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1 **Global environmental costs of China's thirst for milk**

2

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28

29 **Abstract:**

30 China has an ever-increasing thirst for milk, with a predicted 3.2-fold increase in  
31 demand by 2050 compared to the production level in 2010. What are the environmental  
32 implications of meeting this demand, and what is the preferred pathway? We addressed  
33 these questions by using a nexus approach, to examine the interdependencies of  
34 increasing milk consumption in China by 2050 and its global impacts, under different  
35 scenarios of domestic milk production and importation. Meeting China's milk demand  
36 in a business as usual scenario will increase global dairy-related (China and the leading  
37 milk exporting regions) greenhouse gas (GHG) emissions by 35% (from 565 to 764 Tg  
38 CO<sub>2</sub>) and land use for dairy feed production by 32% (from 84 to 111 million ha)  
39 compared to 2010, while reactive nitrogen losses from the dairy sector will increase by  
40 48% (from 3.6 to 5.4 Tg nitrogen). Producing all additional milk in China with current  
41 technology will greatly increase animal feed import; from 1.9 to 8.5 Tg for concentrates  
42 and from 1.0 to 6.2 Tg for forage (alfalfa). In addition, it will increase domestic dairy  
43 related GHG emissions by 2.2 times compared to 2010 levels. Importing the extra milk  
44 will transfer the environmental burden from China to milk exporting countries; current

45 dairy exporting countries may be unable to produce all additional milk due to physical  
46 limitations or environmental preferences/legislation. For example, the farmland area  
47 for cattle-feed production in New Zealand would have to increase by more than 57%  
48 (0.1 million ha) and that in Europe by more than 39% (0.5 million ha), while GHG  
49 emissions and nitrogen losses would increase roughly proportionally with the increase  
50 of farmland in both regions. We propose that a more sustainable dairy future will rely  
51 on high milk demanding regions (such as China) improving their domestic milk and  
52 feed production efficiencies up to the level of leading milk producing countries. This  
53 will decrease the global dairy related GHG emissions and land use by 12% (90 Tg CO<sub>2</sub>  
54 reduction) and 30% (34 million ha land reduction) compared to the business as usual  
55 scenario, respectively. However, this still represents an increase in total GHG  
56 emissions of 19% whereas land use will decrease by 8% when compared with 2010  
57 levels.

58

59 **Keywords:** Greenhouse gas; land use, nitrogen losses; milk trade; cattle feed; Shared  
60 Socio-economic Pathways scenarios (SSPs)

61

## 62 **Introduction:**

63 The increased international trade of agricultural products has received much attention  
64 recently, due to the impacts of production on land use, deforestation and associated  
65 biodiversity loss, impaired nutrient cycling, and greenhouse gas (GHG) emissions.

66 Currently, around 23% of the food produced for human consumption is traded

67 internationally (D'Odorico et al., 2014). It has been estimated that the global trade of  
68 nitrogen (N), embedded in the products, has increased from 3 to 24 Tg N between 1961  
69 and 2010, with the largest contributor relating to animal feed (Lassaletta et al., 2014).  
70 Oita et al (2016) analyzed the reactive N emitted during the global production,  
71 consumption and transportation of commodities, and estimated that 15% of the global  
72 N footprint is from commodities internationally traded. Exportation of beef, soybeans  
73 (*Glycine max*) and wood products was responsible for 12% of the deforestation in seven  
74 countries with high deforestation rates (Henders et al., 2015). Additionally, up to 30%  
75 of global species threats are due to international trade, via production of commodities  
76 in export countries (Lenzen et al., 2012) and 17% of global biodiversity loss occurs due  
77 to commodities destined for exportation (Chaudhary and Kastner, 2016).

78 The trade of milk will likely increase strongly during the next decades due to the  
79 increasing demands from China and some other rapidly developing countries, e.g. India  
80 (Alexandratos and Bruinsma, 2012). In 2013, around 125 Tg milk was traded between  
81 countries, which was an 8-times increase since 1961, and equal to 20% of the global  
82 milk production (FAO, 2016). European Union (EU), New Zealand (NZ) and United  
83 States of America (USA) were the top three milk exporting region and countries,  
84 accounted for more than 80% of total export in 2013 (FAO, 2016). Currently, China is  
85 the leading milk importer, importing 12 Tg fresh milk equivalent in 2013, which was  
86 123-times larger than that in 1961, and equal to 25% of the domestic consumption in  
87 2013 (FAO, 2016).

88 Globally, consumption of animal products is driven by culture, population growth and

89 prosperity (gross domestic production, GDP), with high GDP countries consuming on  
90 average higher amounts per capita (Tilman et al., 2011; Tilman and Clark, 2014). This  
91 holds also for milk, but with significant variation between countries (Fig S1). It is  
92 projected that global milk consumption will increase by 60% between 2010 and 2050,  
93 especially in traditionally lower consumption regions, such as China (Alexandratos and  
94 Bruinsma, 2012). Historically, China had low milk consumption per capita ( $< 2 \text{ kg}$   
95  $\text{capita}^{-1} \text{ y}^{-1}$  in 1961, partially due to the severe food crisis during those years), but given  
96 the growth of its economy and urbanization rate, milk consumption has increased over  
97 25-times during the past 5 decades, leading to China becoming the world's fourth-  
98 largest milk producer (FAO, 2016). Milk consumption is likely to increase further in  
99 China, as a consequence of population and GDP growth. urbanization (Wang et al.,  
100 2017; Fig S2), and a reduction in small traditional dairy production units ( $< 5$  head farm)  
101 towards larger, more resource efficient, intensive units (100 cows +) (Fig S3).

102 China became the world's largest milk importer in 2010, following the melamine  
103 scandal in 2008 which eroded public confidence in domestically produced milk (Pei et  
104 al., 2011; FAO, 2016). China also imports massive amounts of soybean and increasing  
105 amounts of maize (*Zea mays*) and alfalfa (*Medicago sativa*) to feed its increasing  
106 domestic pig, poultry and dairy cattle populations (FAO, 2016). The increasing imports  
107 of animal feed are related to the increasing domestic consumption of animal derived  
108 food and to the relative scarcity of agricultural land and fresh water. Meanwhile, EU  
109 abolished its milk quota system in 2015, and New Zealand and Chile are preparing for  
110 the projected increase in milk demand from China and other rapidly developing

111 countries, e.g. India (Europe Union Commission, 2014; Oenema et al., 2014). The  
112 impact of China's thirst for milk related to resource demands, climate change,  
113 eutrophication and biodiversity loss need to be predicted so pathways for a more  
114 sustainable solution can be mapped. China is facing both food security and water  
115 security challenges as well as vast environmental challenges, which underpin the  
116 importance of researching alternative potential future projections (Piao et al., 2010; Liu  
117 and Yang, 2012).

118 Here, we present the results of a novel nexus approach to examine the  
119 interdependencies of increasing milk consumption in China and its impact on GHG  
120 emissions, N losses, land and water use, and economic performances across the main  
121 feed and milk producing countries. Dairy cattle account disproportionately to GHG  
122 emissions, predominately because of enteric fermentation and the release of methane  
123 (CH<sub>4</sub>) (Steinfeld et al., 2006; Gerber et al., 2013). We analyzed the interrelationships  
124 and interdependencies of the whole 'production-consumption-trade' system for 2050  
125 under contrasting Shared Socio-economic Pathway scenarios (SSP): (i) Business as  
126 usual (BAU) - increase of milk consumption in 2050 aligned to current proportional  
127 contributions of domestic production and import (SSP2), (ii) Produce all additional  
128 milk domestically (PA) – increase of milk consumption in 2050 delivered through  
129 increased domestic output (SSP3), and (iii) Import all additional milk (IM) – increase  
130 of milk consumption in 2050 delivered through increased imports from three leading  
131 producing regions (EU, USA, NZ) (SSP5). Further, we evaluated two extra scenarios  
132 following the Shared Socio-economic Pathway 1 (SSP1) storyline, which focuses on

133 technological improvements: (i) Dairy Production Improvement (DPI) - assuming that  
134 productivity and manure management in China can reach the current level of the leading  
135 milk exporting countries by 2050; and (ii) Farming Systems Improvement (FSI) -  
136 towards crop-dairy integration and forage-based systems with increased productivity of  
137 forages, building on scenario DPI.

138

## 139 **Materials and methods**

140 The approach we took was to split the study into four carefully defined areas to perform  
141 the assessment: i) determine the factors which will drive the prediction of milk  
142 consumption in China; ii) set the system boundary of the study; iii) assign and calculate  
143 multiple sustainability indicators (one economic, three physical and four environmental  
144 indicators); iv) describe the scenarios to be tested to meet the demand and the  
145 consequent impact on the sustainability indicators.

146

### 147 **Prediction of milk consumption in China**

148 We estimated average per capita milk consumption in 2050 using different sources and  
149 the following assumptions. First, we calculated the relations between average milk  
150 consumption per capita and average GDP per capita, and milk consumption per capita  
151 and urbanization rate (Fig S2). Milk consumption in 2050 was then estimated assuming  
152 a mean GDP of 10,904 \$ capita<sup>-1</sup> yr<sup>-1</sup> and an urbanization of 78% in 2050 (FAO, 2016;  
153 World Bank, 2016). Second, a predicted increase in average milk consumption of 1.80%  
154 yr<sup>-1</sup> in developing countries between 2005 and 2050 (Alexandratos and Bruinsma,



155 2012). Third, following the national guidelines for a healthy diet, the average milk  
156 consumption is 300 g capita<sup>-1</sup> d<sup>-1</sup> in 2050 (CSN, 2014).

157 Total milk consumption was calculated as:

$$158 \text{Milk}_{\text{total}} = \text{Population} * \text{Milk}_{\text{average}} \quad [1]$$

159 Where, Milk<sub>total</sub> is the total milk consumption in kg, Population is the total human  
160 population, and Milk<sub>average</sub> is the average milk consumption in kg capita<sup>-1</sup>, calculated  
161 using the three assumptions outlined above. Forecasts suggest that the human  
162 population will be 1.4 billion in China in 2050 (FAO, 2016).

163

#### 164 **System boundary**

165 Milk import was assumed to be from the current top three milk exporting regions,  
166 namely: EU, NZ and the USA in 2010 (FAO, 2016). The resource requirements (feed,  
167 land and water) and environmental performance (GHG emissions, reactive N (Nr)  
168 losses, N and phosphorus (P) excretions) parameters related to dairy production in these  
169 countries were collected from peer-reviewed published literature, and then used to  
170 calculate the domestic and global impacts of supplying the calculated 2050 milk  
171 demand in China (Tables 1, S2-3).

172

#### 173 **Determining the sustainability indicators to be used in the assessment**

174 A total of eight indicators at the herd level (accounting for lactating cow, heifers and  
175 calves. Dairy related beef production was not considered), with three physical  
176 indicators (feed, land and water requirement), one economic indicator (GDP value of

177 milk production) and four environmental impact indicators (GHG emissions and  
178 reactive N losses, N and P excretions), were selected to evaluate the impacts of the  
179 projected increase in milk consumption and production. The economic value of milk  
180 production was derived from the milk production price in 2010 recorded in the FAO  
181 database and used as an indicator of the economic importance, assuming that the milk  
182 price will remain more or less constant (FAO, 2016). In practice, milk price will depend  
183 on the balance of milk demand and supply, which will depend on many factors and  
184 opportunities, however a basal value is required to assess economic performance. Feed  
185 requirement and the related land and water requirements to produce the feed were used  
186 as indicators for resource use. Emissions of GHG and Nr and the production of manure  
187 N and P were chosen as agri-environmental impact indicators, as China is facing severe  
188 challenges associated with current emissions and associated climate change, nutrient  
189 losses and manure management problems (Bai et al., 2016).

190

### 191 **NUFER-dairy model**

192 The resource use and environmental effects of different dairy production systems in  
193 China were calculated by the NUFER-dairy model (Bai et al., 2013; Zhang et al., 2017).

194 The NUFER-dairy model has been developed to quantitatively evaluate GHG  
195 emissions, nutrient flows, and land, water and feed resource requirements for various  
196 systems of operation at animal, herd, and system levels. The model consists of an input  
197 database, a calculator, and an output module. The input database includes herd  
198 demographics, milk yield and feed composition. The calculation module includes a feed

199 intake prediction sub-module and a nutrient balance sub-module. Calculation of feed  
200 intakes by calves, heifers, and milking cows are based on the energy requirements. The  
201 nutrient balance is calculated from the nutrients flows through the whole soil-feed-milk  
202 production chain. The output module provides results for land, water and feed use,  
203 nutrient losses and GHG emissions (Bai et al., 2013; Zhang et al., 2017).

204

### 205 **Three physical indicators (feed, land and water)**

#### 206 *Feed requirement*

207 The feed requirement of dairy cattle was calculated as follows:

$$208 \text{ Feed}_{\text{total}} = \text{Milk}_{\text{produced}} * \text{Feed}_{\text{milk}} \quad [2]$$

209 Where  $\text{Feed}_{\text{total}}$  is the total feed requirement (dry matter) in kg,  $\text{milk}_{\text{produced}}$  is the total  
210 milk produced in each region in kg, and  $\text{Feed}_{\text{milk}}$  is the feed to milk conversion ratio in  
211  $\text{kg kg}^{-1}$  (Tables 1, S1). The feed conversion ratio of China's dairy production was  
212 calculated per production system and their contribution to the total milk production  
213 (Table S2). The feed conversion values for NZ, EU and USA were derived from a  
214 literature review (Appuhamy et al., 2016), and are shown in Table 1.

215

#### 216 *Land requirement*

217 The agriculture land required for dairy production was calculated from total milk  
218 production and the average land demand  $\text{kg}^{-1}$  milk.

$$219 \text{ Land requirement} = \text{Milk}_{\text{produced}} * \text{Land requirement}_{\text{milk}} / 10000 \quad [3]$$

220 Where, Land requirement is the area of arable land and grassland required for feed

221 production, in ha. Land requirement<sub>milk</sub> is the average area of land needed to produce  
222 1 kg of milk, in m<sup>2</sup> kg<sup>-1</sup> milk. The area of cropland and grassland for producing feed for  
223 China's dairy production was calculated using total feed requirement (excluding the  
224 imported feed), and average crop and grassland yields. Information about the land  
225 requirement in the three milk exporting countries is listed in Table 1.

226

### 227 *Water use*

228 The water use was obtained by calculating the blue water (from surface and ground  
229 waters, for irrigation) use for milk production:

$$230 \text{ Water} = \text{Milk}_{\text{produced}} * \text{Water}_{\text{milk}} \quad [4]$$

231 Where Water is the total water requirement in m<sup>3</sup>; Water<sub>milk</sub> is the mean blue water use  
232 for milk production in m<sup>3</sup> kg<sup>-1</sup> milk. The blue water use of China's dairy production  
233 covered the blue water demand of related feed production, i.e. 74 m<sup>3</sup> t<sup>-1</sup> maize, 129 m<sup>3</sup>  
234 t<sup>-1</sup> soybean, 387 m<sup>3</sup> t<sup>-1</sup> rice, and 455 m<sup>3</sup> t<sup>-1</sup> wheat (Mekonnen and Hoekstra, 2011). These  
235 figures do not include the demand for drinking and service water, due to lack of  
236 information and their small contribution to the total water footprint (Mekonnen and  
237 Hoekstra, 2012). The blue water use for milk production by the three main milk  
238 exporters was derived from literature (Table 1). Here, differences in crop water use  
239 efficiency associated with different scenario assumptions have not been considered.

240

### 241 **One economic indicator (GDP value of milk production)**

242 The economic value of dairy production was calculated according to the average milk

243 production value in 2010.

$$244 \text{ Economic value} = \text{Milk}_{\text{produced}} * \text{Costs}_{\text{milk}} \quad [5]$$

245 Where, Economic value is the total economic value of produced milk in US\$ in 2010;

246  $\text{Costs}_{\text{milk}}$  is the average production cost of milk, derived from FAO database in US\$ t<sup>-1</sup>

247 milk. The average milk production cost was 445, 376, and 360 US\$ t<sup>-1</sup> milk for China,

248 NZ and USA, respectively in 2010. For EU, we used a weighted average value, which

249 was 418 US\$ t<sup>-1</sup> milk in 2010 (Table 1). The job opportunities provided by dairy

250 production was calculated from the total GDP of dairy production, and assuming an

251 income of 18,000 Yuan person<sup>-1</sup> yr<sup>-1</sup> in 2010 (China Statistic Yearbook, 2011).

252

#### 253 **Four impact indicators (GHG emissions, N losses, N and P excretion)**

##### 254 *GHG emissions*

255 The GHG emissions (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) from the soil-feed-dairy production and

256 feed-milk transportation chains were calculated as:

$$257 \text{ GHG} = \text{Milk}_{\text{produced}} * \text{GHG}_{\text{milk}} + \text{Milk}_{\text{export to China}} * \text{GHG}_{\text{milk export}} \quad [6]$$

258 Where GHG is the total GHG emissions of dairy production in kg CO<sub>2</sub> equivalents

259 (CO<sub>2</sub>e),  $\text{Milk}_{\text{produced}}$  is the amount of milk produced in each region (China, EU, USA,

260 and NZ) in kg.  $\text{GHG}_{\text{milk}}$  is the carbon footprint in kg CO<sub>2</sub>e kg<sup>-1</sup> milk.  $\text{Milk}_{\text{export to China}}$

261 is the amount of milk exported to China by the top three milk exporting regions

262 (weighted values) in 2010.  $\text{GHG}_{\text{milk export}}$  is the GHG emissions associated with the

263 milk from leading milk exporting regions to China.  $\text{Milk}_{\text{total}}$  is listed in Table S1, and

264 GHG emissions parameters are presented in Table 1. The GHG emissions related to the

265 transportation of milk to China was based on the average transport distance of milk to  
266 China from NZ, EU (the Netherlands) and USA, 11144, 7821 and 11100 km,  
267 respectively (Food Miles, 2016). The average GHG emissions rate was 0.0345 kg CO<sub>2</sub>e  
268 ton<sup>-1</sup> km during shipping (Van Passel, 2013). We assumed all the milk export to China  
269 was as milk powder, as only 2% of the milk transported to China was as fresh milk in  
270 2010 (FAO, 2016). The average fresh milk to dry milk conversion ratio was set at 7:1.

271

### 272 *Nr losses*

273 Nr losses were based on the average Nr losses and milk production of different dairy  
274 production systems calculated by NUFER-dairy (Table S2). In scenarios, Nr losses  
275 were weighted per their share of total dairy production (Tables S3, S4). Nr losses of  
276 leading milk export regions were collected from the literature (Table 1). In our  
277 calculations, the following Nr losses have been considered: nitrate leaching to  
278 groundwater and surface waters and emissions of N<sub>2</sub>O and ammonia (NH<sub>3</sub>) to the  
279 atmosphere, from housing, manure management and soils.

$$280 \text{Nr losses} = \text{Milk}_{\text{produced}} * \text{Nr losses}_{\text{milk}} \quad [7]$$

281 Where Nr losses are the total Nr losses of dairy production in kg. Nr losses<sub>milk</sub> are the  
282 Nr losses per kilo of milk in kg kg<sup>-1</sup> milk, data for China see Table S2 and for other  
283 regions see Table 1. The Nr losses were assessed at the system level (soil-crop-dairy),  
284 and included the losses during feed production.

285

### 286 *N and P excretions*

287 The N and P excretions by dairy cattle was calculated as:

$$288 \text{ N(P) excretion} = \text{Milk}_{\text{produced}} * \text{N(P) excretion}_{\text{milk}} \quad [8]$$

289 Where N(P) excretion is the total amount of manure N(P) produced by dairy cattle in  
290 kg yr<sup>-1</sup>, N(P) excretion<sub>milk</sub> is the average N(P) excretion per kilo of milk produced, in  
291 kg (Table 1).

292

### 293 **Feed use and import, and related land import**

294 Consumption of different feed items was calculated as follows:

$$295 \text{ Feed}_{\text{items}} = \text{Feed}_{\text{total}} * \text{Feed}_{\text{composition}} \quad [9]$$

296 Where, Feed<sub>items</sub> is the consumption of different feed items, i.e. maize, soybeans, and  
297 alfalfa, in kg. Feed<sub>total</sub> is calculated by Equation 5. Feed<sub>composition</sub> is the feed  
298 composition used in different countries in % of Feed<sub>total</sub>. Feed composition was  
299 collected from published studies; Bai et al (2013) for China, Hou et al (2016) for EU,  
300 and Herrero et al (2013) for NZ. The feed import in 2010 was derived from FAO  
301 database (Table S5). No dairy feed was imported into USA. Feed related land import  
302 was calculated based on the feed import and feed productivity in the feed export regions,  
303 which were derived from the FAO database.

304

305 Table 1. Greenhouse gas (GHG) emissions, reactive nitrogen (Nr) losses (including losses during feed production), land and irrigation water  
 306 requirement for feed production, feed requirement, production cost, and N and P excretion by dairy cattle in China, New Zealand, European, and  
 307 United States. The references are indicated with the number (as superscript). The figures without superscript are derived from calculations with  
 308 the NUFER model.

	China						New Zealand	European	United States
	2010	BAU	PA	IM	DPI	FSI			
GHG (kg CO <sub>2</sub> e kg <sup>-1</sup> milk)	2.9	2.9	2.9	2.9	1.9	1.9	2.1 <sup>1</sup>	1.6 <sup>1</sup>	1.9 <sup>1</sup>
Nr losses (g N kg <sup>-1</sup> milk)	34	31	31	32	11	10	12 <sup>2</sup>	9.0 <sup>3</sup>	12 <sup>4</sup>
Land requirement (m <sup>2</sup> kg <sup>-1</sup> milk)	5.2	2.4	2.1	3.8	1.9	1.9	1.3 <sup>2</sup>	2.5 <sup>5</sup>	1.9 <sup>6</sup>
Blue water requirement (m <sup>3</sup> kg <sup>-1</sup> milk)	145	206	213	173	57	51	48 <sup>7</sup>	46 <sup>7</sup>	60 <sup>7</sup>
Feed requirement (kg DM kg <sup>-1</sup> milk)	2.6 <sup>8</sup>	1.7	1.6	1.9	0.9	1.1	1.1 <sup>9</sup>	1.2 <sup>9</sup>	0.9 <sup>9</sup>
Costs (\$ t <sup>-1</sup> milk)	445 <sup>10</sup>	445	445	445	372	383	376 <sup>10</sup>	418 <sup>10</sup>	360 <sup>10</sup>
N excretion (g N kg <sup>-1</sup> milk)	32 <sup>8</sup>	28	28	30	20	24	30 <sup>11</sup>	20 <sup>12</sup>	18 <sup>13</sup>
P excretion (g P kg <sup>-1</sup> milk)	5.6 <sup>8</sup>	4.5	4.4	4.7	2.6	2.8	2.2 <sup>14</sup>	3.0 <sup>12</sup>	2.5 <sup>15</sup>

309 1. Opio et al., 2013; 2. Flysjö et al., 2011; 3. Leip et al., 2014; 4. Powell et al., 2010; 5. Lesschen et al., 2011; 6. Eshel et al., 2015; 7. Mekonnen and Hoekstra, 2011; .8.  
 310 Bai et al., 2013; 9. Appuhamy et al., 2016; 10. FAO, 2016; 11. de Klein et al., 2005; 12. Velthof et al., 2015; 13. Powell et al., 2006; 14. Monaghan et al., 2007; 15.  
 311 Powell et al., 2006.

312 **Scenarios:** BAU (SSP2): Business as usual, with a milk self-sufficiency of 75%; PA (SSP3): Produce all additional milk in 2050 domestically; IM (SSP5): Import all  
 313 additional milk in 2050; DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system improvement, on top of DPI.



314

315 **Development of scenarios**

316 **Business as usual scenario (BAU - Milk self-sufficiency maintained at 75%).** This  
 317 followed the SSP2 storyline, that social, economic and technological trends do not shift  
 318 markedly from historical patterns (O’Neill et al., 2016). Therefore, we assumed that  
 319 milk self-sufficiency in 2050 will be maintained at the current level (75%) (FAO, 2016).  
 320 The milk imported will come from the current top three global milk exporters: EU  
 321 (77%), NZ (13%), and the USA (10%) (FAO, 2016). Domestic milk will be provided  
 322 by grazing systems, medium size systems and industrial systems; following current  
 323 trends in dairy production, their relative contributions will be 6, 13, and 81%,  
 324 respectively (Table 2). We assumed that the ‘traditional’ dairy system ( $\leq 9$  head cattle  
 325 per farm) will have disappeared by 2050 (MOA, 2015).

326

327 Table 2. Key parameters of different dairy production systems for different scenarios.

	BAU	PA	IM	DPI	FSI
Domestic milk self-sufficiency rate (%)	75 <sup>1</sup>	100 <sup>1</sup>	33 <sup>1</sup>	75 <sup>1</sup>	75 <sup>1</sup>
Share of grazing, medium size and industrial system to domestic milk production (%)	6, 13, 81 <sup>1</sup>	4, 10, 86 <sup>1</sup>	14, 30, 56 <sup>1</sup>	6, 13, 81 <sup>1</sup>	33, 33, 33 <sup>1</sup>
Crop and dairy integration rate	Low <sup>1</sup>	Low <sup>1</sup>	Low <sup>1</sup>	High <sup>1</sup>	High <sup>1</sup>
Yield of selected feed (t ha <sup>-1</sup> )	Corn	5.5 <sup>2</sup>	5.5 <sup>2</sup>	5.5 <sup>2</sup>	9.2 <sup>3</sup>
	Soybean	1.8 <sup>2</sup>	1.8 <sup>2</sup>	1.8 <sup>2</sup>	2.0 <sup>3</sup>
	Grass	1.0 <sup>4</sup>	1.0 <sup>4</sup>	1.0 <sup>4</sup>	3.0 <sup>4</sup>
Importation rate of selected feed (%)	Corn	3.9 <sup>2</sup>	3.9 <sup>2</sup>	3.9 <sup>2</sup>	0 <sup>1</sup>
	Soybean	85 <sup>2</sup>	85 <sup>2</sup>	85 <sup>2</sup>	85 <sup>1</sup>

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Alfalfa	10 <sup>1</sup>	11 <sup>1</sup>	6.2 <sup>1</sup>	19 <sup>1</sup>	0 <sup>1</sup>
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328 1. This study; 2. FAO, 2016; 3. Chen et al., 2014; 4. Eisler et al., 2014.

329 **Scenarios:** BAU (SSP2): Business as usual, with a milk self-sufficiency of 75%; PA (SSP3):

330 Produce all additional milk in 2050 domestically; IM (SSP5): Import all additional milk in 2050;

331 DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system

332 improvement, on top of DPI.

333

334 **Scenario: Produce All (PA) – Milk self-sufficiency will increase to 100%.** Scenario

335 PA considered that all required milk will be produced domestically, following the SSP3

336 storyline with governmental policies focusing on national food security. Relative milk

337 production contributions from grazing, collective and industrial systems were assumed

338 to be 4, 10, and 86%, respectively, based on current trends (Table 2). We assumed again

339 that the ‘traditional’ dairy system ( $\leq 9$  head cattle per farm) will have disappeared by

340 2050.

341

342 **Scenario: Import Milk (IM) – Milk self-sufficiency will drop to 33%.** The IM

343 scenario assumes that domestic milk production will remain at the level in 2010 and

344 that all additional milk will be imported. As a result, milk self-sufficiency will drop to

345 33%. Relative milk production from grazing, collective and industrial systems is

346 assumed to be 14, 30, and 56%, respectively (Table 2). Imported milk was assumed to

347 be supplied by the same three countries with the same proportion as in BAU (Table S1).

348

349 **Scenario: Dairy Production Improvement (DPI) – Improved feed, herd and**  
350 **manure management - Milk self-sufficiency maintained at 75%.** The DPI scenario  
351 follows the SSP1 storyline that the world shifts toward a more sustainable path,  
352 emphasizing more inclusive development, with improvements in agricultural  
353 productivity and rapid diffusion of best practices (O’Neill et al., 2016). We assumed  
354 that China’s grazing systems will reach NZ’s current level by the end of 2050 (both in  
355 terms of milk production efficiency and environmental performance, but not for feed  
356 production efficiency, see Table 2). Similarly, we assumed that China’s collective dairy  
357 farms will get close to the EU’s current production efficiency and that China’s industrial  
358 dairy farms will have caught up with the current performance of USA’s large dairy  
359 operations. Thus, under this scenario, the grazing, collective and industrial dairy  
360 production systems were assumed to have a similar production, economic and  
361 environmental performance as the corresponding dairy production systems in NZ, EU  
362 and the USA. Especially for the integration of dairy and feed production, since the  
363 disconnection of crops and livestock could reduce efficiency at the system or global  
364 level even with significant improvements in efficiency at the herd level (Bai et al., 2014;  
365 Lassaletta et al., 2016). Strategies for improved dairy production efficiency and  
366 environmental performance are listed in Table 3.

367

368 Table 3. List of strategies for sustainable pathways of dairy production in China.

	Feed production	Dairy production and manure management
Research, scientists’	<b>Level 1:</b> Integrated Soil-crop System Management technology (ISSM) to	<b>Level 1:</b> Genetic improvements to increase milk productivity, i.e. build

strategy	<p>improve crop productivity<sup>1</sup>;  <b>Level 2:</b> Improve nutrient management in grasslands and production of grass in southern China to boost the high quality grass production<sup>2,3</sup>;  <b>Level 3:</b> Design new human-edible feeds; and design forage and crop production systems in China, i.e. rice-grass rotation in southern China, maize-rye grass rotation in northern China to increase grass production<sup>4</sup>;  <b>Level 4:</b> Water saving irrigation systems to boost feed production in northern and western China<sup>5</sup>.</p>	<p>up the national dairy herd improvement data source<sup>6</sup>; build up the nucleus group; adapt the sex-sorted sperm and embryo transfer technologies<sup>7</sup>; import high performances breeds from abroad.  <b>Level 2:</b> Feed improvement, i.e. using the high quality roughages, whole corn silage and alfalfa silage; total mixed ration feed; improve the quality of corn silage<sup>8</sup>.  <b>Level 3:</b> Herd management, i.e. improved reproduction; select the high performances calves and heifers; decrease the mortality rate; increase disease control and animal welfare control.</p>
Implementation policies	<p><b>Level 1:</b> Economic incentives to adopt new technology;  <b>Level 2:</b> Incentives to design sustainable farming system, for example incentives for grass production and processing;  <b>Level 3:</b> Training and extension services to improve dairy farmer's knowledge of feed production;  <b>Level 4:</b> Incentives for integrated dairy cow and feed production.</p>	<p><b>Level 1:</b> Strict restrictions of milk quality for milk production and recycle of manure;  <b>Level 2:</b> Incentives for importing high performance dairy cows and forage breeds;  <b>Level 3:</b> Incentives for high technique manure management equipment and machinery, to couple crop-dairy production;  <b>Level 4:</b> Build up more effective extension services or farm organizations, i.e. pioneer dairy farm to test the advanced technologies and training of the farmers</p>

369 1. Chen et al., 2011; 2. Li et al., 2007; 3. Li and Lin., 2014; 4. Pan et al., 2007; 5. Deng et al., 2006;

370 6. Zhou et al., 2012; 7. Xu et al., 2006; 8. Wang et al., 2009.

371

372 **Scenario: DPI with Farming Systems Improvement (FSI) - Milk self-sufficiency**

373 **maintained at 75%.** Scenario FSI builds on scenario DPI, while assuming that all milk

374 will be produced in equal portions by grazing, collective and industrial systems, due to

375 the concern of arable land competition, increased natural grassland utilization and  
376 manure local recycling issues. Domestic forage and feed production will have increased  
377 to a level that no forage and feed has to be imported (except for soybean). Mean grass  
378 yields will have increased from 1.0 to 3.0 t ha<sup>-1</sup> (Eisler et al., 2014). Yields of cereals  
379 can be improved through Integrated Soil-crop System Management technology (ISSM)  
380 with nutrient inputs similar to current levels; we assumed that mean crop yields will  
381 increase from 5.5 to 9.2 t ha<sup>-1</sup> for maize, from 6.5 to 7.7 t ha<sup>-1</sup> for rice and from 4.7 to  
382 6.9 t ha<sup>-1</sup> for wheat between 2010 and 2050 (Chen et al., 2014; FAO, 2016). Strategies  
383 for improved feed production are listed in Table 3.

384

385 Note that BAU, PA and IM scenarios shared similar technological level, where the  
386 differences in indicators were due to differences in the share of the dairy production  
387 systems in China, except for production price which was due to lack of information  
388 (Table 1).

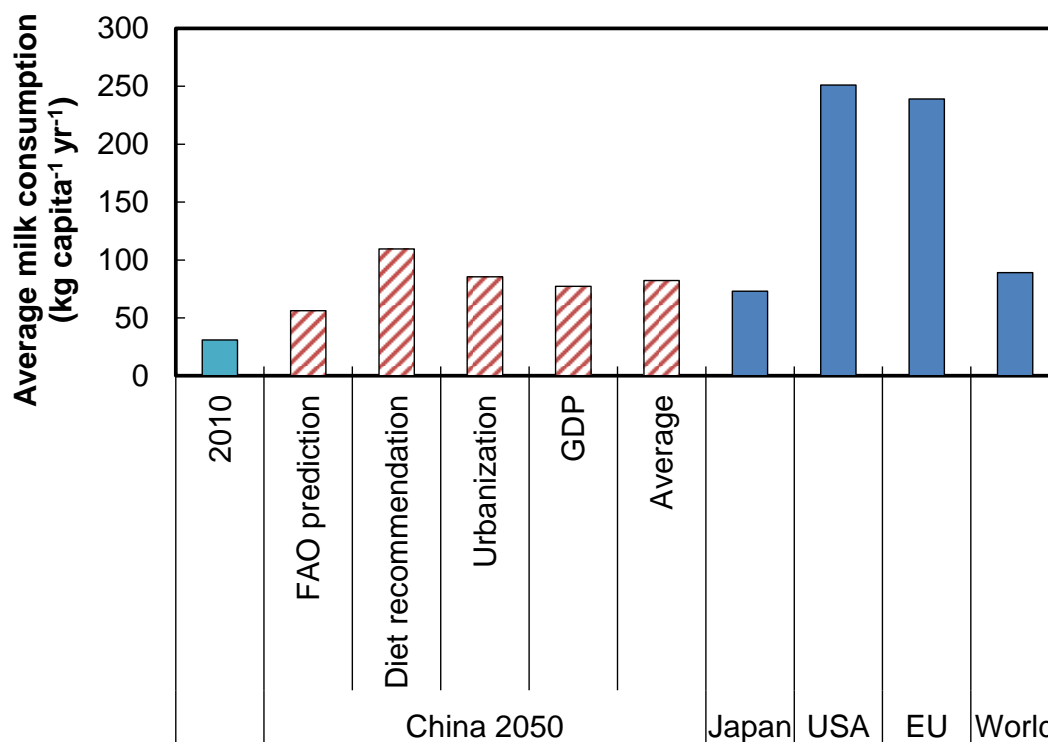
389

## 390 **Results**

### 391 **Prediction of average milk consumption in China in 2050**

392 Current milk consumption in China is 31 kg capita<sup>-1</sup> y<sup>-1</sup>. We estimated the average milk  
393 consumption per capita in 2050 based on various sources of information and  
394 assumptions. The predicted value was smallest based on the FAO prediction (56 kg  
395 capita<sup>-1</sup>) and highest when based on the national guidelines (110 kg capita<sup>-1</sup>). Evidently,  
396 there is a wide range between these estimates, with an average of 82 kg capita<sup>-1</sup> based

397 on all projections (Fig 1).



398

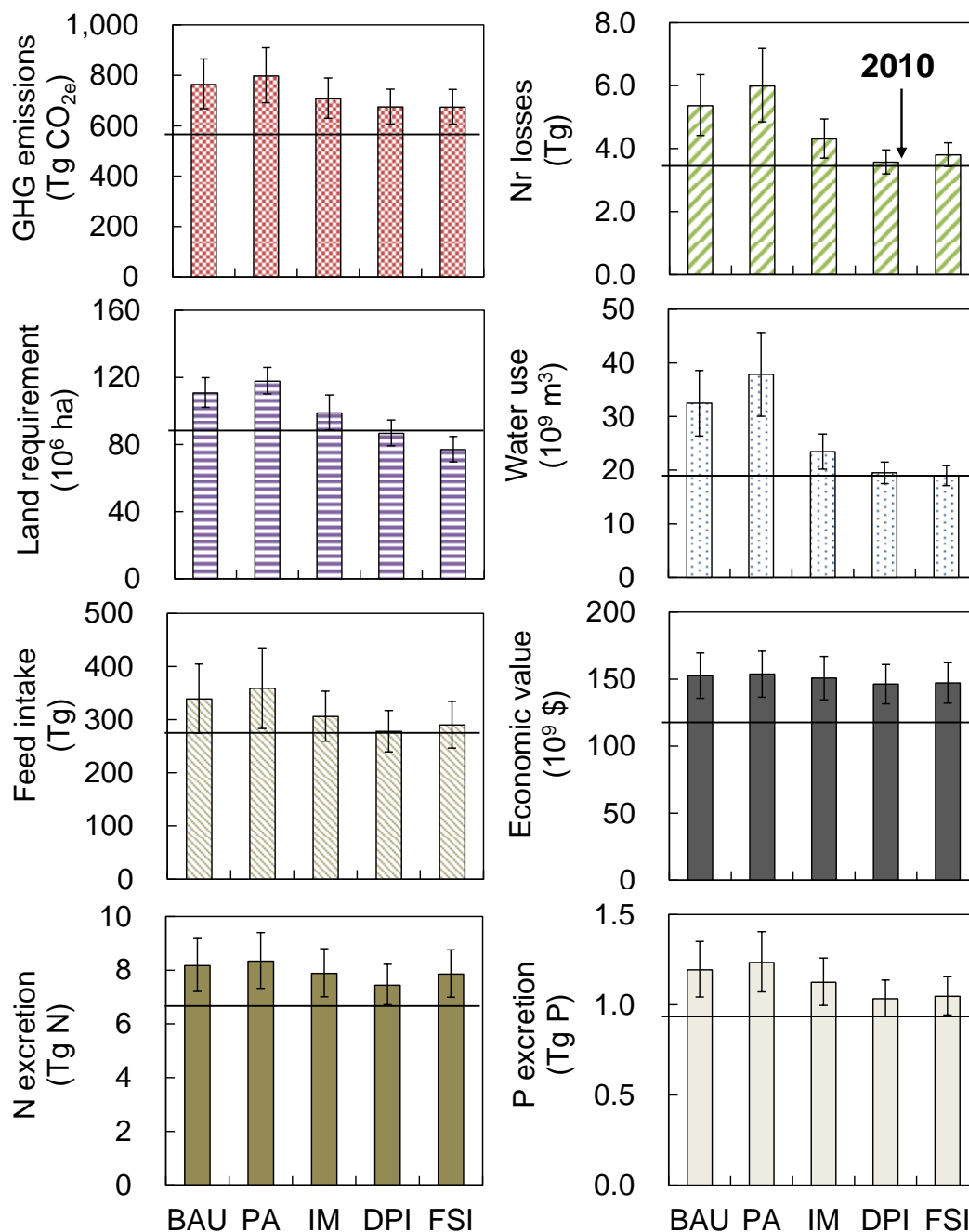
399 Fig 1. The estimated average milk consumption in China in 2050 based on four different  
400 estimation methods, in comparison to the current (2010) milk consumption levels in  
401 China, Japan, United States of America (USA), Europe (EU), and the world.

402

### 403 **Expected impacts of increased milk consumption - Scenario BAU**

404 Total milk production of the global dairy production group (China and the leading milk  
405 exporting regions) will reach up to 375 Tg in BAU scenario, increased by 28%  
406 compared to 2010. Total milk consumption in China will be 116 Tg in 2050 (range 80  
407 - 155 Tg), which is around 3.2-fold the milk consumption level of 2010 (Table S1). The  
408 additional milk demand was assumed to be supplied by industrial production systems.  
409 Results of the BAU scenario show that the global dairy-related GHG emissions will  
410 increase by 18-53%, with an average value of 35% (increase from 565 Tg CO<sub>2</sub> in 2010

411 to 764 Tg CO<sub>2</sub> in BAU) compared with 2010 (Fig 2). The land needed for feed  
 412 production will increase by 32% (from 84 to 111 million ha). Water use and Nr losses  
 413 related to dairy production will increase by 77% (from 18 to 33 billion m<sup>3</sup>) and 32%  
 414 (from 3.6 to 5.4 Tg N), respectively (Fig 2). China's domestic dairy-related GHG  
 415 emissions and total Nr losses will be tripled (Fig 3).



416

417 Fig 2. Impacts of increased milk consumption for the global dairy production (China

418 and with three leading milk export regions) by 2050; results of 5 scenarios (BAU, PA,  
419 IM, DPI and FSI), i.e., greenhouse gas (GHG, Tg CO<sub>2</sub> equivalent) emissions, reactive  
420 nitrogen (Nr, Tg N) losses, land requirement (million ha), irrigated water requirement  
421 (billion m<sup>3</sup>), animal feed intake requirements (Tg dry matter), economic value (billion  
422 \$), nitrogen excretion (Tg N) and phosphorus excretion (Tg P) in the four countries  
423 considered in this study (China, European Union, New Zealand, United States of  
424 America). The solid lines represent the situation in 2010. The error bars reflect the  
425 expected lowest and highest milk consumption in 2050.

426 **Scenarios:** BAU (SSP2): Business as usual, with a milk self-sufficiency of 75%; PA (SSP3):  
427 Produce all additional milk in 2050 domestically; IM (SSP5): Import all additional milk in 2050;  
428 DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system  
429 improvement, on top of DPI.

430

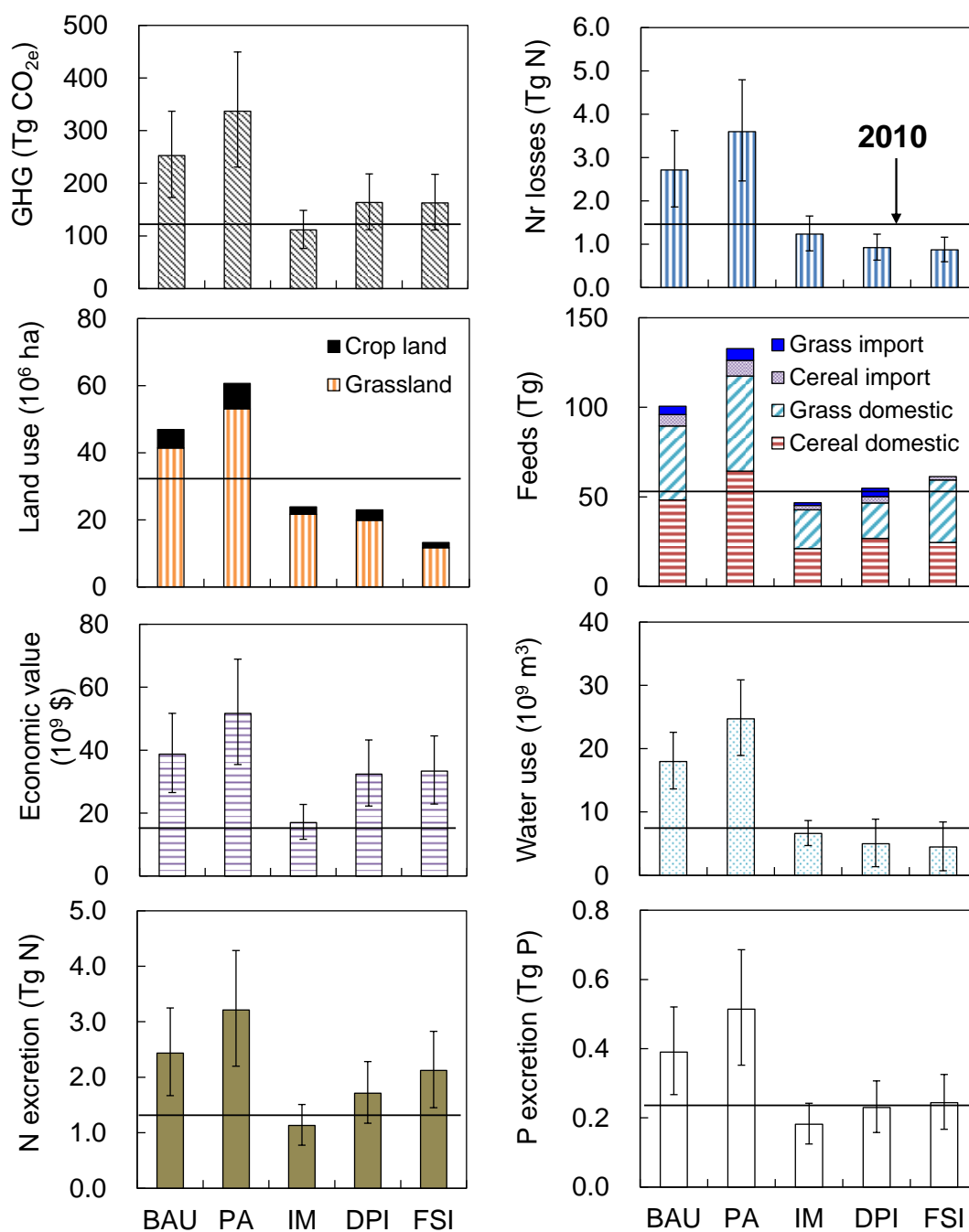
### 431 **Expected impacts of increased milk consumption - Scenario PA**

432 Producing all additional milk domestically (PA) with current technology and  
433 management, will increase total dairy related GHG emissions (China, EU, NZ and USA)  
434 by 34 Tg CO<sub>2e</sub>, compared to BAU (Fig 3). PA will boost the Chinese dairy sector by  
435 nearly 52 billion US\$, and substantially increase domestic employment opportunities  
436 compared to BAU (Figs 3, S6). However, without major improvements in domestic  
437 feed production (yield and quality), it will need to import 8.5 Tg of cereals and protein-  
438 rich crops (mainly from USA and Brazil), and 6.2 Tg forages (mainly from USA and  
439 Canada) (Table 4). The demand of land for feed production will increase by 6% (equal



440 to 7.1 million ha reduction), irrigation water by 17% (equal to 5.4 billion m<sup>3</sup> blue water  
 441 reduction), Nr losses by 12% (equal to 0.6 Tg N reduction) and nutrient excretions by  
 442 2-3% (equal to 0.17 Tg N and 0.04 Tg P reduction) for the four regions considered here,  
 443 compared to BAU (Fig 2).

444



445

446 Fig 3. Impacts of increased milk consumption in China by 2050; results of five

447 scenarios (BAU, PA, IM, DPI and FSI), i.e., GHG emissions, Nr losses, requirement of  
448 crop land and grassland, concentrate feed and forage imported and domestically  
449 produced, economic value, water use, N excretion and P excretion in China. The solid  
450 line represents the situation in 2010. The error bars reflect the expected lowest and  
451 highest milk consumption in 2050.

452 **Scenarios:** BAU (SSP2): Business as usual, with a milk self-sufficiency of 75%; PA (SSP3):  
453 Produce all additional milk in 2050 domestically; IM (SSP5): Import all additional milk in 2050;  
454 DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system  
455 improvement, on top of DPI. All the indicators were calculated based on the total milk production  
456 in China.

457

#### 458 **Expected impacts of increased milk consumption - Scenario IM**

459 If China would import all additional milk (IM), from EU, NZ and USA, then the global  
460 trade of milk will increase by 78 Tg yr<sup>-1</sup>. Milk will become a bulk trade commodity,  
461 almost comparable in size to soybean now (Fig S5). Compared to PA, the land and  
462 water use for dairy feed production would reduce by 16-38% at the global scale, GHG  
463 emissions will decrease by 7%, and total Nr losses will reduce by 28% compared to PA  
464 (Fig 2).

465

466 Table 4. Import of maize and soybean and alfalfa from USA and Canada (CA), Brazil  
467 (BR) and Argentina (AR), for dairy production in China (CN), EU in 2010, and for  
468 scenarios producing all additional milk domestically (scenario PA) and import all of the  
469 additional milk (Scenario IM) in 2050. Unit: Tg y<sup>-1</sup>.

					2010		2050 PA		2050 IM	
					CN	EU	CN	EU	CN	EU
Feed, Tg y <sup>-1</sup>	USA CA	and	Maize	and	1.0	1.2	4.2	1.2	1.2	1.7
			soybean							
	Alfalfa		0.9			6.2		1.3		
	BR AR	and	Maize	and	1.0	1.9	4.3	1.9	1.2	2.5
			soybean							
			Alfalfa							
Land, million ha y <sup>-1</sup>	US CA	and	Maize	and	0.31	0.42	1.3	0.42	0.36	0.57
			soybean							
	Alfalfa		0.17			1.2		0.27		
	BR AR	and	Maize	and	0.33	0.60	1.4	0.60	0.39	0.82
			soybean							
			Alfalfa							

470 Note: New Zealand (NZ) also imports small amounts of feed from Australia, which are not shown.  
471 PA, produce all the milk domestically in China; IM, import all the milk from leading  
472 export regions.  
473

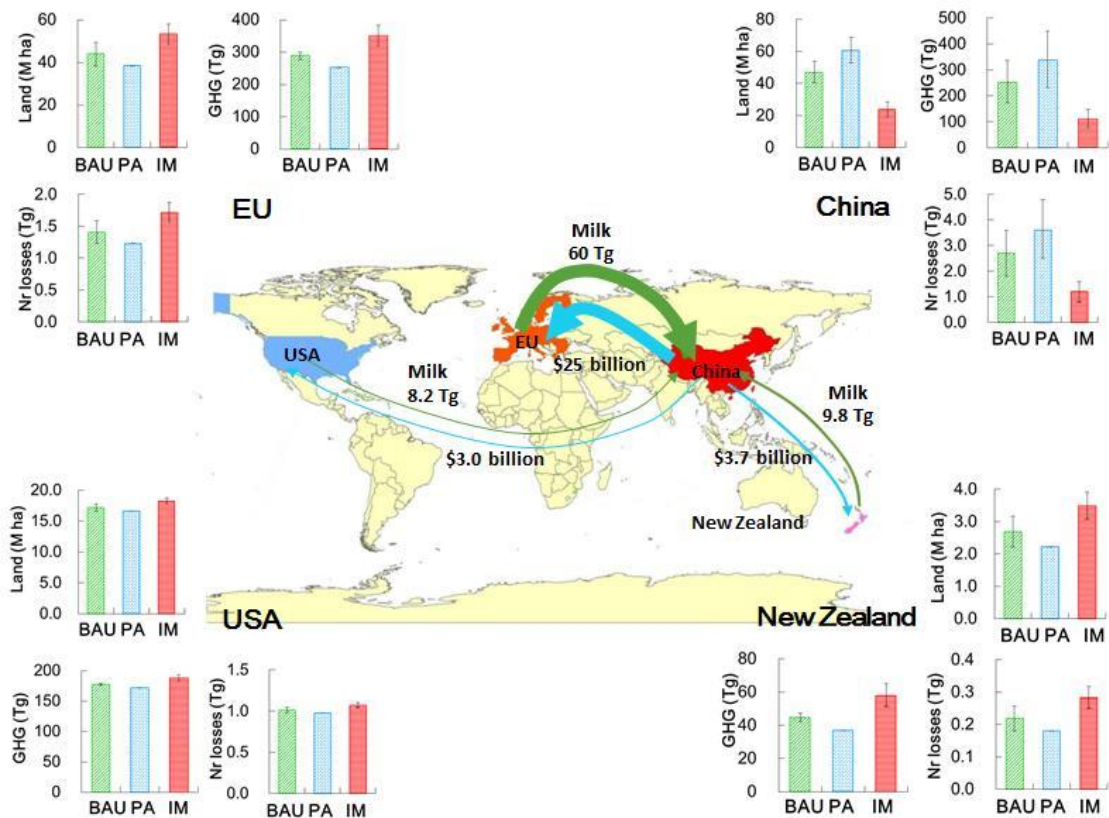
474 The milk imported will come from the EU (60 Tg), NZ (9.8 Tg) and USA (8.2 Tg).  
475 These regions will economically benefit from the milk export; the value of the  
476 additional milk exported by the EU is roughly 25 billion US\$ yr<sup>-1</sup> (Fig 4). By contrast,  
477 milk import will hinder the development of the dairy industry in China, and will lead  
478 to 12 million fewer job opportunities compared with scenario PA (Fig S7). Further, it  
479 may become increasingly difficult to feed all dairy cattle in the milk exporting countries,  
480 due to the limited area of productive land, and significant competition with other land  
481 uses (food, fuel and fiber production and nature conservation). The farmland area for  
482 cattle-feed production in NZ would have to increase by about 57% (from 2.2 to 3.5  
483 million ha) and that in EU by about 39% (from 38 to 53 million ha), and GHG emissions  
484 and Nr losses would increase roughly proportionally with the increase of farmland in  
485 both regions. The EU and NZ may significantly have to increase land productivity and  
486 dairy productivity (Fig 4), and/or increase the import of concentrate feed (Table 4). The

487 results of the IM scenario suggest that GHG emissions from dairy production will  
488 increase by about 39% in the EU, and the Nr losses will also increase by the a similar  
489 proportion.

490

#### 491 **Expected impacts of increased milk consumption - Scenario DPI**

492 In the Dairy Production Improvement (DPI) scenario, dairy related impacts will be  
493 reduced compared to BAU, both in China (GHG emissions: -35%; land requirements:  
494 -51%; Nr losses: -34%) and for the global dairy sector examined here (GHG emissions:  
495 -12%; land requirements: -22%; Nr losses: -33%), due to the improved milk production  
496 performance in China (Figs 2, 3). This illustrates the huge scope for improving the dairy  
497 production efficiency, through meeting EU, NZ and USA standards. However, the area  
498 of crop land in China used for feed production will have to increase significantly  
499 (+54%), and the imports of cereals (+72%) and alfalfa (+414%) will also increase  
500 greatly, compared to 2010 (Fig 2). This indicates that improvements in the productivity  
501 and efficiency of dairy production alone may not be sufficient to relieve the pressure  
502 on land.



503

504 Fig 4. Import of milk from the world's top three milk exporters to China, and the  
 505 economic return (indicated by arrows), for scenario IM in 2050. The bar graphics show  
 506 the changes in agriculture land area, GHG emissions, and Nr losses in China and the  
 507 three exporting countries EU, NZ and USA for the scenarios BAU, PA and IM.

508 **Scenarios:** BAU (SSP2): Business as usual, with a milk self-sufficiency of 75%; PA (SPP3):  
 509 Produce all additional milk in 2050 domestically; IM (SSP5): Import all additional milk in 2050.  
 510 PA represents the same production level in 2010 for EU, NZ and USA.

511

### 512 **Expected impacts of increased milk consumption - Scenario FSI**

513 The FSI scenario aims at better utilizing suitable land and closing the manure nutrient  
 514 cycle, through the integration of crop - livestock production systems spatially. Scenario  
 515 FSI has the potential to reduce the requirement for domestic agricultural land by 72%  
 516 and the import of feed (concentrates: -4.4 Tg; forage: -4.6 Tg), compared to scenario

517 BAU, because of the expected increases in land productivity (Fig 2). Meanwhile, the  
518 global GHG emissions could be reduced by 36% and Nr losses reduce by 68%.  
519 Although the FSI scenario showed similar GHG emissions and 4-7% higher feed  
520 demand and Nr losses compared to DPI at the global level, FSI reduced the global dairy  
521 related land use by 11% compared to DPI. This would leave more land for arable food  
522 production and natural ecosystem services, including species rich native grasslands.  
523 However, FSI still increased GHG emissions by 19% while saving land use by 8%  
524 compared to 2010, part of these land savings will provide potential for carbon stock  
525 and compensate for the increasing GHG emissions.

## 526 **Discussion**

527 The increasing demand for milk in China will have significant impacts on global dairy  
528 related GHG emissions, land use, milk and feed trade, coupled further with increasing  
529 demand from other developing countries exacerbating these problems. We show for  
530 China that producing all additional milk domestically will reduce the environmental  
531 performance of global dairy production, e.g. increase GHG and Nr emissions and feed  
532 import. Importing the additional milk from the leading milk exporting regions will  
533 reduce global dairy related GHG emissions, but the environmental burden is then  
534 transferred to these countries, which may conflict with the objectives of their  
535 environmental protection policies. Improving domestic feed and dairy production  
536 efficiencies in milk demanding countries to the level of the leading milk exporting  
537 countries seems the preferred pathway.

538

539 **Future milk consumption**

540 The traditional lower milk consumption countries of South and East Asia and Sub-  
541 Saharan Africa are experiencing significant increases in milk consumption due to  
542 population growth and higher levels of income (Alexandratos and Bruinsma, 2012). It  
543 is projected that global milk consumption will increase by 60% between 2010 to 2050  
544 (Alexandratos and Bruinsma, 2012), and more than 60% of the additional milk demand  
545 will come from the traditional lower milk consumption regions (less than 100 kg milk  
546 capita<sup>-1</sup> yr<sup>-1</sup> in 2010), i.e. East and North Africa, Sub-Saharan Africa, South Asia and  
547 East Asia, with China having the largest potential future milk demand.

548 We assumed that average milk consumption in China will be 82 kg capita<sup>-1</sup> in 2050,  
549 which is similar to the current level of milk consumption in Japan. Japanese and  
550 Chinese share a similar level of lactose intolerance (Mattar et al., 2012) and China's  
551 average GDP in 2050 may have caught up with Japan's 2016 level (World Bank, 2016).  
552 Yet, future milk consumption in China may be much higher, as the national guidelines  
553 for a healthy diet suggest 300 g capita<sup>-1</sup> d<sup>-1</sup>, which is equivalent to 110 kg capita<sup>-1</sup> yr<sup>-1</sup>  
554 (CSN, 2014). Former Chinese prime minister Wen Jiabao once said he had a dream that  
555 "all Chinese, especially children, can drink a half liter of milk per day" (Xinhua News,  
556 2006). If his dream were to be realized, the average milk consumption would be 180 kg  
557 capita<sup>-1</sup> yr<sup>-1</sup>, still much lower than the current USA and EU levels (FAO, 2016). As  
558 China, has now abolished the one child policy, population may increase faster in the  
559 next few years, which may also further increase the total milk demand in the future.  
560 Evidently, the predicted mean milk consumption in 2050 has a large uncertainty range.

561

562 **Domestic production or importation**

563 Our results show that production of the additional required milk domestically without  
564 large improvements within the dairy industry will increase global dairy related GHG  
565 emissions compared to import of this milk. The average GHG emissions was 2.9 kg  
566 CO<sub>2</sub>e kg<sup>-1</sup> milk in China in 2010, compared with 2.1, 1.6 and 1.9 kg CO<sub>2</sub>e kg<sup>-1</sup> milk for  
567 NZ, EU and USA, respectively (Opio et al., 2013). The higher GHG emissions in China  
568 is due to less efficient feed and milk production. Further, the GHG emissions associated  
569 with the transportation of milk are much smaller than those associated with domestic  
570 production (feed and milk), with the net effect of milk import decreasing total GHG  
571 emissions (Table 1). This was the same for N losses, since the average N<sub>r</sub> loss was 34  
572 g N kg<sup>-1</sup> milk in China, which is 1.8-2.8 larger than that in the leading milk exporting  
573 regions (Table 1).

574 Nitrogen losses associated with dairy production are much smaller in milk exporting  
575 countries than in China (Bai et al., 2013; Bai et al., 2016).

576

577 Production of all extra milk (PA) domestically without improvement of dairy and feed  
578 production will face several domestic and international restrictions. Additional  
579 domestic arable land (5.5 million ha) and grassland (28 million ha) will be required in  
580 PA scenario, equal to 4.5% and 7.0% of total land area in China, respectively (NBSC,  
581 2016). However, this amount of land cannot be met domestically, due to the high  
582 population and food self-sufficiency rate policy. Recently, the area for arable land and



583 grassland was slightly decreased (Fig S8). Environmental regulations have become  
584 stricter in China, with an environmental protection tax due to be implemented at the  
585 beginning of 2018, and a tax will be collected from high polluting dairy farms (NPC,  
586 2016). The PA scenario also requires import of 8.5 Tg concentrates and 6.2 Tg of alfalfa.  
587 Such high levels of import may become increasingly difficult, in part also due to  
588 pressures from the outside world. For example, the drought-stricken western USA  
589 shipped more than 0.2 billion m<sup>3</sup> of water embedded in alfalfa to China in 2012, enough  
590 to supply the annual household needs of half a million families (Culp and Robert, 2012)  
591 and soybean exports from Brazil have been linked to deforestation of the Amazon  
592 (Morton et al., 2006).

593 Global dairy related GHG emissions and Nr losses will be 7% and 28% lower if all  
594 additional milk is imported compared with domestic production. However, there will  
595 be strong physical and environmental constraints in the leading milk export regions.  
596 For example, 1.3 and 15 million ha additional agricultural land would be required in  
597 NZ and EU, which is equivalent to 12% and 8% of their agricultural land in 2010,  
598 respectively (FAO, 2016). These land requirements exceeded local land availability, so  
599 NZ would need to cut down the land used for sheep and beef production, or explore  
600 marginal land which is sometimes too steep or too close to watercourses for dairy  
601 production (MPI, 2012). Besides the physical limitations, environmental protection  
602 policies may also constrain large dairy production increases in the EU and NZ. The  
603 results of the IM scenario suggest that Nr losses and GHG emissions from dairy  
604 production will increase by around 39% in the EU, which will obstruct environmental

605 targets (Westhoek et al., 2014; UNFCCC, 2015). Strong increases in milk production  
606 in NZ will also be met with resistance (MPI, 2012) The environmental constraints on  
607 drastic increases of dairy production in exporting countries suggest that changes in the  
608 balance of supply and demand will shift the global market price of dairy products to  
609 higher levels. A rise in global dairy price will make investments in domestic dairy  
610 production more attractive.

611 Improving domestic feed and dairy production efficiencies may be a preferred pathway  
612 for many milk demanding countries, including China where the prospects are relatively  
613 large for improving feed and dairy production efficiency according the DPI and FSI  
614 scenarios (Fig 2). This needs to be achieved not only through an increase in production,  
615 economic and environmental performance of China's dairy sector to the level of leading  
616 milk export regions (DPI), but total redesign of the dairy production system, to increase  
617 the contribution from grassland and household dairy production systems as they are  
618 more integrated with feed production and cropland (FSI). For example, grassland  
619 covers 3/4 of the agriculture land in China. Most of this land is not suitable for  
620 intensification of feed production due to low rainfall, poor soil quality, over-grazing  
621 and desertification. However, some areas can be utilized to supply forage (1 to 3 Mg  
622 ha<sup>-1</sup> yr<sup>-1</sup>) for dairy cattle when properly managed, grazed, irrigated and fertilized (Kang  
623 et al., 2007). A further benefit of developing well managed grazing systems is to also  
624 to contribute to grassland restoration whilst maintaining emphasis on natural ecosystem  
625 services and biodiversity in native grassland areas (Ren et al., 2016). Achieving this  
626 also requires governments, farmers, ecologists, industry, and researchers to work

627 together to develop transition plans for different regions and farms (Eisler et al., 2014;  
628 Zhang et al., 2016). Likewise other emerging countries will face the same situation and  
629 problems of China, and will also need to improve their dairy and feed production yield,  
630 and integrate dairy and feed production together to meet their milk demand.

631

### 632 **Policy implications**

633 Strategies for improving feed production, dairy production, and manure management  
634 have to be embedded in coherent governmental policies with proper incentives. The  
635 Chinese government is already supporting dairy production via providing subsidies for  
636 the construction of industrial feed-lots. For example, for the construction of a dairy farm  
637 with 300-1000 dairy cattle a lump sum subsidy of 0.8-1.7 million RMB is available  
638 (300-400 US\$ per dairy cow) (MOA, 2014). Investments in manure management and  
639 forage production are also supported by government but less compared to dairy  
640 production. There is a need for a more coherent government policy for developing an  
641 efficient and sustainable dairy sector. Governmental support for the dairy sector has to  
642 be embedded in policies aimed at improving both the production and environmental  
643 performance. These policies should include clear regulations on manure management  
644 to ensure that all manure from housed animals is properly collected, stored and  
645 subsequently applied to arable land and grassland, instead of being discharged to  
646 landfill or water systems as has happened for the past 60 years in the pig production  
647 industry which have greatly decreased N use efficiency at the system level and  
648 increased manure losses to water in China (Bai et al., 2014; Stokal et al., 2016).

649 The Chinese government recently introduced new legislation, and has set goals to  
650 establish a waste recycling system for livestock enterprises through scientifically  
651 evidenced regulation and a clear responsibility for producers to minimize nutrient losses  
652 (SCC, 2017). The central government also invests 0.3 billion each year to subsidize  
653 farmers growing alfalfa.

654 Recently, milk processing factories banned the collection of milk from small household  
655 dairy farms, mainly due to concerns about milk quality. It has been estimated that some  
656 100,000 small dairy farmers have stopped farming each year since 2010 (MOA, 2015).

657 This will also contribute to redesign dairy production in China, through conversion of  
658 traditional dairy production systems to medium size house-hold systems as in EU.

659 Currently, some of China's dairy companies invest overseas rather than in domestic  
660 production, due to eroded public confidence in the quality of domestic milk, low  
661 production efficiency, and high production cost (Sharma and Rou, 2014). Hence, it is  
662 of great importance to regain the consumers and investors' confidence in the Chinese  
663 milk sector, through implementing strict milk quality control and fine policies, such as  
664 the Food Security Law issued in 2015 (NPC, 2015).

665

## 666 **Conclusions**

667 The ever-growing thirst for milk in China comes with significant challenges, and  
668 impacts on global trade of milk and feed, land use, GHG emissions and Nr losses. In  
669 2050, producing all additional required milk domestically with current technologies and  
670 management will require annual imports of 8.5 Tg concentrates and 6.2 Tg forages, and

671 will increase GHG emissions of the global dairy sector by 41% and land demand by  
672 40% compared to 2010. In contrast, importing all additional milk will transfer the  
673 environmental burden from China to milk exporting countries (e.g. EU, NZ and USA).  
674 The optimal option is to produce the additionally required milk in China, but with  
675 greatly improved technology. The prospects and challenges of improving the local dairy  
676 production efficiency, manure and grassland management, and of the integration of  
677 crop-dairy production systems are large. Closing the productivity gaps in domestic  
678 dairy and feed production, accompanied by dairy production system adjustment, greater  
679 utilization of grassland resources along with feed ration improvement and strict milk  
680 quality control systems appears to be the preferred pathway. This pathway should be  
681 guided through governmental policies, mainly focused on improving manure  
682 management, feed production, crop-livestock system integration, and grassland  
683 restoration whilst maintaining emphasis on natural ecosystem services and biodiversity  
684 in native grassland areas.

685

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692

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