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Driving forces of the agricultural land footprint of China's food supply

Xiaoying Zhang [a,b], Qunchao Fang [a], Guichao Dai [a], Jingmeng Wang [a,c], Martin K. van Ittersum [b], Hongliang Wang [a,**], Yong Hou [a,*]

[a] *College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant–Soil Interactions, Ministry of Education, State Key Laboratory of Nutrient Use and Management (SKL-NUM), China Agricultural University, 100193, Beijing, China*

[b] *Plant Production Systems Group, Wageningen University & Research, 6700, AK Wageningen, the Netherlands*

[c] *Soil Biology Group, Wageningen University and Research, P.O. Box 47, 6700, AA Wageningen, the Netherlands*

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ABSTRACT

Dietary changes are closely intertwined with land use changes, and understanding the relative importance of different food items and their driving forces is crucial. Here, we analyzed the changes in China's global cropland footprint for food and feed consumption from 1987 to 2013 and explored the driving forces behind these changes for each food item. China's per capita protein consumption increased by 57%. The global cropland footprint of China's food and feed consumption expanded by 40% during this period. Decomposition analysis demonstrated that population growth was the primary driver of the increased total cropland footprint until 1993, with the subsequent rise in per capita protein consumption becoming the driving force. Thereafter, the increased efficiency of cropland use offset 49% of the total cropland expansion primarily due to improved management technologies. Among the food items analyzed, pork, eggs, and vegetables were identified as the main contributors to the increased total cropland footprint, primarily driven by changes in dietary patterns and their increased inclusion in the human diet. In conclusion, changing human diet towards less monogastric livestock products and improving productivity of concentrate feed crops are essential for mitigating domestic land pressure and ecological degradation in exporting countries.

1. Introduction

Producing enough food to meet the increasing demand while facing limited land resources is a global challenge (Folberth et al., 2020; Waha et al., 2020). Additional demand for food commodities can be met by expanding or intensifying agricultural production. However, agricultural expansion has led to a consequent loss of land cover and increased greenhouse gas emissions. For instance, land-use change in the livestock production sector alone accounts for 9–33% of the total greenhouse gas emissions in the European Union's 27 countries (Bellarby et al., 2013). The intensification of production, achieved through increased inputs such as fertilizers, pesticides, and water, as well as changes in management practices, has also resulted in environmental concerns such as freshwater depletion (Foley et al., 2005) and biodiversity loss (Newbold et al., 2016). With population growth and dietary shifts towards more animal products, land-use change has become a critical issue, particularly in developing economies (Gerbens-Leenes et al., 2010; Willett et al., 2019). Between 1963 and 2005, the global harvested cropland areas expanded from approximately 840 to 1100 Mha, primarily driven by the increasing demand for livestock-based food products, with the largest expansion observed in East Asia (Kastner et al., 2012).

Previous assessments of land-use changes in food systems have typically been conducted at a global or continental scale (Alexander et al., 2017; Bosire et al., 2015; Caro et al., 2018; van Zanten et al., 2016). These global analyses are important for highlighting the potential to save land using specific strategies from either the supply or demand side. However, studies at the country level are limited and reveal substantial differences between countries. For example, the United Kingdom has become highly dependent on land resources from foreign countries through significant food imports (de Ruiter et al., 2016), while other countries such as Brazil may expand exports at the expense of domestic land resources (Caro et al., 2018). Few country-level studies have attempted to distinguish land use by different food products; however, they have usually failed to accurately quantify land use by

* Corresponding author.
** Corresponding author.
E-mail addresses: wang_hl@cau.edu.cn (H. Wang), yonghou@cau.edu.cn (Y. Hou).

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animal-sourced food because of a lack of information on detailed feed composition (de Ruiter et al., 2017; Osei-Owusu et al., 2019). A feed allocation model based on country-specific data, such as feed availability, animal productivity, and livestock herd size, could quantify the cropland footprint for feed by animal category in much detail. Disaggregated data on agricultural land use are essential for developing recommendations for healthy diets with moderate meat consumption and land-saving measures.

Understanding the drivers behind recent changes in agricultural land use is crucial for addressing future land resource and climate change challenges (Stehfest et al., 2019). Previous studies have mainly focused on drivers related to aggregated land-use types such as grassland, cropland, and forest (Meyer and Früh-Müller, 2020; Sarparast et al., 2020; Tian et al., 2019; van Vliet et al., 2015), as well as changes in land use for feed, food, and non-food/feed purposes (Alexander et al., 2015; Duro et al., 2020). However, little attention has been given to decomposing the drivers of land-use change across specific food products, despite historical trends varying among different food items such as cereals, vegetables, milk, and pork. Quantifying the historical changes in driving forces for the demand of individual food items is important for predicting the future demand for food-related land use.

The scale of consumption in China requires special attention. Feeding 19% of the world's population with only 8% of the world's croplands remains a challenge (Food and Agriculture Organization (FAOSTAT, 2021). China's land use is under significant pressure (Qiang et al., 2013). Additionally, the dietary shift toward higher consumption of land-intensive animal products has further increased agricultural land requirements (Jiang et al., 2020). Per capita meat consumption in China has significantly risen from 3.3 kg per year in 1961 to 61.3 kg per year in 2020, surpassing the global average of 42.8 kg per year in 2020 (FAOSTAT, 2021). Recent estimates indicate that land resource requirements have exceeded national boundaries and safe operating spaces for China's food system (Hu et al., 2020). Consequently, China reduced pressure on domestic land use by land grabbing and large-scale commodity transportation overseas (Rulli et al., 2013). The concept of virtual land, embodied in traded commodities, has added complexity to determining land-use efficiency in food production (Bai et al., 2021). In a scenario where land availability is limited, understanding the historical changes in China's global food system's land footprint and the associated driving forces will aid in addressing the nation's land-use challenges.

To provide insights into the driving factors on a disaggregated food category level, we used China as a case study to examine the historical trends in the land footprint and the main drivers of cropland use changes from 1987 to 2013 at a disaggregated food category level. We aimed to answer the key questions: How much land (cropland and grassland) and land-use change have been associated with the production of plant- and animal-sourced food for human consumption? What is the relative importance of population, food consumption, productivity, and cropland structure as drivers of changes in cropland use? How do these drivers differ among food products? This research will provide scientific evidence for the development of efficient land use strategies in future land use policies.

2. Materials and methods

The agricultural land uses selected for this study include grasslands (associated with grazing animals) and croplands. In this study, cropland footprints for food were defined as the area harvested in a given year to provide the prevailing diet in the same year; multicropping was not considered (Kastner et al., 2012). We further divided cropland into areas producing feed crops for animal products (hereafter referred to as "feed") and producing crops for human food (hereafter referred to as "food"). The domestic consumption of China is either supplied by domestic production or by imports; thus, the potential agricultural land use due to imported animal-source produces is not included in this study, because the available data are limited. Since 2014, the Food and Agriculture Organization (FAO) has adopted a new classification methodology in the food balance sheet; for consistency, this study used FAO data from 1987 to 2013.

2.1. Agricultural land footprint for feed and plant-food

2.1.1. Cropland footprint for feed and plant-food

The FAO food balance sheet (http://www.fao.org/faostat/en/#data) provides all the detailed agricultural commodities that can be distinguished for food, feed, and "other uses" (further explanation about "other uses" can be found in the Supplementary Materials). Based on the FAO classification, we aggregated all crops into six categories (cereals, oil crops, starchy roots, fruits, vegetables, and vegetable oils) to quantify their cropland areas (see details in Supplementary Information, e.g., Table S4). The global cropland footprint (including virtual cropland embodied in imported commodities) was quantified using the physical accounting method developed by Kastner et al. (2014), and we assumed all imported crops prioritized for domestic consumption. In addition, the relative proportions of food, feed, and other uses were assumed to be the same for domestic production and imports (de Ruiter et al., 2017). For instance, if wheat was split 50/50 between food and feed use, this proportion was applied equally to domestically produced and imported wheat.

When different co-products are derived from one crop (e.g., oil and oil seed cakes), an economic allocation method is used to determine the share of land attributable to each material (Gerber and Tempio, 2013).

The framework for the cropland footprint method is shown in Fig. 1.

The total cropland footprint is expressed as follows:

$$CLF_{China,supply} = CLF_{domestic,production} + VCLF_{China} \quad (1)$$

where $CLF_{China,\ supply}$ is the cropland footprint (ha) of domestic supply; $CLF_{domestic,\ production}$ is the cropland footprint (ha) of domestic food production; $VCLF_{China}$ is the virtual cropland footprint (ha) associated with commodities imported (expressed in mass weight) from other countries.

To quantify the cropland footprint and virtual cropland area hidden in trade flows, the following data were required.

(1) Source countries and trade quantity of each product. These data were taken from the FAOSTAT database, which provides detailed trade matrices for several agricultural commodities traded internationally.
(2) Yield data. The crop equivalents were converted to cropland areas using country-specific yield data sourced from the FAOSTAT database.
(3) Conversion factors for byproducts into whole products. For example, the mass and economic fraction allocation factors for soybean cake are 0.82 and 0.72, respectively, which indicates that soybean cake contributes 82% of the soybean by weight and 72% in economic terms. Data were sourced from the Technical Conversion Factors in FAOSTAT and the Intergovernmental Panel on Climate Change (Eq. S.1, Table S7).

2.1.2. Grassland footprint for feed

The analysis of grassland areas is more complex because multiple products can be derived simultaneously from the same area of grassland (e.g., ruminant meat and milk), and yield data on grasslands are limited and uncertain. To calculate the grassland area associated with the domestic supply of animal products, we used a feed-use model (Hou et al., 2016) to allocate grass to different ruminant species based on the nutritional and energy requirements of ruminants and the availability of grass biomass.

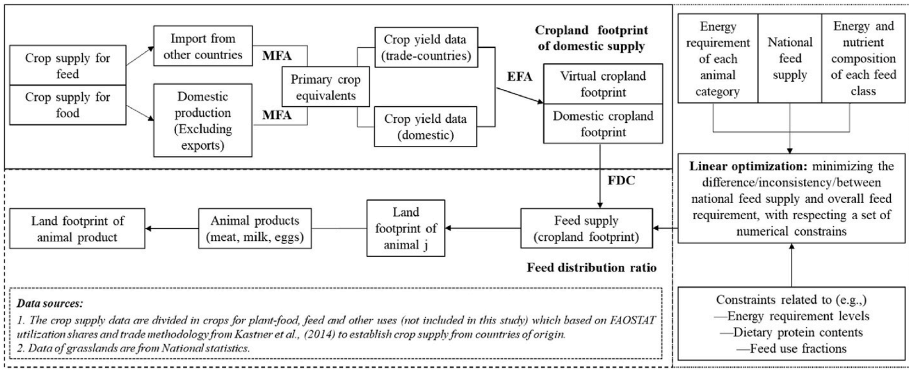

Fig. 1. Overview of the methodology used in the current study. The top left part provides the calculation method of the cropland footprint of China's domestic supply. The bottom left portion provides the land footprint calculation method for different animal types, and the flow chart portion on the right shows the optimal distribution of feed according to the nutritional needs of different animals. EFA: economic fraction allocation; MFA: mass fraction allocation; FDC: animal category-specific feed distribution coefficients.

2.2. Allocation of feed crops to different animal products

Here, we derived animal category-specific feed distribution coefficients (FDC) by linking statistical data and information on the availability (quantity and quality) of feed with animal numbers and energy and protein requirements of the animals (Dai et al., 2023). Animal categories included dairy cattle, other cattle, pigs, laying hens, broilers, sheep, and goats.

$$CLF_{i,k} = CLF_{China,supply} \times FDC_{feed,i,k} \tag{2}$$

$CLF_{i,k}$ is the cropland footprint of feed *i* by animal *k*; $CLF_{China,\ supply}$ is the cropland footprint (ha) of domestic supply; $FDC_{feed,i,k}$ is the distribution ratio of feed item *i* by animal *k*, where k = 1, 2, 3, 4, 5, 6, and 7, denoting dairy cattle, other cattle, pigs, laying hens, broilers, sheep, and goats, respectively, based on the linear optimization of the energy requirement of each animal category.

$$CLF_{animal,k} = \sum_{i=1}^{n} CLF_{i,k} \tag{3}$$

$$CLF_{product,k} = CLF_{animal,k} / Y_k \tag{4}$$

$$CLF_{protein,k} = CLF_{animal,k} / \left(Y_k \times pr_{content,k}\right) \tag{5}$$

where $CLF_{animal,k}$ is the cropland footprint of animal *k* in ha. The main animal product outputs are meat, milk, and eggs. $CLF_{product,k}$ is the cropland footprint expressed per product in animal *k* (pork, chicken, mutton, beef, milk, and other animal products, expressed in $m^2 \cdot kg^{-1}$, eggs in $ha \cdot t^{-1}$); Y_k is the total product yield of animal *k*; $pr_{content,k}$ is the protein content of animal products *k* ($g \cdot kg^{-1}$) (Bai et al., 2016).

2.3. Decomposition and category differences

Decomposition analysis is an important tool for understanding and quantifying the driving forces behind the changes in related indicators (Ang and Zhang, 2000; Duro et al., 2020; Zhao and Chen, 2014). The logarithmic mean Divisia index (LMDI) was selected for reliability and validity (Alexander et al., 2015; Zhao and Chen, 2014). In this study, the LMDI method was used to decompose the driving forces (population, food consumption, productivity, and cropland structure). The index decomposition analysis identity describes the total cropland footprint supply.

$$L = \sum_i \frac{L_i}{L} \frac{L}{Q} \frac{Q}{P} P = \sum_i R_i TEP \tag{6}$$

where L denotes the cropland footprint supply for China; L_i is the cropland footprint of the ith group, where i = 1, 2, … 9, 10, denoting milk, beef, chicken, pork, mutton, eggs, cereals, fruits, vegetables, other crops, respectively; Q refers to the total protein supply; P is the population size; $R_i = (Li/L)$ represents the cropland footprint structure, i.e., the ratio of each food item's cropland footprint account for the total cropland footprint; T = (L/Q) refers to cropland use efficiency (productivity), i.e., the amount of protein that can be produced per unit of cropland (kg protein$\cdot ha^{-1}$); E = (Q/P) represents protein consumption, i.e., the requirement for protein per person (kg protein$\cdot capita^{-1}$). We also performed the same analysis based on calories and biomass weight; the results are shown in the Supplementary Information.

As the additive decomposition approach is easier to use and interpret than multiplicative decomposition, the change in the total cropland footprint in period *t* relative to period 0 can be expressed as follows:

$$\triangle L = L^t - L^0 = \triangle L_{str} + \triangle L_{eff} + \triangle L_{com} + \triangle L_{POP} \tag{7}$$

According to Ang (Ang, 2004), the LMDI decomposition results for each factor are as follows:

$$\triangle L_{pop} = \sum_i \frac{L_i^t - L_i^0}{ln\ L_i^t - ln\ L_i^0} ln \frac{P^t}{P^0} \tag{8}$$

$$\triangle L_{com} = \sum_i \frac{L_i^t - L_i^0}{ln\ L_i^t - ln\ L_i^0} ln \frac{E^t}{E^0} \tag{9}$$

$$\triangle L_{eff} = \sum_i \frac{L_i^t - L_i^0}{ln\ L_i^t - ln\ L_i^0} ln \frac{T^t}{T^0} \tag{10}$$

$$\triangle L_{str} = \sum_i \frac{L_i^t - L_i^0}{ln\ L_i^t - ln\ L_i^0} ln \frac{R_i^t}{R_i^0} \tag{11}$$

where $\triangle L_{str}$, $\triangle L_{eff}$, $\triangle L_{com}$ and $\triangle L_{pop}$ are the cropland footprint changes due to the cropland footprint structure effect, cropland use efficiency effect, protein consumption effect, and population effect, respectively.

3. Results

3.1. Crop and animal products consumption

The total number of crops and animal products consumed by Chinese residents increased from 139 Mt (million tons) in 1987 to 1020 Mt in 2013 (Table 1). Among crop products, growth rates were significantly high for fruits (an increase of 799%) and vegetables (375%) but low for cereals (12%). Among animal products, the fastest-growing demand was for milk (an increase of 934%), whereas the slowest was the demand for

Table 1
Total amount (in million tons) of crop and animal products consumed by Chinese residents in 1987 and 2013. Data are sourced from FAOSTAT, 2021.

Food items	1987	2013	Changes
Animal products (million tons)			
Pork	19.5	55.9	+186%
Eggs	4.9	24.8	+405%
Chicken	1.9	13.3	+592%
Milk	3.4	35.7	+934%
Beef	0.7	5.5	+700%
Mutton	0.7	4.1	+470%
Crop products (million tons)			
Cereals	235.3	263.1	+12%
Vegetables	102.9	489.3	+375%
Fruits	14.5	130.1	+799%
Starchy Roots	91.1	116.6	+28%
Oil crops	6.2	11.4	+85%
Vegetable Oils	5.1	9.9	+96%

pork (186%). Pork made up the largest proportion of total animal products, amounting to 63% in 1987 and 40% in 2013.

3.2. Agricultural land footprint for feed and food

3.2.1. Cropland footprint for feed and food

The total cropland footprint of China's food and feed supply (i.e., domestic+import–export) gradually increased from 121 Mha to 170 Mha between 1987 and 2013 (Fig. 2a). The per capita cropland footprint increased from 1080 m^2 to 1221 m^2 during this period (Fig. 2b). The relative contributions of the different food products to the total cropland footprint also changed. The cropland area used for feed, expressed as a percentage of total cropland in China, increased from 23% to 44% during the 1987–2013 period, while the cropland area used for growing food did not change significantly (an increase of 3%). Vegetable areas showed a faster growth (from 5% to 11% of the national cropland area) than all other food crops. Cereals used directly for human consumption remained the top cropland user; however, their total area decreased gradually from 62.6 Mha (in 1987) to 45.1 Mha (in 2013).

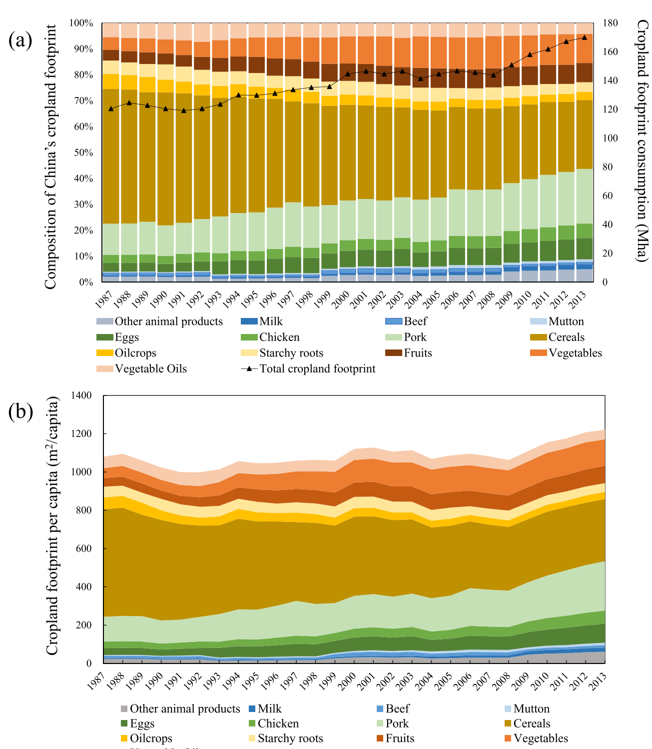

Fig. 2. Historical changes in total cropland footprint and relative contributions by food categories (a) and per capita cropland footprint (b) from 1987 to 2013. The legend, in the order from left to right and top to bottom, corresponds with the colors in the graph from the bottom to the top. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The total cropland footprint of all animal products consumed (i.e., domestic+import–export) in China increased from 27.2 to 74.3 Mha from 1987 to 2013. In 2013, maize (24.8 Mha), soybean cake (23.7 Mha), and starchy roots (5.8 Mha) collectively comprised 73% of the total cropland area (including virtual land) used for feed in China (Fig. 3a). The contribution of soybeans and soybean cake to total cropland used for feed production increased from 8.7% in 1987 to 37.5% in 2013. Croplands associated with the supply of pork, eggs, and chicken (the top three cropland users) accounted for 48%, 19%, and 13% of the total feed cropland area in 2013, respectively (Fig. 3b). The growth rates over the study period were high for croplands used for milk (537%), mutton (257%), and beef (239%).

3.2.2. Grassland footprint for feed

The total grassland footprint increased over the study period because of the increased supply of ruminant animal products (assuming that only ruminants could feed on grassland). From 2009 to 2013, grassland appropriation associated with China's supply was 333 Mha, and 61% of this area was allocated to mutton production (Table 2). Grassland use for milk production almost quadrupled between 1987 and 2013.

3.2.3. Virtual cropland footprint for feed and plant-food

Virtual cropland areas embodied in net imported plant-sourced food and animal feed from overseas to China in 2013 were 10.3 Mha and 18.8 Mha, respectively (Fig. 4a). The virtual cropland footprint accounted for 17% of the global cropland footprint of China in 2013 compared to 6% in 1987. Of the total virtual cropland footprint, 65% was associated with the import of animal feed in 2013, whereas this was only 4% in 1987.

South America became the largest contributor to the total virtual cropland in 2013, followed by North America. Oceania's contribution decreased from 1987 to 2013. Brazil (7.5 Mha), the United States of America (5.7 Mha), and Argentina (1.7 Mha) were the top three countries contributing to the total virtual cropland embodied in imported animal feed in 2013.

3.2.4. Cropland use efficiency of plant and animal-sourced food

In 2013, cropland areas used for feed supply represented 44% of the global cropland footprint of China, whereas it provided only 34% of the total food protein supply for human consumption. Cropland use efficiency (here defined as the amount of food protein produced per unit of cropland area) of ruminant products (e.g., milk, beef) was higher than that of monogastric products as ruminants feed on grassland or crop residues. In 2013, the crop-use efficiency for egg and chicken production exceeded that for pork production.

For plant-sourced foods, cereals were responsible for 30% of the total global cropland footprint and for 40% of the total food protein supply for human consumption; the corresponding values were 52% of the total cropland footprint and 64% of the total food protein supply in 1987 (Fig. 5). Cereals maintained a higher cropland use efficiency than other plant-sourced foods. Fruits had the lowest cropland use efficiency (in terms of protein production) during the study period.

3.3. Drivers for cropland footprint

The food protein consumption per capita and population growth positively correlated with the total global cropland footprint from 1987 to 2013. Since the early 1990s, the impact of food protein consumption per capita has surpassed that of population growth in driving the increase in total global cropland footprint (Fig. 6). Changes in cropland structure (i.e., the relative contribution of food items to global cropland

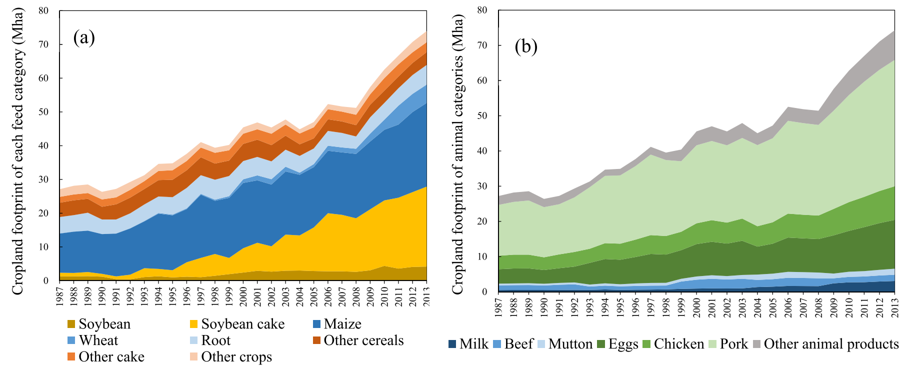

Fig. 3. Historical changes in cropland footprints (million ha = Mha) associated with China's animal-sourced food supply from 1987 to 2013, distinguished by feed categories (a) and animal categories (b).

Table 2
Historical changes in grassland footprints associated with China's milk, beef, and mutton supply from 1987 to 2013.

	Unit	1987–1992	1993–1998	1999–2003	2004–2008	2009–2013
Total grassland footprint	Mha	230	257	305	341	333
Milk	Mha	17	14	16	51	64
Beef	Mha	113	166	171	169	67
Mutton	Mha	100	76	117	121	202

Note: The data are the average values of the corresponding time periods.

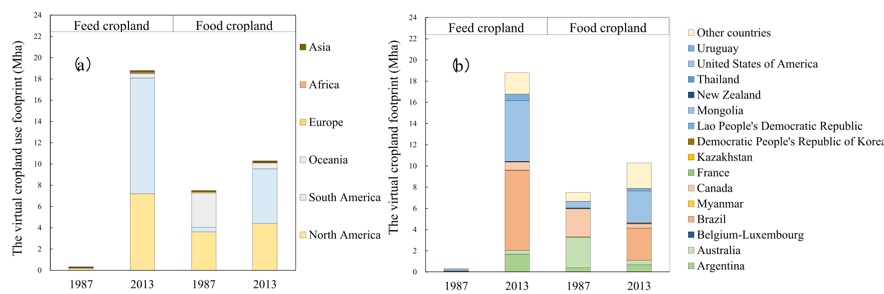

Fig. 4. Estimated virtual cropland footprints embodied in imports of plant-sourced food and animal feed by continents (a) and countries (b) to China in 1987 and 2013.

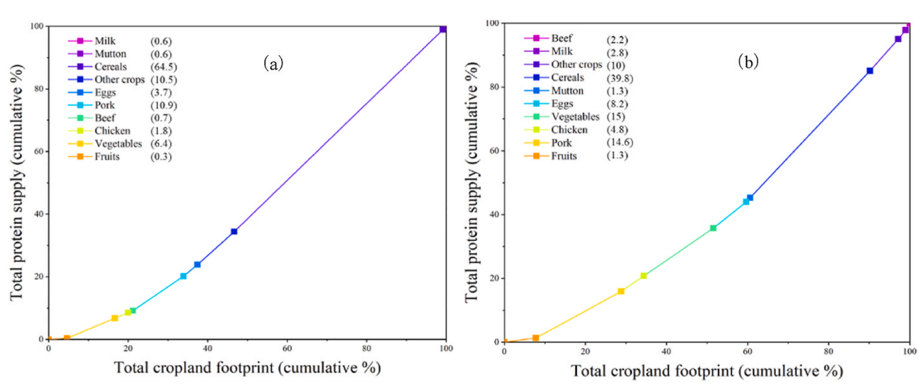

Fig. 5. Total protein supply as cumulative percentage produced versus cumulative total cropland footprint in (a) 1987 (average of 1987–1992) and (b) 2013 (average of 2009–2013). Products appear (from bottom to top) in order to increase land use efficiency for protein production. The data in parentheses represents the share in protein production of different food items.

footprint) had a minor impact over the study period. In contrast, improved productivity (cropland use efficiency) had a strong compensatory effect on the total cropland footprint.

Driving forces were also analyzed at the disaggregated level, i.e., by food item. For the entire study period, cereals were the primary food category contributing to the reduction in total cropland footprint (Fig. 7a). The potentially increased cropland footprint of cereals due to population increase was offset by both the increased productivity effect

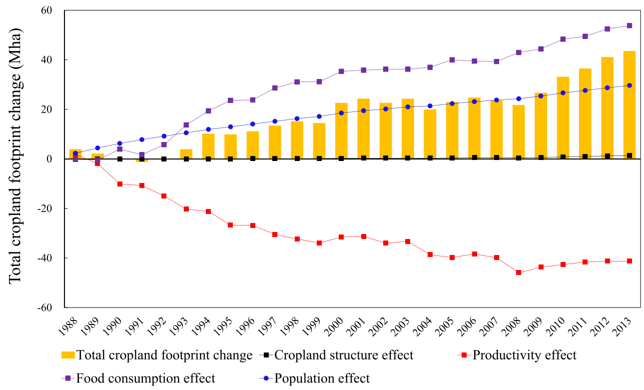

Fig. 6. Decomposition of change in total global cropland footprint of China's food supply (expressed on a protein basis) from 1987 to 2013.

and dietary change (cropland structure effect) towards lower cereal intake. Pork, eggs, vegetables, and fruits made positive contributions to the increased total cropland footprint. Unlike cereals, the increased cropland footprint of these food items was positively related to dietary changes, i.e., increased shares in the human diet over time. For animal-sourced foods, such as pork and eggs, an increase in their cropland use efficiency compensated for the potentially increased cropland demand driven by nutritional requirements and dietary shifts, especially in the middle of the study period (1996–2005). For vegetables, dietary changes positively correlated with increases in the cropland footprint in the 1990s, whereas the rate of growth has recently leveled off. In the last decade of our time series (Fig. 7d), pork became the major driving factor behind the increased cropland requirements, and the growth of cropland use efficiency slowed for all food items.

4. Discussion

The global land (grassland and cropland) footprint of China's food supply has increased in recent decades and is particularly associated with the growing consumption of animal-sourced food. The cropland area used for feed production, specifically animal-sourced food, increased by 173% from 1987 to 2013. In this study, we quantified cropland footprints and associated drivers at the disaggregated food category level. We discuss rationales and consequences of changes in these drivers, which are necessary for the development of targeted land-saving strategies from both food supply and demand perspectives.

4.1. Changes in cropland use for plant-sourced food supply

In the 1980s, approximately 80% of China's global cropland footprint was associated with crops grown for direct human consumption. However, by 2013, this percentage had decreased to 56%. This reduction is primarily attributed to the decreased contribution of cropland to staple food production, such as wheat and rice, consistent with the findings of He (He et al., 2019). The reduction in cropland required for cereals accounts for 63% of the total reduction in cropland in China. Technological innovations, including genetic improvements in crop varieties (Ying et al., 2019; Zhang et al., 2017), soil testing, formulated fertilization (Cui et al., 2018; Zhang et al., 2016), and nutrient management (Chen et al., 2021; Wang et al., 2017; Yin et al., 2019), have increased yield of cereal crops, such as maize, wheat, and rice. However, in China, cereal crops currently produced only about half of their yield potential on average, indicating the potential for further yield increase through narrowing yield gaps. It is possible that greater usage of some technologies may result in environmental issues such as greenhouse gas emissions from mechanisation interventions, misuse of fertilizers, and pesticides. The unwanted environmental problems should be avoided by developing and implementing integrated management technologies along the food supply chain (Chang et al., 2021).

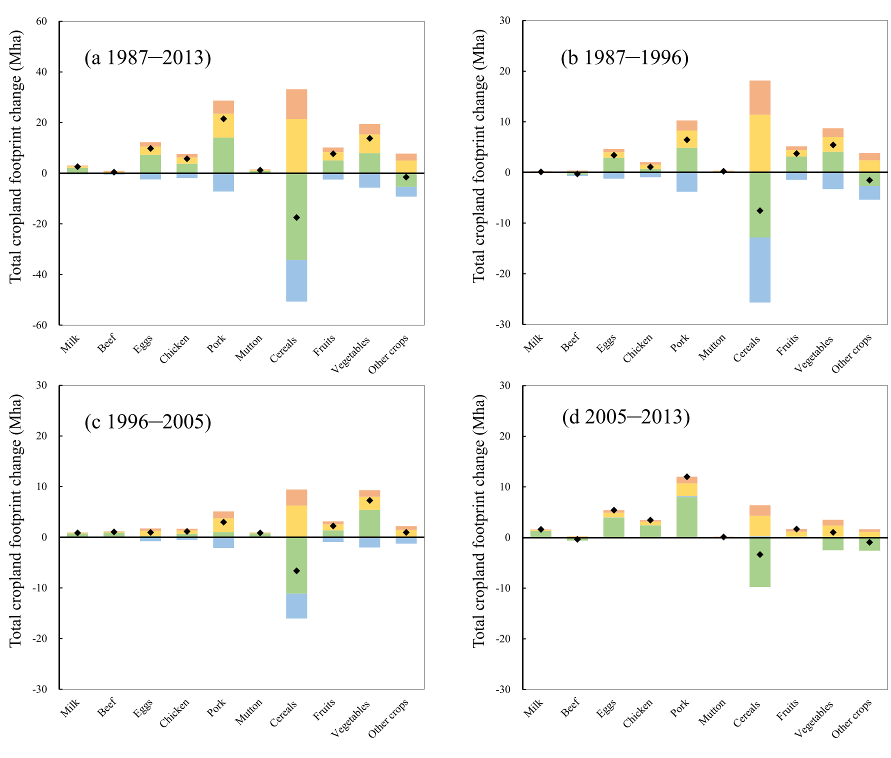

Fig. 7. Decomposition of changes in cropland footprint of different food items in China from 1987 to 2013.

Vegetable production and associated harvested areas have significantly increased over the past three decades. China is the world's primary vegetable-producing country, accounting for half of global vegetable production and 41% of the global harvested vegetable area (FAOSTAT, 2021; Ti et al., 2015). Our results showed a 110% increase in the cropland area dedicated to vegetables and vegetable oils during the study period, contributing 11% to the total global cropland footprint of China's food supply in 2013. The results of a previous study also indicated that the arable land needed for vegetable oils increased about two times from 1981 to 2016 (He et al., 2019). The demand for vegetables in China has continuously increased due to rising income and a shift towards healthier diets. Per capita vegetable consumption in 2021 was 110 kg per year, according to the National Bureau of Statistics, whereas the Chinese Dietary Guidelines (2021) propose a yearly consumption of 182.5 kg per person.

Besides cropland use, other environmental impacts should also be considered. For instance, the nitrogen use efficiency of cereals in China was only 32% in 2017, lower than the global average of 55% (China Ministry of Agriculture, 2017). For vegetables, nutrient losses per unit of cropland were often higher than that of other crops, i.e., 86 kg $N{\cdot}ha^{-1}$ for Chinese vegetable production systems, mostly in the form of nitrate leaching (82% of applied N) (Wang et al., 2021; Zhang et al., 2021, 2022). Strategies should be developed to increase yield while minimizing environmental costs. A recent study demonstrated that an integrated knowledge and production strategy could increase yield by 17%, reduce nitrogen surplus by 65%, and avoid an additional 1.1 Mha of land expansion (Wang et al., 2021).

4.2. Changes in cropland use for animal-sourced food supply

Our results indicated a significant increase in the global cropland footprint of animal-sourced food between 1987 and 2013, accounting for 74 Mha or 44% of China's total cropland footprint for food and feed supply in 2013. The expansion of the livestock production sector in China has been a major driver of global land-use changes (Bai et al., 2021; Winkler et al., 2021). The cropland area used for feed production for pork and eggs has substantially increased over the past decades (Bai et al., 2018). Our findings showed an approximate doubling of per capita pork consumption and a three-fold increase in egg consumption. The development of industrial farms relied more on concentrate feed (e.g., maize, rice, and soybean) from croplands, leading to competition with food production, while animals in traditional farms primarily feed on swill or food waste, which has a smaller or no land footprint (Hou et al., 2021).

The demand for ruminant products (milk, beef, and mutton) has increased significantly over time. Ruminants can efficiently use grassland and marginal land that cannot be directly used for plant-sourced food production (Eshel et al., 2018). From a circular food system perspective, ruminants are considered land-saving animals because they can utilize "low opportunity cost" feedstuffs, such as crop residues and by-products from food processing, thus avoiding feed-food land competition (Röös et al., 2017; van Hal et al., 2019; Van Kernebeek et al., 2016).

The virtual croplands associated with China's crop trade have gradually increased during the study period (Qiang et al., 2013). In 2013, the total virtual cropland of import was 29 Mha, slightly lower than that reported previously (33 Mha) (Xu et al., 2019). In 1987, croplands associated with imports of animal feed accounted for only 4% of the overall virtual croplands, but this percentage increased to 17% by 2013. South American countries, such as Brazil and Argentina, are now the main exporting countries, leading to a growing impact of China's animal food demand on the global environment. For example, soybean imports from South American countries are emission-intensive (Hong et al., 2022; Taherzadeh and Caro, 2019). Brazil accounts for 48% of all humid tropical forest clearing, which presents a notable threat to the conservation of this ecosystem. Meta-analysis revealed that more studies identified agribusinesses (cattle ranching, soybean farming, and plantation agriculture) as drivers of deforestation after 1990 (Rudel et al., 2009; Arima et al., 2011; Macedo et al., 2012; Henders et al., 2015). Previous research revealed that the increased demand for soy was mostly tied to export markets for animal feed in Europe and Asia (Nepstad et al., 2006, 2008). Furthermore, there is evidence linking deforestation to soybean cultivation (Morton et al., 2006; Macedo et al., 2012). China, as the largest importer of soybeans, has become a significant source of globally traded feed nitrogen (Bai et al., 2018; Sun et al., 2018). To address the pressure on cropland use for feed concentrate production (primarily used for pigs and chickens), various key strategies along the feed supply chain can be developed and implemented in practice: (1) insects as feed for livestock production to reduce the utilization of high-protein feed crops (Müller, 2023); (2) tapping into new traits and improving the genetics of animals to enhance resilience and reduce environmental impact (Poppe et al., 2020); (3) implementing integrated soil–crop management to increase feed crop yields (Liu et al., 2021).

4.3. Dietary changes: increase or decrease in cropland use?

Dietary changes play a crucial role in the historical changes in China's cropland footprint. The per capita supply of human food in 2013 increased by 49% relative to 1987. As the increase in population growth during this period was approximately 25%, the change in per capita food consumption (expressed in protein) has exceeded population growth and has become the primary driver behind the increased cropland footprint. Rapid growth in citizen income, urbanization, and demand for animal-sourced food has stimulated per capita food consumption. In particular, consuming more animal-sourced food in diets exerted great pressure on agricultural land in China because richer diets require more cropland for feed production. Currently, the per capita supply of animal products in China is 41.6 g of protein per day, which is lower than the average level in Europe (65.5 g of protein per day) (FAOSTAT, 2021). It is likely that the demand for animal products will continue to increase in the future, further increasing the pressure on land-use changes if effective measures are not implemented.

Choosing more environmentally friendly animal products in the diet can mitigate environmental impacts and alleviate pressure on natural resources (Aleksandrowicz et al., 2016; Hayek et al., 2020; Mertens et al., 2019; Peters et al., 2016; van Zanten et al., 2018). The development of plant-based meat has been suggested as a possibility for replacing livestock products (Mogensen et al., 2020; Smil, 2002). However, these measures come with uncertainties, including higher direct energy requirements and food safety concerns (Alexander et al., 2017; Mattick et al., 2015). Achieving the United Nations' 2030 Sustainable Development Goals requires joint efforts at the national and global levels, with each nation developing policy measures from food supply and demand perspectives (Kanter et al., 2016). Our findings emphasized the importance of analyzing cropland footprints at disaggregated levels to provide more specific dietary advice.

5. Implications and conclusions

The aim of this study was to enhance our understanding of the historical changes in the cropland footprint of China's food supply and the driving forces behind them. We tried to provide insights at a disaggregated food category level, using more detailed land footprint assessment methods compared to previous studies. Our assumptions may have led to some bias in our results, especially the virtual cropland footprint. Also, it is important to acknowledge the limitations of our methods due to data constraints, which prevented us from examining variability within the country. Exploring strategies such as the spatial reallocation of food production between regions could be an effective approach to alleviate land-use pressure. Studies conducted in India have shown that crop redistribution reduced land input by 9% while still meeting the population's micronutrient demands (Damerau et al., 2020). Additionally, we also analyzed the relationship between protein or energy intake and land-use footprint. In future research, it would be beneficial to consider other nutrients, such as trace elements and vitamins, to evaluate the efficiency of land use.

Our findings highlighted the need of assessing cropland footprints at disaggregated levels, as well as the factors that influence cropland footprint variations over time. Moreover, the study revealed data gaps to further improve the prediction of future changes in cropland demand. Furthermore, we can conclude that technological advancements have played a positive role in increasing cereal crop yields, thus preventing the need for extensive cropland expansion. However, the improvement in cropland use efficiency has slowed in recent years, partly due to the increased use of low-efficiency cropland for animal feed. It is crucial to focus on developing enhanced cropland management options for low-efficient feed crop production. The differences observed among food items have implications for agricultural and environmental policies. Our methodology enables the assessment of the potential impacts of changes in agricultural policy (e.g., low protein feeding of animals) and land-use policy (e.g., adjustment of planting structure). This can inform recommendations on improving cropland use efficiency for specific food categories, promoting more targeted diets, and mitigating land-use related environmental impacts.

CRediT authorship contribution statement

Xiaoying Zhang: Data curation, Formal analysis, Visualization, Writing – original draft. **Qunchao Fang:** Data curation, Writing – review & editing. **Guichao Dai:** Data curation, Writing – review & editing. **Jingmeng Wang:** Methodology, Supervision. **Martin K. van Ittersum:** Writing – review & editing. **Hongliang Wang:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Yong Hou:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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