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Changes in agricultural land requirements for food provision in China 2003–2011: A comparison between urban and rural residents

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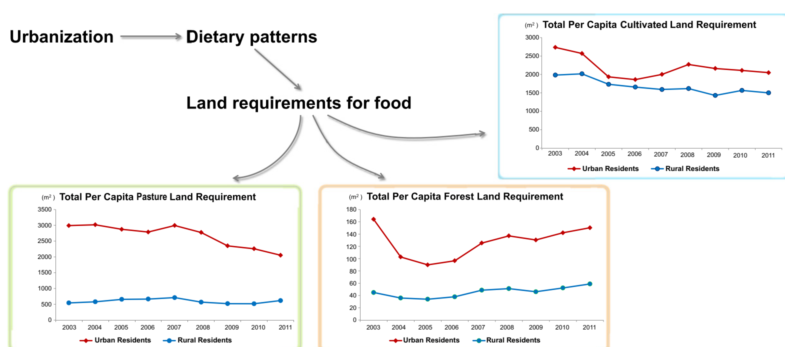
HIGHLIGHTS

- We examine the changes in three types of agricultural land requirements for food.
- Per capita cultivated land requirements for both groups of residents decreased.
- Per capita pasture and forest land requirements for rural residents increased.
- Per capita pasture and forest land requirements for urban residents decreased.
- Dietary changes can have significant consequences on agricultural land demand.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid income growth and urbanization have led to significant changes in food consumption patterns in China. The impact of dietary changes is likely to increase agricultural land demand for food provision. This study investigates the changes in three types of agricultural land requirements for urban and rural residents in China using embodied land use intensities. Our results indicate that total per capita cultivated land requirement of rural residents decreased by 24.3%, from 1984 to 1501 m^2 during the study period, while total per capita cultivated land requirement for urban residents decreased by 25.1%, from 2736 to 2049 m^2. Total per capita pasture land requirement of rural residents increased by 13.6%, from 543 to 617 m^2, while total per capita pasture land requirement of urban residents decreased by 31.4%, from 2991 to 2053 m^2. Total per capita forest land requirement of rural residents increased by 31.0%, from 45 to 59 m^2, while total per capita forest land requirement of urban residents decreased by 8.4%, from 164 to 150 m^2. Our study provides clear implications about the linkages between dietary change and agricultural land demand. Our results imply that without sufficient improvement in production efficiency, pressures posed by dietary change on land resources related to the provision of food will remain high in the future.

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1. Introduction

Given the largest population size and limited land resources in China, the area of available agricultural land plays a fundamental role in maintaining the country's food security. However, challenge exists associated with sufficient food supply due to the increasing scarcity of land with high quality and productivity. In 2015, the area of cultivated land per capita in China was about 0.09 ha, compared to 0.47 ha in the United States and 0.19 ha for the world average (NBSC, 2016). Although certain debate exists, most research shows that China has been experiencing considerable losses of cultivated land (Chien, 2015; Song and Deng, 2015; Zhong et al., 2011). Rapid industrialization, urbanization and the resulting urban land expansion are important drivers of the conversion of cultivated land (Jiang et al., 2012). A more gloomy aspect with respect to food provision is that most urban conversion of cultivated land has taken place in the coastal or southern provinces of the country, the areas highly productive for agriculture (Yue et al., 2010). At the same time, pasture and forest land degradation has aggravated in many regions of China as a result of inappropriate or unsustainable land use and management (Guo et al., 2019). It is expected that with continued urbanization, economic development, and shrinking high-quality agricultural land, there will be a substantial stress on the available land resources and food provision capacity.

Land requirements for food depend on population numbers, dietary patterns, and the production system (Gerbens-Leenes et al., 2002; Kastner and Nonhebel, 2010). Historically, population growth was a crucial factor driving higher demand on agricultural land. As population growth rates decline, the relative importance of dietary change in driving growing land demand for food will increase (Kastner et al., 2012). According to national data in the China Statistical Yearbooks, the annual average growth rate of China's population is 6.7‰ between 1995 and 2011, far below the world average of 12.9‰. During the same period, per capita grain consumption decreased by 16.8% and 34.1% for the diets of urban and rural residents, while per capita consumption for meat increased significantly by 24.9% and 44.6% for the diets of urban and rural residents (NBSC, 1996–2012). Given that producing one unit of livestock products requires more than three times as much land as one unit of grain (Gerbens-Leenes et al., 2002), the rapid rise in the demand of meat and other livestock products may result in a considerable increase in land demand for food. A large number of previous studies have also demonstrated that dietary patterns in China have become diverse and richer, characterized by an increase in the share of animal products, and a decline in the share of grain in total food consumption (Dong and Fuller, 2010; Tian and Yu, 2015; Xiong et al., 2020). The rapid rate of transfer towards more affluent diets has been witnessed in both urban and rural China (Li et al., 2013; Zhen et al., 2010). It is also observed that an urban diet tends to include higher proportions of animal products than a rural diet (Tian and Yu, 2015; Jiang et al., 2015). By contrast, yield increase and efficiency improvements through the supply chain cause less land demand (Kastner et al., 2012). Diets and food production efficiency change over time, leading to changes in land requirements for food, which may vary significantly between the urban and rural populations.

Therefore, understanding the integrated effect of the changes in diets and production efficiency on the area of agricultural land required to feed a person is critical as an evaluation of future food supply. To date, empirical studies that explore land requirements based on food consumption patterns are limited (Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes et al., 2002; Kastner and Nonhebel, 2010; Kastner et al., 2012; Li et al., 2013; Zhen et al., 2010; Jiang et al., 2015). All of these studies focused on cultivated land requirements and relied on crop yield to derive the calculations. Using this method, the land requirements calculated from these previous studies only consider land use in the process of agricultural production, without taking account of land resources required for food provision through the whole supply chain. Unlike the previous studies, our study systematically explores the changes in three types of agricultural lands required—cultivated land, pasture land, and forest land, and considers changing efficiency through the whole supply chain.

To calculate the agricultural land requirements for food provision, we first calculate embodied land use intensities for cultivated land, pasture land, and forest land in China, by using the input-output analysis (IOA). IOA is a well-established approach that enables us to probe into the driving effect of final consumption on resource use or other negative environmental impacts (Leontief, 1970). This approach has not only been extensively used to study energy use (Kan et al., 2019; Liu et al., 2012; Moreau and Vuille, 2018), water use (Guan et al., 2014; Guo and Shen, 2015; Lenzen et al., 2013a; Steen-Olsen et al., 2012), CO_2 and other air pollutant emissions (Mi et al., 2017; Ou et al., 2017; Peters and Hertwich, 2008), but also has been widely applied for land use assessment (Bruckner et al., 2019; Chen et al., 2018; Guo et al., 2014; Kastner et al., 2014).

This study investigates the changes in agricultural land required for food provision in China from 2003 to 2011, with a comparison between the urban and rural residents. We focus specifically on the changes in three types of agricultural lands required—cultivated land, pasture land, and forest land. These three types of lands together account for nearly 95% of total quantity of available agricultural land in China, and therefore play a central role in the provision of food of this country (Moreau and Vuille, 2018). Using the environmentally extended input-output analysis, we ask the following research questions. What are the patterns of changes in cultivated land demand for the two groups of residents? What are the patterns of changes in pasture land demand for the two groups of residents? What are the patterns of changes in forest land demand for the two groups of residents? What is the contribution of various food categories to the development of per capita land demand? What are the linkages between dietary patterns and agricultural land demand for the urban and rural residents?

2. Methodology and data

2.1. Calculating embodied land use intensities and agricultural land requirements

We calculate embodied land use intensities for cultivated land, pasture land, and forest land in China during 2003–2011 based on the environmentally extended input-output analysis, which is recognized as a powerful tool to calculate the total (including direct and indirect) resource use of goods/services through their entire lifetime. Since Leontief integrated the traditional economic input-output analysis into environmental accounting for the first time (Leontief, 1970), this method has been widely applied to account for various ecological elements, including land, water, energy, etc. (Wiedmann, 2009; Wiedmann and Lenzen, 2018). Considering that the economies are increasingly connected with each other via international trade, we calculate the embodied land use intensities of China under the context of global complex trading network using a multi-regional input-output model, which simulates the world as an m region×n sector economic system. The model mainly includes an interregional and inter-sector transaction matrix, a final demand matrix, and a total output matrix. The basic balanced relation could be expressed as:

$$\mathbf{AX} + \mathbf{Y} = \mathbf{X} \tag{1}$$

where $\mathbf{X}$ is the output matrix ($mn\times1$), whose element x_i^r denotes the total output of sector i in region r; $\mathbf{A}$ is the technology coefficient matrix ($mn\times mn$), whose element a_{ij}^{rs} represents the input needed for each unit of output of sector j in region s from sector i in region r; $\mathbf{Y}$ is the final demand matrix ($mn\times1$), whose element y_i^r stands for the output of sector i in region r to satisfy the total final demand.

Eq. (1) can be also converted into:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \tag{2}$$

where $\mathbf{I}$ is the identity matrix and $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ is the Leontief inverse matrix. The Leontief inverse matrix could be calculated as:

$$(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{Y}/\mathbf{X} \tag{3}$$

When the economic input-output analysis is extended to environmental input-output analysis, an additional row L is introduced to represent the direct resource use. If we denote $\mathbf{L}$ as a $1 \times mn$ row vector, whose element l_i^r is the direct land use intensity of sector i in region r, the embodied land use intensity matrix could be calculated as follows:

$$\boldsymbol{\varepsilon} = \mathbf{L}(\mathbf{I} - \mathbf{A})^{-1} \tag{4}$$

where $\boldsymbol{\varepsilon} = (\varepsilon_i^r)_{1\times mn}$, with ε_i^r representing the total land use areas needed for one unit of sectoral output.

To calculate the agricultural land demand for food provision, we investigate the relationship between food expenditure and three types of agricultural lands required during 2003–2011. In this study, agricultural land requirements are restricted to the requirements of cultivated land, pasture land, and forest land. It is assumed that the food consumption of urban and rural residents is either produced within China or imported. We calculate per capita land requirements with data on per capita food expenditures for different food categories and embodied land use intensities, i.e., gross land use through the supply chain for the production of concerned food categories evaluated as per unit monetary value. Except for grain, embodied land use intensities of all food categories are available from the output of the IOA. We calculate embodied land use intensities for grain using embodied land use intensities for wheat and for rice, weighted by per capita consumption of wheat and rice for rural residents. Combining information on per capita food expenditures and embodied land use intensities for cultivated land, pasture land, and forest land of each food category, we are able to derive agricultural land required to sustain an average urban or rural diet during 2003–2011.

2.2. Data

Monetary input-output tables (IOTs) and land use data are both derived from Exiobase3. This database provides the global multi-regional input-output tables as well as the corresponding environmental and social accounts (Stadler et al., 2018). It includes 44 major economies (such as China, USA, 27 EU members, UK, etc.) and 163 sectors. The harmonized and detailed national supply-use tables are based on official government data, and the bilateral trade data are mainly sourced from UN Comtrade database and UN services trade database.

Exiobase3 database is used in this study, largely due to its high sectoral resolution, good data continuity, and the matching environmental accounts. Specifically, Exiobase3 includes 17 specific agriculture-related sectors, while other similar databases, such as Eora global supply chain database, only have an aggregated agriculture sector (Lenzen et al., 2013b). Moreover, IOTs derived from Exiobase3 cover a long period from 1995 to 2011, while those from other databases, such as Global Trade Analysis Project (GTAP) database, are only available for several benchmark years (Aguiar et al., 2016). In addition, Exiobase3 provides the matching land-use database, which includes data for cultivated land, pasture land and forest land. In this study, we use data from Exiobase3 to calculate embodied land use intensities for cultivated land, pasture land, and forest land in China during 2003–2011.

We use data on food consumption and expenditures that are originally from the Urban and Rural Household Income and Expenditure Surveys carried out by the National Bureau of Statistics of China (NBSC). These annual household surveys, which target both urban and rural households at different income levels, aim at collecting information on the livelihoods of the representative households. The data used in the present study are national-level aggregate data for 2003–2011. We obtain data on per capita food consumption, and expenditures for rural and urban households from the China Statistical Yearbooks (NBSC, 2004–2012). These data are then organized into thirteen food categories—grain, oil and fat, vegetables, fruit, pork, beef, mutton, poultry, aquatic products, eggs, dairy, liquor, and other foods. Subtracting the expenditures of the first twelve categories from the total food expenditure for urban households arrives at the expenditure of other foods for urban households. Data on the expenditures of specific categories for rural households are not available. Therefore, the expenditures of the first twelve categories for rural households are inferred by multiplying the quantity of these categories for rural households by the price of these categories, which are derived using data on urban food consumption and expenditures. Again, the expenditure of other foods for rural households is calculated in the same way as that for urban households. The final data sets on food expenditures presented in this study are two panel data sets—one for rural residents and the other for urban residents.

3. Results

3.1. Per capita requirements of three agricultural land categories

3.1.1. Cultivated land requirements

The total cultivated land requirements for urban residents were higher than those for rural residents during 2003–2011 (Tables 1 and 2). In 2011, the total per capita cultivated land demand for urban residents was 2049 m^2, much higher than the amount of 1051 m^2 for rural residents. Except for grain, the urban residents have larger

Table 1
Cultivated land requirements of various food categories per urban resident, 2003–2011.

Food category	Per capita land requirement (m^2)								
	2003	2004	2005	2006	2007	2008	2009	2010	2011
Grain	659.6	700.3	621.9	582.9	541.3	497.6	454.0	586.8	557.5
Oil and fat	369.2	348.5	307.3	290.8	379.9	460.1	345.3	298.8	262.9
Vegetables	99.6	96.0	96.6	96.8	97.1	86.0	87.1	96.2	94.9
Fruit	73.6	70.9	72.3	77.9	75.8	61.7	64.9	72.6	80.9
Pork	976.4	850.6	469.0	464.8	544.2	737.8	750.3	626.5	636.9
Beef	13.9	19.8	18.2	15.3	14.6	14.0	14.5	17.6	16.8
Mutton	9.3	12.1	11.4	8.7	7.6	7.7	8.1	8.7	7.2
Poultry	388.9	311.4	180.1	172.3	228.1	275.2	290.5	239.0	236.5
Aquatic products	28.1	27.1	24.0	21.0	18.8	27.7	34.2	38.6	38.9
Eggs	8.2	10.2	10.8	13.2	9.0	9.8	11.3	14.3	12.5
Dairy	26.6	18.2	18.2	22.5	12.6	20.7	23.6	23.8	23.8
Liquor	59.0	79.7	80.1	68.4	55.1	54.7	61.5	65.6	61.1
Other foods	23.2	24.8	25.5	26.4	17.7	17.5	17.0	21.0	19.0
Total	2735.5	2569.7	1935.2	1861.0	2001.9	2270.8	2162.4	2109.4	2048.9

Table 2
Cultivated land requirements of various food categories per rural resident, 2003–2011.

Food category	Per capita land requirement (m^2)								
	2003	2004	2005	2006	2007	2008	2009	2010	2011
Grain	1197.4	1276.5	1155.3	1095.0	969.2	954.9	720.0	900.4	816.1
Oil and fat	138.3	105.6	111.5	101.5	139.0	147.2	131.9	128.7	129.7
Vegetables	58.6	54.6	57.1	57.4	56.8	42.7	48.5	53.3	51.3
Fruit	14.5	13.9	15.0	17.1	17.2	13.4	16.1	18.1	22.9
Pork	427.4	389.5	248.9	249.2	278.3	297.1	348.2	300.1	308.1
Beef	2.3	2.7	3.5	3.0	2.7	2.2	2.3	3.0	4.1
Mutton	3.5	4.7	4.5	4.0	3.3	2.8	3.4	3.8	3.9
Poultry	87.8	99.9	50.5	50.3	63.5	92.0	80.4	67.3	70.2
Aquatic products	6.4	6.4	6.5	5.6	5.0	7.5	10.1	9.0	9.9
Eggs	2.3	2.9	3.3	4.4	2.9	3.0	3.9	5.1	4.6
Dairy	1.6	1.2	2.0	2.7	1.7	2.9	3.9	4.2	6.2
Liquor	31.3	45.6	59.5	51.9	42.7	42.1	52.8	62.7	63.5
Other foods	12.6	14.2	15.5	16.2	10.4	9.9	9.5	12.0	11.0
Total	1983.8	2017.9	1733.0	1658.2	1592.6	1617.8	1430.9	1567.7	1501.4

quantities of per capita cultivated land demand for all food categories. The more affluent dietary patterns of urban residents which contained more animal products and less grain than rural residents directly resulted in the greater total cultivated land requirements associated with the former.

From 2003 to 2011, decreasing cultivated land requirements were a common feature observed for both groups of residents. This indicates that land-saving effects due to efficiency increases through the supply chain exceeded the influences from changes in dietary patterns. However, large differences between the two groups of residents exist in the rates of decrease as well as changes in the contribution of various categories to per capita cultivated land demand. Total per capita cultivated land demand for rural residents decreased by 24.3%, more slowly than that of the urban residents, from 1984 $m^2$to 1501 m^2. The proportion of cultivated land demand represented by animal products increased for rural residents from 26.8% to 27.1%, while the proportion taken by grain declined from 60.4% to 54.4%. By contrast, the proportions represented by animal products and grain for urban residents showed opposite changing trends compared to rural residents.

3.1.2. Pasture land requirements

There was a large disparity in pasture land requirements between the two groups of residents during 2003–2011 (Tables 3 and 4). In 2011, the total per capita pasture land demand for urban residents was 2053 m^2, around three times the amount of 617 m^2 for rural residents. The primary reason for this was that urban residents consumed much greater quantities of dairy, beef, and mutton than rural residents. These three food categories, which were pasture land intensive in production, together accounted for more than 85% of total pasture land demand for both groups of residents.

From 2003 to 2011, the total per capita pasture land demand for urban residents decreased by 31.4%, while the total per capita pasture land demand for rural residents increased by 13.6%. This suggested that although food production became more area-efficient, the rural residents might experience more significant increases in the consumption of some food categories that were pasture land intensive. It was also found that changes in the contribution of some important categories to per capita pasture land demand varied between urban and rural residents. Notably, the relative proportion of pasture land requirements for rural residents had largely shifted to dairy, which represented 11.9% of pasture land requirement in 2003 and 44.0% in 2011. The proportional share accounted for by dairy for urban residents also increased, but less strongly than that of the rural residents.

3.1.3. Forest land requirements

In general, forest land requirements for both groups of residents were much smaller in magnitude compared to their cultivated and pasture land requirements (Tables 5 and 6). In 2011, the total per capita forest land requirement for urban residents was 150 m^2, about 2.5 times the amount of 59 m^2 for rural residents. The likely reason for this was that urban residents consumed a much greater quantity of poultry than rural residents. The poultry, which needed relatively more forest land area in production, took more than 35% of total forest land demand for both groups of residents in 2011.

From 2003 to 2011, the total per capita forest land requirement for urban residents decreased by 8.4%, while the total per capita forest land requirement for rural residents increased by 31.0%. This implied that although food production became more area-efficient, the rural residents might experience more significant increases in the consumption of some food categories that were forest land intensive, such as

Table 3
Pasture land requirements of various food categories per urban resident, 2003–2011.

Food category	Per capita land requirement (m^2)								
	2003	2004	2005	2006	2007	2008	2009	2010	2011
Grain	0.6	0.7	0.6	0.5	0.4	0.4	1.0	0.5	1.2
Oil and fat	15.7	17.8	18.9	21.5	27.2	39.4	27.4	25.5	30.3
Vegetables	1.2	1.1	1.3	1.1	1.0	0.4	0.3	0.6	0.4
Fruit	0.9	0.8	1.0	0.9	0.8	0.3	0.2	0.4	0.3
Pork	4.3	7.0	6.0	4.7	4.3	6.4	4.8	7.8	8.6
Beef	1006.0	1175.9	1135.8	1118.8	1340.9	1012.2	728.8	714.7	590.1
Mutton	675.7	720.0	712.5	636.0	693.7	556.2	404.2	353.1	251.4
Poultry	151.4	135.7	75.7	61.6	78.4	90.7	91.5	65.9	61.6
Aquatic products	20.0	20.2	19.7	17.3	18.6	26.2	35.3	42.4	45.2
Eggs	4.8	6.7	6.8	6.1	5.4	4.9	8.7	4.7	7.4
Dairy	1084.9	903.8	867.1	892.9	803.4	1019.9	1031.0	1026.9	1042.4
Liquor	14.7	15.2	15.7	14.8	11.6	9.7	10.4	9.8	8.8
Other foods	10.4	12.4	12.0	9.8	8.3	6.4	5.1	5.7	4.7
Total	2990.5	3017.4	2873.1	2786.2	2994.0	2773.1	2348.9	2257.8	2052.5

Table 4
Pasture land requirements of various food categories per rural resident, 2003–2011.

Food category	Per capita land requirement (m^2)								
	2003	2004	2005	2006	2007	2008	2009	2010	2011
Grain	1.0	1.2	1.1	0.9	0.8	0.7	1.6	0.7	1.7
Oil and fat	5.9	5.4	6.9	7.5	10.0	12.6	10.5	11.0	15.0
Vegetables	0.7	0.6	0.8	0.7	0.6	0.2	0.2	0.3	0.2
Fruit	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Pork	1.9	3.2	3.2	2.5	2.2	2.6	2.2	3.7	4.2
Beef	165.0	162.1	218.2	215.8	245.3	156.6	116.9	122.7	144.5
Mutton	250.6	277.3	283.1	289.9	299.4	204.0	169.0	155.9	135.6
Poultry	34.2	43.6	21.2	18.0	21.8	30.3	25.3	18.6	18.3
Aquatic products	4.5	4.8	5.3	4.6	4.9	7.1	10.4	9.9	11.5
Eggs	1.4	1.9	2.1	2.0	1.7	1.5	3.0	1.7	2.7
Dairy	64.6	62.1	94.8	106.5	111.0	141.2	169.6	179.8	271.7
Liquor	7.8	8.7	11.6	11.3	9.0	7.5	8.9	9.3	9.2
Other foods	5.6	7.1	7.3	6.0	4.8	3.6	2.9	3.2	2.7
Total	543.3	578.2	655.8	665.9	711.6	568.0	520.6	516.9	617.4

poultry. The results also show that changes in the contribution of some important categories to per capita forest land demand differed between urban and rural residents. The categories that contributed most strongly to the increase in forest land demand for rural residents were liquor, followed by aquatic products. Poultry was the primary category contributing to the decrease in forest land demand for urban residents.

3.2. Cultivated land requirements related to different processes of food provision

Using grain and pork as two representative food categories, we calculate and compare cultivated land requirements related to different processes of food provision—the production and processing processes (Figs. 1 and 2). These two food categories are selected because grain represents the traditional staple food, while pork takes a dominant share in per capita livestock consumption in China. Specifically, we use the embodied cultivated land use intensities associated with different processes of food provision, and data on per capita food expenditures to conduct the analysis. The results display that the processing process contributed more to cultivated land demand for pork than for grain during 2003–2011. For example, the processing represented 11.6% of cultivated land demand for pork, and only 7.7% of cultivated land demand for grain in 2011. In addition, from 2003 to 2011, the relative share of cultivated land demand taken by the processing decreased for both grain and pork. The share represented by the processing for pork declined from 23.4% to 11.6%, much faster than the decreasing rate for grain. The results of this analysis suggest that indirect cultivated land use during the processes of food processing, packaging, and distribution is likely more significantly contribute to cultivated land demand for livestock provision. Other than agricultural productivity increase linked with the production process, technology upgrading and efficiency improvements during the processing processes are also with great potential in reducing cultivated land demand for the provision of livestock products.

3.3. The contribution of three agricultural land categories to total land demand

We further analyze the changes in the contribution of three agricultural land categories to total land demand in order to understand the linkages between dietary patterns and the land demand structure changes (Figs. 3 and 4). Our results reveal that richer dietary patterns are likely associated with greater shares of total agricultural land demand represented by pasture land and forest land. First, we note that the diets associated with urban residents were more affluent relative to the diets of rural residents. The results of additional analysis showed that the relative share of total agricultural land demand represented by pasture land and forest land for urban residents was significantly higher than that for rural residents during 2003–2011. In 2011, the proportional share accounted for by pasture land and forest land for urban residents was 51.8%, much greater than that of 31.1% for rural residents. Moreover, we note that rural residents underwent rapid dietary changes characterized by a rising consumption of livestock products during 2003–2011. The results of additional analysis indicated that the proportional share accounted for by pasture land and forest land for rural residents increased sharply from 22.8% in 2003 to 31.1% in 2011, while the proportion represented by cultivated land decreased. How to explain this? Richer dietary patterns are characterized by an increased consumption of livestock products, many of which need relatively more pasture and forest land areas in production. For example, according to the embodied land use intensities from our input-output analysis, dairy, beef, and mutton are pasture land intensive, and poultry is forest land intensive in production. This may lead to the greater relative shares represented by pasture land and forest land in richer diets. The results of additional analysis suggest that as dietary change continues and more agricultural lands are dedicated to livestock production, the importance of pasture land and forest land in the provision of food may increase in the future.

In order to check the accuracy of the results of this study, we compare our results on cultivated land requirements with the results in the previous literature. To our knowledge, very few studies examine cultivated land requirements (Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes et al., 2002; Kastner and Nonhebel, 2010; Kastner et al., 2012; Li et al., 2013; Zhen et al., 2010; Jiang et al., 2015), and none determines pasture land requirements and forest land requirements based on food consumption patterns. Compared to the three

Table 5
Forest land requirements of various food categories per urban resident, 2003–2011.

Food category	Per capita land requirement (m^2)								
	2003	2004	2005	2006	2007	2008	2009	2010	2011
Grain	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.6
Oil and fat	4.4	4.5	4.2	4.3	5.8	11.2	7.6	8.6	9.8
Vegetables	4.1	1.9	3.7	4.6	7.6	3.6	0.3	2.6	2.0
Fruit	3.1	1.4	2.7	3.7	6.0	2.6	0.2	2.0	1.7
Pork	2.1	2.6	2.1	1.9	1.3	1.9	2.1	5.9	4.3
Beef	0.2	0.5	0.4	0.3	0.2	0.2	0.4	1.4	0.9
Mutton	0.1	0.3	0.3	0.2	0.1	0.1	0.2	0.7	0.4
Poultry	107.4	60.6	40.8	42.7	56.1	67.1	70.2	64.7	69.4
Aquatic products	14.4	11.2	12.1	10.4	14.8	18.4	21.3	26.5	29.4
Eggs	2.7	2.4	3.0	3.6	4.3	3.7	3.4	4.0	4.1
Dairy	6.3	2.3	2.9	4.4	3.3	7.5	7.6	7.0	8.8
Liquor	11.6	9.2	11.1	13.3	17.1	14.5	12.9	13.3	13.5
Other foods	7.4	5.6	6.5	7.0	8.5	6.1	3.9	5.3	5.5
Total	164.1	102.7	89.9	96.6	125.4	137.1	130.4	142.1	150.3

Table 6
Forest land requirements of various food categories per rural resident, 2003–2011.

Food category	Per capita land requirement (m^2)								
	2003	2004	2005	2006	2007	2008	2009	2010	2011
Grain	0.4	0.4	0.3	0.3	0.4	0.3	0.5	0.5	0.9
Oil and fat	1.7	1.4	1.5	1.5	2.1	3.6	2.9	3.7	4.8
Vegetables	2.4	1.1	2.2	2.8	4.5	1.8	0.2	1.4	1.1
Fruit	0.6	0.3	0.6	0.8	1.4	0.6	0.1	0.5	0.5
Pork	0.9	1.2	1.1	1.0	0.7	0.8	1.0	2.8	2.1
Beef	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.2	0.2
Mutton	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.3	0.2
Poultry	24.2	19.5	11.4	12.5	15.6	22.4	19.4	18.2	20.6
Aquatic products	3.3	2.6	3.3	2.8	3.9	5.0	6.3	6.2	7.5
Eggs	0.8	0.7	0.9	1.2	1.4	1.2	1.2	1.4	1.5
Dairy	0.4	0.2	0.3	0.5	0.5	1.0	1.2	1.2	2.3
Liquor	6.1	5.3	8.2	10.1	13.3	11.2	11.1	12.8	14.0
Other foods	4.0	3.2	3.9	4.3	5.0	3.4	2.2	3.0	3.2
Total	44.9	35.9	34.0	37.9	48.7	51.2	46.1	52.3	58.8

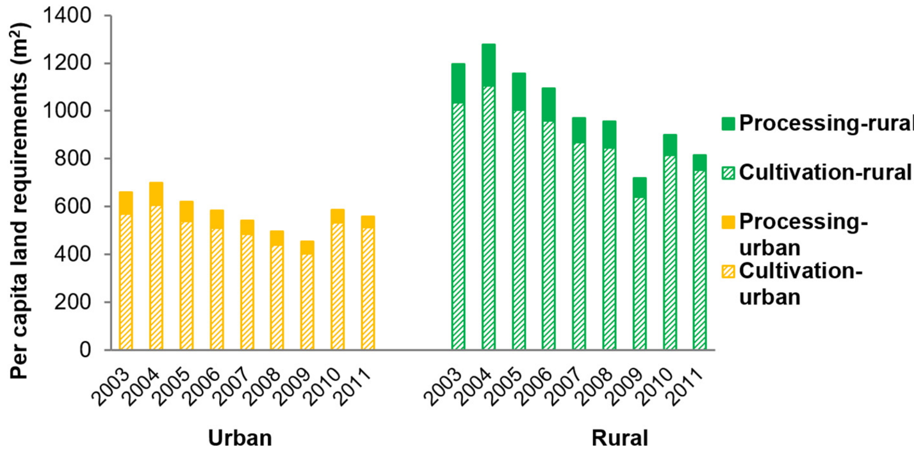

Fig. 1. Per capita cultivated land requirements for grain related to different processes of food provision, 2003–2011.

studies about China (Li et al., 2013; Zhen et al., 2010; Jiang et al., 2015), our estimated total per capita cultivated land requirements are generally larger than those past estimates. For example, our estimated total per capita cultivated land requirement for Chinese rural residents in 2003 is about 1.3 times the estimate for 2004 reported by Zhen et al. Our estimated total per capita cultivated land requirement for Chinese urban residents in 2010 is about 1.5 times the estimate for 2010 reported by Jiang et al. Similar to Li et al., a trend of decrease in total per capita cultivated land requirement is observed for both urban and rural residents in this study. The differences in the magnitude of estimates reported between this study and the previous studies can mainly be explained by the choice of models. Relying on crop yield, the land requirements calculated from all of previous studies only consider land use in the process of agricultural production. Losses in the life cycle of food processing, packaging and distribution cannot be taken account of by using this method. Considering that the environmental extended input-output analysis enables us to trace the amount of land required to sustain the food consumption through the whole supply chain, it is not surprising that the results of this paper are larger.

Our attempt to evaluate the agricultural land requirements for food provision has several limitations. First, ideally longer time series could facilitate the identification of trend. However, the national data on food consumption and expenditures before 2003 are either incomplete or inconsistent. For example, there is inconsistency in specific food categories for the years before 2003, based on which the raw data on food consumption and expenditures need to be organized into thirteen food categories used in this study. Given the data constraint, we are not able to expand the study period to longer time span. Second, uncertainty and inaccuracy exist in our calculations about agricultural land requirements. Due to the lack of information on consumption and expenditure away from home in national data sources, our results do not reflect consumption away from home. Given that both urban and rural residents have consumption away from home and tend to spend more on meat and other land intensive products when they eat outside home (Ma et al., 2006), actual agricultural land requirements are probably greater than our results. Third, the design of this study only examines how much agricultural land was required to provide the respective populations with the prevailing diets. The embodied cross-regional impacts and how dietary patterns in one place affect agricultural land demand in other places are issues worth more exploration.

4. Discussion and policy implications

Our results provide clear implications about the linkages between dietary change and agricultural land demand. The agricultural land requirements for urban residents were much higher in magnitude than those for rural residents during 2003–2011. Due to urban economic development and rising income levels after China's economic reforms in the 1980s, the urban diets tended to include more animal products and processed foods, which had larger land claims in production than plant-based products. The more affluent dietary patterns of urban

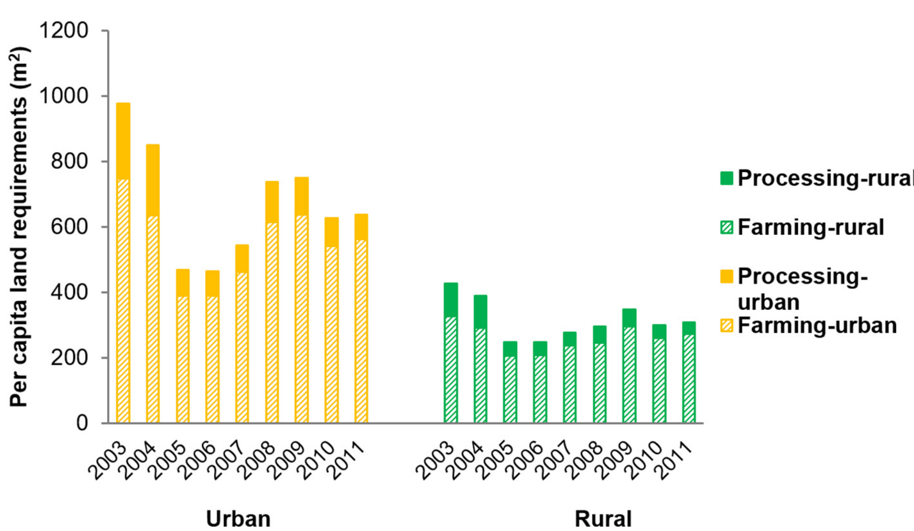

Fig. 2. Per capita cultivated land requirements for pork related to different processes of food provision, 2003–2011.

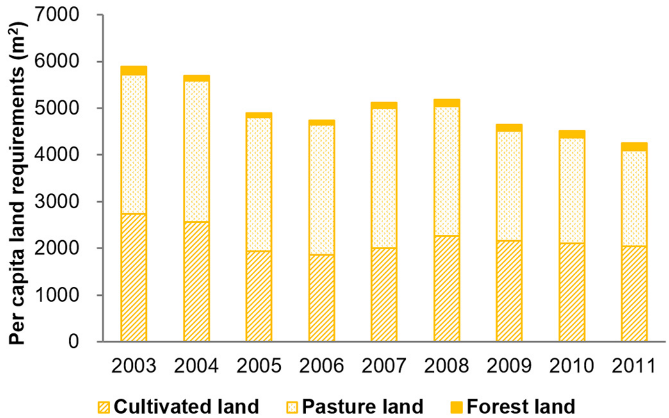

Fig. 3. Per capita requirements of three agricultural land categories for urban residents, 2003–2011.

residents compared to rural residents directly resulted in the greater agricultural land demand associated with the former.

Despite the large difference in agricultural land demand between the urban and rural residents, this difference became smaller during the study period. The reduced gap in agricultural land demand between the two groups of residents basically could be explained by the more rapid dietary change experienced by the rural residents during 2003–2011. Income growth and market development were important socioeconomic factors driving the dietary change. Mainly because of the policy reform promoted by the government aimed at reducing the gap of income between urban and rural areas, the income difference between the two groups of residents became smaller during the study period. The ratio of per capita disposable income of urban residents relative to rural residents declined from 3.23 in 2003 to 3.13 in 2011, and to 2.95 in 2015 (NBSC, 2004–2016). In addition, the market development has accelerated in rural areas since the 2000s. For instance, the expanded retail systems, the involvement of government and overseas investments, and the success of marketing strategies have led to a rapid rise of dairy sector in China (Fuller et al., 2007). Per capita consumption of dairy products for rural residents grew annually at double-digit rates between 2003 and 2011, while per capita consumption of dairy for urban residents exhibited a trend of decrease.

The rapid rate of transfer towards a richer diet of Chinese population implies great pressures on land resources for food provision in the future. We expect that dietary changes may affect future agricultural land demand through two possible trajectories. First, as urbanization proceeds, more people are likely to adopt the more affluent food consumption patterns in urban environments. Second, income growth and market development can induce further structural changes in both urban and rural dietary patterns. Considering the influence from the first trajectory, we can roughly forecast agricultural land demand in China from 2011 to 2050, with the assumption that urban and rural food consumption patterns and production system for the projection years are the same as 2011 (Fig. 5). Data on urbanization rate and total population in China for the projection years are from the 2018 Revision of World Urbanization Prospects (UN, 2018). Our forecasts show that because of urbanization and the resulting dietary shift, the total cultivated land demand, total pasture land demand, and total forest land demand in China will increase from 240.1 to 260.4 million ha, from 182.3 to 237.0 million ha, and from 14.2 to 17.7 million ha respectively during the projection period. Notably, at present, the areas of available cultivated land, pasture land, and forest land in China amounted 134.9, 219.3, and 252.8 million ha (NBSC, 2018). Supplying the Chinese population in 2050 with the dietary patterns and production system in 2011 would suggest that an additional 125.5 and 17.7 million ha of cultivated land and pasture land were required. This will mean tremendous pressures on land resources linked with production and processing of food. Our forecasts also indicate that the pressures on cultivated land will remain the largest among the three agricultural land categories. As indicated by the second trajectory, both urban and rural dietary patterns are likely to move to higher levels. With this influence incorporated, the projected future agricultural land demand and the associated pressures on land resources can be even greater.

Our study sheds some light on the possible solutions for mitigating the pressure on agricultural land. The first solution is further improvement in the efficiency of production and the supply chain. There is evidence that agricultural investments, multiple cropping, land consolidation, and mechanization, which were with great potential for productivity improvement, consistently increased in the inland provinces (Long and Zou, 2010). However, we need to be cautious because many of these options depend on increased use of chemical inputs including fertilizers, pesticides, and fossil fuels, which have substantial environmental consequences. In addition to improvement in agricultural productivity, industrial structure adjustment and the development of tertiary industry such as logistics, transportation, and communication can contribute to the efficiency increase in the supply chain. Note that the results on agricultural land demand presented in this paper are not necessarily equal to the required amount of land under cultivation in the same country, as land displacement takes place more frequently with economic globalization. Therefore, the second possible solution is agricultural trade structure adjustment. As the undergoing dietary change in China is characterized by the rise in the proportion of animal products and processed foods in consumption, increases of land-intensive food and feed imports may alleviate the scarcity of land within the nation. Between 2002 and 2011, imports of oil-crop and soybeans

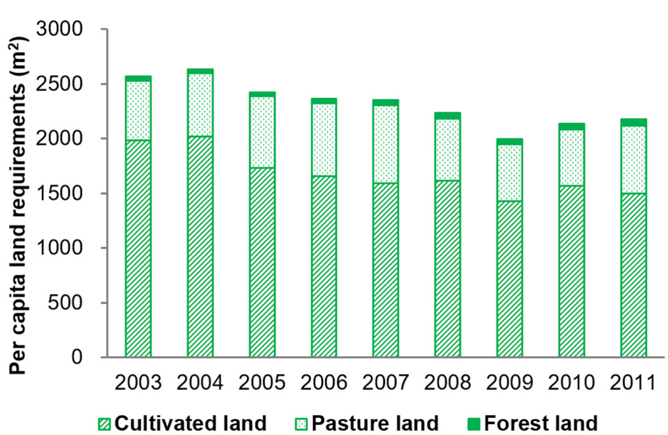

Fig. 4. Per capita requirements of three agricultural land categories for rural residents, 2003–2011.

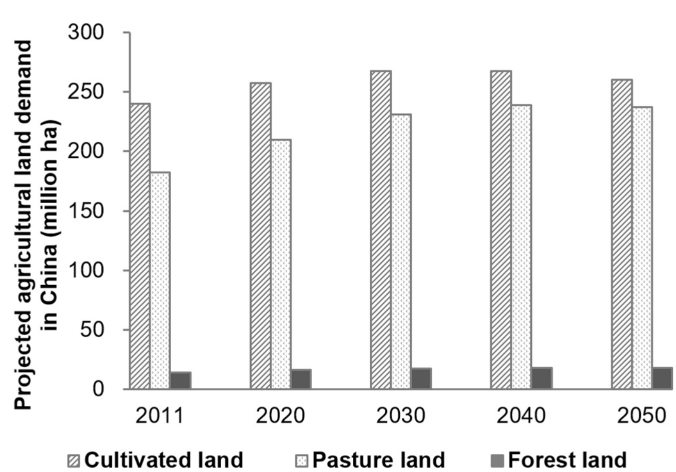

Fig. 5. Projected total agricultural land demand in China from 2011 to 2050.

increased by several folds. China imported more than 80% of the soybeans it consumed in 2011 (NBSC, 2003, 2012). During the same period, imports of beef and mutton increased by 169% and 132% respectively (Li et al., 2013). Imports of dairy products have increased at an annual average rate of 35% since 2003 (NBSC, 2012). The land-saving effects associated with agricultural trade structure adjustment are significant. It was reported that the agricultural sector of China changed from a net exporter to a net importer of cultivated land and pasture land during 1987–2015. The agricultural sector net imported 5.27 million ha of cultivated land in 2007, and net imported 11.16 million ha of pasture land in 2015 via agricultural trade (Guo et al., 2014; Guo et al., 2019).

Our results reveal that a richer dietary pattern is likely associated with an increased share represented by pasture land and forest land in total land demand for food provision. Therefore, in order to achieve the goals of sufficient food provision and land resource protection, land use structure optimization is critical. For example, a nationwide cropland set-aside program known as the Grain for Green was launched by the Chinese government to increase natural land cover and prevent soil erosion on sloped cultivated land (Uchida et al., 2005). In this program, farmers set aside certain types of land and grow trees or grass instead, receiving compensation payment from the central government. However, for the long-term land use sustainability and food security in many less developed regions, land use structure optimization policy needs to consider more elements beyond the Grain for Green. It is suggested that as the low-quality cultivated land is gradually converted into forests and grassland for ecological purposes, the high-quality cultivated land should be protected as basic cropland to meet local people's subsistence (Wang et al., 2007). In addition, investments in agricultural infrastructure and institutions such as tenure security which can enhance the economic returns from farming are also important for maintaining the intensity of the use of the high-quality cultivated land. This will reduce the likelihood of land reconversion from set-aside marginal land back into cultivation.

5. Conclusions

In this paper, we use embodied land use intensities derived from the IOA and food consumption data to investigate the changes in agricultural land requirements for urban and rural residents in China. Particularly, we focus on three types of agricultural lands—cultivated land, pasture land, and forest land. The results show that total per capita cultivated land requirement of rural residents decreased by 24.3%, from 1984 m^2 to 1501 m^2 between 2003 and 2011, while total per capita cultivated land requirement for urban residents decreased by 25.1%, faster than that of the rural residents, from 2736 m^2 to 2049 m^2. Total per capita pasture land demand of rural residents increased by 13.6%, from 543 m^2 to 617 m^2, while total per capita pasture land demand of urban residents decreased by 31.4%, from 2991 m^2 to 2053 m^2. Total per capita forest land demand of rural residents rose by 31.0%, from 45 $m^2$to 59 m^2, while total per capita forest land demand of urban residents decreased by 8.4%, from 164 $m^2$to 150 m^2.

Our results draw attention to the linkages between dietary change and agricultural land demand. Our results suggest that the difference in agricultural land demand between the urban and rural residents became smaller between 2003 and 2011, which could be explained by the more rapid dietary change experienced by the rural residents. Our forecasts indicate that because of urbanization and the resulting dietary shift, the total cultivated land demand, total pasture land demand, and total forest land demand in China will consistently increase from 2011 to 2050. It is expected that without sufficient improvement in production efficiency, pressures posed by dietary change on land resources related to the provision of food will remain high in the future. The promising options for mitigating the pressures on agricultural land include efficiency improvement in production and the supply chain, agricultural trade structure adjustment, and land use structure optimization.

CRediT authorship contribution statement

Li Jiang: Conceptualization, Methodology, Writing - original draft, Writing - review & editing.**Shan Guo:**Methodology, Writing - review & editing.**Gan Wang:**Data curation.**Siyi Kan:**Formal analysis.**Hui Jiang:** 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.

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References

Aguiar, A., Badri, N., Mcdougall, R., 2016. An overview of the GTAP 9 Data Base. Journal of Global Economic Analysis 1 (1), 181–208.
Bruckner, M., Häyhä, T., Giljum, S., Maus, V., Fischer, G., Tramberend, S., et al., 2019. Quantifying the global cropland footprint of the European Union's non-food bioeconomy. Environ. Res. Lett. 14 (4), 045011.
Chen, B., Han, M.Y., Peng, K., Zhou, S.L., Shao, L., Wu, X.F., et al., 2018. Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains. Sci. Total Environ. 613–614 (Supplement C), 931–943.
Chien, S.-S., 2015. Local farmland loss and preservation in China—a perspective of quota territorialization. Land Use Policy 49, 65–74.
Dong, F., Fuller, F., 2010. Dietary structural change in China's cities: empirical fact or urban legend? Can. J. Agric. Econ. 58 (1), 73–91.
Fuller, F., Beghin, J., Rozelle, S., 2007. Consumption of dairy products in urban China: results from Beijing, Shanghai and Guangzhou. Aust. J. Agric. Resour. Econ. 51 (4), 459–474.
Gerbens-Leenes, P.W., Nonhebel, S., 2002. Consumption patterns and their effects on land required for food. Ecol. Econ. 42 (1), 185–199.
Gerbens-Leenes, P.W., Nonhebel, S., Ivens, W.P.M.F., 2002. A method to determine land requirements relating to food consumption patterns. Agric. Ecosyst. Environ. 90 (1), 47–58.
Guan, D., Hubacek, K., Tillotson, M., Zhao, H., Liu, W., Liu, Z., et al., 2014. Lifting China's water spell. Environ. Sci. Technol. 48 (19), 11048–11056.
Guo, S., Shen, G.Q., 2015. Multiregional input–output model for China's farm land and water use. Environ. Sci. Technol. 49 (1), 403–414.
Guo, S., Shen, G.Q., Chen, Z.-M., Yu, R., 2014. Embodied cultivated land use in China 1987–2007. Ecol. Indic. 47, 198–209.
Guo, S., Jiang, L., Shen, G.Q.P., 2019. Embodied pasture land use change in China 2000–2015: from the perspective of globalization. Land Use Policy 82, 476–485.
Jiang, L., Deng, X., Seto, K.C., 2012. Multi-level modeling of urban expansion and cultivated land conversion for urban hotspot counties in China. Landsc. Urban Plan. 108 (2–4), 131–139.
Jiang, L., Seto, K.C., Bai, J., 2015. Urban economic development, changes in food consumption patterns and land requirements for food production in China. China Agricultural Economic Review 7 (2), 240–261.
Kan, S.Y., Chen, B., Wu, X.F., Chen, Z.M., Chen, G.Q., 2019. Natural gas overview for world economy: from primary supply to final demand via global supply chains. Energy Policy 124, 215–225.
Kastner, T., Nonhebel, S., 2010. Changes in land requirements for food in the Philippines: a historical analysis. Land Use Policy 27 (3), 853–863.
Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109 (18), 6868–6872.
Kastner, T., Schaffartzik, A., Eisenmenger, N., Erb, K.-H., Haberl, H., Krausmann, F., 2014. Cropland area embodied in international trade: contradictory results from different approaches. Ecol. Econ. 104, 140–144.
Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., et al., 2013a. International trade of scarce water. Ecol. Econ. 94, 78–85.
Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013b. Building Eora: a global multi-region input–output database at high country and sector resolution. Econ. Syst. Res. 25 (1), 20–49.
Leontief, W., 1970. Environmental repercussions and the economic structure - an input-output approach. Rev. Econ. Stat. 52 (3), 262–271.
Li, G., Zhao, Y., Cui, S., 2013. Effects of urbanization on arable land requirements in China, based on food consumption patterns. Food Security 5 (3), 439–449.
Liu, Z., Geng, Y., Lindner, S., Zhao, H., Fujita, T., Guan, D., 2012. Embodied energy use in China's industrial sectors. Energy Policy 49, 751–758.

Long, H., Zou, J., 2010. Grain production driven by variations in farmland use in China - an analysis of security patterns. Journal of Resources and Ecology 1 (1), 60–67.
Ma, H., Huang, J., Fuller, F., Rozelle, S., 2006. Getting rich and eating out: consumption of food away from home in urban China. Can. J. Agric. Econ. 54 (1), 101–119.
Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., et al., 2017. Chinese CO2 emission flows have reversed since the global financial crisis. Nat. Commun. 8 (1), 1712.
Moreau, V., Vuille, F., 2018. Decoupling energy use and economic growth: counter evidence from structural effects and embodied energy in trade. Appl. Energy 215, 54–62.
NBSC, 1996–2018. China Statistical Yearbooks. China Statistics Press, Beijing, China.
NBSC, 2003–2012. Rural Statistical Yearbooks of China. China Statistics Press, Beijing.
Ou, J., Meng, J., Zheng, J., Mi, Z., Bian, Y., Yu, X., et al., 2017. Demand-driven air pollutant emissions for a fast-developing region in China. Appl. Energy 204, 131–142.
Peters, G.P., Hertwich, E.G., 2008. CO2 embodied in international trade with implications for global climate policy. Environ. Sci. Technol. 42 (5), 1401–1407.
Song, W., Deng, X., 2015. Effects of urbanization-induced cultivated land loss on ecosystem services in the North China Plain. Energies 8 (6), 5678–5693.
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., et al., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multiregional input-output tables. J. Ind. Ecol. 22, 502–515.
Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G., 2012. Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. Environ. Sci. Technol. 46 (20), 10883–10891.
Tian, X., Yu, X., 2015. Using semiparametric models to study nutrition improvement and dietary change with different indices: the case of China. Food Policy 53, 67–81.
Uchida, E., Xu, J., Rozelle, S., 2005. Grain for green: cost-effectiveness and sustainability of China's conservation set-aside program. Land Econ. 81 (2), 247–264.
UN, 2018. The 2018 Revision of World Urbanization Prospects.
Wang, X., Lu, C., Fang, J., Shen, Y., 2007. Implications for development of grain-for-green policy based on cropland suitability evaluation in desertification-affected north China. Land Use Policy 24 (2), 417–424.
Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol. Econ. 69 (2), 211–222.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11 (5), 314–321.
Xiong, X., Zhang, L., Hao, Y., Zhang, P., Chang, Y., Liu, G., 2020. Urban dietary changes and linked carbon footprint in China: a case study of Beijing. J. Environ. Manag. 255, 109877.
Yue, T.-X., Wang, Q., Lu, Y.-M., Xin, X.-P., Zhang, H.-B., Wu, S.-X., 2010. Change trends of food provisions in China. Glob. Planet. Chang. 72 (3), 118–130.
Zhen, L., Cao, S., Cheng, S., Xie, G., Wei, Y., Liu, X., et al., 2010. Arable land requirements based on food consumption patterns: case study in rural Guyuan District, Western China. Ecol. Econ. 69 (7), 1443–1453.
Zhong, T.-Y., Huang, X.-J., Zhang, X.-Y., Wang, K., 2011. Temporal and spatial variability of agricultural land loss in relation to policy and accessibility in a low hilly region of southeast China. Land Use Policy 28 (4), 762–769.