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Farm and product carbon footprints of China's fruit production - life cycle inventory of representative orchards of five major fruits

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1 **Title: Farm and product carbon footprints of China's fruit**
2 **production – Life cycle inventory of representative orchards of five**
3 **major fruits**

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12 **Running title:** Carbon footprint of China's fruit production

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18

19 **Abstract**

20 Understanding the environmental impacts of fruit production will provide fundamental information for
21 policy making of fruit consumption and marketing. This study is to characterize the carbon footprints
22 of China's fruit production and to explore the key greenhouse gas emissions to cut with improved
23 orchard management. Yearly input data of materials and energy in a full life cycle from material
24 production to fruit harvest were obtained via field visits to orchards of 5 typical fruit types from
25 selected areas of China. Carbon footprint (CF) was assessed with quantifying the greenhouse gas
26 emissions associated with the individual inputs. Farm and product CFs were respectively predicted in
27 terms of land use and of fresh fruit yield. Additionally, product CFs scaled by fruit nutrition value
28 (V_C content) and by the economic benefit from fruit production were also evaluated. The estimated
29 farm CF ranged from 2.9 t CO₂-eq ha⁻¹ to 12.8 t CO₂-eq ha⁻¹ across the surveyed orchards. Whereas,
30 the product CF ranged from 0.07 kg CO₂-eq kg⁻¹ to 0.7 kg CO₂-eq kg⁻¹ fruit. While the mean product
31 CFs of orange and pear were significantly lower than of apple, banana and peach, the nutrition-scaled
32 CF of orange (0.5 kg CO₂-eq g⁻¹ V_C on average) was significantly lower than others (3.0~5.9 kg
33 CO₂-eq g⁻¹ V_C). The income-scaled CF of orange and pear (1.20 and 1.01 kg CO₂-eq USD⁻¹,
34 respectively) was higher than apple, banana and peach (0.87-0.39 kg CO₂-eq USD⁻¹). Among the
35 inputs, synthetic nitrogen fertilizer contributed by over 50 % to the total GHG emissions, varying
36 among the fruit types. There were some tradeoffs in product CFs between fruit nutrition value and fruit
37 growers' income. Low carbon production and consumption policy and marketing mechanism should be
38 developed to cut down carbon emissions from fruit production sector, with balancing the nutrition
39 value, producer's income and climate change mitigation.

40 **Key words:** Fruit production; Life cycle assessment; Greenhouse gas emissions; Carbon footprint; N
41 fertilizer; Orchard; Low carbon management

42 **Abbreviations:** CF, carbon footprint; LCA, life cycle assessment; GHG: greenhouse gas;

43

44 **Highlights (for review):**

- 45 ➤ Both farm and product carbon footprints of five major fruit types from China were assessed using
46 orchard survey data;
- 47 ➤ Fruit production had high farm but low product carbon footprint relative to cereal production;
- 48 ➤ Orange was lower in product and nutrition-scaled carbon footprint but higher in income-scaled
49 carbon footprint among the others;
- 50 ➤ Synthetic nitrogen fertilizer use contributed by over 50% to the total carbon footprint;
- 51 ➤ High fruit yield with low product carbon footprint sustained under high efficiency management.

52

53 **Introduction**

54 Global agriculture had been facing a great challenge of accelerated greenhouse gas (GHG)
55 emissions in land use due to excessive agricultural inputs such as fertilizers and pesticides, intensive
56 energy use (Schneider and Smith 2009; Smith et al. 2009; Tilman et al. 2002; Burney et al. 2010). The
57 production, transportation, processing and preparation of food sector contributed 20% to the global
58 anthropogenic GHG emissions (FAO 2012). Particularly, emissions from agricultural production and
59 the associated land use change accounted for 80%-86% of the global total food system emissions
60 (Vermeulen et al. 2012). For assessing environmental impacts of human activities, a full life cycle
61 assessment approach (LCA) had been increasingly used for carbon (Wiedmann and Minx 2008; BSI
62 2011), water (Pfister et al. 2015) and land (van Kernebeek et al. 2015) footprintings. Based on LCA, a
63 carbon footprint (CF) was a measure of an overall potential climate forcing assessed with all direct and
64 indirect carbon emissions in the full life cycle of a product or an activity (Wiedmann and Minx 2008;
65 BSI 2011). Using such framework, CFs of crop production had been often assessed in order to explore
66 low carbon farming systems or mitigation measures in agriculture (Dubey and Lal 2009; Hillier et al.
67 2009; Gan et al. 2011; Knudsen et al. 2014; Yan et al. 2015a,b).

68 In addition to crop production, fruit production had been a key sector of world agriculture,
69 possessing 59.6 million hectares of croplands and producing 676.7 million tons of fresh fruits
70 (FAOSTAT 2013). For the last decade, there had been increasing interests in understanding the
71 environmental impact by the world fruit sector. For example, apple production in fruit farms from
72 eastern Switzerland (Mouron et al. 2006) and New Zealand (Milà i Canals et al. 2006) was analyzed
73 using the LCA methodology to evaluate the variability of different environmental impacts. Using a
74 similar approach, Nemecek et al. (2011) could compare the environmental impacts between integrated
75 and organic farming systems from Swiss and argued that organic farming system was either similar to
76 integrated system in terms of carbon emissions in production or superior to integrated system in terms
77 of resource efficiency and biodiversity in environment benefits. Michos et al. (2012) reported a similar
78 comparative study on GHG emissions between organic, integrated and conventional peach orchards
79 from northern Greece and supported higher energy efficiency and lower GHG emissions by organic
80 farming systems than by conventional ones. While evaluating the CFs of 34 types of fruits and
81 vegetables produced with a large Swiss retailer, Stoessel et al. (2012) argued that environmental
82 impacts by fruit production could be largely reduced by consuming seasonal fruits and vegetables,

83 without additional energy consumption for storage and processing. More recently, Svanes et al (2013)
84 assessed the CF of bananas from cradle to retail and indicated that the GHG emissions from the
85 transport and primary production could be significantly reduced. Thus, LCA carbon footprinting had
86 been a powerful tool to characterize GHGs emissions and to figure out key measures for improving
87 orchard management to cut these emissions, from fruit production.

88 China's agriculture had been challenged with climate change impacts and mitigation demands for
89 the last decades. Quantified with similar CLA methodology, the works by Cheng et al. (2014) and Yan
90 et al. (2015a) on major grain crops, and by Chen et al. (2011) on vegetables had shown that China's
91 agriculture had been already carbon intensive or carbon insufficient, *vice versa*, largely due to high
92 nitrogen fertilizer application and methane emission in rice paddies (Yan et al., 2015b). Fruit
93 production had been a fast increasing sector in China's agricultural production for the last decade (Su
94 2012). Producing 154 million tons of fresh fruit excluding melons in 2013, China had been one of the
95 biggest countries of fruit production in the world (FAOSTAT 2013). Contributing by 60% of China's
96 total fresh fruit production were the five major fruit crops of apple, peach, pear, banana, and orange
97 represented (FAOSTAT 2013). For addressing potential environmental impacts, a work by Liu et al.
98 (2010b) quantified the GHG emissions of pear production from conventional and organic farms over
99 the different production chains. They could highlight storage at processing stage and use of synthetic
100 fertilizers in production stage as the major source for GHGs emission of fruit sector. China had
101 committed to cut 25% of the nation's total anthropogenic emissions by 2025 and enforced low carbon
102 approaches in agriculture (NDRC 2012, 2014). So far, little information had been available on the CFs
103 of major types of fruit production of China.

104 Using farm survey data based on the LCA method up to harvest, the objectives of this study were
105 to (a) quantify the CFs of China's fruit production and (b) evaluate the contributions of different farm
106 inputs to the total CFs, of the five major types of apple, peach, pear, banana and orange. This study also
107 aimed to provide information for policy-makers to identify key options for reducing GHG emissions
108 from China's fruit production.

109

110 **Materials and methods**

111 *Carbon footprinting methodology*

112 Carbon footprint of fruit production was assessed by quantifying the GHG emissions associated
113 with individual inputs for primary production and for orchard management up to harvest (farm gate
114 principle) of yearly fruit production (Fig.1), with a LCA methodology followed in PAS 2050-1 (BSI
115 2012). Emissions of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) directly or
116 indirectly from all different inputs were accounted and expressed in carbon dioxide equivalent (CO₂-eq)
117 using their relative warming forcing values (IPCC 2007), following a general accounting protocol
118 described by Cheng et al (2015). As a result of carbon footprinting, the arm CF, an indicator of carbon
119 intensity, was expressed in term of land use in t CO₂-eq ha⁻¹, and the product CF as a negative
120 indicator of carbon efficiency in terms of fruit yield (here fresh fruit biomass harvested) in kg CO₂-eq
121 kg⁻¹ fruit. Considering the nutrition value of various fruits for consumers and the net income gained by
122 fruit growers, the nutrition-scaled CF in kg CO₂-eq per gram Vitamin C (*V_C*) provided and the
123 income-scaled CF in kg CO₂-eq per United States Dollar (USD) was respectively evaluated, for further
124 addressing the carbon efficiency of fruit production of China.

125 Fig.1
126

127 *Emissions accounting and carbon footprint calculation*

128 Taken into account of carbon footprinting were all the emissions from the manufacturing of the
129 inputs of fertilizers and pesticides for fruit growth, of paper or plastic bags for fruit coverage, emissions
130 caused by farm machinery or associated with irrigation and soil working for orchard management and
131 direct emissions of N₂O caused by applied N fertilizers. The overall carbon footprint of a fruit
132 production was estimated using the following equation:

$$CF_t = \sum(AI_i \times EF_i) \quad (1)$$

134 where, *CF_t*, the total carbon footprint, is the cumuli sum of the GHG emissions (kg CO₂-eq) induced
135 by the *i*-th agricultural input; *i*, *AI_i* and *EF_i* is respectively the kind, the amount (kg for fertilizer,
136 pesticide, plastic and paper bags, or L for diesel oil, or kW h for electricity) and the GHG emission
137 factor (kg CO₂-eq per unit volume or mass) of *i*-th agricultural input or source under accounting. The
138 emission factors (*EF_i*) of the relevant inputs accounted in the present study are given in Table 1.

139 Table 1

140 The direct N₂O emissions from N fertilizer application (CF_N , kg CO₂-eq) were estimated with the
141 following equation:

$$142 \quad CF_N = AI_N \times EF_N \times \frac{44}{28} \times 298 \quad (2)$$

143 where, AI_N is the quantity of N fertilizer applied for fruit production (kg); EF_N is the emission factor of
144 N₂O emission induced by N fertilizer application, and 0.01 kg N₂O-N kg⁻¹ N fertilizer was adopted
145 from IPCC (2006); 44/28 is the molecular weight of N₂ in relation to N₂O; 298 is net global warming
146 potential (GWP) in a 100-year horizon (IPCC 2007).

147 Thus, the farm CF (CF_f), expressed in term of land use, was obtained using the following
148 equation:

$$149 \quad CF_f = \frac{CF_t}{A} \quad (3)$$

150 where, CF_f is the farm CF (kg CO₂-eq ha⁻¹), A is the area (ha) of fruit orchard. Similarly, the
151 product CF (CF_p) was evaluated in terms of fresh fruit yield using the following equation:

$$152 \quad CF_p = \frac{CF_t}{Y} \quad (4)$$

153 where, CF_p is the product CF (CF_p) (kg CO₂-eq kg⁻¹ fruit); Y is the yield of fresh fruit (kg ha⁻¹).

154 Moreover, considering the nutrition value of various fruits for consumers, the nutrition-scaled CF
155 was further evaluated in terms of vitamin C (Vc) provided by fruits, using the following equation:

$$156 \quad CF_n = \frac{CF_p}{C} \quad (5)$$

157 where, CF_n is the nutrition CF scaled on vitamin C content(kg CO₂-eq g⁻¹ Vc), C is the vitamin C
158 content provided by fruits (g Vc kg⁻¹fruit). According to Yang et al. (2002), an averaged Vc content of 4,
159 7, 6, 8 and 28 milligrams vitamin C per 100 grams of fruit was used for apple, peach, pear, banana and
160 orange, respectively.

161 In addition, considering the economic income from fruit production, an income-scaled CF_I was
162 calculated with the following equation:

$$163 \quad CF_I = \frac{CF_p}{I} \quad (6)$$

164 where, CF_I is the CF scaled on income by selling the fruit produced (kg CO₂-eq USD⁻¹); I is the
165 net income from fruit production (USD kg⁻¹ fruit). A higher CF_I suggests higher GHG emission
166 efficiency when fruit growers gained the economic income from their fruit production. Here the net
167 income (I) was the balance between the total sales revenue of fruits and the production cost from a
168 surveyed orchard, which converted to USD using a mean ratio valid in 2013.

169 *Data collection*

170 Total fresh fruit production in orchards of China reached 228 Mt in 2011, predominated by apple
171 (*Malus pumila* Mill.), banana (*Musa nana* Lour.) orange (*Citrus reticulata* Blanco), pear (*Pyrus spp*),
172 and peach (*Amygdalus persica*) (DRSES –NBSC, 2012). These had been produced typically in
173 provinces respectively of Shanxi, Fujian, Hubei, Hebei, and Shanghai/Jiangsu, of China. In a province
174 typical for a specific fruit production, over 5 representative sites were selected (Fig. 2) via information
175 available on fruit market and a total of 7-10 orchards were randomly visited for each type of fruit
176 production during a field survey conducted in 2012/2013. The selected orchards had been managed by
177 the fruit growers making economic income primarily by producing and selling their fruits. The basic
178 information of the sites surveyed was presented in Table 2. During the survey, data of the agricultural
179 inputs and yields were obtained through interview with responsible farmers who managed the orchards.
180 The recorded data included: (1) size of orchard and annual total fruit production, (2) annual amount of
181 fertilizers, pesticides, paper or plastic bags for fruit covering, electricity for irrigation, labor use, fossil
182 fuel for farm mechanical operations, (3) annual costs for all the agricultural inputs (including labor
183 costs) used in the orchard, and sale price of fruit and the annual income. Overall, valid data from 42
184 visited orchards (9 for apple, 8 for peach, 10 for pear, 8 for banana, and 7 for orange) were obtained to
185 form a database (Table 3, Table S1).

186 Fig.2

187 Table 2

188 Table 3

189 *Data processing and Statistical analysis*

190 For addressing N fertilization impact on carbon footprint, a parameter of partial factor N
191 productivity was also calculated following the equation:

192
$$PFP_N = Y/F_N \quad (7)$$

193 Where, PFP_N is the estimated partial factor N productivity (kg fruit kg^{-1} N), Y is the fruit yield (kg
194 ha^{-1}) and F_N is the total N applied (kg N ha^{-1}) for the fruit season.

195 One-way ANOVA and the least significant difference test (LSD) were used to check the
196 differences in fruit CF among the different groups. The level of significance was defined at $p < 0.05$.

197 Data processing was performed using Microsoft Office Excel 2011 and all statistical analyses were

198 conducted using JMP Ver. 9.0.

199

200 **Results**

201 *Overall carbon footprint of fruit production*

202 The estimated CFs of fruit production varied in a range of 2.9 - 12.8 t CO₂-eq ha⁻¹ across the
203 surveyed orchards. As shown in Table 4, the mean farm CF (CF_f) was highest for banana (9.7 t CO₂-eq
204 ha⁻¹), followed by pear, apple, and orange (8.6, 8.2, and 7.1 t CO₂-eq ha⁻¹, respectively) and lowest for
205 peach (5.9 t CO₂-eq ha⁻¹). Varying in a relatively wider range (0.07-0.7 kg CO₂-eq kg⁻¹ fruit), the
206 product CF (CF_p) was lower for orange and pear (0.14 and 0.18 kg CO₂-eq kg⁻¹ fruit on average,
207 respectively) than that for apple, banana and peach (0.24, 0.27 and 0.37 kg CO₂-eq kg⁻¹ fruit on average,
208 respectively).

209 However, considering the nutrition value of the different fruit types, orange had the lower
210 nutrition-scaled CF (CF_n) of 0.5 kg CO₂-eq g⁻¹Vc, compared to other 4 types of fruits studied (3.0-5.9
211 kg CO₂-eq g⁻¹ Vc). Whereas, affected by the economic benefit gained by the fruit growers, the
212 income-scaled CF (CF_i) was 1.20 and 1.01 kg CO₂-eq USD⁻¹ on average for orange and pear
213 respectively, which was much higher than for apple, banana and peach (0.87-0.39 kg CO₂-eq USD⁻¹).

214 Table 4

215 *Contributions of individual inputs to the overall CF*

216 Data of proportions of different inputs to the total CFs is shown in Fig.3. It was obvious that
217 fertilizer application contributed the most, with the lowest for apple (by 49%) and the highest for
218 orange (by 81%). Across the surveyed orchards, almost 95% of the fertilizer induced emissions was by
219 synthetic N fertilizer while organic fertilizer accounted for less than 4% of the total GHG emissions.
220 Moreover, the product CFs of the surveyed orchards were shown very significantly correlated to the N
221 fertilizer application rates across all the surveyed orchards (Fig.4). However, the product CFs were
222 observed to decrease with the enhanced partial factor N productivity across these orchards (Fig. 5).

223 Use of pesticides was seen as an important contributor, second to fertilizer, being the lowest for
224 banana (4%) and the highest for peach (26%). In addition, irrigation management made also a
225 significant contribution to the overall CFs for banana, apple and pear, accounting for 23%, 21% and 14%
226 of their total GHG emissions respectively. Emissions with irrigation were induced by machineries
227 pumping surface water for banana in southern China but mostly underground water for pear and apple
228 in northern China, generally with furrow irrigation in the orchards. However, irrigation was not a
229 player in the farm CF for peach and orange. Besides, accounting for less than 8% of the total GHG

230 emissions, bag coverage made a small contribution to total CF for the fruits except for orange. Fossil
231 fuel use for farm mechanical operations also contributed by 9% and 17% to the total CF for apple and
232 pear, respectively.

233 Fig. 3

234 Fig. 4

236 Fig. 5

237

238 *Carbon footprint difference between management systems*

239 While plotting the product CFs against fresh fruit yields using the whole data, there was an overall
240 very significant negative correlation of product CFs to fresh fruit yield (Fig. 6). When grouping by the
241 fruit types, however, such negative correlation was valid for apple (Fig.6a) and banana (Fig. 6b)
242 production but not in peach, pear and orange production (Fig.6c-e). Based on the information from Fig.
243 5 and Fig. 6f, orchards surveyed were divided into low and high management efficiency systems (Table
244 5). Consequently, higher fruit yields but lower product CFs were found under high efficiency
245 management compared to low efficiency management. There were some differences in GHG intensities
246 from individual inputs between orchard managements. In particular, inputs of fertilizers and irrigation

Fig. 6

247 exerted higher GHG intensities under low
248 efficiency management than under high
efficiency management.

Table 5

250

251

252

253

254 **Discussions**

255 *GHG emissions from fruit production*

256 In this study, there were wide variation of carbon footprints across the surveyed orchards, with a
257 range of 2.9-12.8 t CO₂-eq ha⁻¹ in farm CF and of 0.07-0.7 kg CO₂-eq kg⁻¹ fruit in product CF,
258 respectively. On average, the product CF was 0.24, 0.27, 0.14, 0.37 and 0.18 kg CO₂-eq kg⁻¹ fruit
259 respectively for apple, banana, orange, peach and pear. The mean CFs in arrange of was similar to the
260 fruit sector from Switzerland in a range of 0.08-0.36 kg CO₂-eq kg⁻¹, which included the emissions in
261 cultivation, storage and distribution (Stoessel et al. 2012). In a work by Liu et al. (2010b), Chinese pear
262 production under different farm types was shown CFs in a range of 0.06-0.38 kg CO₂-eq kg⁻¹ fruit
263 though the emissions involved in sorting and storage post production was accounted. Production of
264 banana from cradle to retail was shown at a GHG emission cost of 1.37 kg CO₂-eq kg⁻¹ fruit on average,
265 of which only 16% was exhausted with primary production in orchard (Svanes et al. 2013). However,
266 quantified by Milà i Canals et al. (2006), apple production was seen much lower in CFs in New
267 Zealand, ranging from 0.04 kg CO₂-eq kg⁻¹ to 0.10 kg CO₂-eq kg⁻¹. Compared to these reported CFs
268 from western countries and other regions of the world, primary production of China's fruit sector
269 seemed already carbon intensive in land use and carbon inefficiency in product. Thus, China's fruit
270 production could likely lead to higher impacts on climate change than the western countries. The high
271 carbon intensity raised a big challenge for the sustainability of the fast increasing sector concerning
272 both the environmental impacts and the livelihood for almost 100 million farmers (Su, 2012).

273 The averaged farm CF and product CF was in a range of 5.9-9.7 t CO₂-eq ha⁻¹ and of 0.14 – 0.37
274 kg CO₂-eq kg⁻¹ fruit respectively, across the major fruit types. Farm CF, carbon intensity in land use of
275 fruit production, was found in a range of 2.9-12.8 t CO₂-eq ha⁻¹ across the orchard surveyed. The farm
276 CFs were 9.7, 8.6, 8.2, and 7.1 and 5.9 t CO₂-eq ha⁻¹ on average respectively for banana, pear, apple,
277 and orange and peach. In our previous works, the mean farm CF of rice, wheat and maize was 6.0, 3.0
278 and 2.3 t CO₂-eq ha⁻¹ using farm survey (Yan et al. 2015a) and 9.0, 2.9 and 2.9 t CO₂-eq ha⁻¹ using
279 statistical data (Cheng et al., 2014), and of vegetables in a range of 3.2-7.5 t CO₂-eq ha⁻¹ from a
280 regional survey (Chen et al. 2011). Obviously, orchards for fruit production studied here could be
281 concerned highly carbon intensive land use compared to grain production. However, this was not the
282 case for product CF. Respectively of rice, wheat and maize, a mean product CF was predicted of 0.80,
283 0.66 and 0.33 kg CO₂-eq kg⁻¹ in a farm survey study by Yan et al (2015a) and of 1.36, 0.51 and 0.44 kg

284 CO₂-eq kg⁻¹ in a study using statistical data by Cheng et al. (2014). Comparatively, the product CFs of
285 fruit production here, scaled by fresh fruit yield harvested, were lower than these estimates for grain
286 production of China. Therefore, fruit production in terms of harvested fresh fruit was relatively higher
287 carbon efficiency than grain production in China. Up to 2013, a total of 154 million tons of fruit was
288 produced in a total fruit production area of 13.2 Mha (NBSC 2014). A potential carbon emissions from
289 the primary production of these fruits could be predicted only 15.5 Mt CO₂e in 2013. In comparison, a
290 potential carbon emission of 438 Mt CO₂e was predicted for 556 Mt total grain production of rice,
291 wheat and maize, exhausting a total cropland of 88.6 Mha, of China in 2011 (Cheng et al., 2014). Of
292 course, the potentially increasing carbon emissions with the fast increasing fruit cultivation should be
293 given much attention for its high emission intensity in land use in China's agricultural production
294 sector.

295 *Mitigation options in fruit production*

296 Of the total CF, fertilizer use made a major contribution across the fruit types. Fertilizer induced
297 GHGs possessed half of the CF for apple and pear and almost 70% for peach and banana up to 90% for
298 orange. Overall, the GHG emissions from N inputs through synthetic fertilizer application contributed
299 by 47%-75% (93-204 kg CO₂-eq t⁻¹ fruit) to the total GHG emissions. N fertilizer induced emissions
300 was in a proportion of 70%-80% to total CF for conventional pear production at the farm gate from
301 China (Liu et al. 2010b). In apple production from New Zealand, less fertilizer use contributed about
302 25%-51% to the total GHG emissions (Milà i Canals et al. (2006).

303 In this study, synthetic N fertilizer use was seen playing a determinant role in overall carbon
304 footprint of primary production of China's fruit (Fig. 3). An excessive N input (297-567 kg N ha⁻¹) was
305 seen in our surveyed orchards and such luxury N input led to a high emission from N fertilizer (3.3-6.3
306 t CO₂-eq ha⁻¹, Fig. 5). Particularly, N-fertilizer input for apple here (348 kgN ha⁻¹ on average) seemed
307 very high compared to that of 62 kg N ha⁻¹ on average used in apple orchards from Switzerland
308 (Mouron et al. 2006). However, fresh apple yield was similar between this study (37 t ha⁻¹ on average)
309 and the study by Mouron et al. (2006) (31 t ha⁻¹ on average). The issue of excessive N input applied for
310 fruit cultivation in China was also critically concerned with other studies (Zhao et al. 2012, 2013; Ju et
311 al. 2006). In an extensive survey of 6863 Chinese fruit orchards, Zhang et al. (2013) reported an
312 excessive N fertilizer as much as 550 kg N ha⁻¹ on average for an average fruit yield of 36.7 t ha⁻¹.
313 Similarly, in a survey of 34 apple orchards, Ju et al. (2006) reported a high N application rate up to 661

314 kg N ha⁻¹ on average. All these again evidenced that China's fruit production had been already N
315 excessive and thus highly carbon intensive, being similar to China's cereals production (Cheng et al.,
316 2011; Yan et al., 2015a).

317 While the product CF largely depended on N application rate (Fig. 4), increasing partial factor N
318 productivity (PFP_N) led to a sharp decrease in product CF (Fig.5). The overall product CF could
319 decrease to as low as 0.2 t CO₂-e per ton fresh fruit produced when PFP_N reached up to 100 kg fresh
320 fruit per kg N. Zhang et al. (2009) considered an application rate of 150-250 kg N ha⁻¹ suitable for fruit
321 production in China. Recently, Zhao et al. (2012) recommended N fertilization in a range of 240-360
322 kg N ha⁻¹ for apple yield in a range of 25-45 t ha⁻¹ across China, based on the results from their
323 experiment and expert design of fruit orchard fertilization. Therefore, to reduce N application rates
324 with enhanced N efficiency would be of priority demand to cut greenhouse gas cost of China's fruit
325 production. According to the comparison in Table 5, high fruit yield could be sustained even N
326 fertilization greatly reduced. Generally, 15%-24% of GHG emissions could be avoided when 30% of N
327 inputs could be saved in the surveyed orchards. Among the potential measures to save synthetic N
328 fertilizer use, increase the relative proportion of manure of the total fertilizers used could help increase
329 fertilizer use efficiency and thereby reducing GHG emissions (Zhang et al. 2013). Organic manure
330 amendment at 40-60 t ha⁻¹ could be suitable for fruit cultivation in China (Zhao et al. 2012, 2013;
331 Wang et al. 2013). Application of chemical fertilizers combined with organic manure could not only
332 increase the fruit yield but also improve fruit quality (Zhao et al. 2013). Best farm management
333 practices to enhance orchard productivity could also help reduce the product CF, which was in a
334 significantly negative correlation to fresh fruit yield for apple and banana (Fig. 6). Data in Table 5
335 depicted a great a great potential to increase fruit yield through improving orchard management. With
336 low efficiency management, mean fruit yield of 33 ton per hectare exhausted N induced emission of
337 almost 200 kg CO₂-eq per ton fresh fruit produced. With high efficiency management, however, an
338 overall mean fruit yield of 46 t ha⁻¹, could be reached at a N-induced emission cost of 72 kg CO₂-eq
339 per ton fresh fruit produced. This is very close to a N emission cost of 82 kg CO₂-eq per ton of fruit in
340 the study by Mouron et al. (2006). In the present study, improving by 15% fruit yield could save GHG
341 emissions by about 13% on average. Overall, the important options for mitigating environmental
342 impacts in China's fruit production included reducing the synthetic N application and increasing
343 organic manure use, improving N fertilizer use efficiency as well as other good management practices

344 to increase fruit yield.

345 *Low carbon production and consumption of fruit*

346 In 2013, consumption of fresh fruits reached 37.8 kg per capita in China (NBSC 2014), compared
347 to the mean of 61 kg globally and of 83 kg in OECD countries. China launched a national planning for
348 people's nutrition in 2014, which aimed to realize a target of 60 kg per capita per year of fresh fruit
349 consumption in 2020 (SCC 2014). Low carbon dietary consumption had been advocated for balancing
350 the food supply and land exploitation (van Kernebeek et al. 2015). The total fruit consumption of fruit
351 planned for 2020 would result in a total carbon emission of 18.7 Mt CO₂-eq, using the mean product
352 CF value (0.24 kg CO₂-eq kg⁻¹ fruit) here. However, if orange, high in Vc but low in product CF, could
353 be chosen for fruit consumption, a total of 8 million ton of CO₂-eq would be saved. This would be
354 even saving land, since orange was generally most productive among the surveyed fruit types (Table 4).
355 It would be particularly important for China for its cropland area had been already tightening due to its
356 fast urbanization. Of course, low carbon fruit could not necessarily bring high income for fruit
357 producers (Table 4). This issue had been considered with marketing mechanisms such as low carbon
358 labelling or even potential carbon tax (Cros et al. 2010; Jungbluth et al. 2011). China had a great
359 ambition to cut its huge GHG emission and recently launched a national strategy for tackling climate
360 change. For this, low carbon dietary consumption had been recommended among a couple of attainable
361 approaches (NDRC 2014). To compensate the carbon benefits to climate mitigation, national incentives
362 or marketing mechanisms should be to develop. Overall, low carbon production and consumption
363 should be encouraged so that fruit production could be sustained not only for climate change mitigation
364 but also for land sustainability for a great country with huge population. Nevertheless, there is still a
365 knowledge gap as how to balance fruit yield and quality, the environment impacts, fruit grower's
366 income and human nutrition intake from agro-products.

367

368 **Conclusions**

369 The fruit production was characterized by a high farm carbon footprint but a relative low product
370 carbon footprint compared to grain production in China's agriculture. Orange had a lower product
371 carbon footprint but higher income- and nutrition (*Vc content*)-scaled carbon footprint than apple,
372 banana and peach. Synthetic N fertilizers contributed over half to the total greenhouse gas emissions
373 from primary production of fruit and reducing synthetic N fertilizer application should be of priority
374 demand to cut greenhouse gas emission from the fruit production sector. In addition, there could be
375 tradeoffs in product CF between nutrition and economic income. However, to stabilize or even to cut
376 carbon emissions and to save the land of fruit production sector, national policies and market
377 mechanism for low carbon dietary consumption should be developed. For this, how to balance nutrition
378 requirement and incomes for fruit growers is still a great challenge.

379

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387

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Figure captions

Fig.1 System boundary of fruit production in this study.

Fig.2 Site location of the apple, peach, pear, banana, and orange orchards surveyed (The value in parenthesis is the number of orchards surveyed).

Fig.3 Contribution of individual inputs to the total GHG emissions.

Fig.4 Correlation of the product carbon footprint (CF) with N fertilizer application rate (a, apple; b, banana; c, orange; d, peach; e, pear and f, total).

Fig.5 Change in product carbon footprint (CF) with the partial factor productivity from applied N (PF_{N}) (a, apple; b, banana; c, orange; d, peach; e, pear and f, total).

Fig.6 Correlation of the product carbon footprint (CF) with fruit yield.