



## Mitigation of Multiple Environmental Footprints for China's Pig Production Using Different Land Use Strategies

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1 Mitigation of Multiple Environmental Footprints for  
2 China's Pig Production Using Different Land Use  
3 Strategies

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14

15 **ABSTRACT**

16 Pig production contributes considerably to land use, greenhouse gas (GHG), and reactive  
17 nitrogen (Nr) emissions. Land use strategies were widely proposed, but the spillover effects on

18 biological flow are rarely explored. Here we simultaneously assessed carbon (C), nitrogen (N),  
19 and cropland footprints of China's pig production at the provincial scale in 2017. The  
20 environmental impacts of land use strategies were further evaluated. Results show that one kg live-  
21 weight pig production generated an average of 1.9 kg CO<sub>2</sub>-eq and 59 g Nr emissions, occupying  
22 3.5 m<sup>2</sup> cropland, with large regional variations. A large reduction in GHG (58-64%) and Nr (12-  
23 14%) losses and occupied cropland (10-11%) could be achieved simultaneously if combined  
24 strategies of intensive crop production, improved feed-protein utilization efficiency, and feeding  
25 co-products were implemented. However, adopting a single strategy may have environmental side-  
26 effects. Reallocating cropland that pigs used for feed to plant food alternatives would enhance  
27 human-edible energy (3-20 times) and protein delivery (1-5 times) and reduce C and N footprints,  
28 except for rice and vegetables. Reallocating cropland to beef and milk production would decrease  
29 energy and protein supply. Therefore, a proper combination of land use strategies is essential to  
30 alleviate land use changes and nutrient emissions without sacrificing food supply.

31

## 32 INTRODUCTION

33 The livestock sector is a key consumer of natural resources (e.g., land, water, energy) and  
34 also a major contributor to climate change, reactive nitrogen (Nr) pollution, and land use change.<sup>1</sup>  
35 Global livestock production is estimated to contribute 13-18% of the total anthropogenic  
36 greenhouse gas (GHG) emissions,<sup>2</sup> 40% of the global anthropogenic ammonia (NH<sub>3</sub>),<sup>3</sup> and occupy  
37 nearly 70% of global cropland area for producing animal feed.<sup>4</sup> The pork sector contributed to  
38 48% of the worldwide meat supply in 2017.<sup>5</sup> China, as the world's largest producer, supplies 46%  
39 of the world's pork production in 2017, via a production growth rate of 1% per year over the past  
40 three decades<sup>5</sup> and a rapid transition towards intensive production.<sup>6</sup> But this rapid expansion in pig  
41 production in China has come at the expense of the environment, and the development of more  
42 sustainable production systems, therefore, needs to be prioritized.

43 Among these impacts, land use is a central concern as it is a major driver of environmental  
44 change at local and global scales, with important impacts on biogeochemical cycling, ecosystem  
45 function, and GHG emissions.<sup>7, 8</sup> About 75% of the Chinese pigs are currently raised in medium  
46 and large-scale intensive farms, relative 22% in 2000.<sup>9</sup> Intensification improves productivity,  
47 primarily via an increased proportion of grain feed in pig diets.<sup>6</sup> Producing human-edible grain  
48 feed crops in China relies on the overuse of synthetic N fertilizer, which may increase the N  
49 emission intensity of pig production. The increasing cultivation of feed crops is also associated  
50 with land use change domestically and overseas.<sup>10</sup> China has gradually increased the import of  
51 high-protein feed, such as soybean, which contributes to deforestation and associated GHG  
52 emissions in soybean-exporting countries (i.e., Brazil and Argentina).<sup>11</sup> Changes in feed  
53 composition can also affect nutrient excretions and emissions from the entire manure management  
54 chain.<sup>6</sup> Environmental assessment of the whole pork supply chain is therefore essential, and has

55 been previously conducted at the farm, country (e.g., European countries, Brazil, and China),<sup>12-15</sup>  
56 and global level.<sup>16</sup> However, Country-level evaluations often overlook variations among regions.  
57 There has been a lack of environmental assessment at sub-national and provincial scales, limiting  
58 the opportunity for governments to develop region-specific policies.

59 To reduce ecological burdens related to land use, three groups of efficient land use strategies  
60 in agricultural systems are usually proposed: 1) to close yield gaps by increasing land productivity,  
61 which is in line with intensive crop production;<sup>10, 17</sup> 2) to improve feed-protein utilization  
62 efficiency (e.g., lowering dietary crude protein content) at animal level;<sup>10, 18</sup> and 3) to use  
63 ecological leftovers, such as co-products of food processing and food waste, to reduce cropland  
64 used for feed production.<sup>10, 19</sup> However, these previous studies often focused on either a specific  
65 strategy only or a particular environmental pollutant (mainly GHG emissions), with limited  
66 understanding on changes in land use. The environmental consequences of these strategies can be  
67 interlinked. Assessing the broader synergistic and antagonistic impacts (e.g., GHG emissions, Nr  
68 emissions, and land use) of a full range of land use strategies is therefore needed to better inform  
69 future policy.<sup>20</sup>

70 The ‘saved’ cropland could be reallocated to produce more efficient alternative food items  
71 (food that require less environmental resource per unit protein or energy) or conserved, negating  
72 further environmental degradation. The sacrifice of unchosen alternatives is the so-called  
73 “opportunity cost.”<sup>7</sup> One recent study indicated the possible potential of resource (fertilizer, land,  
74 and water) saving when repurposing cropland used for beef feed to other plant- and animal-based  
75 alternatives in the United States (US).<sup>8</sup> Redirection of intensively utilized cropland to natural forest  
76 may increase biodiversity and soil carbon sequestration.<sup>21</sup> If some cropland shifted from grain feed  
77 to human-edible food alternatives in China, what would be the key implications for food supply

78 and environmental impacts? There is as yet little information about these implications in China, in  
79 particular when GHG emissions, Nr emissions, and food (energy and protein) supply are  
80 considered simultaneously.

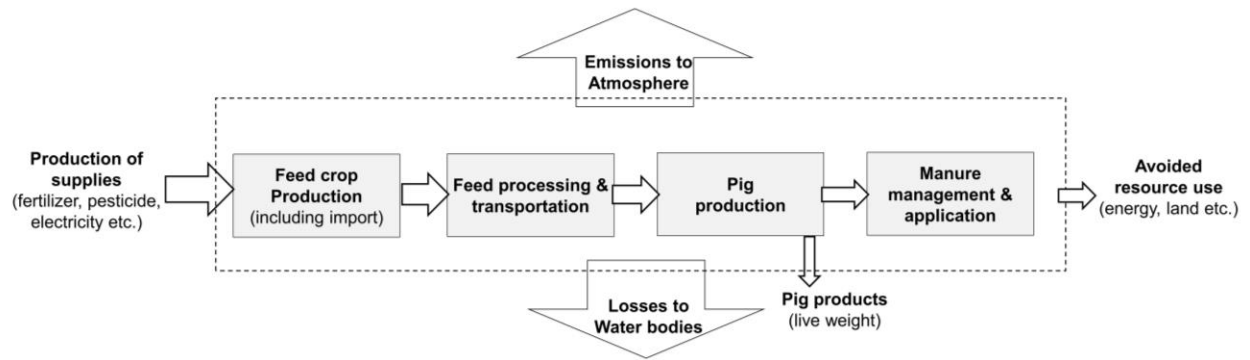
81 The objectives of this study were to i) assess carbon (C), nitrogen (N), and cropland footprints  
82 of pig production at the provincial scale in China for the year 2017 (the latest year for which most  
83 activity data from statistics are available) using a life cycle assessment (LCA) approach, and to ii)  
84 evaluate how alternative land use scenarios affect these environmental footprints. Further, the  
85 implications of reallocation of ‘saved’ cropland to produce plant- and animal-based food  
86 alternatives were also explored.

## 87 **MATERIALS AND METHODS**

88 **System boundary of life cycle assessment.** We used an LCA approach to evaluate the C, N,  
89 and cropland footprints of China’s pig production system in 2017. The system boundary and main  
90 components of this life cycle, in terms of ancillary inputs production, feed production, feed  
91 processing and transportation, manure storage (indoor and outdoor) and treatment, and manure  
92 application to cropland, are presented in Figure 1 & S2. The functional unit (FU) was defined as  
93 one kg of pig live weight (LW). Carbon, nitrogen, and cropland footprints per FU were expressed  
94 as kg CO<sub>2</sub>-eq FU<sup>-1</sup>, kg Nr FU<sup>-1</sup>, and m<sup>2</sup> FU<sup>-1</sup>, respectively. Three main pig breeding systems were  
95 categorized in this study because of the differences in feed composition and manure management  
96 used in, i) smallholder farm (< 50 slaughtered pigs per farm), ii) medium farm (50-3000  
97 slaughtered pigs per farm), and iii) industrial farm (>3000 slaughtered pigs per farm).<sup>6, 22</sup>  
98 Information on herd and management characteristics of these three breeding systems is provided

99 in Table S1-2. The ratio of the three breeding systems in each province of China in 2017 is  
100 presented in Figure S1.

101



102  
 103 **Figure 1.** An illustration of simplified life-cycle system boundary of pig production in China, with  
 104 the main processes for feed crop production, feed processing and transportation, pig production,  
 105 and manure management and application

106



107           **Carbon and Nitrogen Footprint Analysis.** The C footprint includes the emission sources of  
108 GHG emissions, i.e., nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>), and/or carbon dioxide (CO<sub>2</sub>), from the  
109 production of chemical fertilizer, seed, agricultural film, and pesticide, application of chemical  
110 fertilizers and manure, feed processing and transportation, energy use, enteric fermentation, and  
111 manure management. Indirect N<sub>2</sub>O emissions resulting from the NH<sub>3</sub> volatilization, N leaching,  
112 and runoff from cropland were also included. CO<sub>2</sub> emissions from manure management were  
113 excluded. Emissions of CH<sub>4</sub> and N<sub>2</sub>O were converted to CO<sub>2</sub>-eq, using the global warming  
114 potentials (GWP) of CH<sub>4</sub> and N<sub>2</sub>O of 25 and 298 times of CO<sub>2</sub>, respectively.<sup>23</sup> The N footprint  
115 includes emissions of Nr (all nitrogen species except N<sub>2</sub>) losses,<sup>24</sup> in terms of atmospheric  
116 emissions of NH<sub>3</sub>, N<sub>2</sub>O, and nitrogen oxides (NO<sub>x</sub>), as well as N lost to water bodies. The emission  
117 sources of NH<sub>3</sub>, N<sub>2</sub>O, and NO<sub>x</sub> were almost the same as that of GHG emissions. Nitrogen lost to  
118 water bodies mainly included leaching, runoff, and erosion from cropland and manure  
119 management.<sup>25, 26</sup> The C and N footprints were quantified based on process-specific emission  
120 factors so that the effects of changes in specific processes could be addressed from the life cycle  
121 aspect. The calculations, parameters, activity data employed in our analysis, as well as the  
122 sensitivity analysis were detailed in Supporting Information (SI). The main calculation procedures  
123 are summarized below.

124           *Feed crop production:* Emissions embodied in agricultural inputs (e.g., chemical fertilizer  
125 and pesticide) were quantified as a function of emission intensity per unit product (Table S4-6)  
126 and the consumption of products applied for corresponding feed crops. Feed sources include both  
127 domestic production and imported production (i.e., 86% of soybean was imported).<sup>5</sup> Emissions of  
128 soil N<sub>2</sub>O and CH<sub>4</sub> (paddy rice), as well as CO<sub>2</sub> derived from urea application, were quantified  
129 according to the IPCC Tier 2 approach,<sup>23</sup> N losses from crop production in China were quantified

130 using the mass flow model, NUFER (NUtrient flows in Food chains, Environment and Resources  
131 use).<sup>25, 26</sup> In China, cropland used for domestic feed production has been under cultivation for  
132 hundreds of years; therefore, these emissions associated with direct land use change were  
133 excluded.<sup>23</sup> GHG emissions of land use change from soybean production in Central West of Brazil  
134 (0.96 kg CO<sub>2</sub>-eq kg<sup>-1</sup> soybean) and Argentina (0.72 kg CO<sub>2</sub>-eq kg<sup>-1</sup> soybean) were accounted for  
135 analysis because of deforestation or the conversion of pasture and shrubland to cropland.<sup>11, 27-29</sup>

136 *Feed processing and transportation:* Emissions (e.g., CO<sub>2</sub>) embodied in energy consumption  
137 during feed processing were quantified according to the emission intensity for a range of energy  
138 sources and the amount of energy used by feed types. Emissions from non-plant feed ingredients  
139 (e.g., minerals, fish meal, whey powder, amino acids) production were also considered. Emissions  
140 from national and international transport (truck and ship) of feed were calculated as a function of  
141 transportation distance and emission coefficients per product.

142 *Direct Energy use:* Farm energy consumption varied between the three pig breeding systems,  
143 and data were extracted from the National Data Compilation of Revenue and Cost of Agricultural  
144 Products.<sup>30</sup> Calculation of emissions from on-farm energy consumption adopted the same method  
145 for calculating the emissions embodied in energy consumption during feed processing.

146 *Pig production and manure management:* Manure management practices include indoor and  
147 outdoor storage of manure, manure treatment, and manure application to cropland. The leading  
148 treatment technologies in China include solid-liquid separation, anaerobic digestion, and  
149 composting.<sup>31</sup> The proportion of housing (slatted, solid, or litter-based floor) and storage types and  
150 the adaption of treatment techniques varied among different breeding systems (Table S7). Nr  
151 emissions from manure were analyzed according to manure N flows and process-specific emission

152 factors (Table S8).<sup>25, 26</sup> Quantification of N<sub>2</sub>O and CH<sub>4</sub> emissions (including enteric fermentation)  
153 was based on IPCC guidelines.<sup>23</sup> The model calculations have been published previously<sup>32</sup> and are  
154 briefly described in SI.

155 **Cropland Footprint Analysis.** The cropland footprint here refers to the cropland occupation  
156 areas (CLO; measured in m<sup>2</sup> per year), which indicates the use of land cover for a certain period  
157 and is calculated by multiplying the occupied area by time.<sup>33</sup> In our study, we calculated the  
158 maximum land area occupied by the feed crops during the cultivation phase within a year; that is  
159 to say, we did not consider cultivation methods like intercropping or rotation. For feed ingredients  
160 as co-products (e.g., soybean meal), their CLO needs to be multiplied by the corresponding  
161 allocation coefficients.

162 **Allocation method.** Economic allocation is the most commonly used allocation method in  
163 environmental LCAs of livestock products,<sup>34</sup> and was, therefore, used in our study. Distribution  
164 was carried out twice in this study. The first allocation was only used for wheat production to  
165 partition environmental impacts associated with crop cultivation between wheat grain and wheat  
166 straw.<sup>35</sup> The second allocation was applied for maize, wheat, soybean, rice, peanut, and rapeseed,  
167 to divide environmental impacts related to crop cultivation, processing, and land use between feed  
168 ingredients and corresponding co-products. The allocation coefficients and mass ratio of different  
169 products are shown in SI (Table S3).

170 **Data Sources.** Data related to domestic feed crop production (i.e., crop yield and agricultural  
171 inputs) and pig production data were obtained from Chinese official statistics.<sup>9, 30</sup> Data concerning  
172 imported soybean cultivation was based on previous studies for exporting countries.<sup>11, 28, 36</sup>  
173 Literature data were used for the emission parameters of agricultural inputs production when

174 available; otherwise, values from the Ecoinvent 3 database were used.<sup>35</sup> GHG and Nr emissions  
175 factors during feed crop production and manure management were derived from IPCC (2006), and  
176 the NUFER model.<sup>23, 25, 26</sup> Feed formulas (Table S10) and manure management data (i.e., housing  
177 and storage types, and the adaption of treatment techniques, Table S7) were obtained from a survey  
178 conducted for 531 medium farms and 219 industrial farms across China, a national study  
179 concentrated on manure treatment (> 42,000 farms), and relevant literature.<sup>6, 37, 38</sup>

180 **Defining Scenarios.** Effects of efficient land use strategies on the C, N, and cropland  
181 footprints of pig production in China were examined through scenario analysis. For the C footprint,  
182 the “opportunity cost of land (soil C sequestered by conversion of cropland into natural forest)”  
183 were also included in these scenarios (see SI for details).<sup>39, 40</sup> The assessment focuses on exploring  
184 the trade-offs and co-benefits between environmental impacts when strategies for alleviating feed-  
185 food competition are implemented. Seven scenarios with alternative measures were compared with  
186 the reference system, China’s pig production system in 2017. The assessment was conducted at  
187 the provincial level. Scenarios include 1) intensive crop production with increased crop yields  
188 (S1); 2) intensive pig production with improved feed-protein utilization efficiency (S2); 3) feeding  
189 pigs on ecological leftovers, such as co-products of food processing (S3-4); and combinations of  
190 the strategies mentioned above (S5-7). Feed formulas of these scenarios are detailed in SI (Table  
191 S11).

192 *Intensive crop production (S1):* A set of Integrated Soil-Crop System Management (ISSM)  
193 practices were assumed to be adopted by all farmers growing the three main kinds of cereal (maize,  
194 wheat, and rice) in China. ISSM was designed based on the local environment, drawing upon  
195 appropriate crop varieties, sowing dates, densities, and advanced nutrient management.<sup>41</sup> The  
196 potential increase in yields (20.4-24.4%, 15.8-21.9% and 16.9-23.7% of increases for maize,

197 wheat, and rice) and decrease in N fertilizer inputs (6.3-22.7%, 9.2-18.9%, and 3.2-16.0% of  
198 decrease for maize, wheat, and rice) for each crop at provincial levels, resulting from ISSM  
199 practices, were derived from > 13,000 field-experiment sites across China (Table S9).<sup>41</sup> Apart from  
200 ISSM implementation, all other practices are assumed to be unchanged in this scenario.

201 *Intensive pig production (S2)*: Improvement in feed-protein utilization efficiency was  
202 achieved through a low crude protein (CP) feeding strategy with the inclusion of specific amino  
203 acids (AA). It aims to lower the CP level to better match pig growth demand and not impair growth  
204 performance.<sup>42</sup> Since soybean meal was the most commonly used protein feed in pig diets,  
205 reducing CP level in diet could help relieve pressure on imported soybean. This low CP strategy  
206 (lowering CP content by 1-2% in absolute value) was assumed to be only adopted by medium and  
207 industrial farms, in part due to the low CP content observed on smallholder farms (Table S11).  
208 This assumption is also in line with the scope of national action, released by China's Ministry of  
209 Agriculture in 2017, for promoting this strategy.

210 *Ecological leftovers (S3-4)*: Here, the emphasis was on increasing the consumption of co-  
211 products from food processing, building on S2 (lowering dietary CP level). Assumptions include  
212 using maize dried distillers grains with solubles (DDGS) (S3) and a combination of oil seed meal  
213 (peanut and rapeseed meal) (S4) to reduce the amount of soybean meal in pig diets, which also  
214 only aims at medium and industrial farms (see feed formulas in Table S11). These low economic  
215 value co-products with low available energy density were chosen as representatives of "ecological  
216 leftovers" to reduce resource use and the cost of pig diets.<sup>10, 43</sup> DDGS (a co-product of maize  
217 ethanol production), with low starch, high protein, and high digestible fiber content, is generally  
218 considered to be a reasonable choice to replace soybean meal in pig and poultry feed.<sup>44</sup> Domestic

219 oil seed meals were considered here because it is assumed to reduce transport distance and  
220 associated land use change of imported high-protein feed, such as soybean.

221 *Combination of measures (S5-7):* Three combinations of measures were designed to explore  
222 the upper boundaries of the potential impacts when implementing these proposed strategies. The  
223 combined scenarios S5-7 represent intensive crop production (S1) in combination with S2 (=S5),  
224 S3 (=S6), and S4 (=S7), respectively.

225 **Opportunity cost.** We further quantified opportunity magnitudes of reallocating the ‘saved’  
226 land resulted from combinations of land use strategies (scenarios S5-7) to produce food  
227 alternatives, focusing on C and N footprints and food (energy and protein) delivery. For this  
228 opportunity cost analysis, we assumed that there are opportunities for using the saved land to  
229 produce food alternatives other than pig feed (see Figure S6). Parameters regarding these footprints  
230 for individual food alternatives were sourced from global-scale analyses (see Table S12). The  
231 adoption of global averages in the present study was because of the lack of country-specific data  
232 for all these food alternatives and an assumption of the food supply in a globalized context.<sup>45, 46</sup>  
233 To allow comparisons between indicators (C and N footprints and food delivery), we express these  
234 savings as changes in intake per capita on a weekly basis and percentages of the amount currently  
235 used for the production of pig feed on the reallocated cropland (see SI for details).

## 236 **RESULTS**

237 **Carbon Footprint.** The total GHG emissions from China’s pig production were 152  
238 teragrams (Tg) CO<sub>2</sub>-eq yr<sup>-1</sup> in 2017, with 89% being from domestic sources and 64% from  
239 medium-size farms (Figure 2a). Feed crop production and manure management accounted for 46%  
240 and 23% of total emissions, respectively. GHG emissions intensity varied nearly three-fold at the

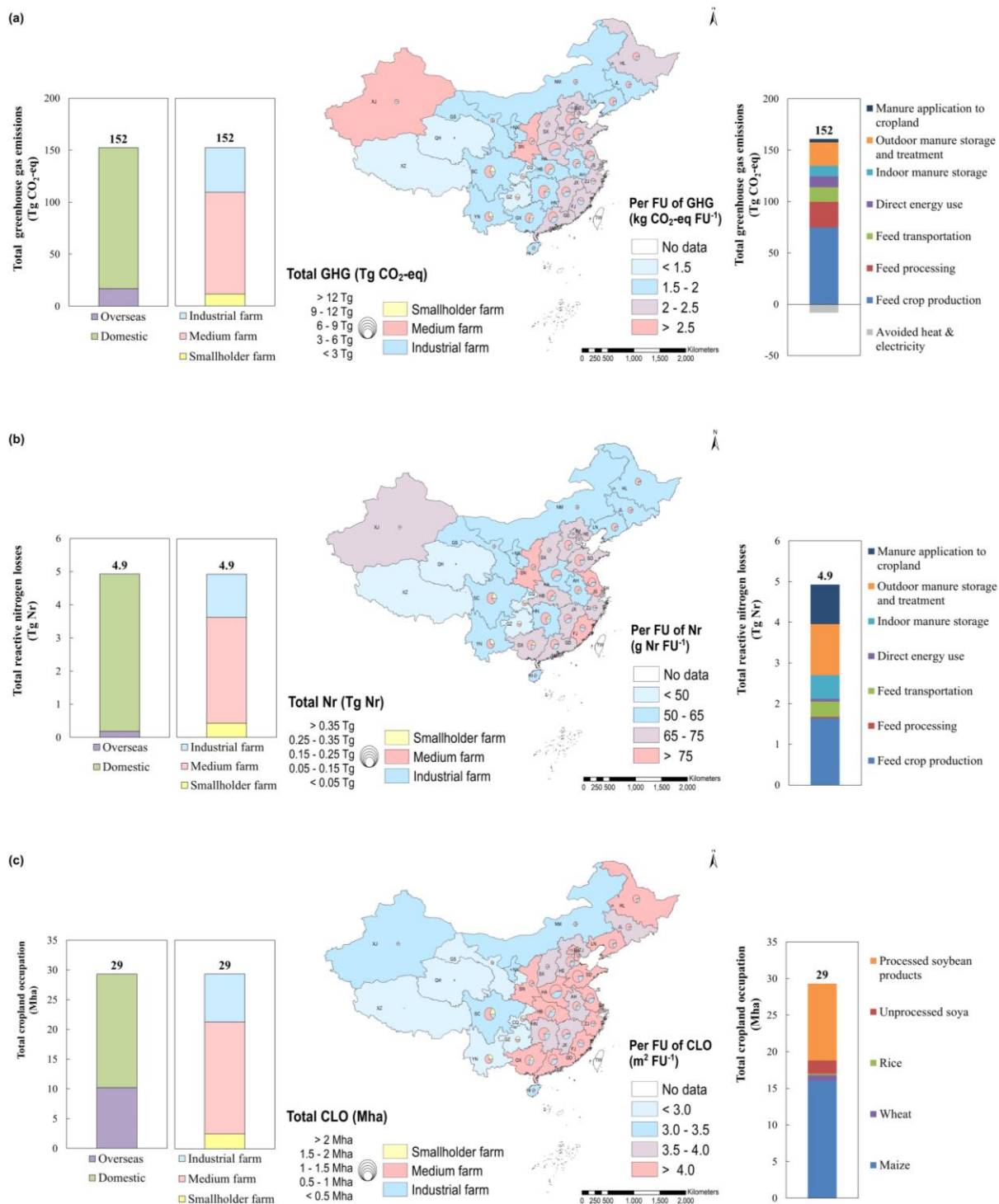
241 regional scale (from 1.2 kg CO<sub>2</sub>-eq FU<sup>-1</sup> in Guizhou to 3.0 kg CO<sub>2</sub>-eq FU<sup>-1</sup> in Xinjiang) (Figure  
242 S3a). The regions with relatively low GHG emission intensity, e.g., Sichuan, Yunnan, and Guizhou  
243 (in Southwest China), have a larger share of smallholder farms (0.6, 2.4, and 2.2 kg CO<sub>2</sub>-eq FU<sup>-1</sup>  
244 for the smallholder, medium, and industrial farms, respectively; Figure S4a). The contribution of  
245 feed supply to the total C footprint in smallholder farms (28%) was less than that in medium (76%)  
246 and industrial (76%) farms. By-products and food waste were dominant in pig diets of smallholder  
247 farms (Table S10), which are often considered relatively lower environmental impacts than grain-  
248 based feed.<sup>47</sup>

249 **Nitrogen Footprint.** The total Nr losses from China's pig production were 4.9 Tg Nr yr<sup>-1</sup> in  
250 2017, with 96% from domestic sources and 65% from medium-scale farms (Figure 2b). Manure  
251 management contributed 57% of total emissions, followed by feed production (33%). Nr emission  
252 intensity ranged from 38 g Nr FU<sup>-1</sup> in Qinghai to 77 g Nr FU<sup>-1</sup> in Jiangsu (Figure S3b). Most  
253 regions with relatively high emission intensity were in Eastern and Central China. Smallholder  
254 farms (20 g Nr FU<sup>-1</sup>) had, on average, a lower Nr emission intensity than medium (76 g Nr FU<sup>-1</sup>)  
255 and industrial (64 g Nr FU<sup>-1</sup>) size farms (Figure S4b). Manure management contributed to higher  
256 Nr emissions in smallholder farms (78%) than in medium (53%) and industrial (50%) farms.  
257 Nitrogen flows (kg N per FU) in the aforementioned farming systems were presented in Figure  
258 S5.

259 **Cropland Footprint.** The total cropland footprint of China's pig production was 29 million  
260 hectares (Mha) yr<sup>-1</sup> in 2017, 35% of which occurred overseas (Figure 2c). Maize products and  
261 processed soybean products contributed to 55% and 36% of the total land footprint, respectively.  
262 The cropland footprint differed from 2.1 m<sup>2</sup> FU<sup>-1</sup> in Qinghai to 4.5 m<sup>2</sup> FU<sup>-1</sup> in Fujian (Figure S3c)  
263 due to the regional differences in feed production and manure management as a function of farm

264 scales (Figure S4c). The low cropland footprint was observed in smallholder farms due to the large  
265 portion of feed sourced from by-products and food waste that have minute impacts on land use,  
266 which is in line with a global assessment.<sup>3</sup>





267

268 **Figure 2.** National environmental footprint characteristics of China's pig sector. The bar charts  
 269 show the contribution of emissions sources (overseas or domestic), three main pig breeding  
 270 systems in each province of China (excluding Hongkong, Macao, Taiwan, and Nansha Islands),  
 271 and different processes of pig supply chain to (a) total greenhouse gas (GHG; Tg CO<sub>2</sub>-eq)  
 272 emissions, (b) total reactive nitrogen (Nr; Tg Nr) losses, and (c) total cropland occupation (CLO;

273 Mha). The background maps indicate (a) per FU of GHG ( $\text{kg CO}_2\text{-eq FU}^{-1}$ ) emissions, (b) per FU  
274 of Nr ( $\text{kg Nr FU}^{-1}$ ) losses, and (c) per FU of CLO ( $\text{m}^2 \text{FU}^{-1}$ ) in corresponding provinces. The pie  
275 charts within maps represent the contribution of three main pig breeding systems in each province  
276 of China to (a) total GHG (Tg  $\text{CO}_2\text{-eq}$ ) emissions, (b) total Nr (Tg Nr) losses, and (c) total CLO  
277 (Mha), and their sizes indicate total GHG, Nr, and CLO amount. FU = Functional Unit. NM =  
278 Inner Mongolia. LN = Liaoning. JL = Jilin. HL = Heilongjiang. BJ = Beijing. TJ = Tianjin. HE =  
279 Hebei. HA = Henan. SD = Shandong. SX = Shanxi. AH = Anhui. HN = Hunan. JX = Jiangxi. GD  
280 = Guangdong. HI = Hainan. JS = Jiangsu. ZJ = Zhejiang. FJ = Fujian. SH = Shanghai. HB = Hubei.  
281 SN = Shaanxi. GS = Gansu. QH = Qinghai. NX = Ningxia. XJ = Xinjiang. CQ = Chongqing. SC  
282 = Sichuan. YN = Yunan. GZ = Guizhou. XZ = Tibet. GX = Guangxi. HK = Hongkong. MC =  
283 Macao. TW = Taiwan.

284

285           **Scenario Analysis.** Scenarios of different land use strategies were compared with the  
286 reference situation for the year 2017 (Table 1 and Figure 3).

287           *Carbon Footprint:* Implementing the single mitigation options (S1-4) was found to decrease  
288 the C footprint of China’s pig production by 19-36%, with the largest reduction (19-30%)—due to  
289 the “opportunity cost of land” (Figure 3a). In addition to land use impacts, intensive crop  
290 production (S1) resulted in another 5% reduction from feed crop production. A combination of  
291 measures (S5-7) decreased the C footprint by 58-64% (or 7-8% when land use impacts were  
292 excluded).

293           *Nitrogen Footprint:* Intensive crop production (S1) decreased Nr emissions by 6% (mainly  
294 from feed crop production) relative to the reference (Figure 3b). Feeding strategies (S2-4) reduced  
295 Nr emissions by 5-7%, mostly from manure management. Increased emissions from feed crop  
296 production were observed in the ecological leftover – oil seed meal scenario (S4), compared with  
297 the DDGS scenario (S3), because of the increased emissions from growing the additional seed oil  
298 meal. Implementing combined measures (S5-7) resulted in a reduction of 12-14% in total Nr  
299 emissions.

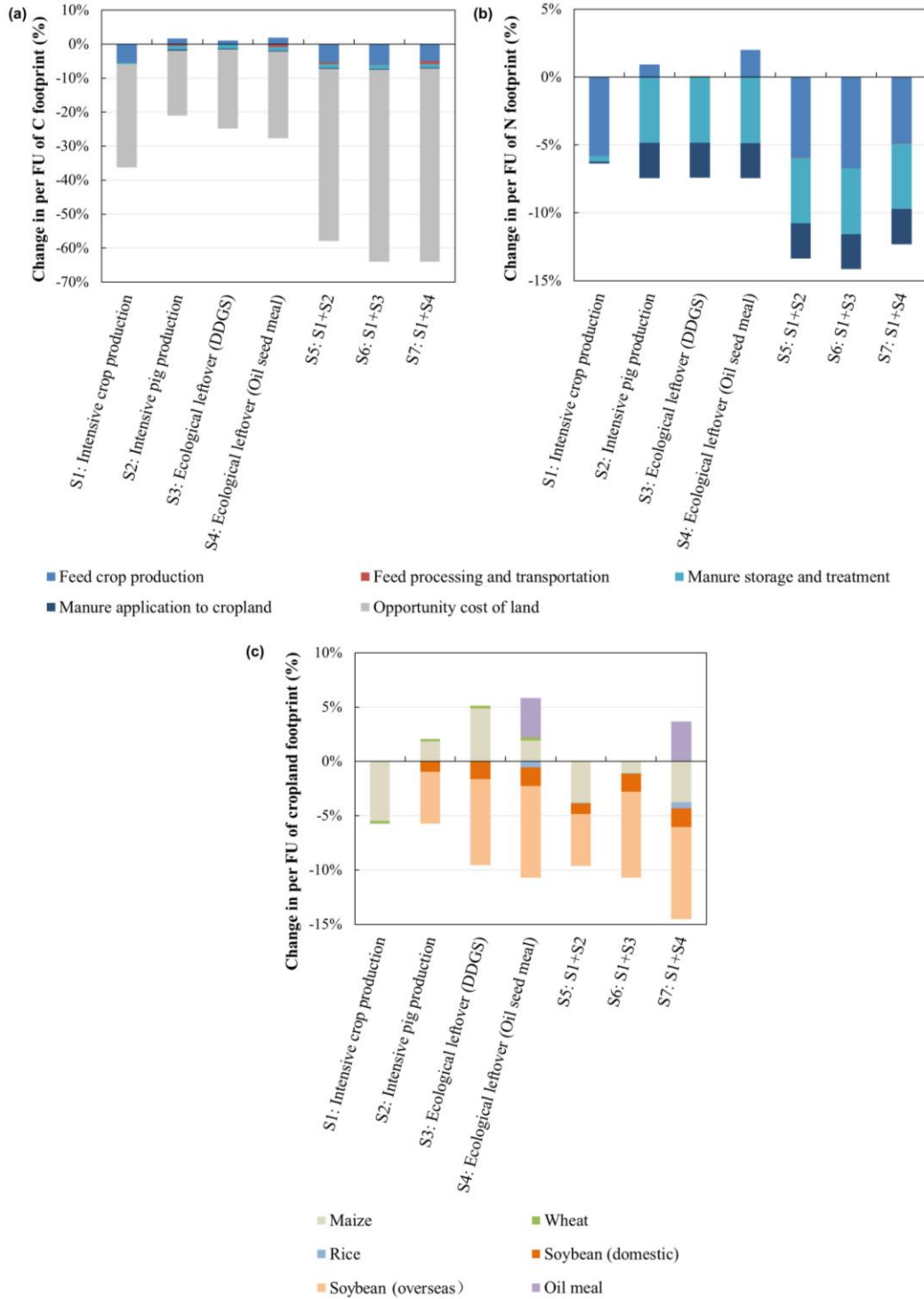
300           *Cropland Footprint:* The cropland occupation area per FU decreased by 4-6%, resulting from  
301 the adoption of single measures (S1-4) (Figure 3c). Intensive crop production (S1) reduced  
302 cropland use for maize as feed by 6%. For all three feeding strategies (S2-4), land used for  
303 producing soybean decreased by 6-10% (mainly overseas) but was largely offset by increased land  
304 use for producing additional maize and processing domestic co-products. Implementing combined  
305 strategies (S5-7) decreased both domestic and overseas cropland used for feed, a decrease of 10-  
306 11% in total.

307 **Table 1. Environmental footprints (per functional unit) in the reference and**  
 308 **land use scenarios.**

Scenarios	C footprint <sup>a</sup> (kg CO <sub>2</sub> -eq FU <sup>-1</sup> )	N footprint (g Nr FU <sup>-1</sup> )	Cropland footprint (m <sup>2</sup> FU <sup>-1</sup> )
S0: Reference	1.9	59	3.5
S1: Intensive crop production	1.2	56	3.3
S2: Intensive pig production	1.5	56	3.4
S3: Ecological leftover (DDGS) <sup>b</sup>	1.4	55	3.4
S4: Ecological leftover (Oil seed meal)	1.4	56	3.4
S5: S1 + S2	0.8	51	3.2
S6: S1 + S3	0.7	51	3.2
S7: S1 + S4	0.7	52	3.2

309 <sup>a</sup> C footprint (kg CO<sub>2</sub>-eq FU<sup>-1</sup>) including the “opportunity cost of land.” <sup>b</sup> DDGS = dried distillers grains  
 310 with solubles, a co-product of maize processing into ethanol.

311

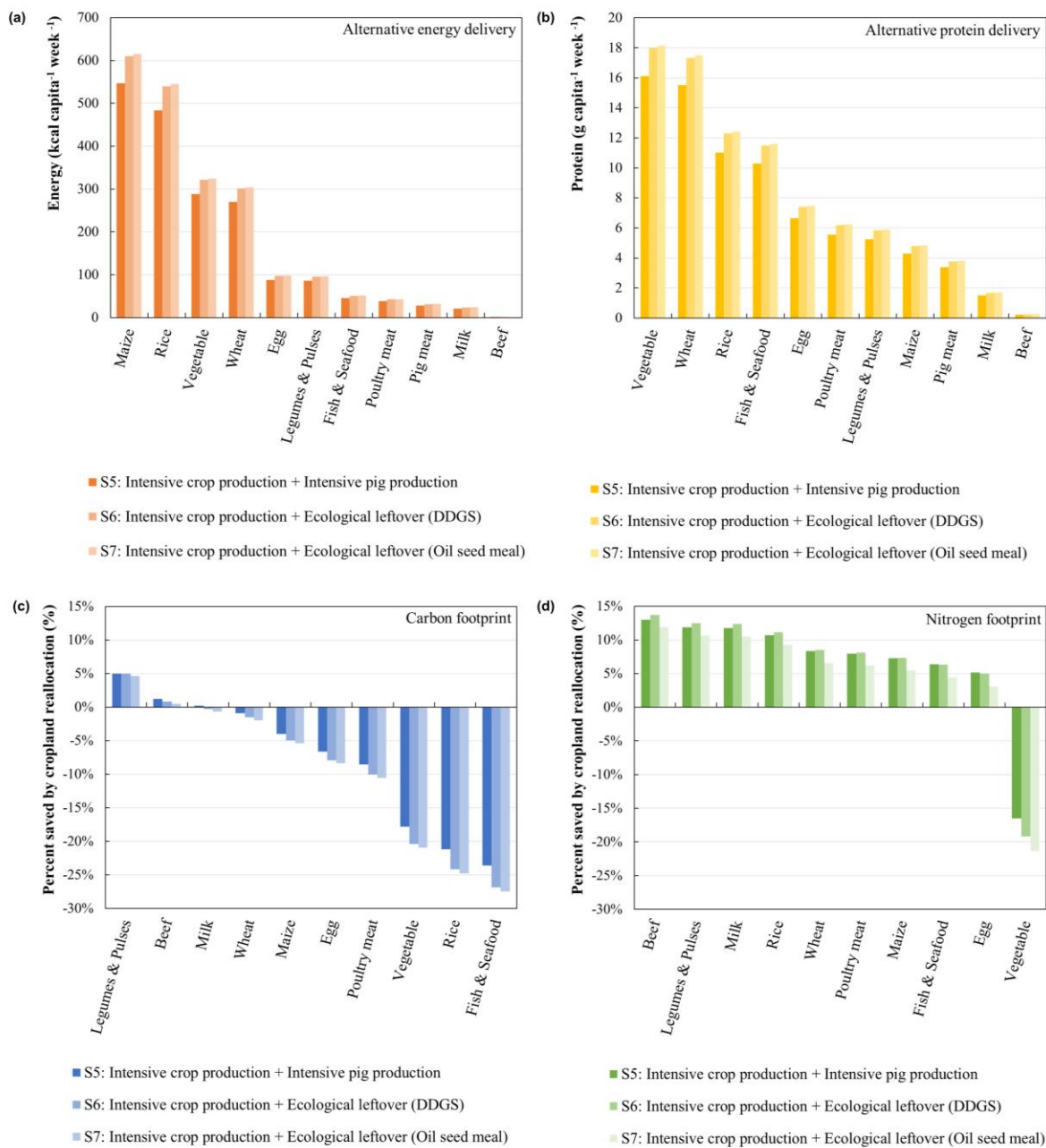


312

313 **Figure 3.** Changes in per FU of (a) C footprint (kg CO<sub>2</sub>-eq FU<sup>-1</sup>), (b) N footprint (kg Nr FU<sup>-1</sup>),  
 314 and (c) cropland footprint (m<sup>2</sup> FU<sup>-1</sup>) from the whole chain following the implementation of feed  
 315 manipulation scenarios, relative to a situation without feed manipulation. FU = Functional Unit.  
 316 DDGS = dried distillers grains with solubles, a co-product of maize processing into ethanol.

317           **Opportunity cost.** The consequences of the ‘saved’ cropland reallocation were explored and  
318 shown in Figure 4. Reallocation to all the human food crop alternatives increased energy delivery  
319 (compared to pork) 3 to 20 times and protein delivery 1 to 5 times. This was accompanied by  
320 reduced environmental consequences for maize, wheat, and legumes and pulses (a reduction of  
321 5% for C footprint and 5-12% for N footprint), or increased environmental consequences for rice  
322 and vegetables (an increase of 18-25% for C footprint, 17-21% for N footprint). Reallocating  
323 cropland that pig used for crop-based feed to beef and milk would decrease energy and protein  
324 supply, with a decline in the N (11-14%) footprints.

325



326

327 **Figure 4.** Opportunity cost for China's pig production calculated by global environmental  
 328 footprints. (a) Alternative energy (kcal capita<sup>-1</sup> week<sup>-1</sup>) and (b) protein delivery (g capita<sup>-1</sup> week<sup>-1</sup>)  
 329 associated with reallocating the saved land for the production of animal and plant food alternatives.  
 330 The percentage (%) of (c) carbon (Tg CO<sub>2</sub>-eq) and (d) nitrogen footprint (Tg Nr) saved by cropland  
 331 reallocation to animal and plant food alternatives. The positive values indicate the environmental  
 332 footprints of animal and plant food alternatives under the combination of measures (S5-7) are less  
 333 than that in the reference scenario.

## 334 DISCUSSION

335 **Carbon Footprint.** In this study, the estimated total GHG emissions (152 Tg CO<sub>2</sub>-eq in 2017)  
336 from China's pig production amount to 11% of total agriculture GHG emissions (1410 Tg CO<sub>2</sub>-eq  
337 in 2013) in China.<sup>48</sup> GHG emission intensities on most medium (2.0-3.4 kg CO<sub>2</sub>-eq FU<sup>-1</sup> at the  
338 provincial level) and industrial (1.7-3.0 kg CO<sub>2</sub>-eq FU<sup>-1</sup>) pig farms in China were higher than the  
339 reported averages in European Union (EU) (2.0-2.4 kg CO<sub>2</sub>-eq kg<sup>-1</sup> LW) and United States (US)  
340 (1.8-2.7 kg CO<sub>2</sub>-eq kg<sup>-1</sup> LW).<sup>49, 50</sup> About 2.2 kg CO<sub>2</sub>-eq kg<sup>-1</sup> LW was estimated for pig production  
341 by a study evaluating C footprints of 22 plant-based foods and 6 animal-based foods in China,  
342 close to our estimate.<sup>51</sup> Feed supply contributed over 71% of C footprint in the medium to  
343 industrial farms, which was much higher than that in the EU (45%) and the US (49%).<sup>52, 53</sup> This is  
344 mainly due to the overuse of chemical fertilizer during feed production in China.<sup>54</sup> Maize grain, as  
345 the dominant feedstuff, was produced with an average application of 305 kg N ha<sup>-1</sup> in China, about  
346 four times the worldwide average (74 kg N ha<sup>-1</sup>).<sup>55</sup> Smallholder farms with residue-based feed had  
347 much lower GHG emissions than medium and industrial farms with grain-based feed. Smallholder  
348 farms still accounted for about 25% of current China's pig production,<sup>9</sup> so the national average C  
349 footprint was relatively low compared to developed countries. The large regional variations in  
350 GHG emission intensities were observed (Figure 2), attributing to differences in relative  
351 contributions of small and large size farms (Figure S1), fertilizer application rates, and irrigation  
352 practices during feed crop production. The amount of N fertilizer rate varied between 133-335 kg  
353 N ha<sup>-1</sup> for maize production among provinces in China.<sup>30</sup>

354 **Nitrogen Footprint.** The estimated total Nr emissions (4.9 Tg Nr in 2017) from China's pig  
355 production amounted to 22% of chemical N fertilizer use in China.<sup>56</sup> The N footprint largely varied  
356 among regions (38-77 g Nr FU<sup>-1</sup>), attributing to regional differences in farm size and fertilizer



357 application rates. The intensification levels of pig farms were high in East and Central China,  
358 relative to the Southwest (over 60% of pigs raised in small-sized farms in Sichuan and Guizhou).<sup>30</sup>  
359 Eutrophication is a key environmental consequence of Nr leakages to waterbodies. Surface water  
360 in large areas of the Huang-Huai-Hai Region and the Yangtze River basin of China are severely  
361 contaminated and identified as hotspots of eutrophication.<sup>57, 58</sup> The discharges and application of  
362 manure were found as the main sources.<sup>59</sup> Pig production in these regions accounted for about 40%  
363 of the national total, and therefore, mitigation of Nr losses from pig production needs more  
364 attention. Although it is difficult to consistently compare with other studies as a result of different  
365 system boundaries, methods, and assumptions, the relatively high N footprint (medium farms: 65-  
366 104 g Nr FU<sup>-1</sup> at the provincial level; industrial farms: 55-87 g Nr U<sup>-1</sup>) of China's pig production  
367 is evident, compared to the EU average (68 g Nr kg<sup>-1</sup> LW).<sup>60</sup> A country-scale estimate indicates  
368 the N footprint of 136 g Nr kg<sup>-1</sup> LW for pork production in China,<sup>61</sup> which is slightly higher than  
369 that in our study where much detailed practices of feed production and manure management are  
370 considered. Both feed production (e.g., overuse of surface-applied urea) and poorly managed  
371 manures were identified as primary sources of Nr emission. The estimated recycling ratio of  
372 manure N to the field (32% of total N excretion) in China was far below the values reported in the  
373 US (75%)<sup>62</sup> and the EU countries (80%).<sup>63</sup> In these developed countries, environmental regulations  
374 were largely implemented. For example, the EU National Emission Ceiling Directive<sup>64</sup> and the  
375 Gothenburg protocol of the UNECE Convention on Long-range Transboundary Air Pollution<sup>65</sup>  
376 were established to decrease NH<sub>3</sub> and NO<sub>x</sub> emissions; the UN-FCCC Kyoto protocol<sup>66</sup> to reduce  
377 N<sub>2</sub>O emission; the EU Nitrates Directive<sup>67</sup> to minimize N leaching to groundwater and surface  
378 waters. Through the implementation of these policies, nitrogen mitigation measures for livestock  
379 manure have been adopted in many EU countries. For example, covering slurry stores and adopting

380 low-NH<sub>3</sub> emission manure application methods have been adopted by >90% of farmers in the  
381 Netherlands and Denmark.<sup>32</sup> However, less than 20 % of pig farms have adopted low-NH<sub>3</sub>  
382 emissions measures, according to surveys taken in few regions of China (Table S7).

383 **Cropland footprint.** The overall cropland occupation area from China's pig production was  
384 estimated as 29 Mha in 2017, accounting for 21% of arable land (135 Mha in 2017) in China.<sup>68</sup>  
385 The land demand is mainly from cropland occupied by cereals (especially maize), which is suitable  
386 for food production for human consumption. Of that, nearly 35% (10 Mha) occurred overseas as a  
387 result of imported soybean. Medium (3.8-5.8 m<sup>2</sup> FU<sup>-1</sup> at the provincial level) and industrial (3.3-  
388 5.2 m<sup>2</sup> FU<sup>-1</sup>) pig farms in China, despite large variations among provinces, occupied far more  
389 cropland than those case farms in the Netherlands (4.4 m<sup>2</sup> kg<sup>-1</sup> LW)<sup>69</sup> and France (3.98 m<sup>2</sup> kg<sup>-1</sup>  
390 LW).<sup>18</sup> Differences between regions and countries were attributed to variations in pig rearing, in  
391 terms of feed conversion ratio (FCR) and feed composition, and in crop production depending on  
392 how efficient land is used (e.g., crop productivity). The average FCR of pig production in China,  
393 especially for smallholder farms (3.4), was much higher than that in the EU (1.7-2.8)<sup>18, 52</sup> and US  
394 (2.75).<sup>70</sup> Maize grain yield in China (7.5 t ha<sup>-1</sup> in 2017) was lower than the EU average (8.9 t ha<sup>-1</sup>)  
395 and US (11.8 t ha<sup>-1</sup>).<sup>5, 30</sup> It is therefore evident that China's pig sector would require more land  
396 resources.

397 **Implications of Scenario Analysis.** Several policies have been implemented to reduce  
398 fertilizer use in China. The 'zero fertilizer growth' policy issued in 2015 has effectively slowed  
399 the increase in fertilizer use.<sup>71</sup> Field experiments have proved that reduced fertilizer use could go  
400 hand in hand with closing yield gaps in China. Integrated Soil-crop System Management (ISSM)  
401 practices have been tested and promoted for maize, wheat, and rice in China, which have been  
402 shown to be agronomically robust and economically acceptable.<sup>41</sup> Our results show that the pork

403 supply chain can primarily benefit from this ISSM in reducing C and N footprints and saving land  
404 for food production. The promotion of the ISSM approach in smallholder farms that dominate the  
405 crop landscape can be constrained by social and logistical barriers beyond research-oriented  
406 experiments. This may require the implementation of appropriate incentives, such as establishing  
407 a national campaign network and scientific technology backyards in China, to allow farmers to  
408 adopt more knowledge-intensive techniques.<sup>41</sup>

409 It is worth noting that environmental impacts from feed crop production can be further  
410 reduced through improved fertilizer production technologies. Although a detailed analysis is  
411 beyond the scope of this study, here we provide a brief indication of the additional reduction in the  
412 C footprint by improving fertilizer production efficiency. Coal-based nitrogen fertilizer production  
413 is still predominant in China, where every ton of N fertilizer manufactured emits 8.3 t CO<sub>2</sub>-eq,<sup>54</sup>  
414 compared with 4.8 t CO<sub>2</sub>-eq in EU.<sup>72</sup> Mitigation opportunities, including improving methane  
415 recovery during coal mining and enhancing energy efficiency in fertilizer manufacture, can reduce  
416 N fertilizer-related GHG emissions by 30-43%.<sup>54</sup> Taking improved fertilizer manufacture into  
417 account, the ISSM scenario (S1) resulted in an additional 3-4% reduction in the C footprint of  
418 China's pig production.

419 Improving feed protein utilization efficiency within livestock production systems has been  
420 shown previously to increase the N use efficiency of the entire food system.<sup>18</sup> National standards  
421 on feed formulation for pigs and chicken, aimed at reducing protein levels in feed rations, were  
422 recently released by China's government.<sup>73</sup> For the first time, the multiple environmental impacts  
423 of such a policy (S2) were evaluated in our scenario analysis. The C footprint and cropland demand  
424 were generally decreased, mainly due to reduced imports of high-protein feeds (i.e., soybean),  
425 especially from South America with relatively high GHG emission from land use change.<sup>11,27</sup> The

426 N footprint was reduced mostly through the reduction in the amount of manure N generation.  
427 Feeding pigs ecological leftovers from food processing (i.e., DDGS and oil meal; S3-4), combined  
428 with lowering feed protein content, play an essential role in further alleviating land use changes  
429 and associated GHG emissions that occur overseas. China is taking action to increase the domestic  
430 supply of soybean and oil crops mainly through crop redistribution and increased yield, which in  
431 part supports the increased demand for high-protein feed.<sup>74</sup>

432 These feeding options on GHG emissions were insignificant if the “opportunity cost of land”  
433 were not considered (Figure 3). The reason was that reduced GHG emissions from imports of feed  
434 were offset by emissions from the increased supply of domestic feed that had high emission  
435 intensity. These feeding strategies also lead to an increased domestic cropland footprint, and the  
436 reduction in Nr emissions from crop cultivation was small. Given the possible antagonistic effects,  
437 incorporating sustainable crop intensification with these feeding options is essential to achieve  
438 synergistic mitigation in China’s pig production. It, therefore, calls for joint efforts between crop  
439 production and animal production sectors in policy decision-making.

440 Manure management strategies can also reduce GHG and/or Nr emissions along the pig  
441 production chain but may not much affect cropland use footprint,<sup>6, 75</sup> which is therefore not the  
442 focus of our study. To extend the discussion, we did additional scenarios to illustrate the impacts  
443 of manure management options on these emissions (see SI for details). Adopting low-emission  
444 measures during manure storage and banning manure discharge could reduce N footprint by 6-  
445 10%, with limited effects on C footprint. Promoting anaerobic digestion could reduce C footprint  
446 by 3%, yet slightly increase N footprint. A combination of these management options is expected  
447 to have a relatively large mitigation potential of Nr losses (22%; Figure S9). A previous estimate  
448 indicated a reduction of nearly two-thirds in manure-sourced N losses from China’s pig production

449 (excluding feed supply stage) if combined options of manure management were implemented in  
450 2030.<sup>6</sup> Although the system boundary and timeframe of this early research were not exactly  
451 consistent with our study, it still confirms a large reduction potential in N losses via proper manure  
452 management. Achieving substantial abatement of C and N footprints from pork production chain  
453 requires a holistic policy package promoting efficient land use and manure management measures.

454       Implementing a combination of land use strategies considered in the present study would  
455 reduce the cropland footprint of China's pig production by 10-11% (Figure 3). This would allow  
456 repurposing high-quality croplands that are currently used to grow feed for pig production for  
457 other, more environmentally friendly, and nutritious food types. Our results indicate human food  
458 crop alternatives would deliver 3-20 and 1-5 folds more energy and protein, respectively, than the  
459 replaced pork on the basis of per ha cropland (Figure 4), which is because of their higher human-  
460 edible energy and protein conversion efficiency than animal products in general.<sup>8</sup> This strategy has  
461 implications for providing 18-40 million more population in terms of energy supply or 2-34 million  
462 more population in terms of protein supply (according to 1048 Mcal calories and 30 kg protein  
463 intake per capita per year) in China.<sup>5</sup> Reallocating land to vegetables, wheat, and rice would  
464 generate a relatively large increase in protein delivery, attributing to their high protein yield (420,  
465 410, and 290 kg ha<sup>-1</sup>, respectively) relative to pork (90 kg ha<sup>-1</sup>). Although legumes and pulses are  
466 protein-dense crops, increased protein delivery may be marginal due to their low yields in China.  
467 The average yield of soybean was 2.1 t ha<sup>-1</sup> in China while it was 3.3 t ha<sup>-1</sup> in the US.<sup>5, 30</sup> For the  
468 animal food alternatives, the possible reduction in protein and energy delivery can be found when  
469 using the saved land to feed ruminants, such as beef cattle. This is because of the low human-  
470 edible energy and protein conversion efficiency for beef cattle (3%) relative to pork (9%).<sup>76</sup> These

471 outcomes have implications for policy development regarding the promotion of more plant-based  
472 dietary patterns characterized by less consumption of red meat (e.g., pork and beef).

473 The environmental consequences of land reallocation are not consistent depending on food  
474 alternatives (Figure 4). Repurposing the saved cropland to the production of rice and vegetables  
475 was found to increase C and/or N footprints due to the high CH<sub>4</sub> emission intensity from paddy  
476 rice fields<sup>77</sup> and the overuse of fertilizers to grow vegetables.<sup>61</sup> An average increase of 17% in  
477 vegetable yields through improved soil and crop management was observed in experimental sites  
478 across China, with decreased N fertilizer use by 38%,<sup>78</sup> offering significant mitigation potential in  
479 case of cropland reallocation to grow vegetables. Repurposing cropland to legumes and pulse can  
480 alleviate both C and N footprints, which can be considered a targeted policy to tackle these  
481 interconnected environmental challenges. For animals (e.g., beef and milk), there is mitigation  
482 potential for Nr losses, but not for GHG emissions (Figure 4). Although C and N footprints per kg  
483 of animal products for beef and dairy cattle are found to be higher than that for pork, the differences  
484 may be varied (or reversed) on the basis of per ha of utilized agricultural land. This is because the  
485 global average land use of ruminants (e.g., 328 m<sup>2</sup> kg<sup>-1</sup> beef) is generally larger than that of pork  
486 (18 m<sup>2</sup> kg<sup>-1</sup> product). This tendency on emissions per ha land is in line with some previous studies  
487 in the US.<sup>79, 80</sup> For consistency with other studies, the global average footprints of food products  
488 were used in this study. However, we also recalculated the opportunity cost using country-specific  
489 information whenever available (see Figure S7). Despite absolute differences in final values, the  
490 general tendency was similar between the two estimates. These findings illustrate the importance  
491 of incorporating opportunity cost within LCA and have implications for national and region-  
492 specific policies for agricultural structure changes (including spatial reallocation of cropping). We

493 believe that the policy options explored in the present study are also applicable to other industrial  
494 livestock systems in China and other nations facing similar challenges from livestock production.

## 495 **ASSOCIATED CONTENT**

### 496 **Supporting Information**

497 The Supporting Information is available free of charge on the ACS Publications website at DOI.  
498 Here you can find additional text, 9 figures, and 12 tables with details on the data, methods, and  
499 models used for calculating the multiple environmental footprints (PDF).

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### 506 **Notes**

507 The authors declare no competing financial interest.

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737 **Abstract Art**

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