Global environmental costs of China's thirst for milk

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Abstract:

China has an ever-increasing thirst for milk, with a predicted 3.2-fold increase in demand by 2050 compared to the production level in 2010. What are the environmental implications of meeting this demand, and what is the preferred pathway? We addressed these questions by using a nexus approach, to examine the interdependencies of increasing milk consumption in China by 2050 and its global impacts, under different scenarios of domestic milk production and importation. Meeting China's milk demand in a business as usual scenario will increase global dairy-related (China and the leading milk exporting regions) greenhouse gas (GHG) emissions by 35% (from 565 to 764 Tg CO_2) and land use for dairy feed production by 32% (from 84 to 111 million ha) compared to 2010, while reactive nitrogen losses from the dairy sector will increase by 48% (from 3.6 to 5.4 Tg nitrogen). Producing all additional milk in China with current technology will greatly increase animal feed import; from 1.9 to 8.5 Tg for concentrates and from 1.0 to 6.2 Tg for forage (alfalfa). In addition, it will increase domestic dairy related GHG emissions by 2.2 times compared to 2010 levels. Importing the extra milk will transfer the environmental burden from China to milk exporting countries; current

dairy exporting countries may be unable to produce all additional milk due to physical limitations or environmental preferences/legislation. For example, the farmland area for cattle-feed production in New Zealand would have to increase by more than 57% (0.1 million ha) and that in Europe by more than 39% (0.5 million ha), while GHG emissions and nitrogen losses would increase roughly proportionally with the increase of farmland in both regions. We propose that a more sustainable dairy future will rely on high milk demanding regions (such as China) improving their domestic milk and feed production efficiencies up to the level of leading milk producing countries. This will decrease the global dairy related GHG emissions and land use by 12% (90 Tg CO_2 reduction) and 30% (34 million ha land reduction) compared to the business as usual scenario, respectively. However, this still represents an increase in total GHG emissions of 19% whereas land use will decrease by 8% when compared with 2010 levels.

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

Introduction:

The increased international trade of agricultural products has received much attention recently, due to the impacts of production on land use, deforestation and associated biodiversity loss, impaired nutrient cycling, and greenhouse gas (GHG) emissions. Currently, around 23% of the food produced for human consumption is traded internationally (D'Odorico et al., 2014). It has been estimated that the global trade of nitrogen (N), embedded in the products, has increased from 3 to 24 Tg N between 1961 and 2010, with the largest contributor relating to animal feed (Lassaletta et al., 2014). Oita et al (2016) analyzed the reactive N emitted during the global production, consumption and transportation of commodities, and estimated that 15% of the global N footprint is from commodities internationally traded. Exportation of beef, soybeans (*Glycine max*) and wood products was responsible for 12% of the deforestation in seven countries with high deforestation rates (Henders et al., 2015). Additionally, up to 30% of global species threats are due to international trade, via production of commodities in export countries (Lenzen et al., 2012) and 17% of global biodiversity loss occurs due to commodities destined for exportation (Chaudhary and Kastner, 2016).

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

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

China became the world's largest milk importer in 2010, following the melamine scandal in 2008 which eroded public confidence in domestically produced milk (Pei et al., 2011; FAO, 2016). China also imports massive amounts of soybean and increasing amounts of maize (*Zea mays*) and alfalfa (*Medicago sativa*) to feed its increasing domestic pig, poultry and dairy cattle populations (FAO, 2016). The increasing imports of animal feed are related to the increasing domestic consumption of animal derived food and to the relative scarcity of agricultural land and fresh water. Meanwhile, EU abolished its milk quota system in 2015, and New Zealand and Chile are preparing for the projected increase in milk demand from China and other rapidly developing countries, e.g. India (Europe Union Commission, 2014; Oenema et al., 2014). The impact of China's thirst for milk related to resource demands, climate change, eutrophication and biodiversity loss need to be predicted so pathways for a more sustainable solution can be mapped. China is facing both food security and water security challenges as well as vast environmental challenges, which underpin the importance of researching alternative potential future projections (Piao et al., 2010; Liu and Yang, 2012).

Here, we present the results of a novel nexus approach to examine the interdependencies of increasing milk consumption in China and its impact on GHG emissions, N losses, land and water use, and economic performances across the main feed and milk producing countries. Dairy cattle account disproportionally to GHG emissions, predominately because of enteric fermentation and the release of methane (CH_4) (Steinfeld et al., 2006; Gerber et al., 2013). We analyzed the interrelationships and interdependencies of the whole 'production-consumption-trade' system for 2050 under contrasting Shared Socio-economic Pathway scenarios (SSP): (i) Business as usual (BAU) - increase of milk consumption in 2050 aligned to current proportional contributions of domestic production and import (SSP2), (ii) Produce all additional milk domestically (PA) – increase of milk consumption in 2050 delivered through increased domestic output (SSP3), and (iii) Import all additional milk (IM) – increase of milk consumption in 2050 delivered through increased imports from three leading producing regions (EU, USA, NZ) (SSP5). Further, we evaluated two extra scenarios following the Shared Socio-economic Pathway 1 (SSP1) storyline, which focuses on technological improvements: (i) Dairy Production Improvement (DPI) - assuming that productivity and manure management in China can reach the current level of the leading milk exporting countries by 2050; and (ii) Farming Systems Improvement (FSI) - towards crop-dairy integration and forage-based systems with increased productivity of forages, building on scenario DPI.

Materials and methods

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

Prediction of milk consumption in China

We estimated average per capita milk consumption in 2050 using different sources and the following assumptions. First, we calculated the relations between average milk consumption per capita and average GDP per capita, and milk consumption per capita and urbanization rate (Fig S2). Milk consumption in 2050 was then estimated assuming a mean GDP of 10,904 \$ capita^{-1} yr^{-1} and an urbanization of 78% in 2050 (FAO, 2016; World Bank, 2016). Second, a predicted increase in average milk consumption of 1.80% yr^{-1} in developing countries between 2005 and 2050 (Alexandratos and Bruinsma, 2012). Third, following the national guidelines for a healthy diet, the average milk consumption is 300 g capita^{-1} d^{-1} in 2050 (CSN, 2014).

Total milk consumption was calculated as:

$$Milk_{total} = Population * Milk_{average} \quad [1]$$

Where, $Milk_{total}$ is the total milk consumption in kg, Population is the total human population, and $Milk_{average}$ is the average milk consumption in kg capita^{-1}, calculated using the three assumptions outlined above. Forecasts suggest that the human population will be 1.4 billion in China in 2050 (FAO, 2016).

System boundary

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

Determining the sustainability indicators to be used in the assessment

A total of eight indicators at the herd level (accounting for lactating cow, heifers and calves. Dairy related beef production was not considered), with three physical indicators (feed, land and water requirement), one economic indicator (GDP value of milk production) and four environmental impact indicators (GHG emissions and reactive N losses, N and P excretions), were selected to evaluate the impacts of the projected increase in milk consumption and production. The economic value of milk production was derived from the milk production price in 2010 recorded in the FAO database and used as an indicator of the economic importance, assuming that the milk price will remain more or less constant (FAO, 2016). In practice, milk price will depend on the balance of milk demand and supply, which will depend on many factors and opportunities, however a basal value is required to assess economic performance. Feed requirement and the related land and water requirements to produce the feed were used as indicators for resource use. Emissions of GHG and Nr and the production of manure N and P were chosen as agri-environmental impact indicators, as China is facing severe challenges associated with current emissions and associated climate change, nutrient losses and manure management problems (Bai et al., 2016).

NUFER-dairy model

The resource use and environmental effects of different dairy production systems in China were calculated by the NUFER-dairy model (Bai et al., 2013; Zhang et al., 2017). The NUFER-dairy model has been developed to quantitatively evaluate GHG emissions, nutrient flows, and land, water and feed resource requirements for various systems of operation at animal, herd, and system levels. The model consists of an input database, a calculator, and an output module. The input database includes herd demographics, milk yield and feed composition. The calculation module includes a feed intake prediction sub-module and a nutrient balance sub-module. Calculation of feed intakes by calves, heifers, and milking cows are based on the energy requirements. The nutrient balance is calculated from the nutrients flows through the whole soil-feed-milk production chain. The output module provides results for land, water and feed use, nutrient losses and GHG emissions (Bai et al., 2013; Zhang et al., 2017).

Three physical indicators (feed, land and water)

Feed requirement

The feed requirement of dairy cattle was calculated as follows:

$$Feed_{total} = Milk_{produced} * Feed_{milk} \quad [2]$$

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

Land requirement

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

$$Land\ requirement = Milk_{produced} * Land\ requirement_{milk} /10000 \quad [3]$$

Where, Land requirement is the area of arable land and grassland required for feed production, in ha. Land requirement $_{milk}$ is the average area of land needed to produce 1 kg of milk, in m^2 kg^{-1} milk. The area of cropland and grassland for producing feed for China's dairy production was calculated using total feed requirement (excluding the imported feed), and average crop and grassland yields. Information about the land requirement in the three milk exporting countries is listed in Table 1.

Water use

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

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

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

One economic indicator (GDP value of milk production)

The economic value of dairy production was calculated according to the average milk production value in 2010.

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

Where, Economic value is the total economic value of produced milk in US$ in 2010; Costs $_{\text{milk}}$ is the average production cost of milk, derived from FAO database in US$ t^{-1} milk. The average milk production cost was 445, 376, and 360 US$ t^{-1} milk for China, NZ and USA, respectively in 2010. For EU, we used a weighted average value, which was 418 US$ t^{-1} milk in 2010 (Table 1). The job opportunities provided by dairy production was calculated from the total GDP of dairy production, and assuming an income of 18,000 Yuan $person^{-1}$ yr^{-1} in 2010 (China Statistic Yearbook, 2011).

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

GHG emissions

The GHG emissions (CO_2, CH_4, and N_2O) from the soil-feed-dairy production and feed-milk transportation chains were calculated as:

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

Where GHG is the total GHG emissions of dairy production in kg CO_2 equivalents (CO_2e), Milk $_{\text{produced}}$ is the amount of milk produced in each region (China, EU, USA, and NZ) in kg. GHG $_{\text{milk}}$ is the carbon footprint in kg CO_2e kg^{-1} milk. Milk $_{\text{export to China}}$ is the amount of milk exported to China by the top three milk exporting regions (weighted values) in 2010. GHG $_{\text{milk export}}$ is the GHG emissions associated with the milk from leading milk exporting regions to China. Milk $_{\text{total}}$ is listed in Table S1, and GHG emissions parameters are presented in Table 1. The GHG emissions related to the transportation of milk to China was based on the average transport distance of milk to China from NZ, EU (the Netherlands) and USA, 11144, 7821 and 11100 km, respectively (Food Miles, 2016). The average GHG emissions rate was 0.0345 kg CO_2e ton^{-1} km during shipping (Van Passel, 2013). We assumed all the milk export to China was as milk powder, as only 2% of the milk transported to China was as fresh milk in 2010 (FAO, 2016). The average fresh milk to dry milk conversion ratio was set at 7:1.

Nr losses

Nr losses were based on the average Nr losses and milk production of different dairy production systems calculated by NUFER-dairy (Table S2). In scenarios, Nr losses were weighted per their share of total dairy production (Tables S3, S4). Nr losses of leading milk export regions were collected from the literature (Table 1). In our calculations, the following Nr losses have been considered: nitrate leaching to groundwater and surface waters and emissions of N_2O and ammonia (NH_3) to the atmosphere, from housing, manure management and soils.

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

Where Nr losses are the total Nr losses of dairy production in kg. Nr losses $_{\text{milk}}$ are the Nr losses per kilo of milk in kg kg^{-1} milk, data for China see Table S2 and for other regions see Table 1. The Nr losses were assessed at the system level (soil-crop-dairy), and included the losses during feed production.

N and P excretions

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

$$N(P)\ excretion = Milk_{produced} * N(P)\ excretion_{milk} \quad [8]$$

Where N(P) excretion is the total amount of manure N(P) produced by dairy cattle in kg yr^{-1}, N(P) excretion $_{milk}$ is the average N(P) excretion per kilo of milk produced, in kg (Table 1).

Feed use and import, and related land import

Consumption of different feed items was calculated as follows:

$$Feed_{items} = Feed_{total} * Feed_{composition} \quad [9]$$

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

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

	China						New Zealand	European	United States
	2010	BAU	PA	IM	DPI	FSI			
GHG (kg CO_2e kg^{-1} milk)	2.9	2.9	2.9	2.9	1.9	1.9	2.1[1]	1.6[1]	1.9[1]
Nr losses (g N kg^{-1} milk)	34	31	31	32	11	10	12[2]	9.0[3]	12[4]
Land requirement (m^2 kg^{-1} milk)	5.2	2.4	2.1	3.8	1.9	1.9	1.3[2]	2.5[5]	1.9 [6]
Blue water requirement (m^3 kg^{-1} milk)	145	206	213	173	57	51	48[7]	46[7]	60[7]
Feed requirement (kg DM kg^{-1} milk)	2.6[8]	1.7	1.6	1.9	0.9	1.1	1.1[9]	1.2[9]	0.9[9]
Costs (\$ t^{-1} milk)	445[10]	445	445	445	372	383	376[10]	418[10]	360[10]
N excretion (g N kg^{-1} milk)	32[8]	28	28	30	20	24	30[11]	20[12]	18[13]
P excretion (g P kg^{-1} milk)	5.6[8]	4.5	4.4	4.7	2.6	2.8	2.2[14]	3.0[12]	2.5[15]

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. 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. Powell et al., 2006.

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 additional milk in 2050; DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system improvement, on top of DPI.

Development of scenarios

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

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

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

	Alfalfa	10[1]	11[1]	6.2[1]	19[1]	0[1]

1. This study; 2. FAO, 2016; 3. Chen et al., 2014; 4. Eisler et al., 2014.

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 additional milk in 2050; DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system improvement, on top of DPI.

Scenario: Produce All (PA) – Milk self-sufficiency will increase to 100%. Scenario PA considered that all required milk will be produced domestically, following the SSP3 storyline with governmental policies focusing on national food security. Relative milk production contributions from grazing, collective and industrial systems were assumed to be 4, 10, and 86%, respectively, based on current trends (Table 2). We assumed again that the 'traditional' dairy system (≤9 head cattle per farm) will have disappeared by 2050.

Scenario: Import Milk (IM) – Milk self-sufficiency will drop to 33%. The IM scenario assumes that domestic milk production will remain at the level in 2010 and that all additional milk will be imported. As a result, milk self-sufficiency will drop to 33%. Relative milk production from grazing, collective and industrial systems is assumed to be 14, 30, and 56%, respectively (Table 2). Imported milk was assumed to be supplied by the same three countries with the same proportion as in BAU (Table S1).

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

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

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

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

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

Scenario: DPI with Farming Systems Improvement (FSI) - Milk self-sufficiency maintained at 75%. Scenario FSI builds on scenario DPI, while assuming that all milk will be produced in equal portions by grazing, collective and industrial systems, due to the concern of arable land competition, increased natural grassland utilization and manure local recycling issues. Domestic forage and feed production will have increased to a level that no forage and feed has to be imported (except for soybean). Mean grass yields will have increased from 1.0 to 3.0 t ha^{-1} (Eisler et al., 2014). Yields of cereals can be improved through Integrated Soil-crop System Management technology (ISSM) with nutrient inputs similar to current levels; we assumed that mean crop yields will increase from 5.5 to 9.2 t ha^{-1} for maize, from 6.5 to 7.7 t ha^{-1} for rice and from 4.7 to 6.9 t ha^{-1} for wheat between 2010 and 2050 (Chen et al., 2014; FAO, 2016). Strategies for improved feed production are listed in Table 3.

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

Results

Prediction of average milk consumption in China in 2050

Current milk consumption in China is 31 kg $capita^{-1}$ y^{-1}. We estimated the average milk consumption per capita in 2050 based on various sources of information and assumptions. The predicted value was smallest based on the FAO prediction (56 kg $capita^{-1}$) and highest when based on the national guidelines (110 kg $capita^{-1}$). Evidently, there is a wide range between these estimates, with an average of 82 kg $capita^{-1}$ based on all projections (Fig 1).

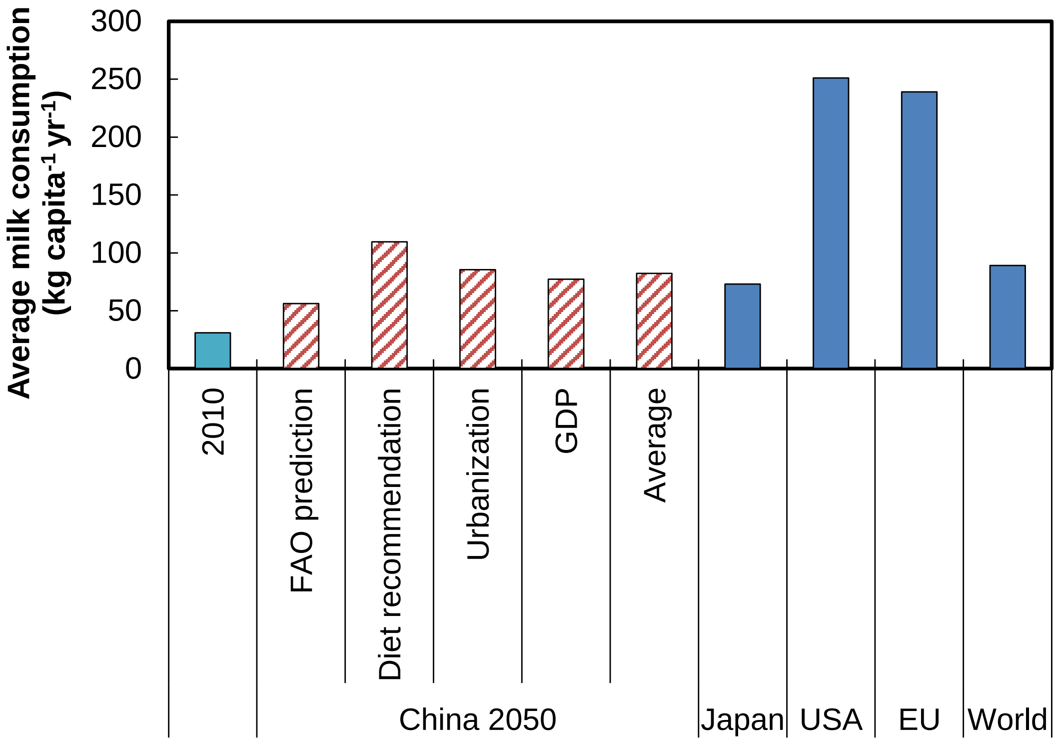

Fig 1. The estimated average milk consumption in China in 2050 based on four different estimation methods, in comparison to the current (2010) milk consumption levels in China, Japan, United States of America (USA), Europe (EU), and the world.

Expected impacts of increased milk consumption - Scenario BAU

Total milk production of the global dairy production group (China and the leading milk exporting regions) will reach up to 375 Tg in BAU scenario, increased by 28% compared to 2010. Total milk consumption in China will be 116 Tg in 2050 (range 80 - 155 Tg), which is around 3.2-fold the milk consumption level of 2010 (Table S1). The additional milk demand was assumed to be supplied by industrial production systems. Results of the BAU scenario show that the global dairy-related GHG emissions will increase by 18-53%, with an average value of 35% (increase from 565 Tg CO_2 in 2010 to 764 Tg CO_2 in BAU) compared with 2010 (Fig 2). The land needed for feed production will increase by 32% (from 84 to 111 million ha). Water use and Nr losses related to dairy production will increase by 77% (from 18 to 33 billion m^3) and 32% (from 3.6 to 5.4 Tg N), respectively (Fig 2). China's domestic dairy-related GHG emissions and total Nr losses will be tripled (Fig 3).

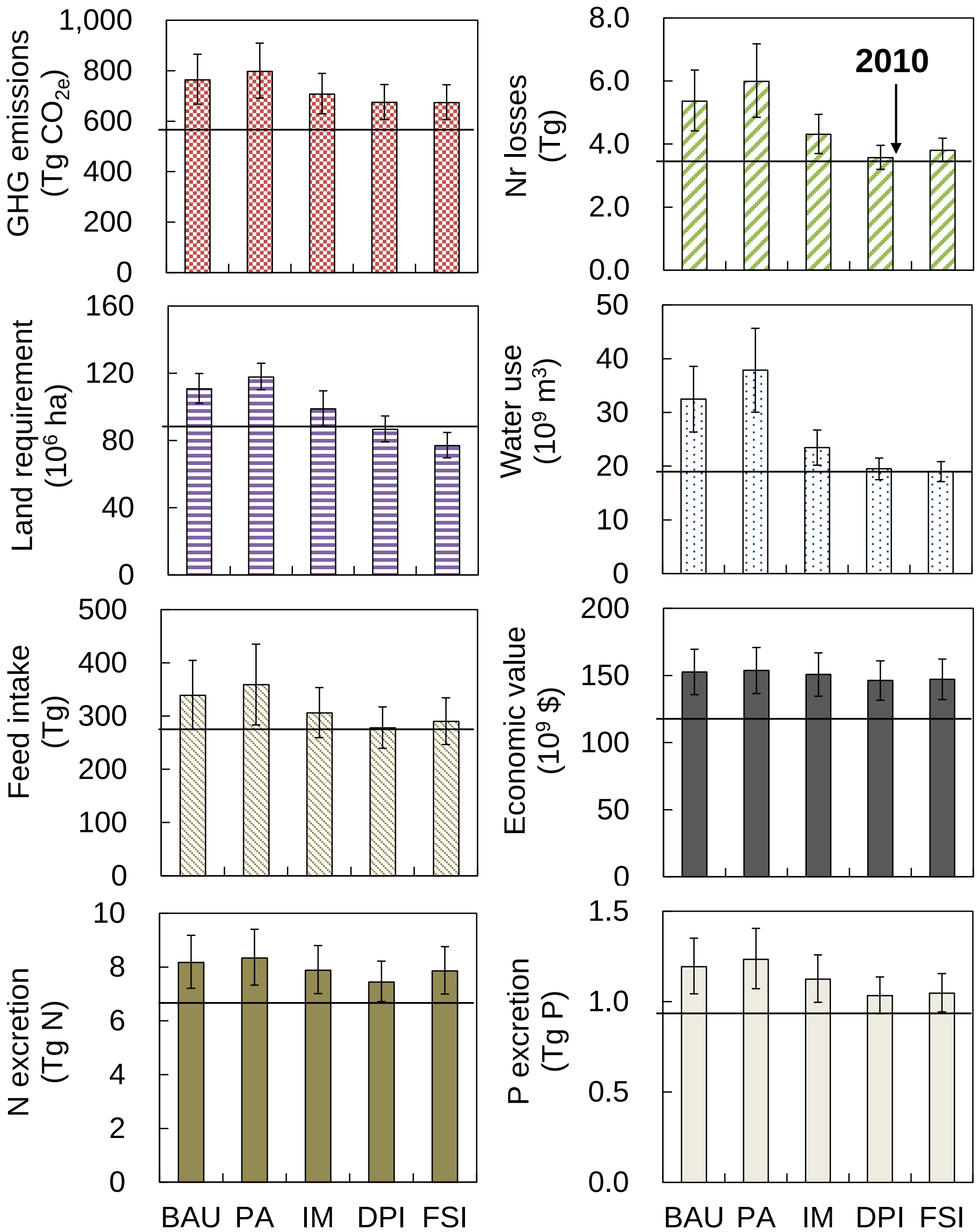

Fig 2. Impacts of increased milk consumption for the global dairy production (China

and with three leading milk export regions) by 2050; results of 5 scenarios (BAU, PA, IM, DPI and FSI), i.e., greenhouse gas (GHG, Tg CO_2 equivalent) emissions, reactive nitrogen (Nr, Tg N) losses, land requirement (million ha), irrigated water requirement (billion m^3), animal feed intake requirements (Tg dry matter), economic value (billion $), nitrogen excretion (Tg N) and phosphorus excretion (Tg P) in the four countries considered in this study (China, European Union, New Zealand, United States of America). The solid lines represent the situation in 2010. The error bars reflect the expected lowest and highest milk consumption in 2050.

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 additional milk in 2050; DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system improvement, on top of DPI.

Expected impacts of increased milk consumption - Scenario PA

Producing all additional milk domestically (PA) with current technology and management, will increase total dairy related GHG emissions (China, EU, NZ and USA) by 34 Tg CO_{2e}, compared to BAU (Fig 3). PA will boost the Chinese dairy sector by nearly 52 billion US$, and substantially increase domestic employment opportunities compared to BAU (Figs 3, S6). However, without major improvements in domestic feed production (yield and quality), it will need to import 8.5 Tg of cereals and protein-rich crops (mainly from USA and Brazil), and 6.2 Tg forages (mainly from USA and Canada) (Table 4). The demand of land for feed production will increase by 6% (equal to 7.1 million ha reduction), irrigation water by 17% (equal to 5.4 billion m^3 blue water reduction), Nr losses by 12% (equal to 0.6 Tg N reduction) and nutrient excretions by 2-3% (equal to 0.17 Tg N and 0.04 Tg P reduction) for the four regions considered here, compared to BAU (Fig 2).

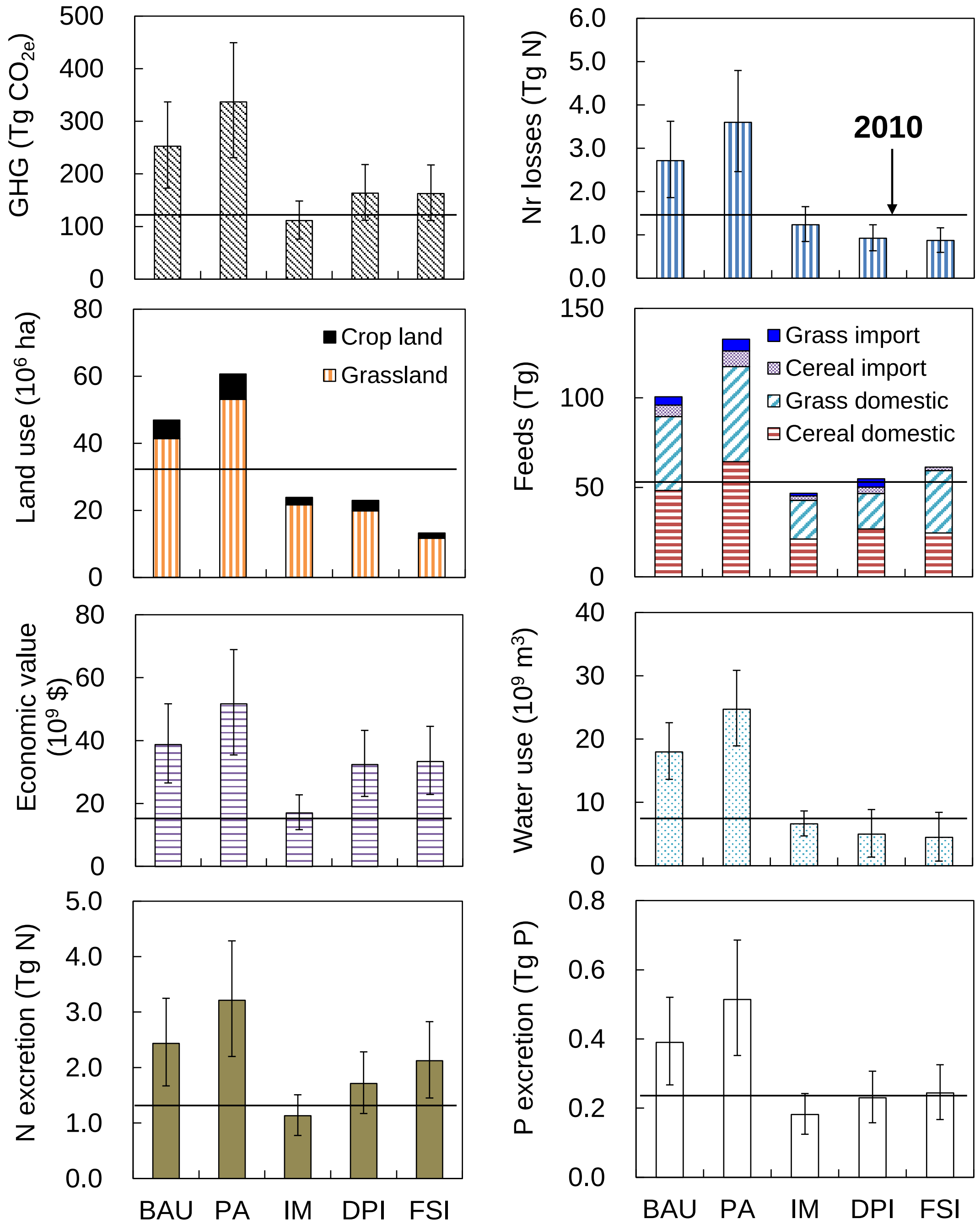

Fig 3. Impacts of increased milk consumption in China by 2050; results of five

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

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 additional milk in 2050; DPI (SSP1a): Dairy production Improvement, on top of BAU; FSI (SSP1b): (Farming system improvement, on top of DPI. All the indicators were calculated based on the total milk production in China.

Expected impacts of increased milk consumption - Scenario IM

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

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

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

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

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

Expected impacts of increased milk consumption - Scenario DPI

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

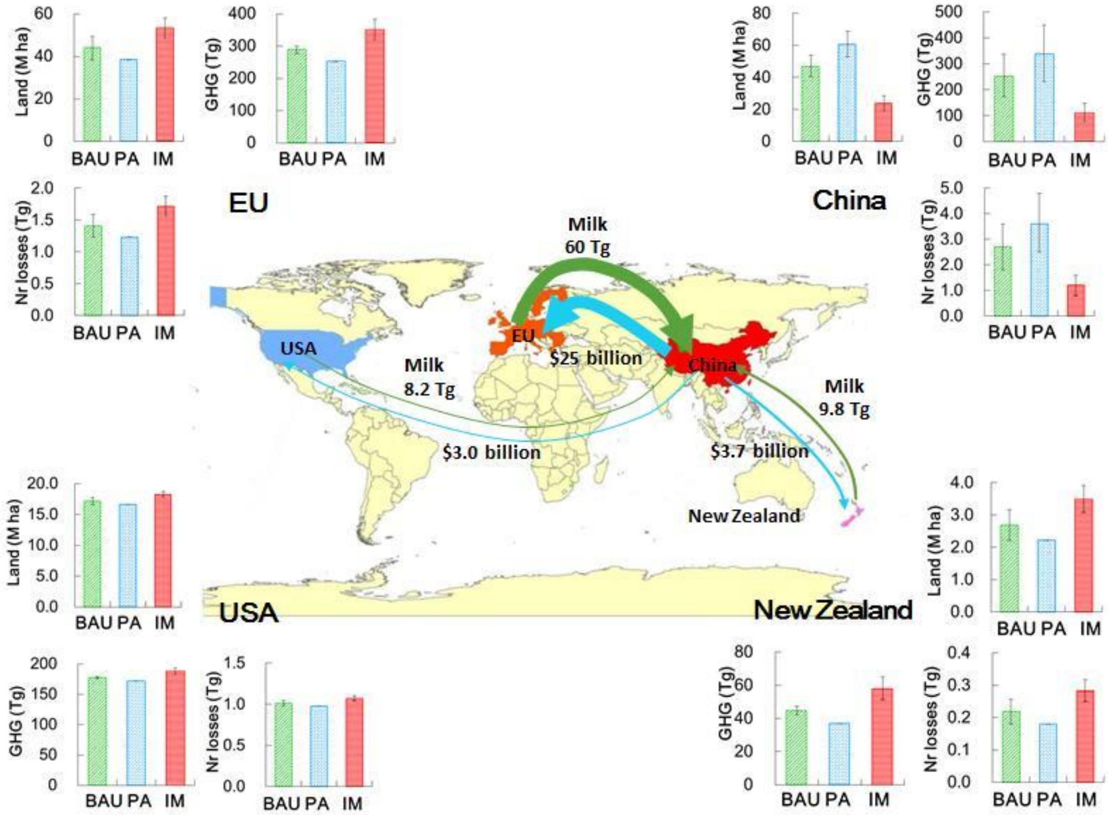

Fig 4. Import of milk from the world's top three milk exporters to China, and the economic return (indicated by arrows), for scenario IM in 2050. The bar graphics show the changes in agriculture land area, GHG emissions, and Nr losses in China and the three exporting countries EU, NZ and USA for the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

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

Expected impacts of increased milk consumption - Scenario FSI

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

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

Discussion

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

Future milk consumption

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

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

Domestic production or importation

Our results show that production of the additional required milk domestically without large improvements within the dairy industry will increase global dairy related GHG emissions compared to import of this milk. The average GHG emissions was 2.9 kg CO_2e kg^{-1} milk in China in 2010, compared with 2.1, 1.6 and 1.9 kg CO_2e kg^{-1} milk for NZ, EU and USA, respectively (Opio et al., 2013). The higher GHG emissions in China is due to less efficient feed and milk production. Further, the GHG emissions associated with the transportation of milk are much smaller than those associated with domestic production (feed and milk), with the net effect of milk import decreasing total GHG emissions (Table 1). This was the same for N losses, since the average Nr loss was 34 g N kg^{-1} milk in China, which is 1.8-2.8 larger than that in the leading milk exporting regions (Table 1).

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

Production of all extra milk (PA) domestically without improvement of dairy and feed production will face several domestic and international restrictions. Additional domestic arable land (5.5 million ha) and grassland (28 million ha) will be required in PA scenario, equal to 4.5% and 7.0% of total land area in China, respectively (NBSC, 2016). However, this amount of land cannot be met domestically, due to the high population and food self-sufficiency rate policy. Recently, the area for arable land and grassland was slightly decreased (Fig S8). Environmental regulations have become stricter in China, with an environmental protection tax due to be implemented at the beginning of 2018, and a tax will be collected from high polluting dairy farms (NPC, 2016). The PA scenario also requires import of 8.5 Tg concentrates and 6.2 Tg of alfalfa. Such high levels of import may become increasingly difficult, in part also due to pressures from the outside world. For example, the drought-stricken western USA shipped more than 0.2 billion m^3 of water embedded in alfalfa to China in 2012, enough to supply the annual household needs of half a million families (Culp and Robert, 2012) and soybean exports from Brazil have been linked to deforestation of the Amazon (Morton et al., 2006).

Global dairy related GHG emissions and Nr losses will be 7% and 28% lower if all additional milk is imported compared with domestic production. However, there will be strong physical and environmental constraints in the leading milk export regions. For example, 1.3 and 15 million ha additional agricultural land would be required in NZ and EU, which is equivalent to 12% and 8% of their agricultural land in 2010, respectively (FAO, 2016). These land requirements exceeded local land availability, so NZ would need to cut down the land used for sheep and beef production, or explore marginal land which is sometimes too steep or too close to watercourses for dairy production (MPI, 2012). Besides the physical limitations, environmental protection policies may also constrain large dairy production increases in the EU and NZ. The results of the IM scenario suggest that Nr losses and GHG emissions from dairy production will increase by around 39% in the EU, which will obstruct environmental targets (Westhoek et al., 2014; UNFCCC, 2015). Strong increases in milk production in NZ will also be met with resistance (MPI, 2012) The environmental constraints on drastic increases of dairy production in exporting countries suggest that changes in the balance of supply and demand will shift the global market price of dairy products to higher levels. A rise in global dairy price will make investments in domestic dairy production more attractive.

Improving domestic feed and dairy production efficiencies may be a preferred pathway for many milk demanding countries, including China where the prospects are relatively large for improving feed and dairy production efficiency according the DPI and FSI scenarios (Fig 2). This needs to be achieved not only through an increase in production, economic and environmental performance of China's dairy sector to the level of leading milk export regions (DPI), but total redesign of the dairy production system, to increase the contribution from grassland and household dairy production systems as they are more integrated with feed production and cropland (FSI). For example, grassland covers 3/4 of the agriculture land in China. Most of this land is not suitable for intensification of feed production due to low rainfall, poor soil quality, over-grazing and desertification. However, some areas can be utilized to supply forage (1 to 3 Mg ha^{-1} yr^{-1}) for dairy cattle when properly managed, grazed, irrigated and fertilized (Kang et al., 2007). A further benefit of developing well managed grazing systems is to also to contribute to grassland restoration whilst maintaining emphasis on natural ecosystem services and biodiversity in native grassland areas (Ren et al., 2016). Achieving this also requires governments, farmers, ecologists, industry, and researchers to work together to develop transition plans for different regions and farms (Eisler et al., 2014; Zhang et al., 2016). Likewise other emerging countries will face the same situation and problems of China, and will also need to improve their dairy and feed production yield, and integrate dairy and feed production together to meet their milk demand.

Policy implications

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

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

Recently, milk processing factories banned the collection of milk from small household dairy farms, mainly due to concerns about milk quality. It has been estimated that some 100,000 small dairy farmers have stopped farming each year since 2010 (MOA, 2015). This will also contribute to redesign dairy production in China, through conversion of traditional dairy production systems to medium size house-hold systems as in EU. Currently, some of China's dairy companies invest overseas rather than in domestic production, due to eroded public confidence in the quality of domestic milk, low production efficiency, and high production cost (Sharma and Rou, 2014). Hence, it is of great importance to regain the consumers and investors' confidence in the Chinese milk sector, through implementing strict milk quality control and fine policies, such as the Food Security Law issued in 2015 (NPC, 2015).

Conclusions

The ever-growing thirst for milk in China comes with significant challenges, and impacts on global trade of milk and feed, land use, GHG emissions and Nr losses. In 2050, producing all additional required milk domestically with current technologies and management will require annual imports of 8.5 Tg concentrates and 6.2 Tg forages, and will increase GHG emissions of the global dairy sector by 41% and land demand by 40% compared to 2010. In contrast, importing all additional milk will transfer the environmental burden from China to milk exporting countries (e.g. EU, NZ and USA). The optimal option is to produce the additionally required milk in China, but with greatly improved technology. The prospects and challenges of improving the local dairy production efficiency, manure and grassland management, and of the integration of crop-dairy production systems are large. Closing the productivity gaps in domestic dairy and feed production, accompanied by dairy production system adjustment, greater utilization of grassland resources along with feed ration improvement and strict milk quality control systems appears to be the preferred pathway. This pathway should be guided through governmental policies, mainly focused on improving manure management, feed production, crop-livestock system integration, and grassland restoration whilst maintaining emphasis on natural ecosystem services and biodiversity in native grassland areas.

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References:

1) Alexandratos N and Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. ESA Work. Pap 3.
2) Appuhamy JA, France J, Kebreab E (2016) Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. Global Change Biology, 22(9): 3039-3056.
3) Bai ZH, Ma L, Oenema O et al. (2013) Nitrogen and phosphorus use efficiencies in dairy production in China. Journal Environment Quality, 42(4), 990-1001.
4) Bai Z, Ma L, Qin W et al. (2014) Changes in Pig Production in China and Their Effects on Nitrogen and Phosphorus Use and Losses. Environmental Science & Technology, 48: 12742−12749.
5) Bai Z, Ma L, Jin S et al. (2016) Nitrogen, Phosphorus, and Potassium Flows through the Manure Management Chain in China. Environmental Science & Technology, 50(24), 13409-13418.
6) Chaudhary A and Kastner T (2016) Land use biodiversity impacts embodied in international food trade. Global Environmental Change, 38, 195-204.
7) Chen X, Cui Z, Vitousek PM et al. (2011) Integrated soil–crop system management for food security. Proceedings of the National Academy of Sciences of the United States of America, 108, 6399–6404.
8) Chen X, Cui Z, Fan M et al. (2014) Producing more grain with lower environmental costs. Nature, 514, 486–489.
9) Chinese Society of Nutrition (CSN), 2014. The Chinese Dietary Guidelines,

<http://dg.cnsoc.org/upload/images/source/20140718174702431.jpg>. Accessed in Dec 2016.

10) China Statistic Yearbook, 2011. <http://www.stats.gov.cn/tjsj/ndsj/2011/indexch.htm> Accessed in Dec 2016.

11) Culp P and Robert G (2012) Parched in the West, but shipping water to China, bale by bale. Wall Street Journal.

12) de Klein CA and Ledgard SF (2005) Nitrous oxide emissions from New Zealand agriculture–key sources and mitigation strategies. Nutrient Cycling Agroecosystem, 72, 77-85 (2005).

13) Deng XP, Shan L, Zhang H et al (2006) Improving agricultural water use efficiency in arid and semiarid areas of China. Agricultural Water Management, 80(1), 23-40.

14) D'Odorico P, Carr JA, Laio F (2014) Feeding humanity through global food trade. Earth's Future, 2014, 2(9): 458-469.

15) Eisler MC, Lee MR, Tarlton JF et al (2014) Agriculture: Steps to sustainable livestock. Nature, 507(7490), 32.

16) Eshel G, Shepon A, Makov T et al (2015) Partitioning United States' feed consumption among livestock categories for improved environmental cost assessments. Journal of Agricultural Science, 153(03), 432-445.

17) Europe Union Commission. 2014. <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.148.01.0088.01.ENG>. Accessed in Dec 2016.

18) Food and Agriculture Organization (FAO), 2016. http://faostat.fao.org/. Accessed in Dec 2016.

19) Food Miles. Food Miles, <http://www.foodmiles.com/> (2016). Accessed in Dec 2016.

20) Flysjö A, Henriksson M, Cederberg C et al (2011) The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agricultural System, 104(6), 459-469.

21) Gerber PJ, Steinfeld H, Henderson B et al (2013) Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

22) Henders S, Persson UM, Kastner T (2015) Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. Environmental Research Letter, 10(12), 125012.

23) Herrero M, Havlík P, Valin H et al (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences of the United States of America, 110(52), 20888-20893.

24) Hou Y, Bai Z, Lesschen JP et al (2016). Feed use and nitrogen excretion of livestock in EU-27." Agricultural Ecosystem Environment, 218: 232-244.

25) Kang L, Han X, Zhang Z et al (2007) Grassland ecosystems in China: review of current knowledge and research advancement. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 362(1482): 997-1008.

26) Lassaletta L, Billen G, Grizzetti B, et al. (2014) Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. Biogeochemistry, 118(1-3): 225-241.

27) Leip A, Weiss F, Lesschen JP et al (2014) The nitrogen footprint of food products in the European Union. Journal of Agricultural Science, 152(S1), 20-33.

28) Lenzen M, Moran D, Kanemoto K et al (2012) International trade drives biodiversity threats in developing nations. Nature, 486(7401), 109-112.

29) Lesschen JP, Van den Berg M, Westhoek HJ (2011) Greenhouse gas emission profiles of European livestock sectors. Animal Feed Science Technology, 166, 16-28.

30) Li R and Lin H (2014) Developing the agro-grassland system to insure food security of China. Journal of Agricultural Chemistry Environ, 3(03), 9.

31) Li XL, Wan LQ, He F (2007) Potential of grassland agriculture in southern China and its significance to food security. Science Technology Review, 9-15. (In Chinese).

32) Liu J and Yang W (2012) Water sustainability for China and beyond. Science 337, 649-650.

33) Mattar R, de Campos Mazo DF, Carrilho FJ (2012) Lactose intolerance: diagnosis, genetic, and clinical factors. Clinical and Experimental Gastroenterology, 5, 113-121.

34) Ministry of Agriculture (MOA) (2014) http://www.moa.gov.cn/govpublic/CWS/201407/t20140721_3973828.htm accessed June 2016.

35) Ministry of Agriculture (MOA) 2015. China Dairy Statistical Summary, <http://www.moa.gov.cn/govpublic/XMYS/201109/t20110921_2292641.htm>. Accessed in Dec 2016.

36) Ministry for Primary Industries (MPI) 2012. Pastoral input trends in New Zealand: A snapshot, <https://www.mpi.govt.nz/document-vault/4168>. Accessed in Dec 2016.

37) Mekonnen MM and Hoekstra AY (2011) National water footprint accounts: the green, blue and grey water footprint of production and consumption.

38) Mekonnen MM and Hoekstra AY (2012) A global assessment of the water footprint of farm animal products. Ecosystems, 15, 401-415.

39) Monaghan RM, Hedley MJ, Di HJ et al (2007) Nutrient management in New Zealand pastures—recent developments and future issues. New Zealand Journal of Agricultural Research, 50, 181-201.

40) Morton DC, DeFries RS, Shimabukuro YE et al (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Proceedings of the National Academy of Sciences of the United States of America, 103(39), 14637-14641.

41) National Bureau of Statistic of China (NBSC) 2016. http://www.stats.gov.cn/tjsj/ndsj/. Accessed in Dec 2016.

42) National People's Congress of China (NPC) 2015. http://www.npc.gov.cn/npc/cwhhy/12jcwh/2015-04/25/content_1934591.htm. Accessed in Dec 2016.

43) National People's Congress of China (NPC) 2016 http://www.npc.gov.cn/npc/xinwen/2016-12/25/content_2004993.htm Accessed in Dec 2016.

44) Oenema O, de Klein C, Alfaro M (2014) Intensification of grassland and forage use: driving forces and constraints. Crop Pasture Science, 65(6), 524-537.

45) Oita A, Malik A, Kanemoto K (2016) Substantial nitrogen pollution embedded in international trade. Natural Geoscience, 9(2), 111-115.

46) O'Neill BC, Elmar K, Keywan R et al (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122(3): 387-400.

47) Opio C, Gerber P, Mottet A et al (2013) Greenhouse Gas Emissions From Ruminant Supply Chains – A Global Life Cycle Assessment. Food and Agriculture Organization of the United Nations (FAO), Rome.

48) Pan GY, Ouyang Z, Li P, (2007) Cultivation pattern and development of quality forage in the North China Plain. Resources Science, 229(2), 15-20. (In Chinese).

49) Pei X, Tandon A, Alldrick A (2011) The China melamine milk scandal and its implications for food safety regulation. Food Policy, 36, 412-420.

50) Piao S, Ciais P, Huang Y et al (2010) The impacts of climate change on water resources and agriculture in China. Nature, 467(7311), 43-51.

51) Powell JM, Gourley CJP., Rotz C (2010) Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. Environmental Science Policy, 13(3), 217-228.

52) Powell JM. Jackson-Smith DB, McCrory DF (2006) Validation of feed and manure data collected on Wisconsin dairy farms. Journal of Dairy Science, 89(6), 2268-2278.

53) Ren Y, Lü Y, Fu B, (2016) Quantifying the impacts of grassland restoration on biodiversity and ecosystem services in China: A meta-analysis. Ecological Engineering, 95: 542-550.

54) Sharma S and Rou Z (2014) China’s Dairy Dilemma. Institute for Agriculture and Trade Policy.

55) Steinfeld H, Gerber P, Wassenaar TD et al (2006) Livestock's long shadow: environmental issues and options. Food & Agriculture Org (FAO), Roma.

56) State Council of China (SCC). 2017. http://english.gov.cn/policies/latest_releases/2017/06/12/content_281475684141592.htm (In Chinese) Accessed 21 June 2017.

57) Strokal M, Ma L, Bai Z et al. (2016) Alarming nutrient pollution of Chinese rivers as a result of agricultural transitions. Environmental Research Letters, 11(2): 024014.

58) Tilman D and Clark M (2014) Global diets link environmental sustainability and human health. Nature 515, 518.

59) Tilman D, Balzer C, Hill J (2011) Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America, 108(50): 20260-20264.

60) Van Passel S (2013) Food miles to assess sustainability: a revision. Sustainable

Development, 21, 1-17.
61) Velthof GL, Hou Y, Oenema O, (2015) Nitrogen excretion factors of livestock in the European Union: a review. Journal of Science Food Agriculture, 95(15), 3004-3014.
62) Wang J, Wang J, Bu D et al (2009) Thought on Accelerating the Application of TMR Feeding Technique in China. China Animal Husbandry Vet Med, (2), 101-104. (In Chinese)
63) Wang, M, Kroeze C, Strokal M et al (2017) Reactive nitrogen losses from China's food system for the shared socioeconomic pathways (SSPs). Science of The Total Environment, 605, 884-893.
64) Westhoek H, Lesschen JP, Rood T et al (2014) Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Global Environmental Change, 26, 196-205.
65) United Nations Framework Convention on Climate Change (UNFCCC) (2015) http://unfccc.int/meetings/paris_nov_2015/meeting/8926.php Accessed in Dec 2016.
66) World Bank. 2016. http://data.worldbank.org/indicator/NY.GDP.MKTP.CD?page=5 Accessed in Dec 2016.
67) Xinhua News. 2006. Wen Jiabao investigation in Chongqing city: Every Chinese can drink 0.5 kg milk every day. (In Chinese.) http://news.xinhuanet.com/fortune/2006-04/24/content_4470619.htm accessed

24 Apr. 2016.

68) Xu J, Guo Z, Su L et al (2006) Developmental potential of vitrified Holstein cattle embryos fertilized in vitro with sex-sorted sperm. Journal of Dairy Science, 89(7), 2510-2518.

69) Zhang N, Bai Z, Luo J et al (2017) Nutrient losses and greenhouse gas emissions from dairy production in China: Lessons learned from historical changes and regional differences. Science of Total Environment, 598, 1095.

70) Zhang W, Cao G, Li X et al (2016) Closing yield gaps in China by empowering smallholder farmers. Nature 537(7622): 671-674.

71) Zhou AL, Li S, Zhang W et al (2012) The impacts of DHI technology on performance of dairy cattle. China Dairy Cattle, 24: 011. (In Chinese).