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Sustainable Production and Consumption 38 (2023) 186–198

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

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ARTICLE INFO

Editor: Prof. Shabbir Gheewala

Keywords:
Chinese food consumption
Chinese milk production
Dairy systems
Water footprint
Land footprint
Carbon footprint

ABSTRACT

Chinese food consumption shifts towards larger milk consumption. Traditional dairy systems depended on China's grasslands, but modern industrial systems using feed from croplands increase rapidly. The question is whether China can fulfill future milk demand using its natural resources and remain within greenhouse gas emission boundaries. To determine this, this study combines three footprint analyses - water footprint (WF), land footprint (LF) and carbon footprint (CF) - estimated via production chain approach. It compares WFs, LFs and CFs of milk, meat, and manure from six dairy systems in three categories: traditional grazing, traditional mixed, and modern industrial systems. It estimates future footprints for five production scenarios for low and high milk demand. Between 2000 and 2020, industrial systems increased, accounting for 79 % of production in 2020, while traditional production decreased. Traditional grazing systems have large green WFs per kg (17.2 m^3), negligible blue WFs and large LFs (46 m^2 low quality grassland). Traditional mixed systems have large CFs per kg (2.93 kg CO_2) due to low efficiency. Modern industrial systems rely partly on irrigated croplands and have small green WFs, but large blue WFs per kg (0.54 m^3), grey WFs (0.24 m^3) and small LFs (1.80 m^2 cropland). The findings indicate that with dominating industrial systems, milk production relies more on irrigation and limited croplands. In a realistic low demand situation, milk consumption stabilizes. However, consumption triples if the Chinese follow nutritional advice, resulting in 4 to 6 times larger WFs, LFs and CFs in 2035 depending on production scenarios. In 2035, population is largest, from 2035 to 2050 footprints decrease again. However, China cannot produce the milk for a high consumption situation limited by grassland and cropland availability. Alternatively, China could import feed or milk. However, it is questionable whether these huge quantities are available on the global market.

1. Introduction

Human diets depend on the availability of nutritious foods, either from animals or plants. Humans are omnivores, and their diets consist of different fractions of animal and plant-based foods (Katz, 2017). To obtain these foods, for a long time in history, humans depended on the possibilities of their local environment. If there was arable land of good quality available, agricultural crop production flourished; if there were grazing lands, people relied on their herds to provide them animal foods. About 11 % of the world's land surface is applied for arable crops (FAO, 2003; Robinson et al., 2011) and 25 % for extensive grazing (FAO, 1991; Steinfeld et al., 2006). High quality arable land providing plant-based foods, therefore, is scarcer than lower quality grazing land providing animal foods. Extensive grazing lands are rangelands where natural vegetation is the main feed resource, while intensive grazing lands are artificial seeded pastures (FAO, 1991). Extensive grazing requires far more land than intensive grazing systems (FAO, 1991).

Animal food production includes many different livestock farming systems (Robinson et al., 2011) with three separate classification clusters, i.e. the grazing, mixed and industrial systems. The grazing system only applies feed from grazing lands, the mixed system uses a combination of feed from grazing and crops, while the industrial systems rely on croplands. In China, these dairy systems coincide. The grazing systems dominantly rely on grassland production, the mixed systems use a combination of hay and maize, while the industrial systems apply a combination of different crops, including soybean from Brazil (Bai et al., 2013).

Historically, China has never been a country consuming much milk.

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https://doi.org/10.1016/j.spc.2023.04.004
Received 19 January 2023; Received in revised form 3 April 2023; Accepted 6 April 2023
Available online 13 April 2023

However, in the last fifty years, dairy has become more popular and milk consumption increased 25 fold. Since 2010, China purchased milk on the global market and became the world's largest milk importer (FAO, 2022). Possibly, China needs to become more milk self-sufficient, since milk exporting countries face resource and environmental constraints (Bai et al., 2018b).

Originally, Chinese milk production took place in the north and northwest where local conditions favored cattle due to the availability of huge grassland areas. In the regions with arable land, traditionally cows were used as draft animals (Xiu and Klein, 2010). This explains why average Chinese milk consumption has always been relatively small (FAO, 2022). As a result, 86 % of the adult population does not digest milk well caused by lactose malabsorption (Wang et al., 1984). In countries where cow milk was an important contribution to the diet, there was an evolutionary pressure to develop the ability to digest lactose. For example, in The Netherlands, only 12 % of the population does not digest lactose well (Storhaug et al., 2017). This translates into huge differences in milk consumption. In China in 2019, average daily per capita milk consumption was only 64 g, whereas in the Netherlands consumption was 860 g (FAO, 2022). Consumption in China in 2019 was even large compared to 1961 with a negligible consumption of 6 g per capita per day. In the eighties of the last century, the government stimulated milk consumption, because it contributes to a healthy diet, especially for children (Xiu and Klein, 2010). Before the melamine scandal in 2008 (Xiu and Klein, 2010), China's milk consumption increased gradually to around 90 g per capita per day, but afterwards decreased to 63 g in 2019. Over the past 10 years, production decrease caused changes of dairy farm structures where the number of dairy cows increased till 2014 and then declined rapidly. However, at the same time, the number of industrial farms with more than 100 cows increased (Hemme, 2019). In 2008, they included 25 % of the dairy cows, and it is expected that in 2029, intensive farms will include 75 % (Ministry of Agriculture of China, 2020). With this intensification, the traditional grazing systems gradually change into mixed and industrial systems (Bai et al., 2013).

In China, 82 % of the milk production takes place in ten provinces: Inner Mongolia, Heilongjiang, Hebei, Shandong, Henan, Xinjiang, Ningxia, Liaoning, Shaanxi and Shanxi. Milk production developed in different ways in the milk producing provinces. From 2014 to 2017, production increased in Xinjiang and Ningxia, in the other eight provinces production decreased by 10 to 40 % (National Bureau of Statistics of China, 2022).

In general, milk production goes along with an intensive use of natural resources, especially land (Bosire et al., 2015) and water (Gerbens-Leenes et al., 2013; Mekonnen and Hoekstra, 2012), while it emits huge amounts of greenhouse gases (IPCC, 2006). Steinfeld et al. (2006) estimated that the livestock sector, including dairy systems, is responsible for 18 % of the human greenhouse gas emissions. To assess the sustainability of food systems, the environmental footprint family that incudes land, water and carbon footprints, is a useful tool, because it includes the footprints in a whole production chain and addresses the constraints of the planetary boundaries, especially for food systems (Vanham et al., 2019), such as dairy production systems.

In the last century, Wackernagel and Rees (1998) introduced the ecological footprint concept showing the huge land requirement, including land for carbon sequestration, related to human consumption. Ecological footprints of nations are large (Wackernagel et al., 1999). The land footprint (LF), sometimes used to replace the ecological footprint, is defined as the amount of land used to produce goods and services, excluding carbon sequestration, and is expressed in area per unit of product. LFs differ among foods, especially animal foods, such as milk, have large LFs influenced by the specific cow feed composition (Gerbens-Leenes et al., 2002). The water footprint (WF) measures the freshwater appropriated to produce specific goods or services, such as milk, expressed as the WF per unit of product (Hoekstra et al., 2011). The WF includes three components: the green WF (evapotranspiration of rainwater from the field to produce, for example, a crop), the blue WF (water consumption from surface or groundwater) and the grey WF (the volume of freshwater required to assimilate pollutants to accepted water quality standards). The carbon footprint (CF) refers to greenhouse gas (GHG) emissions, expressed in CO_2 equivalents (CO_2 eq.) associated with a product, process or service. The CF includes the three main gases of the Kyoto protocol: carbon dioxide (CO_2), methane (CH_4) and dinitrogen oxide (N_2O) (IPCC, 2006).

Different dairy farm types have different land and water requirements and cause different greenhouse gas emissions. Capper et al. (2009), for example, assessed the LFs of dairy in the US showing that between 1944 and 2007, LFs for dairy decreased, mainly due to a feed composition shift in which grass and hay were replaced by corn and alfalfa silage so that dairy production more relied on arable lands than on grasslands. Mekonnen and Hoekstra (2012) showed that grazing livestock systems have relatively small blue (irrigation water) and grey (related to nitrogen pollution) WFs compared to industrial systems, because, in general, grazing systems do not irrigate grasslands, while industrial systems use more feed based on irrigated crops that also receive fertilizer and pesticides. Morais et al. (2018) analyzed the CF of milk produced in a mixed system on the Azores (Portugal) arriving at a CF of 0.83 kg CO_2 eq. per kg of raw milk, which was in line with data from their literature study ranging between 0.56 and 1.96 kg CO_2 eq. per kg of raw milk. Wilkes et al. (2020) studied CFs related to milk production in Kenya arriving at a footprint between 2.19 and 3.13 kg CO_2 eq./kg FPCM (fat and protein corrected milk). That study showed that CFs mainly depend on milk yields, concentrate use and herd structure. Many studies included only one footprint, however, to make a comprehensive assessment, more indicators might give better information. For example, Ibidhi et al. (2017) assessed the sustainability of meat production in Tunisia using LFs, WFs and CFs, indicating trade-offs among systems.

There are many environmental case studies related to dairy production in China, published not only in international journals, but also in Chinese ones (see Section 2). However, studies often applied different indicators and functional units, making it difficult to compare results. Described production systems include small scale, traditional, extensive grazing systems, traditional mixed systems where cows graze and receive feed indoors (Huang et al., 2014), and modern industrial systems where cows are kept indoors and receive feed mainly based on crops (Wang et al., 2018). The characteristics of these Chinese dairy systems, therefore, are available, including their herd size, feed use, milk, meat and manure production and energy use. However, studies that include three footprints and compare Chinese dairy production for different systems and developments in time are not available yet. Moreover, there is no information on future dairy production and consumption, related environmental footprints and options for China to fulfill its milk thirst using its own natural resources.

The Chinese population reaches a maximum of 1.5 billion in 2035 and then decreases to 1.4 billion in 2050 (Guo et al., 2019). Moreover, in 2050, China aims to be a developed country according to its second Centenary Goal (The State Council of China, 2020) with affluent food consumption patterns, including more dairy.

The objective of this study is to assess the environmental footprints (LF, WF and CF) of milk, beef and manure, expressed per unit of product, for six Chinese dairy systems from three classification clusters (i.e., traditional grazing, traditional mixed, and modern industrial systems). It also calculates the national environmental footprints of milk production for the period 2000 to 2020. Next, based on a scenario analysis, it estimates footprints for future milk demand in 2035, when population peaks, and in 2050, the year China has become a developed country. The study includes the grazing areas, WFs of energy in the production chain and grey WFs related to nitrogen use for feed crops. Our three research questions are: (i) what are the WFs (green, blue and grey), LFs and CFs of milk, beef and manure for six different dairy production systems from three classification clusters (traditional grazing, traditional mixed and modern industrial) in China? (ii) What are the impacts of the expansion of dairy production on total LFs, WFs and CFs for the period 2000 to 2020?; (iii) Is it possible to scale up dairy production to comply to China's future milk demand in 2035 and 2050?

The study first gives an overview of existing environmental studies on China's milk production. It includes general studies and case studies, not only published in international journals in English, but also in Chinese. For the footprint assessment, the study used six dairy production system types representative for dairy production in China and distinguished between LFs related to low quality grazing land, high quality arable land and LFs outside China. It also includes the blue WFs of energy. The footprint results will give an indication whether or not China is able to fulfill its future milk requirement.

2. Literature review

A search for publications on greenhouse gas emissions (GHG), water and land use of China's milk production in English and Chinese in the Web of Science and the China national knowledge infrastructure (CNKI) database showed that since 2012, twenty one studies on GHG, water or land use for dairy production in China were published in international journals, and three in Chinese journals. Next, there are six master thesis studies available. Table 1 gives an overview of the international studies and Table 2 of the Chinese ones. The first international study included the water footprints (WFs) of Chinese milk (Mekonnen and Hoekstra, 2012), followed by a study on methane emissions of dairy in 2013 (Na et al., 2013).

Table 1 shows that studies on greenhouse gas (GHG) emissions of dairy production dominate, sixteen studies included GHG, while four studies used water as an indicator and only one land use. Three studies used three indicators for the assessment of environmental sustainability of dairy production, i.e. GHG emissions, water and land use. Thirteen studies covered the whole country, while seven studies are case studies that focus on a Chinese region. However, most studies applied different functional units, e.g. total milk production, kg of fat and protein corrected milk (FPCM), kg of energy corrected milk (ECM), tonne of milk, milk production per farm or per cow, or kg of milk powder, making results difficult to compare. Only one study, Bai et al. (2018b), included three indicators, GHG emissions, water and land use and is the most complete one. Those authors suggested that in the future, we should focus on improving manure management, feed production, crop-livestock system integration, and grassland restoration, while maintaining emphasis on natural ecosystem services and biodiversity in native grassland areas.

Table 2 shows that the environmental studies of dairy in Chinese include nine studies related to GHG emissions, while only two include GHG emissions, water and land use together. Three studies focus on the country as a whole, while the other six are regional case studies. Like in the studies published in international journals, also the Chinese publications apply different functional units, making the results difficult to compare too. Wang et al. (2018) and Huang et al. (2021) provided solutions to decrease environmental footprints. Wang et al. (2018) showed that for the North China Plain, improving dairy cow productivity and herd structure (i.e. increased dairy cow fraction), combining various manure management systems, and encouraging dairy farmers to return manure to nearby croplands are promising measures to decrease environmental impacts. Huang et al. (2021) concluded that mitigation of environmental impacts of milk production could be realized if dairy farms increase maize croplands and imply technological improvements to increase crop and milk yields.

3. Methods and data

3.1. Dairy systems in China

There are three categories of dairy systems in China: traditional grazing, traditional mixed and modern industrial systems (Bai et al., 2018c). Traditional dairy farms are small, with less than twenty milking cows. Traditional grazing systems rely on grazing lands in the pastoral areas; traditional mixed systems are located in the crop areas and often include collective feedlots with medium farm sizes where animals receive residues or by-products of crops grown on land nearby and feedlot manure is reused. Modern industrial systems are intensive and cows are kept indoors. They sometimes own grasslands and always buy feed concentrates. Many industrial systems started between 2000 and 2005 (Bai et al., 2018c). If we compare feed ingredients per system, hay and crop residues in the traditional systems with grains used in the modern systems, the protein content, digestibility and gross energy content per kg of dry matter of hay and residues are smaller compared to grains (China Feed Industry Center, 2009). This means that the feed quality of the modern industrial system is better than the quality of the traditional systems.

Table 1
Overview of publications on greenhouse gas emissions, water and land use for dairy in China or regions in China from international journals.

Publication	Region	Indicator	Functional unit	Citations
(Bai et al., 2018a)	China	GHG[a], water, land	Total Chinese milk consumption	39
(Wang et al., 2018)	North China Plain	GHG[a], water, land	kg milk (FPCM)[b]	25
(Huang et al., 2021)	China	GHG[a], water, land	kg milk (FPCM)[b]	4
(Wang et al., 2016a)	Guanzhong Plain of China	GHG[a], land	kg milk (FPCM)[b]	21
(Xue et al., 2014)	China	Methane	Total Chinese milk consumption	25
(Zhang et al., 2021a)	China	GHG[1]	Total Chinese milk consumption	18
(Ledgard et al., 2019)	Shaanxi, Hebei, Beijing	GHG[1]	kg milk (FPCM)[b]	16
(Zhu et al., 2014)	China	methane and dinitrogen oxide	Milk production per cow	15
(Wang et al., 2019)	South Western China	GHG[a]	kg milk (FPCM)[b]	14
(Fan et al., 2018)	China	GHG[a]	Tonne of milk	14
(Zhang et al., 2017a)	China	GHG[a]	kg of milk	13
(Gao et al., 2014)	China	methane and dinitrogen oxide	Total Chinese milk consumption	13
(Ding et al., 2016)	Northern China	GHG[a]	Milk production per farm	10
(Na et al., 2013)	China	Methane	Milk production per cow	4
(Jia et al., 2022)	East China	GHG[a]	kg milk (ECM)[c]	0
(Zhang et al., 2021b)	China	GHG[a]	kg milk powder	0
(Mekonnen and Hoekstra, 2012)	China	Water footprint	Tonne of milk	1323
(Huang et al., 2014)	Northeast China	Water	kg milk (FPCM)[b]	41
(Bai et al., 2018a)	China	Water	Total Chinese milk consumption	35
(Lu et al., 2018)	Northern China	Water	kg milk (FPCM)[b]	8
(He et al., 2021)	China	Land	Milk production per farm	3

[a] GHG is greenhouse gasses.
[b] FPCM is fat and protein corrected milk.
[c] ECM is energy corrected milk.

Table 2
Overview of publications in Chinese journals and master theses on greenhouse gas emissions, water and land use for dairy systems in China or regions in China.

Publication	Region	Publication type	Indicator	Function unit	Citations
(Liu, 2018)	Guanzhong Plain China	Master thesis	GHG[a], water, land	kg DM[b] feed	9
(Huang, 2021)	China	Master thesis	GHG[a], water, land	Tonne of milk	2
(Wang et al., 2012)	Northwest China	Journal paper	GHG[a]	kg milk (FPCM)[c]	60
(Duan, 2019)	Northwest China	Master thesis	GHG[a]	kg manure	13
(Huang, 2016)	China	Master thesis	GHG[a]	kg milk (FPCM)[c]	13
(Bai et al., 2017)	Beijing	Journal paper	GHG[a]	kg milk (FPCM)[c]	11
(Gan, 2019)	China	Master thesis	GHG[a]	Total Chinese milk production	7
(Chen et al., 2014)	Northwest China	Journal paper	GHG[a]	kg milk	6
(Fen, 2017)	Beijing	Master thesis	GHG[a]	kg milk (raw, FPCM[c] or ECM[d])	1

[a] GHG is greenhouse gasses.
[b] DM is dry matter.
[c] FPCM is fat and protein corrected milk.
[d] ECM is energy corrected milk.

The three Chinese dairy system categories include six dairy system types, termed here A-F. System A is a small scale, traditional, extensive grazing system, for example in Inner-Mongolia, where cows graze from June to September and consume hay when indoors. Milk production per cow is relatively low and most calves are raised on farm to replace dairy cows and produce veal (Liu et al., 2020). System B is a small-scale, traditional mixed system, for example in Southwest China, where cows are kept indoors. Cows consume a mixture of maize, vegetable residues and by-products of beverages (Wang et al., 2019). System C is a traditional, mixed, intermediate scale, collective feedlot system, for example in Northeast China. Cows consume a mixture of maize, wheat, soybean meal, grain and straw (Huang et al., 2014). System D is an industrial, large-scale, grassland-based system, for example in Inner-Mongolia, where cows are indoors. They consume a mixture of hay, alfalfa, oats, maize silage, and concentrates (Liu et al., 2020). System E is an industrial, large-scale, intensive system located in, for example, Northwest China where cows are kept indoors. Cows consume a mixture of 80 % maize and hay and 20 % concentrates based on wheat bran and soybean meal (Wang et al., 2016a). System F is a large-scale, intensive system located on the North China Plains where cows are kept indoors. Cows mainly consume a mixture of 40 % maize and leymus and 40 % concentrates consisting of soybean meal, cotton meal and rapeseed meal. Milk production is relatively high (Wang et al., 2018).

In China, dairy production is limited by the availability of cropland and grassland. Most feed ingredients depend on cropland. In 2020, the cropland area for feed production was 117 million ha (FAO, 2022), only 5 % (6 million ha) was used for dairy feed (National Bureau of Statistics of China, 2022). The area of high quality grassland most suitable for grazing is only 6.5 % of the total grassland. Most grassland is of low quality, vulnerable for animal grazing (National Bureau of Statistics of China, 2022). Fig. 1 shows China's suitability for grazing and crop growth. In the West, there are the pastoral areas with grazing lands, in the Northeast, East and Southwest the crop areas. An important agro-pastoral zone is located on both sides of the so termed Hu Line, a geo-demographic demarcation line dividing China into two parts (Hu, 1935). In 2015, 94 % of China's population lived east of the line which accounts for only 36 % of the total land surface, whereas only 6 % lived in the west on 64 % of China's territory in the pastoral areas (National Bureau of Statistics of China, 2022)., All six dairy system types can be found in the agro-pastoral zone.

Inputs of dairy systems consist of inputs for feed production, transportation and farm operations. Outputs not only include economic outputs like milk, meat and manure, but also emissions in the form of greenhouse gas (GHG) emissions and nitrogen losses from fertilizer.

Fig. 1. Location of the pastoral, agro-pastoral and crop areas in China. The dotted box represents the agro-pastoral zone. The six types of dairy production systems can all be found in the agro-pastoral zone where both grasslands and croplands occur. The red line is the Hu Line indicating the demarcation of densely populated areas in the east and the scarcely populated areas in the west. The red pentagrams represent the location of six dairy system types (A-F). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

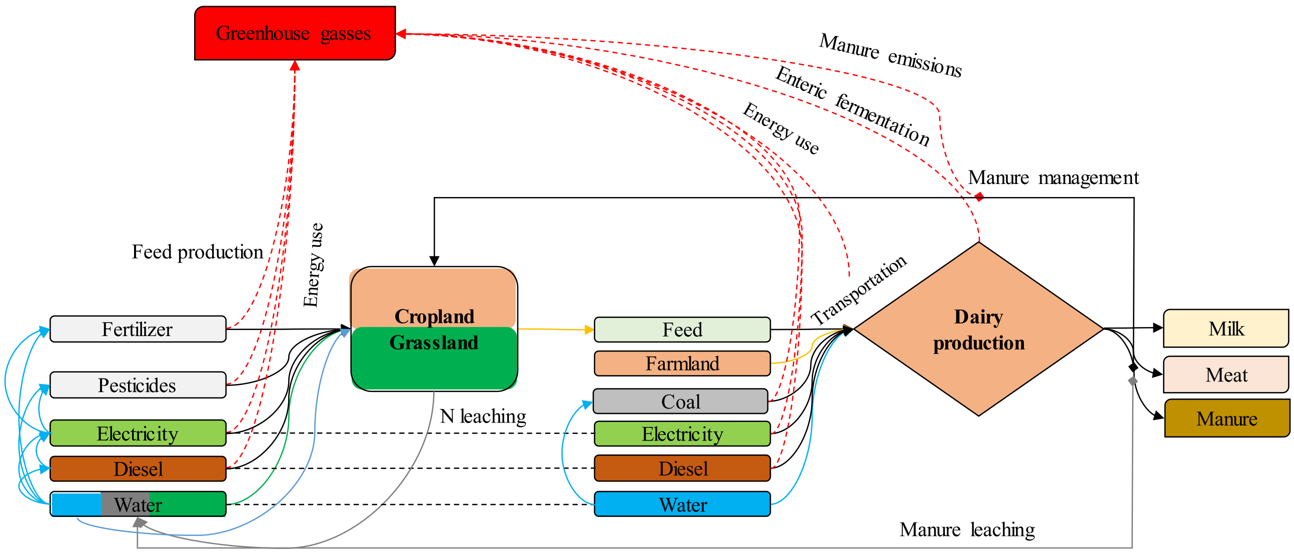

Fig. 2. Overview of inputs and outputs for dairy systems in China.

Fig. 2 shows the inputs and outputs for Chinese dairy systems.

To produce milk, meat and manure, on farm animal production needs inputs of land for the farm itself, water for drinking and cleaning, and energy in the form of diesel for tractors to transport manure, electricity, for example for milking machines, cooling equipment and lighting. In the Northeast of China, where winters are cold, stables are often heated using coal (Huang et al., 2014). Greenhouse gas emissions, CH_4 and CO_2, are related to enteric fermentation and energy use on farm. Cow feed includes grass (or hay) and crops. In grazing systems, cows collect the grass themselves; when cows are kept in stables, grass needs to be harvested using machines running on diesel. The inputs of feed crop production are water, i.e. precipitation, irrigation water and water to dilute the nitrogen from fertilizers to accepted water quality standards (Hoekstra et al., 2011), land, chemical fertilizers, manure, pesticides and energy in the form of diesel for tractors and transport fuels for feed transportation. The production of chemical fertilizers and pesticides also requires energy and therefore emits GHGs (Chen et al., 2015; Zhang et al., 2016). Electricity generation in China is mainly based on coal, hydropower, natural gas, oil, nuclear energy and renewables (solar and wind)(International Energy Agency, 2022) Electricity generation also requires water, e.g. for the cooling of thermal power plants or for hydropower. GHG emissions, i.e. CO_2 and N_2O, are related to energy use for feed production and the inputs of feed production.

In China, demand for more affluent foods, such as meat and milk, have increased rapidly during the past four decades (Bai et al., 2018c). The Chinese Nutrition Society recommends daily intake of dairy products, equivalent to 300 g of liquid milk (Wang et al., 2016b), especially for children and elderly people. China's milk consumption increased from 2.3 million tonnes (MT) in 1980 to 43 MT in 2019 (FAO, 2022). However, there is a limit to Chinese milk consumption, because the majority (86 %) of the Chinese have lactose malabsorption (Wang et al., 1984). Production was following demand increase, from 2.8 MT in 1980 to 36 MT in 2019 (Hemme, 2019).

3.2. Selection of dairy systems in China

For the assessment of the water footprints (WFs), land footprints (LFs) and carbon footprints (CFs) of milk, calves, beef and manure from dairy systems in China, we selected six systems (A-F) representative for dairy production in China. System A has indigenous Chinese cow types, system B to F include Holstein cow types. Table s1 in the supporting information (SI) gives the characteristics per dairy production system. Fig. 1 shows the location of the six systems. System A and D are located in a pastoral area with grasslands (Liu et al., 2020). System B is located in a sub-tropic crop area (Wang et al., 2019), system C in a relatively cold crop area (Huang et al., 2014), system E in a warm and semi-arid crop area (Wang et al., 2016a) and system F in a warm and semi-humid crop area (Wang et al., 2018). Fig. 1 shows that there are six provinces, Inner Mongolia, Gansu, Ningxia, Xinjiang, Qinghai and Tibet, located in the pastoral area. The other provinces are located in the crop area. System A and D are in the pastoral areas, the other four types in crop areas. We assumed that system A represents dairy systems with less than 20 cows and D systems with more than 20 cows in pastoral areas. System B, C, E and F represent dairy systems in crop areas with cow numbers below 20, 20–100, 100–500 and above 500 respectively.

3.3. Calculation of green, blue and grey water footprints and land footprints milk, beef and manure

To assess the green, blue and grey WFs and LFs of milk, beef and manure produced in China, this study used seven calculation steps. The calculation of: 1. WFs of feed crops (m^3/ha); 2. WFs (m^3/kg) and LFs (m^2/kg) of the dry weight of feed; 3. Total WFs (m^3/year) and LFs (m^2/year) of feed per dairy system; 4. WFs (m^3/year) and LFs (m^2/year) on farm; 5. WFs of energy use (m^3/year); 6. Total WFs (m^3/year) and LFs (m^2/year) per dairy system; and 7. WFs (m^3/kg) and LFs (m^2/kg) of milk, meat and manure. WF calculations were adopted from the WF manual (Hoekstra et al., 2011). Fig. 3 shows the steps and data sources for the calculations that are described in the SI.

3.4. Calculation of carbon footprints milk, beef and manure

To assess the carbon footprints (CFs) of milk, beef and manure produced in China, this study used nine calculation steps, the calculation of CFs of: 8. feed crops (kg CO_2 equivalent, eq./ha); 9. Fresh weight feed (kg CO_2 eq./tonne); 10. Feed transportation (kg CO_2 eq./tonne); 11. Total annual feed per dairy system (kg CO_2 eq./year); 12. Enteric fermentation (kg CO_2 eq./year); 13. Manure management (kg CO_2 eq./year); 14. Energy (kg CO_2 eq./year); 15. Total dairy system (kg CO_2 eq./year); 16. Milk, meat and manure (kg CO_2 eq./kg). Fig. 4 shows the steps and data sources for the calculations that are described in the SI.

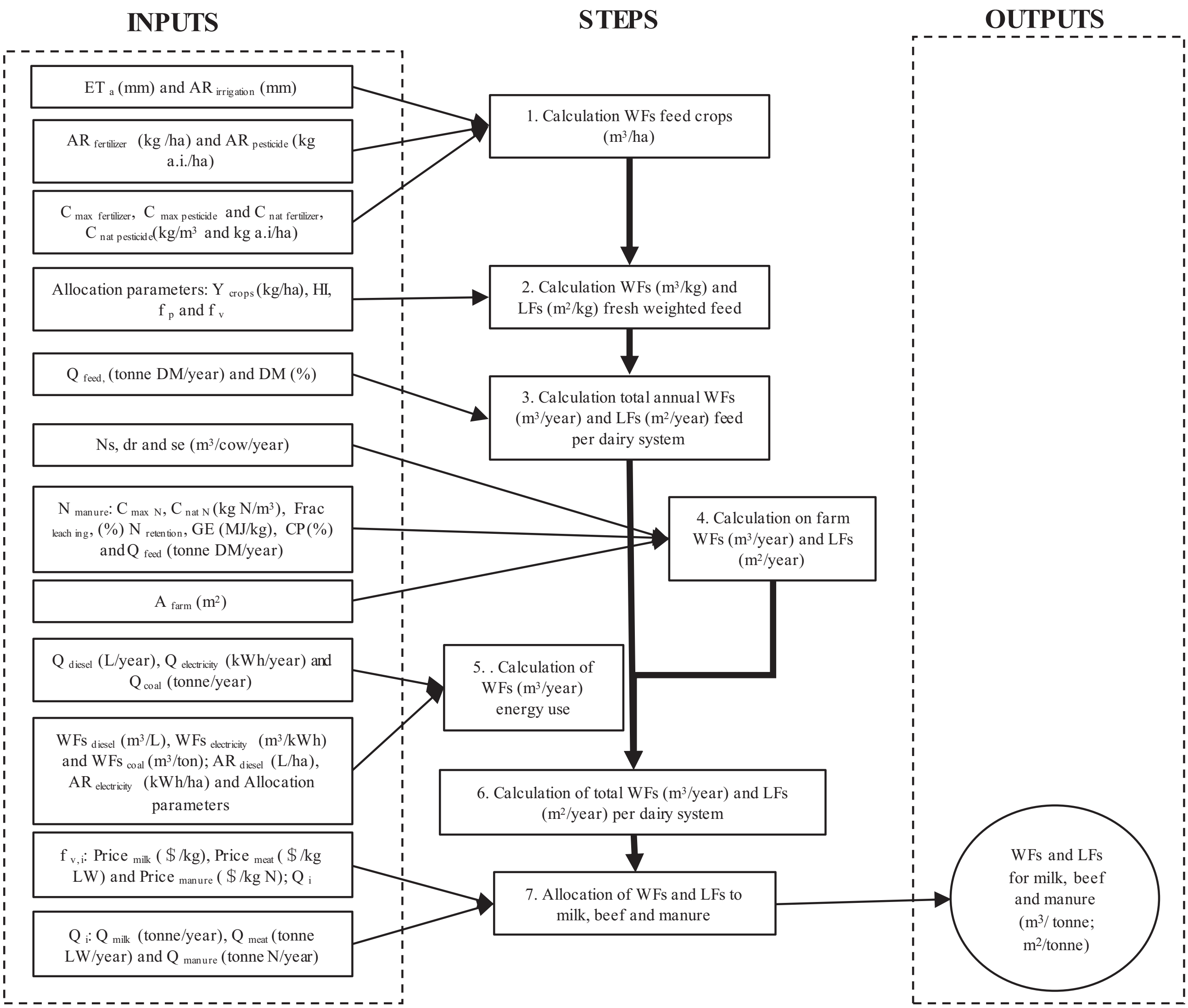

Fig. 3. Calculation steps and data input water and land footprints milk, beef and manure in China.
Abbreviations: ET_a: actual water evapotranspiration feed crops; $AR_{irrigation}$: Irrigation; $AR_{fertilizer}$: application rate nitrogen, phosphorus and potassium; $AR_{pesticides}$: application rate pesticides; $C_{max\ fertilizer}$: maximum acceptable nitrogen, phosphorus and potassium concentration; $C_{max\ pesticide}$: maximum acceptable pesticide (active ingredients) concentration; $C_{nat\ fertilizer}$: natural concentration nitrogen, phosphorus and potassium; $C_{nat\ pesticide}$: natural concentration pesticides; Y_{crops}: crop yield; HI: harvested index; fv: value fraction; fp: product fraction; DM: dry matter; Q_{feed}, feed quantity; $WFs_{drinking\ and\ serving}$: drinking and serving water on farm; N_{manure}: nitrogen flows manure; $C_{max\ N}$, maximum acceptable nitrogen; $C_{nat\ N}$ natural concentration nitrogen, $Frac_{leaching}$: fraction N leaching; $N_{retention}$: fraction N intake retain by cows; GE: gross energy; A_{farm}: area dairy farm; Q_{diesel}: diesel consumption; $Q_{electricity}$: electricity use; Q_{coal}: coal use; WF_{diesel}: water footprint diesel, $WF_{electricity}$: water footprint electricity; WF_{coal}: water footprint coal; $Price_{milk}$: milk price; $Price_{meat}$: meat price; $Price_{manure}$: manure price; Q_{milk}: milk production; Q_{meat}: meat production; Q_{manure}: manure production; WFs: water footprints; LFs: land footprints.

3.5. Calculation of total water, land and carbon footprints dairy production in China for 2000–2020

To assess total WFs, LFs and CFs of China's milk production for the period 2000 to 2020 per five years (2000, 2005, 2010, 2015 and 2020), this study combined footprints of dairy production systems A to F with the production per system type in China. The total WFs of milk production for China in year y, TWF_y (10^9 m^3/year) was calculated as:

$$TWF_y = \sum_{s=1}^{n} \left(WF_{milk,c,s} * Q_{milk,y,s} / f_{v,s}[milk] \right) \tag{1}$$

in which $WF_{milk,c,s}$ is the annual WF of color c from dairy system s (m^3/kg), $Q_{milk,y,s}$ is the milk production from year y from dairy system s and $f_{v,s}[milk]$ is the value fraction of milk from dairy system s. We calculated the total LFs and CFs of milk production for China in the same way. The $Q_{milk,y,s}$, was calculated as:

$$Q_{milk,y,s} = Q_{milk,y} * P_{s,y} \tag{2}$$

in which $Q_{milk,y}$ is the milk production in year y and $P_{s,y}$ the percentage of milk produced from dairy system s in year y. Data on $Q_{milk,y}$ was taken from the National Bureau of Statistics of China (NBS, 2001–2020). $P_{s,y}$ was calculated as:

$$P_{s,y} = Y_{milk,y,s} * N_{cow,y} * P_{cow,y,s} \Big/ \sum_{s=1}^{n} \left(Y_{milk,y,s} * N_{cow,y,s} * P_{cow,y,s} \right) \tag{3}$$

in which $Y_{milk,y,s}$ is the milk yield in year y from dairy system s (kg/cow/year), $N_{cow,y}$ the number of cows in year y and $P_{cow,y,s}$ the percentage of cows in year y from dairy system s. Table s9 and s10 in the SI give these data and references.

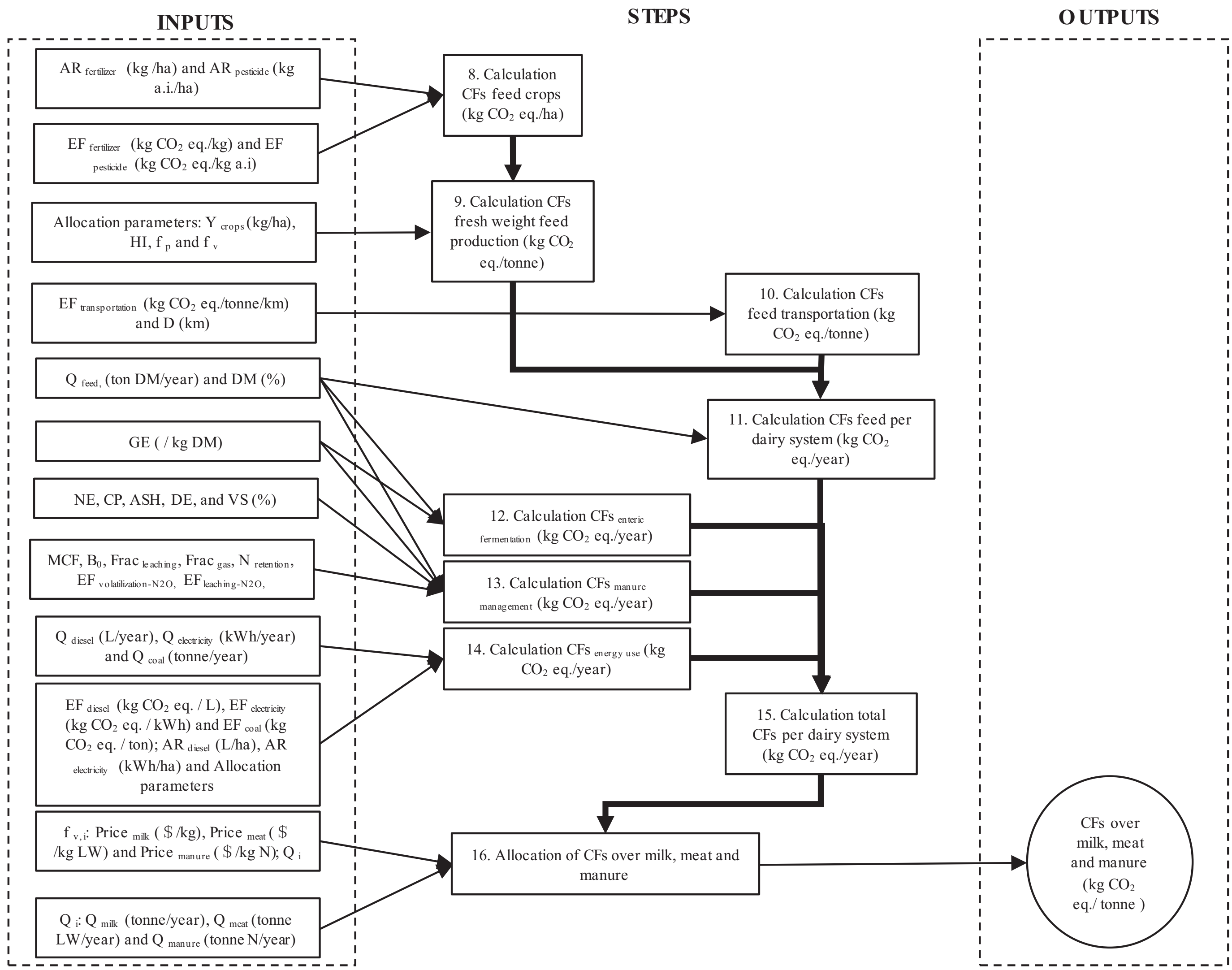

Fig. 4. Calculation steps and data input carbon footprints milk, beef and manure in China.
Abbreviations: $AR_{fertilizer}$: application rate nitrogen, phosphorus and potassium; $AR_{pesticides}$: application rate pesticides; $EF_{fertilizer}$: emission factors nitrogen, phosphorus and potassium; $EF_{pesticides}$: emission factors pesticides; Y_{crops}: crop yield; HI: harvested index; fv: value fraction; fp: product fraction; DM: dry matter; Q_{feed}, feed quantity; $EF_{transportation}$, emission factor transportation; D, distance of transportation; GE: gross energy; CP: crude protein; DE: digestibility; ASH: ash; VS: volatile solid excretion; MCF: methane conversion fraction; B_o: maximum methane producing capacity; $Frac_{leaching}$: fraction N leaching; $Frac_{leaching}$: fraction N leaching; $N_{retention}$: fraction N intake retain by cows; $EF_{volatilization\text{-}N2O}$: emission factor for N_2O from atmospheric deposition of N on soils and surface; $EF_{leaching\text{-}N2O}$: emission factor for N_2O from N leaching and runoff; Q_{diesel}: diesel consumption; $Q_{electricity}$: electricity use; Q_{coal}: coal use; EF_{diesel}: emission factor diesel, $EF_{electricity}$: emission factor electricity; EF_{coal}: emission factor coal; $Price_{milk}$: milk price; $Price_{meat}$: meat price; $Price_{manure}$: manure price; Q_{milk}: milk production; Q_{meat}: meat production; Q_{manure}: manure production; CFs: carbon footprints.

3.6. Scenarios of WFs, LFs and CFs for China's milk consumption and production in 2035 and 2050

China's future milk consumption depends on the population size and milk consumption per capita. In general, different age categories have different milk consumption. For future milk consumption, this study estimated low and high consumption in 2035 and 2050. We calculated low consumption for a situation in which people cannot digest milk, i.e. 86 % of the population (Wang et al., 1984) and assumed that above four years, people do not consume milk anymore. Next, we calculated high consumption assuming that everybody follows the national nutritional advice. We divided the population into four groups with different milk consumption advise: (i) age group of zero to one year (advise 584 g per day); (ii) one to two years (495 g per day); (iii) two to four years (500 g per day); (iv) everybody above four years of age (average daily advise 300 g) (Wang et al., 2016b). Table s11 in the SI shows data and data source for milk consumption in 2035 and 2050 for low and high level consumption.

To produce milk to meet China's demand in 2035 and 2050, we assumed that all milk is produced domestically and we created five production scenarios: 1) the contribution of dairy system A–F remains the same as in 2020 (BAU Scenario); 2) based on the growth rates between 2000 and 2020, 38 % of milk originates from system D and 62 % from F while other systems disappear (T Scenario); 3) based on scenario T, 80 % of milk production originates from system D and 20 % from F by reallocating dairy cows from crop areas to pastoral areas (R Scenario); 4) based on scenario T, system D and F are optimized into system G (38 %) and H (62 %) (O Scenario); 5) based on scenario O, the contribution of system G and H to total milk production change to 80 % and 20 % (R + O Scenario). Tables s12 and s13 in the SI give the characteristics for the optimized dairy system G and H.

The total WFs, LFs and CFs of dairy production to meet the demand in 2035 and 2050 were calculated using Eqs. (1) and (2). Based on the total 117 Mha of cropland for feed (FAO, 2022) and 5 % of dairy feed concentrate (NBS, 2022), we estimated the available cropland for dairy farming at 5.9 Mha. The high quality grassland in China is about 25.8 Mha (Li et al., 2020), in which there 12.9 Mha available for grazing.

4. Results

4.1. Milk production dairy systems in China from 2000 to 2020

Fig. 5 shows the development of the contribution of six dairy systems to total milk production in China from 2000 to 2020.

Fig. 5 shows that between 2000 and 2005, milk production in China tripled. All systems show an increase of their production caused by larger demand in combination with an increase of the milk yields. Fig. 5 also shows that between 2000 and 2020, especially the modern industrial system F increased production, followed by system D, accounting for almost 50 and 20 % of Chinese milk production in 2020, respectively. The small, traditional, mixed system B increased and dominated in the period 2000 to 2010, and then decreased again in the following ten years to about the production level of 2000. This increase and later decrease was mainly due to demand changes and intensification after the scandal in 2009. Table s6 in the SI gives the production data per system between 2000 and 2020.

4.2. Water, land and carbon footprints dairy systems in China

Fig. 6a shows the green, blue and grey water footprints (WFs) both in China as well as outside China, Fig. 6b the land footprint (LF) for grassland and cropland in and outside China and Fig. 6c the carbon footprint (CF) per kg of milk produced in six dairy systems in China.

Fig. 6a shows that the six dairy systems have different green, blue and grey WFs. Especially system A based on grazing lands has a relatively large green WF of 17.2 m^3 per kg of milk, but small blue and grey WFs. WFs are located in the country itself. System F shows the largest blue WF (located in China), due to the use of irrigated feed crops. System C, D, E and F have a relatively small green WF located outside China due to the use of imported feed crops. System B has the smallest total WF, however the grey WF caused by nitrogen leakage is larger than in system A that has the smallest grey WF.

Fig. 6b shows LF variation among the six systems. System A uses a relatively huge amount of grassland, mainly of low quality with low grass productivity. All systems use cropland, mainly located in China. System B and E have relatively small LFs, they do not use grassland, and relatively small cropland use. System E shows the largest LF outside China due to feed import.

Fig. 6c shows the differences among CFs. Small and traditional grazing and mixed system A and B have the largest CFs of 2.7 and 2.9 kg CO_2 eq./kg of milk. System A has a relatively small milk yield. System B uses feed that mainly consists of crop residues and by-products. In the

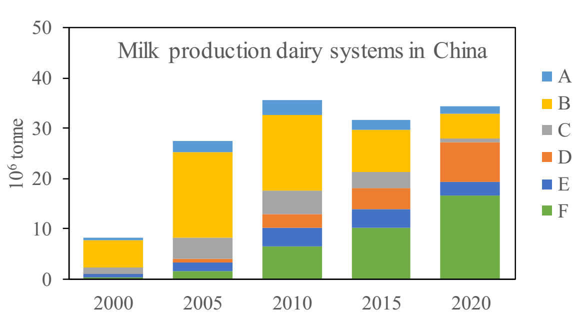

Fig. 5. Development of the contribution of six dairy systems to total milk production in China from 2000 to 2020. System A is a traditional grazing system, system B and C traditional mixed systems in crop areas. The other three systems, D-F, are modern, intensive systems. System D is located in pastoral areas, E and F crop areas.

modern industrial systems, total emissions are similar, about 2.3 kg CO_2 eq./kg of milk. In all systems, enteric fermentation is the main contributor to the CF. However, differences among contributions of feed production, enteric fermentation, manure emissions and energy use provide options for improvement.

Fig. 6a–c shows that system A has the largest green WF and LF (grassland), as well as large CFs, due to small milk and grass yields compared to other systems, while the modern industrial system D has relatively small WFs, LFs and CFs. System B has the smallest WFs and LFs. Although it needs the largest feed input per cow, WFs and LFs of crop residues and by-products are relatively small. However, the feed causes large methane emissions so that system B has the largest CFs. The modern industrial systems E and F in crop areas have moderate WFs and LFs, and small CFs. Compared to system E, system F has larger WFs and LFs, but smaller CFs. To reach larger milk yields, system F increases concentrate and high quality roughage use which have larger blue WFs and LFs. Table s13 in the SI gives the WFs, LFs and CFs per kg of milk, beef and manure for the six systems in China.

Fig. 5 shows that from 2010 to 2020, traditional systems (A and B) were replaced by modern industrial systems (D and F). This development resulted in an increased total blue WF and LF in China due to larger irrigation and cropland use. Table s6 and Fig. s1 in the SI give the development of the contribution of the six dairy systems to total WFs, LFs and CFs in China from 2000 to 2020.

4.3. Future milk consumption in China

Fig. 7 shows the total low and high milk consumption in China in 2035 and 2050 compared to milk consumption in 2020.

Fig. 7 shows that low milk consumption in 2050 decreases by 36 %, but triples for high consumption compared to consumption in 2020. When Figs. 7 and 5 are compared, China's self-sufficiency of milk was 67 % in 2020.

4.4. Water, land and carbon footprint of future dairy production in China

The low milk consumption does not increase WFs, LFs and CFs substantially (Fig. s2 in the SI). Fig. 8a shows the total green, blue and grey WFs, Fig. 8b the total LF of grassland and cropland and Fig. 8c the total CF of dairy production in 2050 in China for high milk consumption.

For high milk consumption (Fig. 7), the WFs, LFs and CFs of dairy production in the BAU or T scenario increase four to six times compared to low milk consumption and exceed available cropland for milk and high quality grassland. By optimizing and reallocating the dairy systems, O + R have the smallest blue WFs and cropland LFs which are below the limitations of cropland and high quality grassland. Table 3 shows the ratio of dairy land footprints compared to available cropland and grassland in China (%) based on low and high level milk consumption for five production scenarios in 2035 and 2050. Figs. s3 and s4 in the SI show the production scenario results for the year 2035.

Table 3 shows that the availability of cropland and grassland is an important constraint for high milk consumption for all five scenarios. If China consumes the high level of milk in the future, it will partly depend on milk or feed import. Low milk consumption is possible within the land availability constraints. In that case, the best scenarios with the smallest land use are scenario O and R + O.

5. Discussion

5.1. Assumptions and uncertainties

To assess WFs, LFs and CFs per kg of milk, meat and manure from different dairy systems, to estimate the total footprints related to total milk production by different systems in China from 2000 to 2020, and to predict the footprints to meet demand in 2035 and 2050, we had to make some assumptions and encountered uncertainties.

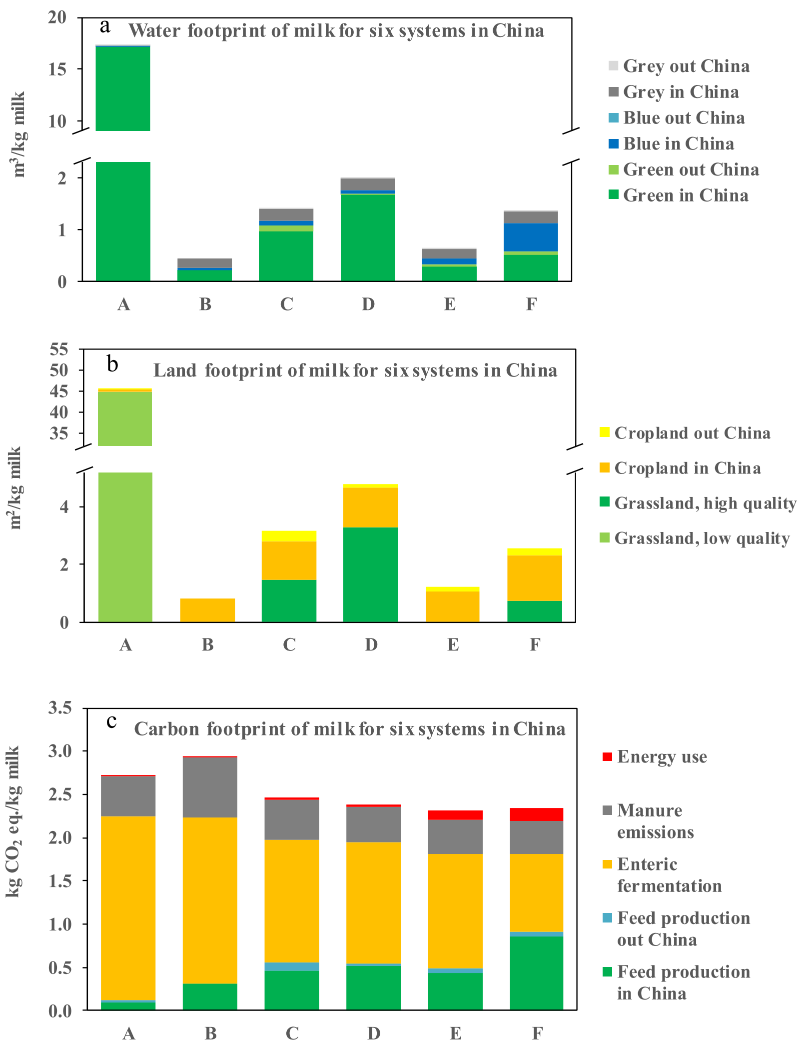

Fig. 6. a–c. Fig. 6a shows the green, blue and grey water footprints (WFs) in China and outside China, Fig. 6b the land footprint (LF) of grassland and cropland in and outside China and Fig. 6c the carbon footprint (CF) per kg of milk for six dairy systems in China. System A is a traditional grazing system, system B and C traditional mixed systems in crop areas. The other three systems, D–F, are modern, intensive systems. System D is located in pastoral areas, E and F crop areas. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

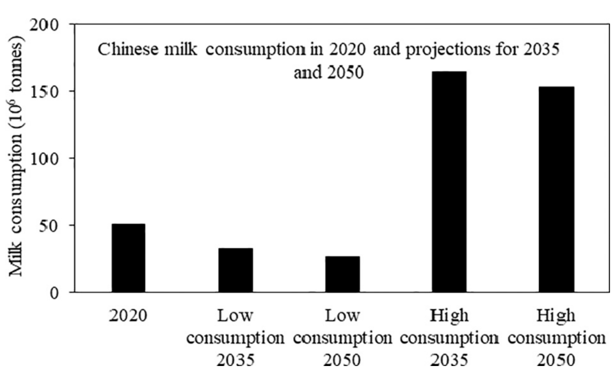

Fig. 7. Total low and high milk consumption in China in 2035 and 2050 compared to milk consumption in 2020.

First, we collected data from available environmental studies, assuming these data are correct. However, for the grazing systems, we re-estimated feed intake from grazing. Second, we selected six systems to represent three classification clusters based on FAO criteria and used farm sizes to estimate milk contribution per system between 2000 and 2020. Third, production in 2035 and 2050 was estimated based on the growth rates between 2000 and 2020. Fourth, in crop areas, we included four systems depending on farm size, i.e. small traditional, intermediate mixed, large and very large industrial systems. In the pastoral areas, we assumed there are only two systems, small grazing and large industrial systems. Fifth, we made two extreme milk demand scenarios for 2035 and 2050, one in which people who cannot digest milk, i.e. 86 % of the population above four years, does not consume milk and one in which everybody follows the nutritional advise for milk consumption. However, the reality might be situated in between. Sixth, we used the global warming potential indicator of 100 years (GWP100) from the IPCC (2006) to make results comparable to previous studies. However, the latest report indicates that methane cannot exit in the air for 100 years and using GWP20 might be better. This will increase CFs by a factor of 1.8 to 2.6 depending on the dairy system. Seventh, we allocated the footprints over the output products using the allocation method from WF analysis (Hoekstra et al., 2011) based on the product and value fraction. However, there are also other ways to allocate, e.g. using nutritional energy content or mass. We also allocated footprints to manure, which is not common in dairy studies. We argue that manure also has a value that even might go up in China in the future due to agricultural policy that aims for manure use efficiency of 80 % for 2025 and 90 % for 2035 (Wei et al., 2021). These assumptions and uncertainties have an impact on the final results that should not be considered at face value, but as indicators that give an impression of the direction of change.

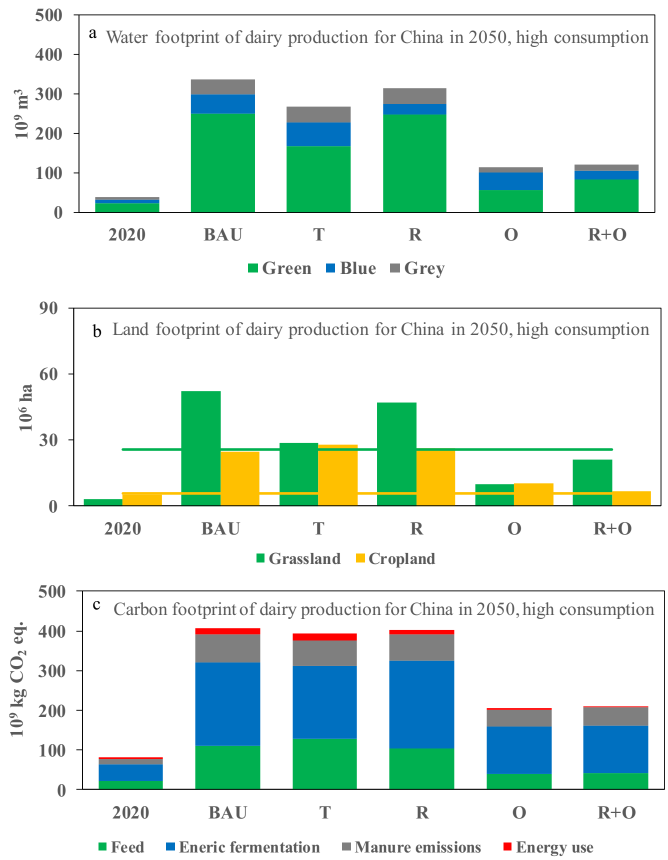

Fig. 8. a–c. The green, blue and grey water footprint (WF) (8a), land footprint (LF) of grassland and cropland (8b) and carbon footprint (CF) (8c) of dairy production in 2050 for China, for high milk consumption for five production scenarios (BAU: the same contributions of system A-F for milk production with 2020, T: 38 % of milk from system D and 62 % from F, R: 80 % of milk from system D and 20 % from F, O: 38 % of milk from system G and 62 % from H, O + R: 80 % of milk from system G and 20 % from H). The green and yellow lines in Fig. 8b represent available grassland and cropland for dairy farming. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
The ratio of dairy land footprints compared to available cropland and grassland in China (%) based on low and high level milk consumption for five production scenarios in 2035 and 2050.

Year	Consumption level	Land type	Scenarios				
			BAU	T	R	O	R + O
2035	Low	Cropland	90	101	94	38	24
		Grassland	43	24	38	8	17
	High	Cropland	455	513	479	192	122
		Grassland	216	120	195	41	87
2050	Low	Cropland	72	81	76	30	19
		Grassland	34	19	31	7	14
	High	Cropland	424	478	447	179	114
		Grassland	202	112	182	38	81

BAU: the business as usual scenario where the contribution of dairy system A–F remains the same as in 2020; T: based on the growth rates between 2000 and 2020, 38 % of milk originates from system D and 62 % from F while other systems disappear; R: based on scenario T, 80 % of milk production originates from system D and 20 % from F by reallocating dairy cows from crop areas to pastoral areas; O: based on scenario T, system D and F are optimized into system G (38 %) and H (62 %); R + O: based on scenario O, the contribution of system G and H to total milk production change to 80 % and 20 %.

5.2. Comparisons of footprints with other studies

When we compare our results with results of other studies on the footprints of milk from mixed and industrial systems, results are similar. For example, the total WF of 1.40 m^3/kg of milk from a mixed system is about the same as the total average WF of milk produced in China of 1.26 m^3/kg from Mekonnen and Hoekstra (2012). In our study, blue WFs of milk range between 0.06 and 0.54 m^3/kg for industrial systems which is in line with blue WFs of 0.15 (Bai et al., 2018b) to 0.40 m^3/kg (Huang et al., 2021). For mixed systems we find a blue WF of milk of 0.08 m^3/kg, where Mekonnen and Hoekstra (2012) report a value of 0.15 m^3/kg. For grazing systems, we find a green WF of milk of 17.2 m^3/kg, where Mekonnen and Hoekstra (2012) report an average value for grazing systems of 1.6 m^3/kg. The reason for this difference might be that we applied detailed data for grazing systems in China that might give a good reflection of the actual situation, while Mekonnen and Hoekstra (2012) used more general data for grazing systems.

We estimated that the LF of cropland of milk from industrial systems is between 1.2 and 4.8 m^2/kg, comparable to the value of 1.58 to 1.83 m^2/kg (Huang et al., 2021). Our results show that the total LF ranges between 0.8 and 45.5 m^2/kg, with a weighted average of 5.5 m^2/kg, where Bai et al. (2018b) report a similar LF of 5.2 m^2/kg.

Our CFs of milk vary from 2.3 to 2.9 kg CO_2 eq./kg, similar to the value of 2.9 kg CO_2 eq./kg (Bai et al., 2018b). For industrial systems, we find 2.3 to 2.4 kg CO_2 eq./kg of milk, where Huang et al. (2021) report a value of 1.3 to 1.4 kg CO_2 eq./kg. The reason for our larger value is that we expanded the system boundary and also included emissions of feed production and transportation.

5.3. Limits to China's milk production

The contribution of grazing systems to milk production in China declined from 7 % in 2000 to 4 % in 2020. Probably, this system will disappear before 2035. Blue WFs, LFs and CFs of total milk production in China have shown significant growth between 2000 and 2020. For instance, the contribution of the blue WF of milk to the total agricultural blue WF (National Bureau of Statistics of China, 2022) increased from 0.2 % in 2000 to 3 % in 2020. The LF of cropland for milk accounted for 1 % of total cropland in China in 2000 and 4 % in 2020 (National Bureau of Statistics of China, 2022). For total grassland, milk production contributed 1 % in 2000, 5 % in 2010, and decreased to 3 % again in 2020 (National Bureau of Statistics of China, 2022). However, in the past, milk production depended on high quality grassland. The percentage of high quality grassland used for milk was 11 % in 2000, increased to 60 % in 2010, and decreased to 41 % in 2020 (Li et al., 2020). The CF of milk production contributed 3 % in 2000, 12 % in 2010 and 11 % in 2020 to total agricultural emissions (FAO, 2022). The contributions of feed, enteric fermentation, manure and energy use for milk to total agriculture were 1 %, 6 %, 3 % and 0.2 % respectively in 2000 and increased to 5 %, 24 %, 11 % and 3 % in 2020. The examples above show the large impact of increasing milk production in China on natural resource use and the increased contribution to greenhouse gas emissions.

Considering the footprints of low milk consumption, they are possible within the environmental constraints. However, for future high milk consumption, limitations come. We assumed the grazing and traditional systems will be replaced by the industrial ones based on the annual growth rate over the past 20 years. A limitation for high consumption is the low quality of grassland and availability of crop residues. On the one hand, the average grass production per year was about 760 kg/ha (Liu et al., 2008), because of the limited amount of high quality grassland in China. For example, the area of grassland on the Qinghai-Tibet Plateau accounts for about 30 % of the total grassland (Li et al., 2020), but the hay yield in this region is only 100 to 300 kg/ha (Liu et al., 2008). On the other hand, because of the separation of crop and livestock production, it is difficult to transport bulky residues to dairy farms, decreasing residue availability. Next, Chinese farmers are stimulated to return residues to the soil through a national project to improve soil quality (Zhang et al., 2017b).

Results also show that we cannot produce all milk without optimizing and reallocating the dairy systems. However, options are limited by the availability of high quality grassland and cropland. In China, only 8 % of total grassland is of high quality (Li et al., 2020). Moreover, temperature and precipitation limit hay productivity in Northern China to below 2000 kg/ha (Liu et al., 2008), while the scattered distribution of grassland in the south limits hay productivity to 2000 to 3000 kg/ha (Liu et al., 2008). Cropland availability for feed crops, for example maize, is also limited. In China, maize is mainly grown in the North China Plain and in Northeast China. However, there is an increasing competition for land for specific crops. For example, rice production decreased in the South and increased in the Northeast causing competition between rice for food and maize for feed in this region (Wang et al., 2022). Similarly, these specific food and feed crops will compete over irrigation water, i.e. blue WFs, because blue water is limited in China (National Bureau of Statistics of China, 2022). Moreover, owning to Chinese governmental policy to achieve carbon neutrality in 2060 (The State Council of China, 2020), increasing GHG emissions of milk production should have an offset elsewhere. Considering these limitations, China might need to import feed in the future. For instance, maize, soybean, alfalfa and hay from large global producers like the United States, Brazil, Argentina, Australia and New Zealand (FAO, 2022). Compared to importing milk from the global market, trading feed might be more convenient. Moreover, in this way, China could also produce beef that could replace pork and in this way decrease pork footprints.

6. Conclusions

This study made a comprehensive environmental assessment of milk production in China in terms of WFs, LFs and CFs for three dairy classification clusters traditional grazing, traditional mixed and modern industrial systems. First, we showed that modern industrial dairy production systems developed rapidly and that their contribution to total production increased from 14 % in 2000 to 79 % in 2020. The small traditional production systems increased and dominated in the period 2000 to 2010, and then decreased again in the following ten years to about the production level of 2000.

Different dairy systems have different footprints per unit of milk, beef and manure. The traditional grazing system relying on low quality grassland has the largest green WF (17.2 m^3), LF (45.5 m^2 grassland) and a relatively large CF (2.7 kg CO_2 eq.) per kg of milk. The small traditional mixed system has the smallest total WF (0.4 m^3) and LF (0.8 m^2) per kg of milk. The medium traditional mixed system has a relatively large WF, LF and CF. The large industrial system has relatively large blue and grey WFs (0.54 and 0.24 m^3) and a large LF of high quality cropland of 1.8 m^2 per kg of milk. Beef WFs range between 1.3 and 38.1 m^3 per kg, beef LFs between 2.4 and 100 m^2 per kg, and beef CFs between 6.0 and 8.4 kg CO_2 eq. per kg. The traditional grazing system has the largest WF and LF, but the smallest CF, while the small traditional system has the smallest WF and LF, but the largest CF of beef. For manure, traditional grazing and mixed production systems have no footprints. For the industrial systems, WFs, LFs and CFs of manure range from 0.5 to 1.7 m^3, 1.1 to 4.1 m^2 and 2.0 to 2.1 kg CO_2 eq. per kg of manure.

The development of different dairy production systems in China, especially of the industrial systems, was the reason that dairy farming needed more croplands and irrigation over the past 20 years, but the contribution of dairy production to total agricultural land and water use in China is still small. However, if the Chinese follow the nutritional advice, milk demand in 2035 and 2050 might triple compared to consumption in 2020. If China would produce all milk needed in the future, WFs, LFs and CFs of total milk production increase four to six times. However, there are natural constraints to this increased production. China probably cannot produce this milk volume, because the country is limited by the availability of domestic grassland and cropland. This availability of cropland and grassland is an important constraint for high milk consumption causing a dependency on milk or feed import. Low milk consumption is possible within the land availability constraints. In that case, the best scenarios with the smallest land use are intensive, high production dairy systems. The Chinese diets depend on the availability of nutritious foods, either from animals or plants, preferably produced in China itself. If the Chinese increase the fraction of animal-based foods, e.g. milk, this would imply that Chinese milk consumption might cause a huge pressure on the availability of milk and animal feed on the global market.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was funded by the China Scholarship Council (CSC), file number 201806350266. The CSC is a non-profit institution affiliated with the Ministry of education of the P.R. China. The support is greatly acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.04.004.

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