

Rothamsted Repository Download

A - Papers appearing in refereed journals

Bai, Z., Lee, M. R. F., Ma, L., Ledgard, S., Oenema. O., Velthof, G. L., Ma, W., Guo, M., Zhao, Z., Wei, S., Li, S., Liu, X., Havlik, P., Luo, J., Hu, C. and Zhang, F. 2018. Global environmental costs of China's thirst for milk. *Global Change Biology*. pp. 1-14.

The publisher's version can be accessed at:

- <https://dx.doi.org/10.1111/gcb.14047>

The output can be accessed at: <https://repository.rothamsted.ac.uk/item/846xq>.

© 7 February 2018, Rothamsted Research. Licensed under the Creative Commons CC BY.

Global environmental costs of China's thirst for milk

Zhaohai Bai^{1,2} | Michael R. F. Lee^{3,4} | Lin Ma¹  | Stewart Ledgard⁵ |
 Oene Oenema^{2,6} | Gerard L. Velthof⁶ | Wenqi Ma⁷ | Mengchu Guo⁸ |
 Zhanqing Zhao¹ | Sha Wei⁸ | Shengli Li⁹ | Xia Liu¹⁰ | Petr Havlík¹¹ | Jiafa Luo⁵ |
 Chunsheng Hu¹ | Fusuo Zhang⁸

¹Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, Shijiazhuang, China

²Department of Soil Quality, Wageningen University, Wageningen, The Netherlands

³Rothamsted Research, Sustainable Agriculture Science, North Wyke, UK

⁴School of Veterinary Science, University of Bristol, Langford, UK

⁵AgResearch Limited, Ruakura Research Centre, Hamilton, New Zealand

⁶Wageningen Environmental Research, Wageningen, The Netherlands

⁷College of Resources & Environmental Sciences, Agricultural University of Hebei, Baoding, China

⁸College of Resources and Environmental Sciences, China Agriculture University, Beijing, China

⁹State Key Laboratory of Animal Nutrition, College of Animal Science and Technology, China Agricultural University, Beijing, China

¹⁰School of Mathematics and Science, Hebei GEO University, Shijiazhuang, China

¹¹Ecosystems Services and Management Program, International Institute for Applied Systems Analysis, Laxenburg, Austria

Correspondence

Lin Ma, Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, Shijiazhuang, China. Email: malin1979@sjziam.ac.cn

Funding information

National Natural Science Foundation of China, Grant/Award Number: 31572210, 31272247; President's International

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_{2eq}) 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% (1.3 million ha) and that in Europe by more than 39% (15 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_{2eq} 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, respectively.

Fellowship Initiative, Grant/Award Number: 2016DE008, 2016VBA073; Program of International S&T Cooperation, Grant/Award Number: 2015DFG91990; Hundred Talent Program of the Chinese Academy of Sciences

KEYWORDS

cattle feed, greenhouse gas, land use, nitrogen losses, milk trade, shared socio-economic pathways scenarios

1 | 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 & Carr, 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, Malik, and Kanemoto (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, Persson, & Kastner, 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 & 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, for example, India (Alexandratos & 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 (Food and Agriculture Organization (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, Balzer, & Hill, 2011; Tilman & Clark, 2014). This holds also for milk, but with significant variation between countries (Figure 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 & Bruinsma, 2012). Historically, China had low milk consumption per capita (<2 kg capita⁻¹ year⁻¹ in 1961, partially due to the severe food crisis), 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 and importation is likely to increase further in China, because of population and GDP growth and urbanization (Wang, Kroeze, Strokal, & Ma, 2017; Figure S2), and a halt of milk production due to the reduction in small traditional dairy production units (<5 head farm; Figure S3), which facilitates the milk quality control.

China became the world's largest milk importer in 2010, following the melamine scandal in 2008 which eroded public confidence in domestically produced milk (FAO, 2016; Pei, Tandon, & Alldrick, 2011). 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, for example, India (European Union Commission, 2014; Oenema, de Klein, & Alfaro, 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 future projections (Liu & Yang, 2012; Piao et al., 2010).

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 disproportionately to GHG emissions, predominately because of enteric fermentation and the release of methane (CH₄; Gerber et al., 2013; Steinfeld, Gerber, Wassenaar, Castel, & de Haan, 2006). 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 in milk consumption in 2050 aligned to current proportional contributions of domestic production and import (SSP2), (ii) Produce all additional milk domestically (PA) – increase in milk consumption in 2050 delivered through increased domestic output (SSP3), and (iii) Import all additional milk (IM) – increase in milk consumption in 2050 delivered through increased imports from three leading producing regions (EU, USA, NZ; SSP5). Furthermore, 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) - toward crop-dairy integration and forage-based systems with increased productivity of forages, building on scenario DPI.

2 | 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 to analyze the consequent impact on the sustainability indicators.

2.1 | 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 (Figure S2). Milk consumption in 2050 was then estimated assuming a mean GDP of 10,904\$ capita⁻¹ year⁻¹ and an urbanization of 78% in 2050 (FAO, 2016; World Bank, 2016). Second, a predicted increase in average milk consumption of 1.80% per year in developing countries between 2005 and 2050 (Alexandratos &

Bruinsma, 2012). Third, following the national guidelines for a healthy diet, the average milk consumption is 300 g capita⁻¹ day⁻¹ in 2050 (Chinese Society of Nutrition (CSN), 2014).

Total milk consumption was calculated as:

$$\text{Milk}_{\text{total}} = \text{Population} \times \text{Milk}_{\text{average}}, \quad (1)$$

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, calculated using the three assumptions outlined above. Forecasts suggest that the human population will be 1.4 billion in China in 2050 (FAO, 2016).

2.2 | 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 (Table 1 and Tables S2–S3).

2.3 | 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

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, the European Union, and the United States

	China						New Zealand	European	United States
	2010	BAU	PA	IM	DPI	FSI			
GHG (kg CO ₂ eq/kg 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 milk)	34	31	31	32	11	10	12 ²	9.0 ³	12 ⁴
Land requirement (m ² /kg 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 milk)	145	206	213	173	57	51	48 ⁷	46 ⁷	60 ⁷
Feed requirement (kg DM/kg 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 milk)	445 ¹⁰	445	445	445	372	383	376 ¹⁰	418 ¹⁰	360 ¹⁰
N excretion (g N/kg milk)	32 ⁸	28	28	30	20	24	30 ¹¹	20 ¹²	18 ¹³
P excretion (g P/kg milk)	5.6 ⁸	4.5	4.4	4.7	2.6	2.8	2.2 ¹⁴	3.0 ¹²	2.5 ¹⁵

The references are indicated with the number (as superscript). The figures without superscript are derived from calculations with the NUFER model. 1. Opio et al. (2013); 2. Flysjö, Henriksson, Cederberg, Ledgard, and Englund (2011); 3. Leip, Weiss, Lesschen, and Westhoek (2014); 4. Powell, Gourley, and Rotz (2010); 5. Lesschen, Van den Berg, and Westhoek (2011); 6. Eshel, Shepon, Makov, and Milo (2015); 7. Mekonnen & Hoekstra (2011); 8. Bai et al. (2013); 9. Appuhamy et al. (2016); 10. Food and Agriculture Organization (FAO) (2016); 11. de Klein & Ledgard (2005); 12. Velthof, Hou, and Oenema (2015); 13. Powell, Jackson-Smith, and McCrory (2006); 14. Monaghan et al. (2007); 15. Powell et al. (2006).
 OScenarios: 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.

four environmental impact indicators (GHG emissions, reactive N losses, and 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).

2.4 | NUFER-dairy model

The resource use and environmental effects of different dairy production systems in China were calculated by the NUFER-dairy model (Bai, Ma, Oenema, Chen, & Zhang, 2013; Zhang et al., 2017). The 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 submodule and a nutrient balance submodule. 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, N losses and GHG emissions (Bai et al., 2013; Zhang et al., 2017).

2.5 | Three physical indicators (feed, land and water)

2.5.1 | Feed requirement

The feed requirement of dairy cattle was calculated as follows:

$$\text{Feed}_{\text{total}} = \text{Milk}_{\text{produced}} \times \text{Feed}_{\text{milk}}, \quad (2)$$

where $\text{Feed}_{\text{total}}$ is the total feed requirement (dry matter) in kg, $\text{milk}_{\text{produced}}$ is the total milk produced in each region in kg, and $\text{Feed}_{\text{milk}}$ is the feed to milk conversion ratio in kg/kg (Table 1 and Table 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, France, & Kebreab, 2016), and are shown in Table 1.

2.5.2 | Land requirement

The agriculture land required for dairy production was calculated from total milk production and the average land demand per kg milk.

$$\text{Land requirement} = \text{Milk}_{\text{produced}} \times \text{Land requirement}_{\text{milk}}/10000, \quad (3)$$

where, Land requirement is the area of arable land and grassland required for feed production, in ha. $\text{Land requirement}_{\text{milk}}$ is the average area of land needed to produce 1 kg of milk, in m^2/kg milk. The area of arable land 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.

2.5.3 | Water use

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

$$\text{Water} = \text{Milk}_{\text{produced}} \times \text{Water}_{\text{milk}}, \quad (4)$$

where Water is the total water requirement in m^3 ; $\text{Water}_{\text{milk}}$ is the mean blue water use for milk production in m^3/kg milk. The blue water use of China's dairy production covered the blue water demand of related feed production, that is, 74 m^3/t maize, 129 m^3/t soybean, 387 m^3/t rice, and 455 m^3/t wheat (Mekonnen & Hoekstra, 2011). These figures do not include the demand for drinking and service water, due to lack of information and their small contribution (<5%) to the total water footprint (Mekonnen & 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.

2.6 | One economic indicator (GDP value of milk production)

2.6.1 | Economic value

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

$$\text{Economic value} = \text{Milk}_{\text{produced}} \times \text{Costs}_{\text{milk}}, \quad (5)$$

where, Economic value is the total economic value of produced milk in US\$ in 2010; $\text{Costs}_{\text{milk}}$ is the average production cost of milk, derived from FAO database in US\$/t milk. The average milk production cost was 445, 376, and 360 US\$/t milk for China, NZ and USA, respectively in 2010. For EU, we used a weighted average value, which was 418 US\$/t 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 in 2010 (China Statistic Yearbook, 2011).

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

2.7.1 | GHG emissions

The GHG emissions (CO₂, CH₄, and N₂O) from the soil-feed-dairy production and feed-milk transportation chains were calculated as follows:

$$\text{GHG} = \text{Milk}_{\text{produced}} \times \text{GHG}_{\text{milk}} + \text{Milk}_{\text{exporttoChina}} \times \text{GHG}_{\text{milkexport}}, \quad (6)$$

where GHG is the total GHG emissions of dairy production in kg CO₂ equivalents (CO₂eq), Milk_{produced} is the amount of milk produced in each region (China, EU, USA, and NZ) in kg. GHG_{milk} is the carbon footprint in kg CO₂eq/kg milk. Milk_{export to China} is the amount of milk exported to China by the top three milk exporting regions (weighted values) in 2010. GHG_{milk export} is the GHG emissions associated with the transportation of milk to China. Milk_{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 were based on the average transport distance of milk to China from NZ, EU (the Netherlands) and USA, 11,144, 7,821 and 11,100 km, respectively (Food Miles, 2016). The average GHG emissions rate was 0.0345 kg CO₂eq/ton km during shipping (Van Passel, 2013). We assumed that 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.

2.7.2 | 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). 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 N₂O and ammonia (NH₃) to the atmosphere, from animal housing, manure management, and soils.

$$\text{Nr losses} = \text{Milk}_{\text{produced}} \times \text{Nr losses}_{\text{milk}}, \quad (7)$$

where Nr losses are the total Nr losses of dairy production in kg. Nr losses_{milk} are the Nr losses per kilo of milk in kg/kg 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.

2.7.3 | N and P excretions

The N and P excretions by dairy cattle were calculated as follows:

$$\text{N(P)excretion} = \text{Milk}_{\text{produced}} \times \text{N(P)excretion}_{\text{milk}}, \quad (8)$$

where N(P) excretion is the total amount of manure N(P) produced by dairy cattle in kg/year, N(P) excretion_{milk} is the average N(P) excretion per kilo of milk produced, in kg (Table 1).

2.8 | Feed use and import, and related virtual land import

Consumption of different feed items was calculated as follows:

$$\text{Feed}_{\text{items}} = \text{Feed}_{\text{total}} \times \text{Feed}_{\text{composition}}, \quad (9)$$

where, Feed_{items} is the consumption of different feed items, that is, 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 S4). No dairy feed was imported into the United States. Feed import-related land virtual import was calculated based on the feed import and feed productivity in the feed export regions, which were derived from the FAO database.

2.9 | Development of scenarios

2.9.1 | 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., 2014). 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 (Ministry of Agriculture (MOA), 2015).

2.9.2 | 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.

2.9.3 | 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

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)					
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).

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

2.9.4 | 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., 2014). 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 the 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 New Zealand, the European Union and the United States. 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, Ma, Oenema, Chen, & Zhang, 2014; Lassaletta et al., 2014). Strategies for improved dairy production efficiency and environmental performance are listed in Table 3.

2.9.5 | 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 (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 for maize, from 6.5 to 7.7 t/ha for rice and from 4.7 to 6.9 t/ha 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).

3 | RESULTS

3.1 | Prediction of average milk consumption in China in 2050

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

3.2 | Expected impacts of increased milk consumption - Scenario BAU

Total milk production of the global dairy production and supply group (China and the leading milk exporting regions) will increase by

TABLE 3 List of strategies for sustainable pathways of dairy production in China

	Feed production	Dairy production and manure management
Research, scientists' strategy	Level 1: Integrated Soil-crop System Management technology (ISSM) to 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, that is, 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 .	Level 1: Genetic improvements to increase milk productivity, that is, build 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, that is, 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, that is, 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, that is, pioneer dairy farm to test the advanced technologies and training the farmers

1. Chen et al. (2011); 2. Li, Wan, and He (2007); 3. Li & Lin (2014); 4. Pan, Ouyang, and Li (2007); 5. Deng, Shan, Zhang, and Turner (2006); 6. Zhou, Li, Zhang and Yeertai (2012); 7. Xu et al. (2006); 8. Wang et al. (2009).

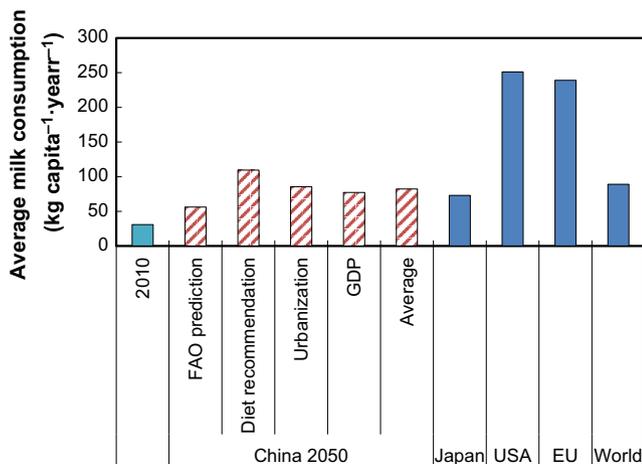


FIGURE 1 The estimated average milk consumption in China in 2050 based on four different estimation methods, in comparison to the current (2010) milk consumption levels in China, Japan, United States of America (USA), Europe (EU), and the world

28% compared to 2010, and reach up to 375 Tg in BAU scenario. Total milk consumption in China will be 116 Tg in 2050 (range 80–155 Tg), which is around 3.2-fold the milk production 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_{2eq} in 2010 to 764 Tg CO_{2eq} in BAU) compared with 2010 (Figure 2a). The land needed for feed production will increase by 32% (from 84

to 111 million ha; Figure 2c). Water use and Nr losses related to dairy production will increase by 77% (from 18 to 33 billion m³) and 32% (from 3.6 to 5.4 Tg N) when compared to 2010, respectively (Figure 2b,d). China's domestic dairy-related GHG emissions and total Nr losses will be tripled (Figure 3a, b).

3.3 | 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_{2eq}, compared to BAU (Figure 2a). PA will boost the Chinese dairy sector to nearly 52 billion US \$, and substantially increase domestic employment opportunities compared to BAU (Figure 3e, Figure 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), irrigation water by 17% (equal to 5.4 billion m³ blue water), Nr losses by 12% (equal to 0.6 Tg N) and nutrient excretions by 2–3% (equal to 0.17 Tg N and 0.04 Tg P) for the four regions considered here, compared to BAU (Figure 2b, c, g, h).

3.4 | 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/year. Milk will

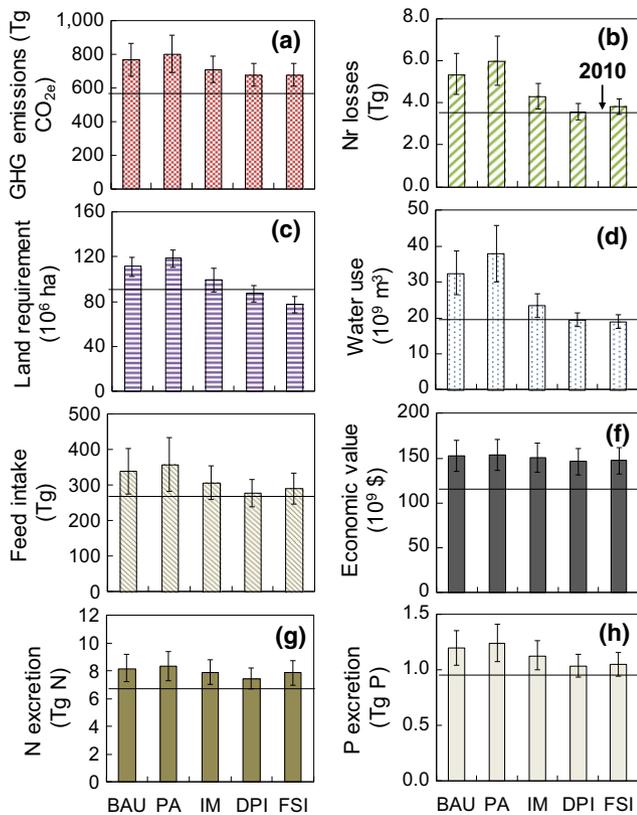


FIGURE 2 Impacts of increased milk consumption for the global dairy production by 2050; results of five scenarios (BAU, PA, IM, DPI and FSI), i.e., GHG emissions (a), Nr losses (b), land requirement (c), water use (d), animal feed intake requirements (e), economic value (f), nitrogen excretion (g) and phosphorus excretion (h) 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)

become a bulk trade commodity, almost comparable in size to soybean now (Figure 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 (Figure 2a–d).

The milk imported will come from the European Union (60 Tg), NZ (9.8 Tg) and the United States. (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\$/year (Figure 4b). 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 (Figure 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

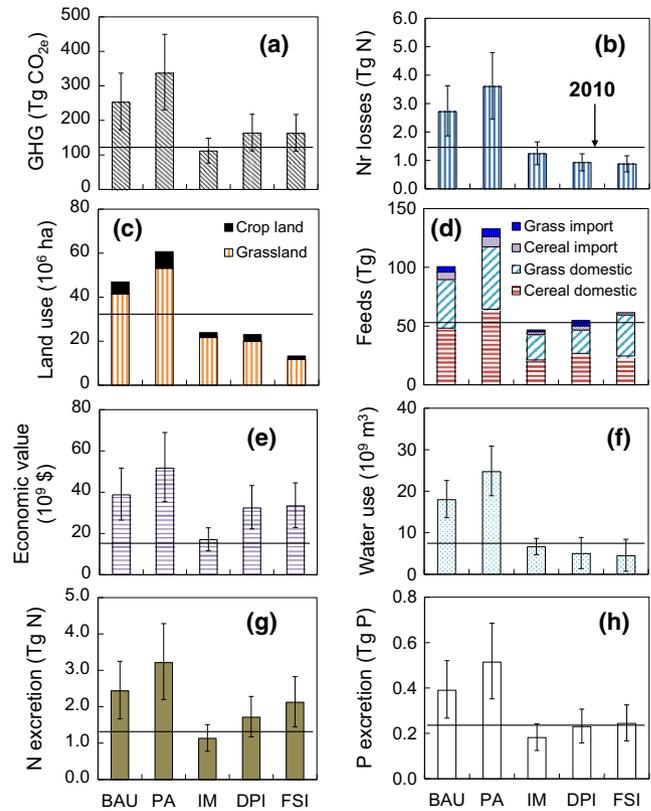


FIGURE 3 Impacts of increased milk consumption in China by 2050; results of five scenarios (BAU, PA, IM, DPI and FSI), i.e., GHG emissions (a), Nr losses (b), requirement of crop land and grassland (c), concentrate feed and forage imported and domestically produced (d), economic value (e), water use (f), N excretion (g) and P excretion (h) 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)

for cattle-feed production in New Zealand would have to increase by about 57% (from 2.2 to 3.5 million ha) and that in the European Union 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 (Figure 4b,c). The European Union and New Zealand may significantly have to increase land productivity and dairy productivity, 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 European Union, and the Nr losses will also increase by a similar proportion.

3.5 | 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

TABLE 4 Import of maize and soybean and alfalfa from the United States of America (USA) and Canada (CA), Brazil (BR) and Argentina (AR), for dairy production in China (CN), European Union (EU) in 2010, and for scenarios producing all additional milk domestically (PA) and import all of the additional milk (IM) in 2050

	2010		PA		IM	
	CN	EU	CN	EU	CN	EU
Feed, Tg/year						
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/year						
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						

New Zealand 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.

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 (Figures 2a–c and 3a–c). This illustrates the huge scope for improving the dairy production efficiency, through meeting EU, NZ and US standards. However, the area of arable 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 (Figure 3c,d). This indicates that improvements in the productivity and efficiency of dairy production alone may not be sufficient to relieve the pressure on land.

3.6 | 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 (Figure 2c, Table 4). Meanwhile, the global GHG emissions could be reduced by 36% and Nr losses reduce by 68% (Figure 2a). 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 (Figure 2c). 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 (Figure 2a, c).

4 | DISCUSSION

The increasing demand for milk in China will have significant impacts on global dairy related GHG emissions, land use and milk, and feed trade. We show for China that producing additional milk domestically will reduce the environmental performance of global dairy production, for example, increase in GHG and Nr emissions and feed import. Importing 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.

4.1 | 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 & Bruinsma, 2012). It is projected that global milk consumption will increase by 60% between 2010 to 2050 (Alexandratos & Bruinsma, 2012), and more than 60% of the additional milk demand will come from the traditional lower milk consumption regions (<100 kg milk capita $^{-1}$ year $^{-1}$ in 2010), that is, East and North Africa, sub-Saharan Africa, South Asia, and East Asia, with China having the largest potential future milk demand.

We assumed that the average milk consumption in China will be 82 kg/capita 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, de Campos Mazo, & Carrilho, 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 $^{-1}$ day $^{-1}$, which is equivalent to 110 kg capita $^{-1}$ year $^{-1}$ (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 $^{-1}$ year $^{-1}$, still much lower the current US 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

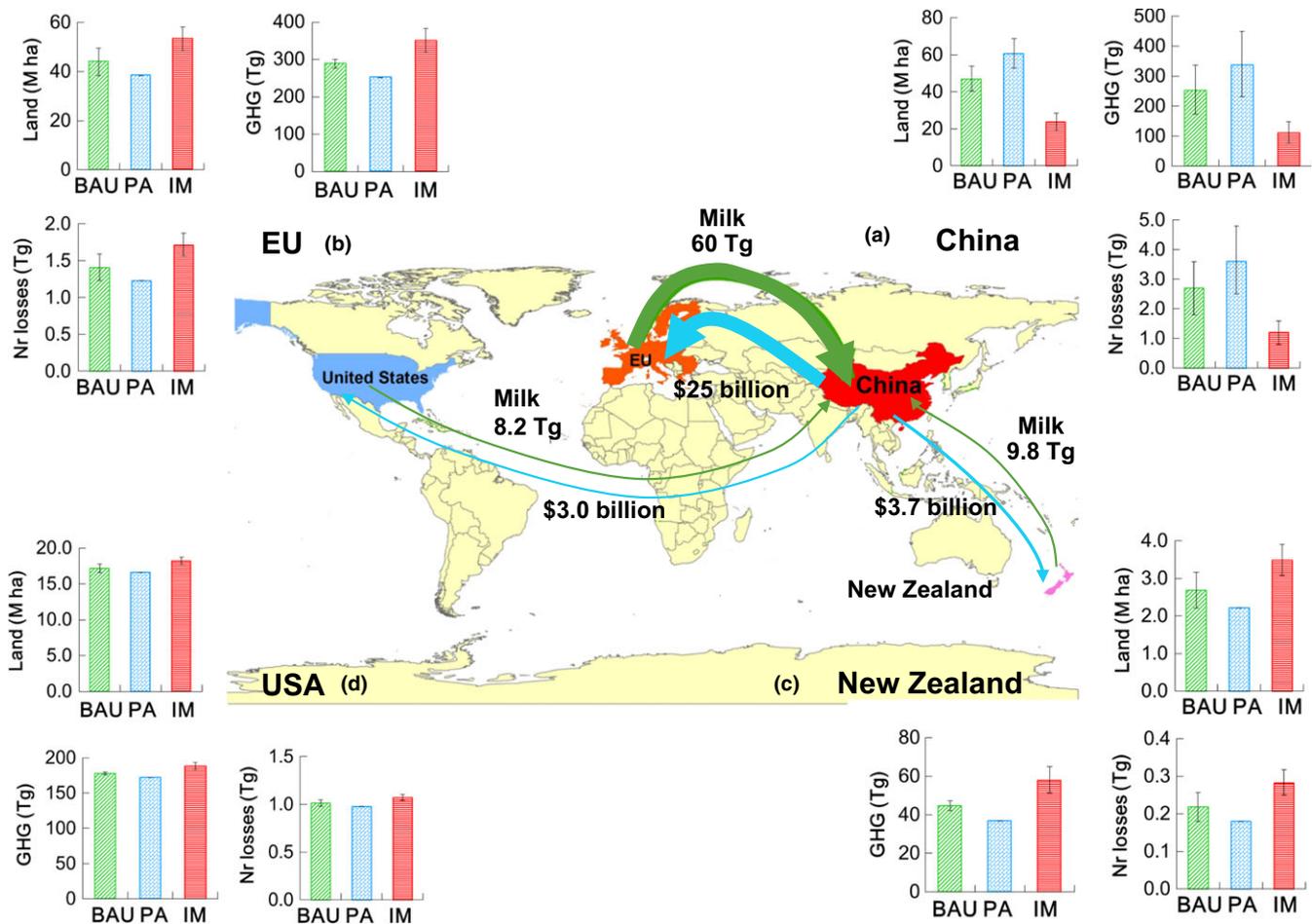


FIGURE 4 Import of milk from the world's top three milk exporters to China, and the economic return (indicated by arrows), for scenario IM in 2050. The bar graphics show the changes in agriculture land area, GHG emissions, and Nr losses in China (a) and the three exporting countries EU (b), NZ (c) and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

predicted mean milk consumption in 2050 has a large uncertainty range.

4.2 | 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 CO₂e/kg milk in China in 2010, compared with 2.1, 1.6 and 1.9 kg CO₂e/kg milk for New Zealand, the European Union and the United States, respectively (Opio et al., 2013). The higher GHG emissions in China are due to less efficient feed and milk production. Furthermore, 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 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, 2016).

Production of all the extra milk (PA) domestically without improvement of dairy and feed production will face several domestic and international constraints. In total 5.5 million ha of domestic arable land and 28 million ha of grassland will be required additionally in the PA scenario, equal to 4.5% of arable land and 7.0% of grassland area in China, respectively (National Bureau of Statistic of China (NBSC), 2016). However, additional land area is not available domestically. Recently, the areas for arable land and grassland were slightly decreased (Figure S8). Furthermore, environmental regulations have become stricter in China, with an environmental protection tax due to be implemented at the beginning of 2018. Also a tax will be collected from high polluting dairy farms (National People's Congress of China (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 United States shipped more than 0.2 billion m³ of water embedded in alfalfa

to China in 2012, which would be enough to supply annual household needs of half a million families (Culp & 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 New Zealand and the European Union, which is equivalent to 12% and 8% of their agricultural land in 2010, respectively (FAO, 2016). These land requirements exceed local land availabilities, so New Zealand 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 (Ministry for Primary Industries (MPI), 2012). Besides the physical limitations, environmental protection policies may also constrain large dairy production increases in the European Union and New Zealand. 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 (United Nations Framework Convention on Climate Change (UNFCCC), 2015; Westhoek et al., 2014). 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 to the DPI and FSI scenarios (Figure 2). This needs to be achieved not only through an increase in production and in the economic and environmental performances of China's dairy sector, to the level of leading milk export regions (DPI), but also through a redesign of the dairy production systems, to increase the contribution from grassland and to integrate dairy production systems spatially 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, overgrazing and desertification. However, some areas can be utilized to supply forage (1 to 3 Mg ha⁻¹ year⁻¹) for dairy cattle when properly managed, grazed, irrigated, and fertilized (Kang, Han, Zhang, & Sun, 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, Lü, & Fu, 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 may face the same situation and problems of China, and

may also need to improve their dairy and feed production yield, and integrate dairy and feed production together to meet their milk demand in a more sustainable manner.

4.3 | Policy implications

Searching for the other alternatives, such as soybean milk, can be other possible options to alleviate China's high milk demand, and impacts on global sustainability. 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 feedlots. For example, for the construction of a dairy farm with 300–1,000 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 for in 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; Stokal 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 (State Council of China (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 contributes to a redesign of dairy production in China, through conversion of traditional dairy production systems to medium sized household systems. 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 & 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).

Overall, 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 the US). 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.

ACKNOWLEDGEMENTS

This work was financially supported by the National Natural Science Foundation of China (31572210, 31272247), Program of International S&T Cooperation (2015DFG91990), the Hundred Talent Program of the Chinese Academy of Sciences (CAS), President's International Fellowship Initiative, PIFI of CAS (2016DE008, 2016VBA073), and Sustainable Development Solutions Network.

ORCID

Lin Ma  <http://orcid.org/0000-0003-1761-0158>

REFERENCES

- Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper 3.
- Appuhamy, J. A., 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. <https://doi.org/10.1111/gcb.13339>
- Bai, Z., Ma, L., Jin, S., Ma, W., Velthof, G. L., Oenema, O., & Zhang, F. (2016). Nitrogen, phosphorus, and potassium flows through the manure management chain in China. *Environmental Science & Technology*, 50(24), 13409–13418. <https://doi.org/10.1021/acs.est.6b03348>
- Bai, Z. H., Ma, L., Oenema, O., Chen, Q., & Zhang, F. S. (2013). Nitrogen and phosphorus use efficiencies in dairy production in China. *Journal Environment Quality*, 42(4), 990–1001. <https://doi.org/10.2134/jeq2012.0464>
- Bai, Z. H., Ma, L., Oenema, O., Chen, Q., & Zhang, F. S. (2014). Changes in pig production in china and their effects on nitrogen and phosphorus use and losses. *Environmental Science & Technology*, 48, 12742–12749. <https://doi.org/10.1021/es502160v>
- Chaudhary, A., & Kastner, T. (2016). Land use biodiversity impacts embodied in international food trade. *Global Environmental Change*, 38, 195–204. <https://doi.org/10.1016/j.gloenvcha.2016.03.013>
- Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., & Deng, X. (2014). Producing more grain with lower environmental costs. *Nature*, 514, 486–489. <https://doi.org/10.1038/nature13609>
- Chen, X. P., Cui, Z. L., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J. S., & Zhang, F. S. (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. <https://doi.org/10.1073/pnas.1101419108>
- China Statistic Yearbook (2011). Retrieved from <http://www.stats.gov.cn/tjsj/ndsj/2011/indexch.htm>
- Chinese Society of Nutrition (CSN) (2014). The Chinese Dietary Guidelines. Retrieved from <http://dg.cnsoc.org/upload/images/source/20140718174702431.jpg>.
- Culp, P., & Robert, G. (2012). Parched in the West, but shipping water to China, bale by bale. *Wall Street Journal*, A13.
- de Klein, C. A., & Ledgard, S. F. (2005). Nitrous oxide emissions from New Zealand agriculture—key sources and mitigation strategies. *Nutrient Cycling Agroecosystem*, 72, 77–85. <https://doi.org/10.1007/s10705-004-7357-z>
- Deng, X. P., Shan, L., Zhang, H., & Turner, N. C. (2006). Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural Water Management*, 80(1), 23–40. <https://doi.org/10.1016/j.agwat.2005.07.021>
- D'Odorico, P., & Carr, J. A. (2014). Laio F (2014) Feeding humanity through global food trade. *Earth's Future*, 2(9), 458–469. <https://doi.org/10.1002/2014EF000250>
- Eisler, M. C., Lee, M. R., Tarlton, J. F., Martin, G. B., Beddington, J., Dun-gait, J. A., & Misselbrook, T. (2014). Agriculture: Steps to sustainable livestock. *Nature*, 507(7490), 32. <https://doi.org/10.1038/507032a>
- Eshel, G., Shepon, A., Makov, T., & Milo, R. (2015). Partitioning United States' feed consumption among livestock categories for improved environmental cost assessments. *Journal of Agricultural Science*, 153(3), 432–445. <https://doi.org/10.1017/S0021859614000690>
- European Union Commission (2014). Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.148.01.0088.01.ENG.
- Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., & Englund, J. E. (2011). The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agricultural System*, 104(6), 459–469. <https://doi.org/10.1016/j.agry.2011.03.003>
- Food and Agriculture Organization (FAO) (2016). Retrieved from <http://faostat.fao.org/>.
- Food Miles (2016). Retrieved from <http://www.foodmiles.com/>.
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., & . . . , G. (2013). *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).
- Henders, S., Persson, U. M., & 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. <https://doi.org/10.1088/1748-9326/10/12/125012>
- Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., & Obersteiner, M. (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. <https://doi.org/10.1073/pnas.1308149110>
- Hou, Y., Bai, Z., Lesschen, J. P., Staritsky, I. G., Sikirica, N., Ma, L., & Oenema, O. (2016). Feed use and nitrogen excretion of livestock in EU-27. *Agricultural Ecosystem Environment*, 218, 232–244. <https://doi.org/10.1016/j.agee.2015.11.025>
- Kang, L., Han, X., Zhang, Z., & Sun, O. J. (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. <https://doi.org/10.1098/rstb.2007.2029>

- Lassaletta, L., Billen, G., Grizzetti, B., Garnier, J., Leach, A. M., & Galloway, J. N. (2014). Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. *Biogeochemistry*, 118(1–3), 225–241. <https://doi.org/10.1007/s10533-013-9923-4>
- Leip, A., Weiss, F., Lesschen, J. P., & Westhoek, H. (2014). The nitrogen footprint of food products in the European Union. *Journal of Agricultural Science*, 152(S1), 20–33. <https://doi.org/10.1017/S0021859613000786>
- Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., & Geschke, A. (2012). International trade drives biodiversity threats in developing nations. *Nature*, 486(7401), 109–112. <https://doi.org/10.1038/nature11145>
- Lesschen, J. P., Van den Berg, M., & Westhoek, H. J. (2011). Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science Technology*, 166, 16–28. <https://doi.org/10.1016/j.anifeedsci.2011.04.058>
- Li, R., & Lin, H. (2014). Developing the agro-grassland system to insure food security of China. *Journal of Agricultural Chemistry Environ*, 3(3), 9. <https://doi.org/10.4236/jacen.2014.33B002>
- Li, X. L., Wan, L. Q., & He, F. (2007). Potential of grassland agriculture in southern China and its significance to food security. *Science Technology Review*, 25(9), 9–15 (In Chinese).
- Liu, J., & Yang, W. (2012). Water sustainability for China and beyond. *Science*, 337, 649–650. <https://doi.org/10.1126/science.1219471>
- Mattar, R., de Campos Mazo, D. F., & Carrilho, F. J. (2012). Lactose intolerance: Diagnosis, genetic, and clinical factors. *Clinical and Experimental Gastroenterology*, 5, 113–121. <https://doi.org/10.2147/CEG>
- Mekonnen, M. M., & Hoekstra, A. Y. (2011). National water footprint accounts: The green, blue and grey water footprint of production and consumption. *Ecological Economics*, 70, 749–758.
- Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems*, 15, 401–415. <https://doi.org/10.1007/s10021-011-9517-8>
- Ministry for Primary Industries (MPI) (2012). Pastoral input trends in New Zealand: A snapshot. Retrieved from <https://www.mpi.govt.nz/document-vault/4168>.
- Ministry of Agriculture (MOA) (2014). Retrieved from http://www.moa.gov.cn/govpublic/CWS/201407/t20140721_3973828.htm.
- Ministry of Agriculture (MOA) (2015). China Dairy Statistical Summary. Retrieved from http://www.moa.gov.cn/govpublic/XMYS/201109/t20110921_2292641.htm.
- Monaghan, R. M., Hedley, M. J., Di, H. J., McDowell, R. W., Cameron, K. C., & Ledgard, S. F. (2007). Nutrient management in New Zealand pastures—recent developments and future issues. *New Zealand Journal of Agricultural Research*, 50, 181–201. <https://doi.org/10.1080/00288230709510290>
- Morton, D. C., DeFries, R. S., Shimabukuro, Y. E., Anderson, L. O., Arai, E., del Bon Espirito-Santo, F., & Morissette, J. (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. <https://doi.org/10.1073/pnas.0606377103>
- National Bureau of Statistic of China (NBSC) (2016). Retrieved from <http://www.stats.gov.cn/tjsj/ndsj/>.
- National People's Congress of China (NPC) (2015). Retrieved from http://www.npc.gov.cn/npc/cwhhy/12jcw/2015-04/25/content_1934591.htm.
- National People's Congress of China (NPC) (2016). Retrieved from http://www.npc.gov.cn/npc/xinwen/2016-12/25/content_2004993.htm.
- 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. <https://doi.org/10.1071/CP14001>
- Oita, A., Malik, A., & Kanemoto, K. (2016). Substantial nitrogen pollution embedded in international trade. *Natural Geoscience*, 9(2), 111–115. <https://doi.org/10.1038/ngeo2635>
- O'Neill, B. C., Krieglner, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., & van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, 122(3), 387–400. <https://doi.org/10.1007/s10584-013-0905-2>
- Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., & Steinfeld, H. (2013). *Greenhouse gas emissions from ruminant supply chains – a global life cycle assessment*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).
- Pan, G. Y., Ouyang, Z., & Li, P. (2007). Cultivation pattern and development of quality forage in the North China Plain. *Resources Science*, 22(2), 15–20. (In Chinese).
- Pei, X., Tandon, A., & Alldrick, A. (2011). The China melamine milk scandal and its implications for food safety regulation. *Food Policy*, 36, 412–420. <https://doi.org/10.1016/j.foodpol.2011.03.008>
- Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., & Friedlingstein, P. (2010). The impacts of climate change on water resources and agriculture in China. *Nature*, 467(7311), 43–51. <https://doi.org/10.1038/nature09364>
- Powell, J. M., Gourley, C. J. P., & Rotz, C. (2010). Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environmental Science Policy*, 13(3), 217–228. <https://doi.org/10.1016/j.envsci.2010.03.007>
- Powell, J. M., Jackson-Smith, D. B., & McCrory, D. F. (2006). Validation of feed and manure data collected on Wisconsin dairy farms. *Journal of Dairy Science*, 89(6), 2268–2278. [https://doi.org/10.3168/jds.S0022-0302\(06\)72298-6](https://doi.org/10.3168/jds.S0022-0302(06)72298-6)
- 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. <https://doi.org/10.1016/j.ecoleng.2016.06.082>
- Sharma, S., & Rou, Z. (2014). *China's dairy dilemma*. Washington, DC: Institute for Agriculture and Trade Policy.
- State Council of China (SCC) (2017). Retrieved from http://english.gov.cn/policies/latest_releases/2017/06/12/content_281475684141592.htm (In Chinese).
- Steinfeld, H., Gerber, P., Wassenaar, T. D., Castel, V., & de Haan, C. (2006) *Livestock's long shadow: Environmental issues and options*. Roma, Italy: Food & Agriculture Org (FAO).
- Strokal, M., Ma, L., Bai, Z., Luan, S., Kroeze, C., Oenema, O., & Zhang, F. (2016). Alarming nutrient pollution of Chinese rivers as a result of agricultural transitions. *Environmental Research Letters*, 11(2), 024014. <https://doi.org/10.1088/1748-9326/11/2/024014>
- 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. <https://doi.org/10.1073/pnas.1116437108>
- Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, 515, 518. <https://doi.org/10.1038/nature13959>
- United Nations Framework Convention on Climate Change (UNFCCC) (2015). Retrieved from http://unfccc.int/meetings/paris_nov_2015/meeting/8926.php.
- Van Passel, S. (2013). Food miles to assess sustainability: A revision. *Sustainable Development*, 21, 1–17. <https://doi.org/10.1002/sd.485>
- Velthof, G. L., 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. <https://doi.org/10.1002/jsfa.7248>
- Wang, M., Kroeze, C., Strokal, M., & Ma, L. (2017). Reactive nitrogen losses from China's food system for the shared socioeconomic pathways (SSPs). *Science of The Total Environment*, 605, 884–893. <https://doi.org/10.1016/j.scitotenv.2017.06.235>

- Wang, J., Wang, J. Q., Bu, D. P., Guo, W. J., Wei, H. Y., Zhou, L. Y., & Liu, K. L. (2009). Thought on accelerating the application of TMR feeding technique in China. *China Animal Husbandry Veterinary Medicine*, 2, 101–104 (In Chinese).
- Westhoek, H., Lesschen, J. P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., & Oenema, O. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change*, 26, 196–205. <https://doi.org/10.1016/j.gloenv.2014.02.004>
- World Bank (2016). Retrieved from <http://data.worldbank.org/indicator/NY.GDP.MKTP.CD?page=5>.
- Xinhua News (2006). Wen Jiabao investigation in Chongqing city: Every Chinese can drink 0.5 kg milk every day (In Chinese). Retrieved from http://news.xinhuanet.com/fortune/2006-04/24/content_4470619.htm.
- Xu, J., Guo, Z., Su, L., Nedambale, T. L., Zhang, J., Schenk, J., & Yang, X. (2006). Developmental potential of vitrified Holstein cattle embryos fertilized in vitro with sex-sorted sperm. *Journal of Dairy Science*, 89(7), 2510–2518. [https://doi.org/10.3168/jds.S0022-0302\(06\)72326-8](https://doi.org/10.3168/jds.S0022-0302(06)72326-8)
- Zhang, N., Bai, Z., Luo, J., Ledgard, S., Wu, Z., & Ma, L. (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. <https://doi.org/10.1016/j.scitotenv.2017.04.165>
- Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., & Mi, G. (2016). Closing yield gaps in China by empowering smallholder farmers. *Nature*, 537(7622), 671–674. <https://doi.org/10.1038/nature19368>
- Zhou, A. L., Li, S., Zhang, W., & Yeertai, S. H. (2012). The impacts of DHI technology on performance of dairy cattle. *China Dairy Cattle*, 24, 011. (In Chinese).

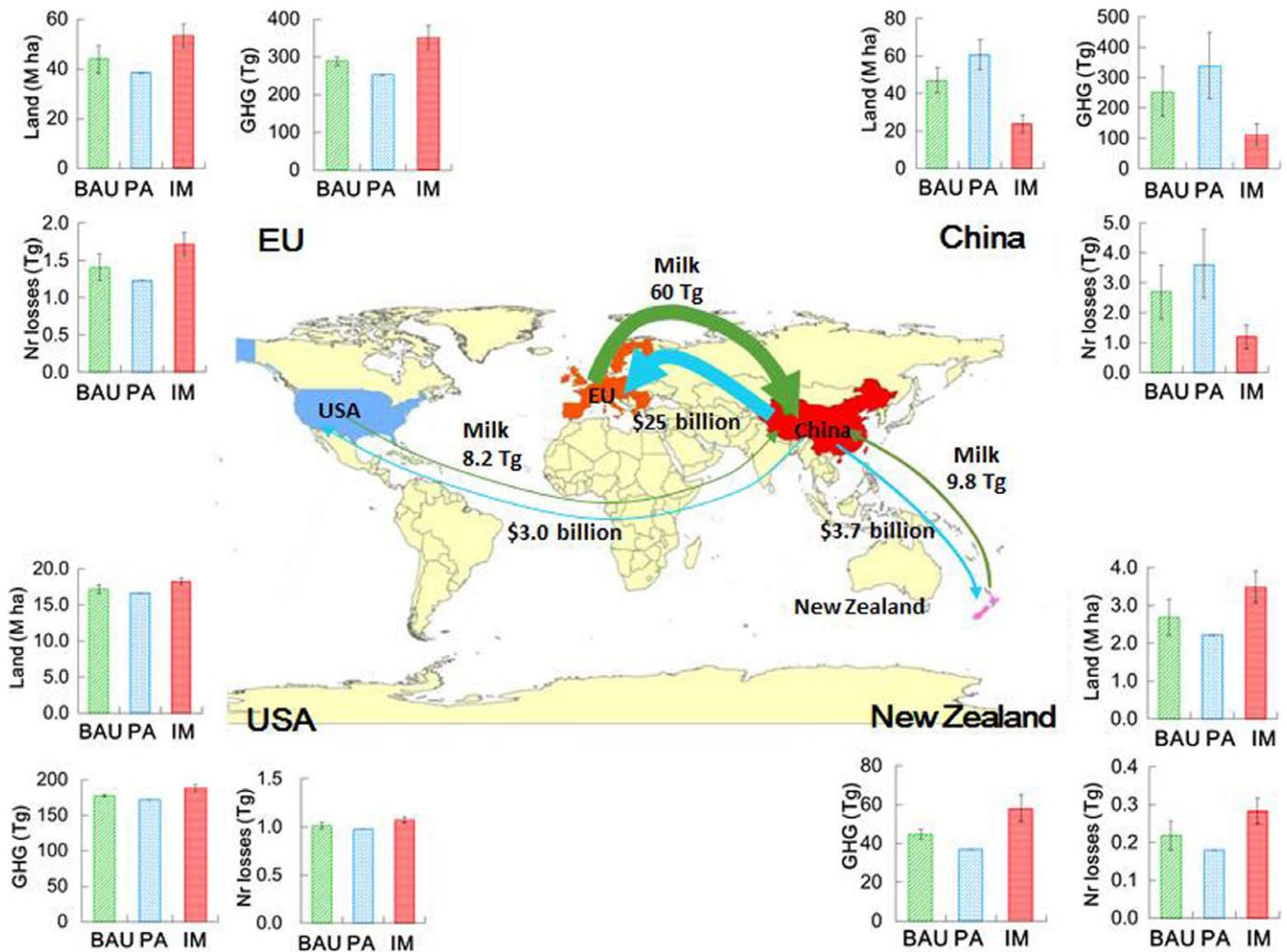
SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Bai Z, Lee MRF, Ma L, et al. Global environmental costs of China's thirst for milk. *Glob Change Biol*. 2018;00:1–14. <https://doi.org/10.1111/gcb.14047>

Graphical Abstract

The contents of this page will be used as part of the graphical abstract of html only.
It will not be published as part of main article.



The ever increasing milk demand in China will pose great pressure of sustainability either on cattle feed export or milk export regions in 2050, due to their physical limitations or environmental preferences/legislation, if there was no improvement China's domestic dairy production. 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 to meet with milk demand in China, and also in other high milk demand regions.