content. NE, N, NW, E, SC, SW and AVG refer to northeast, north, northwest, east, south and central, southwest China, and national average, respectively.

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