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A Bite of China: Food consumption and carbon emission from 1992 to 2007

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ABSTRACT

In conjunction with the rapid rise in household food expenditures per capita, China's food consumption has increased greatly. At the same time, dietary patterns have changed dramatically, as between 1992 and 2007 China underwent a transition to a more animal-based westernized diet. This rise in food consumption and shift in dietary structure may contribute substantially to climate change. In this paper, an input-output model is used to explore the food-related carbon emissions of Chinese urban households in 1992 and 2007. The results indicate that the physical volume of and economic expenditures on food consumption have increased by 20.7% and 35.9%, respectively. However, food-related carbon emissions per capita in 2007 had decreased nearly 21% compared to emissions in 1992. Based on parametric estimates of environmental Engel Curves and the Oaxaca-Blinder decomposition, the variation in household income may lead to a hypothetical carbon emissions increase of 1.694 tons. However, the improvement in energy use efficiency had offset the impact from income growth and dietary transition and led to the drop in China's food-related carbon emissions from 1992 to 2007.

1. Introduction

Food systems have profound impacts on global climate change and human health. Throughout the entire food system, the input of fertilizers and animal feed during preproduction activities, agricultural practices and land-use changes during production activities, and the input of food processing, transportation, retailing, and storage during postproduction activities can contribute significantly to greenhouse gas (GHG) emissions in both direct and indirect ways. Globally, food systems have been estimated to be responsible for between 19% and 29% of anthropogenic GHG emissions (Vermeulen, Campbell, & Ingram, 2012). Moreover, accumulating evidence suggests a link between dietary transition and human health (McMichael et al., 2007; Nishida et al., 2004). In conjunction with the rising incomes and transitions to modern urban lifestyles, global consumers are in the midst of a nutritional transition (Gale, 2002). The switch from a traditional plant-based diet to a more animal-based westernized diet has led to potentially serious health risks (Horrigan, Lawrence, & Walker, 2002; Peters et al., 2010). The current obesity epidemic in developed countries is considered to be correlated with the excessive consumption of animal-based foods (Heller & Keoleian, 2015). The transition to diets that rely heavily on meat and dairy products may, in addition to obesity, also increase the incidence of several chronic non-communicable diseases, including type II diabetes, coronary heart disease and some cancers (McMichael et al., 2007; Tilman & Clark, 2014).

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Diets heavy in meat and dairy products can not only do harm to human health, they also produce much higher GHG emissions compared to traditional plant-based diets. Evidence has shown that there are huge differences in the climate impacts of various food types (Virtanen et al., 2011). From a life cycle perspective, the GHG emissions from red meat have been shown to be approximately 4 times larger than those from vegetables in the USA (Weber & Matthews, 2008). Tilman and Clark (2014) have also found that, per unit, meat consumption resulted in GHG emissions that were more than ten times as high as GHG emissions from grains. Based on a national economic input-output life cycle assessment model (EIO-LCA), Virtanen et al. (2011) have indicated that in Finland meat products account for 25% of the carbon footprint of food consumption, while grain products only account for 11%. Concerns about the food security, human health, and climate change trilemma have gained increasingly more attention in recent years, and the climate and health benefits of different dietary choices have been explored. Reducing the intake of animal-sourced foods has been found to simultaneously result in significant GHG emission reductions and positive health outcomes (Meier & Christen, 2012). Westhoek et al. (2014) have indicated that the adoption of German Nutrition Society dietary recommendations – with reduced meat consumption compared to current levels – can achieve 11% of GHG emission reductions from the food sector and generate valuable health benefits. Tilman and Clark (2014) have also proven that adoption of a healthier diet with less meat and more vegetables would result in a 1.8 Gt yr^{-1} reduction in GHG emissions worldwide, which is equal to the total of worldwide transportation emissions in 2010. According to a study conducted by Springmann et al. (2016), dietary shifting to fewer animal-based foods and more plant-based foods could not only reduce global mortality by 6–10%, it could also cut food-associated GHG emissions by 29–70% compared with a reference scenario by 2050. Monetizing the value of co-benefits, the economic benefits of improved diets have been estimated to be equivalent to 0.4–13% of global gross domestic product (GDP) in 2050.

With the accelerated growth in household income, food consumption has increased significantly and the composition of foods consumed in China has changed considerably in the past several decades (Gale, 2002; Kearney, 2010; Zhou, Yu, & Herzfeld, 2015). On the one hand, total energy intake has increased from 1742 kcal per capita per day in 1950 to 2386 kcal per capita per day in 2000 (Du et al., 2002). On the other hand, China is also transitioning to a more animal-based westernized diet. Meat consumption increased by 349% from 1963 to 2003, while the consumption of cereals peaked in the late 1990s and then showed a declining trend (Kearney, 2010). In terms of nutrient intake, the proportion of energy from fat increased from 21.8% in 1991 to 32.0% in 2011, and this increase was even larger in mega cities such as Shanghai, Beijing and Chongqing, which was 36.9% in 2011 (Zhai et al., 2014).

China's increased food consumption and its transition in dietary structure may make major contributions to climate change. As the largest food consumer and the biggest GHG emitter worldwide, China is also facing the food security, human health, and climate change trilemma. To guarantee the food supply for 1.3 billion people, China's grain output has increased greatly, mainly due to increasing use of fertilizer in the last several decades. From 1980 to 2010, emissions emanating from fertilizer manufacture and use in China tripled. In particular, nitrogen fertilizer-related emissions contributed 7% of national GHG emissions in 2010 (Zhang et al., 2013). Moreover, in 2006 China surpassed the USA and became the world's largest emitter of CO_2; it emitted 8.33 billion tons of CO_2 in 2010, which accounted for 25.1% of global emissions (Feng et al., 2013; Zhang et al., 2014). To reduce the impact of climate change, in 2015 China submitted “Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions” to the Secretariat of the United Nations Framework Convention on Climate Change. According to the document, China intends to reach the peak of its carbon dioxide emissions in approximately 2030 and to lower its carbon dioxide emissions per unit of GDP by 60% to 65% of the 2005 level (National Development and Reform Commission(NDRC), 2015). In terms of national GHG emission reduction, understanding the climate impact of food consumption and dietary change, which account for a large proportion of national GHG emissions, as well as the drivers of change in food-related GHG emissions, is thus very important.

In this study, an economic input-output model has been applied to estimate the CO_2 emissions of food consumption from 1992 to 2007 in China. To investigate the impact of household characteristics on food-related emissions, a non-parametric estimate and parametric analysis have also been conducted. The following section describes the methodology for the calculation of CO_2 emissions based on household consumption, including food consumption. Section 3 presents the results of CO_2 emissions associated with household food expenditures for the period 1992–2007, as well as the results of the non-parametric and parametric estimates. Section 4 provides discussion of the results and Section 5 concludes with some policy implications.

2. Methodology

Carbon dioxide emissions associated with household consumption can generally be divided into direct and indirect emissions. Direct emissions refer to emissions from household energy commodities consumption, i.e., electricity, coal, gasoline, diesel and others. Indirect emissions refer to carbon emissions produced along the supply chain of all other household consumption, including emissions from the manufacturing of food, clothes, furniture, services, etc. Many studies have used life cycle assessments to calculate the GHG emissions of household diets, including emissions from agriculture, food processing, packaging, transport, and wholesale (Pelletier et al., 2011; Song et al., 2015; Tilman & Clark, 2014). In China, life cycle emission parameters over time are not readily available, especially data for the last century. Moreover, using the same emission factors for each type of food for the duration of the timeline cannot reflect the influence of technological innovation in China. Therefore, to better investigate the change in carbon dioxide emissions associated with the Chinese dietary shift over the time scale, an input-output model has been utilized in this paper. The input-output model, which has generally been expanded with environmental data, can reflect commodities flows among different sectors and therefore cover all upstream emissions (Liu et al., 2011; Vermeulen et al., 2012; Weber & Matthews, 2008).

In the input-output model, the economic output can be expressed as the sum of intermediate demand and final demand. The standard input-output relationship can be formulated as follows:

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

where X is the economic output, and I represents the identity matrix. A stands for the direct input-output coefficients matrix. Y refers to the final consumption.

In this study, only indirect CO_2 emissions from the energy input used in producing the commodities and services consumed by households have been included. Methane emissions from ruminants used as meat and nitrous oxide emissions from the crop growth stage, which are also attributable to food consumption, have not been considered in this paper due to data limitations. Moreover, CO_2 emissions from industrial processes, mainly emissions from cement production, have also not been included. By combining the energy intensity, the emission factor of each energy type and the volume and composition of household consumption, the indirect CO_2 emissions of household consumption C for each household can be calculated as follows:

$$C_i = \sum_k f_k \times e_k \times (I - A)^{-1} \times F_i \tag{2}$$

where i refers to each urban household in China and k captures the type of energy use. In this paper, 12 types of primary energy have been considered, including raw coal, clean coal, other washed coal, coke, coke gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas and natural gas. e_k is the direct energy intensity of each production sector, f_k stands for the CO_2 emission factor of k energy use. F_i is the aggregate final consumption of household i.

To investigate the indirect emissions embodied in Chinese household consumption from 1992 to 2007, China's input-output tables for the years 1992 and 2007 (National Bureau of Statistics (NBS), 1994, 2009) have been used in this paper. To retain the interdependencies among sectors in the Chinese economy detailedly, the finest-scale input-output tables for the years 1992 and 2007 were applied. All the input-output data are in current prices. There are slightly different industry classifications for different years, namely 118 sectors for 1992 and 135 sectors for 2007. To ameliorate the considerable overlap in the sector classifications and keep data consistent, this study has aggregated the input-output table to achieve a uniform 88-sector format, on the basis of the Classification and Code Standard of the National Economy Industry in China (National Bureau of Statistics (NBS), 1984, 2011), see Table A1.

To obtain the energy intensity matrix, the China Energy Statistics Yearbook for each year has been applied to derive the sectoral emission inventory (National Bureau of Statistics (NBS), 1993a, 2008a). According to the definition in the Chinese energy statistics, the total energy consumption for each sector can be expressed as the sum of the sector's final energy consumption and energy loss as well as its primary energy inputs. However, in the Chinese energy statistics data, energy loss has not been included in final energy consumption (Peters, Weber, & Liu, 2006). Consequently, total energy loss on the national scale has been allocated to each sector on the basis of the proportion of that sector's final energy consumption compared to national final energy consumption.

To reconcile the energy data with the aggregated input-output data, the sectoral energy consumption data, which primarily used a 44-sector format (36 sectors for 1992) in the Chinese energy statistics, were further disaggregated into an 88-sector format. In this paper, we first calculated the proportion of the cash flows for each sector in the aggregated input-output tables compared to the sum of cash flows for the more aggregated macro-sectors in the China Energy Statistics Yearbook for each year. We then allocated energy consumption proportionally under the unique sectoral price assumption to obtain the energy intensity matrix at a disaggregated level of 88 sectors. In addition, the CO_2 emission factors for each energy type are mainly from the Intergovernmental Panel on Climate Change reference approach (Eggelston et al., 2006) and Wang et al., (2012).

In this study, all household expenditure data are derived from China's Urban Household Income and Expenditure Survey (UHIES) for each year (National Bureau of Statistics (NBS), 1993b, 2008b). In the UHIES, living expenditure[1] covers eight categories of spending: food, clothing, residence, household facilities and services, medicine and medical services, transport and communication services, education, cultural and recreation services and miscellaneous commodities and services; there are 151 total types of commodities and services. For food consumption specifically, there are nine different types of food, including (1) grains & oils, (2) meat, poultry, eggs and aquatic products, (3) vegetables, (4) seasoning, (5) sugar, tobacco, alcohol and beverages, (6) fruits, (7) pastry, milk and dairy products, (8) other food, as well as (9) catering services; these can be further decomposed into 44 types of commodities and services. Additionally, the classification of the different types of commodities and services included as living expenditures for the UHIES dataset did not match those of the input-output tables. In the reconciliation of the UHIES dataset and the input-output tables, some sources of uncertainty were observed, including multiple goods in one sector, multiple technologies for one good and multiple producers of one good, presumably using different technologies (Hondo, Sakai, & Tanno, 2002). To resolve these problems, this study used the solution applied by Golley, Meagher, and Meng (2008); Golley and Meng (2012) to match the commodities and services in the UHIES dataset to the input-output sectors. In this paper, subsamples of 9081 and 34,460 households from the UHIES for the years 1992 and 2007, respectively, were included to quantify household carbon emissions.

[1] Since the 1980s, China's National Bureau of Statistics (NBS) has carried out the UHIES, based on stratified sampling. The UHIES covers household-level income, expenditures, and personal information of family members, such as age, education, and gender. In the UHIES, household expenditures are divided into six types: Living Expenditures, Business Expenditures, Expenditures on Properties, Transfer Expenditures, Social Security Expenditures, and Expenditures on Home Purchase and Construction. Among all types of household expenditures, only living expenditures can be effectively incorporated into the input-output model, and thus are the only expenditures considered in this study.

It is worth noting that food consumed away from home (FAFH) accounts for a large share of national household food consumption, especially for meat, which, on average, constitutes approximately 30–33% of total household meat consumption (Min et al., 2015; Xiao et al., 2015). To further investigate the climate impact of FAFH, expenditures on FAFH have been redistributed to food expenditures and service expenditures. Generally, the material cost of eating out varies between 20% and 50% of the total expenditure of eating out. In this paper, one-third of the cost of eating out is attributable to food expenditure and the remainder is service cost, as shown in Golley, Meagher, and Meng (2008). First, the cost has been reallocated to the major food types, including grains & oils, meat, poultry, eggs and aquatic products, vegetables, fruits, pastry, milk and dairy products on the basis of the respective expenditure proportion compared to total household food expenditures. Second, emissions embodied in service costs were also induced by food consumption; therefore, in this paper, we also redistributed the emissions embodied in the remaining service cost across the above-mentioned food types, also based on the respective expenditure ratio.

3. Results

3.1. Carbon emissions embodied in household consumption

As household income increased, household consumption in China also rose during 1992–2007. Total expenditures rose approximately 132%, from 1633.91 Yuan per capita in 1992 to 3792.07 Yuan per capita in 2007. Eight types of household consumption have increased to different degrees: Food, Clothing, Residence, Household facilities and services, Transport and communication services, Education, Cultural and recreation services, Medicine and medical services and Miscellaneous commodities and services. Specifically, food consumption retained its dominant position among all types of household expenditures in both 1992 and 2007, while its contribution to total household expenditures shows a downward trend. Although per capita food consumption increased from 867.18 Yuan in 1992 to 1383.96 Yuan in 2007, food expenditure as a proportion of total household expenses dropped from >50% in 1992 to only 36.5% in 2007. In comparison, much more money was spent on transport and education in 2007 than in 1992, and the expenditure ratio (i.e., transport and education compared to total household expenses) increased to 12.77% and 13.40%, respectively (see Fig. 1). This can be explained by the fact that, in conjunction with China's tremendous economic gains and income growth, we have witnessed a significant transformation as households in China began to consume new commodities and services once they became affordable. In particular, classes with higher incomes were eager to enjoy a quality of life characterized by high quality food, comfortable living, and health care (Hubacek et al., 2009). This thirst gave rise to structural changes in related consumption of commodities and services and associated carbon emissions.

Note: The prices in Fig. 1 have been converted in constant 1990 prices based on the CPI index from China's Statistical Yearbook (National Bureau of Statistics (NBS), 2010).

During the period 1992–2007, carbon emissions embodied in household consumption showed an upward trend and their composition changed greatly. Total carbon emissions indirectly related to household consumption increased approximately 51%: from 1.36 tons per capita in 1992 to 2.06 tons per capita in 2007. Compared to the rise in household expenditures, related carbon emissions have shown a much more moderate increase, indicating that energy use efficiency improved during this period. In 1992, energy consumption was 7.60 tons of standard coal equivalent (tce) per ¥10,000 GDP output, while by 2007 energy intensity had decreased to 1.55 tce per ¥10.000 GDP output (National Bureau of Statistics (NBS), 2010). Energy efficiency greatly improved during this period. In terms of carbon emissions due to different types of household consumption between 1992 and 2007, as shown in Fig. 2, food consumption made the largest contribution to carbon emissions related to household consumption; these

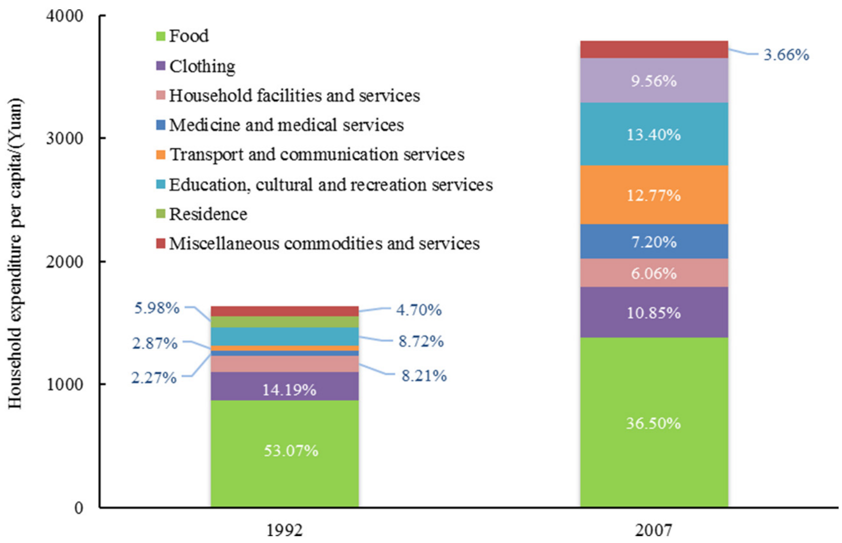

Fig. 1. Breakdown of household expenditures in 1992 and 2007.

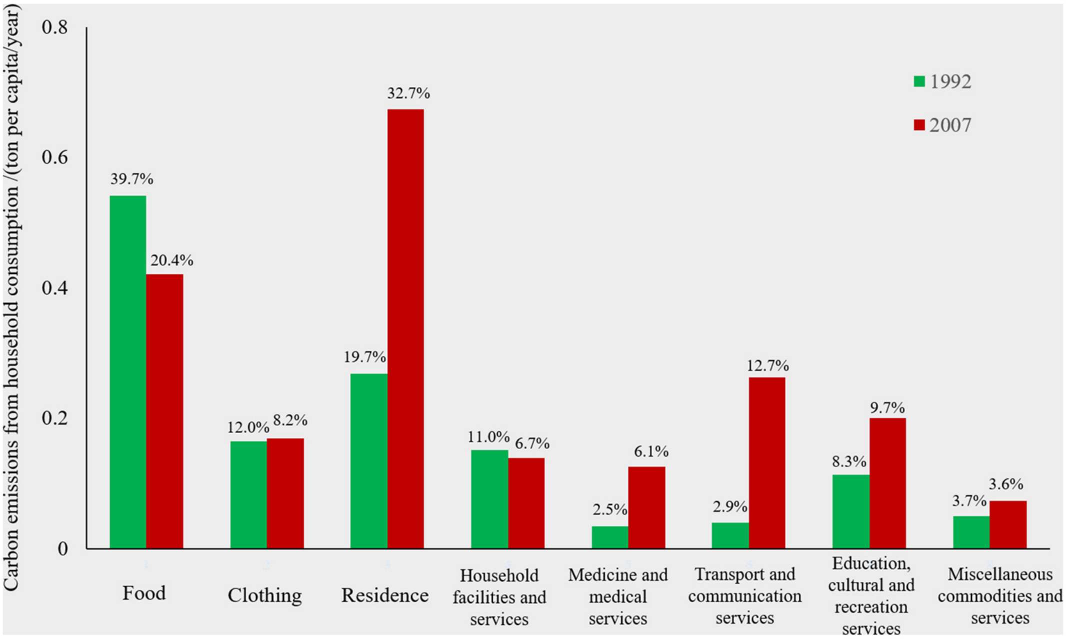

Fig. 2. Carbon emissions embodied in household consumption in 1992 and 2007.

emissions were 0.54 tons per capita and accounted for 39.73% of total emissions in 1992. Residence took second place, which was 0.27 tons per capita and approximately 19.69% of total emissions. Turning to 2007, residence became the largest contributor, which was 0.67 tons per capita and accounted for 32.67% of total carbon emissions embodied in household consumption. At the same time, the contribution of food consumption to total emissions decreased to only 20.40%, and the emissions volume was only 0.43 tons per capita in 2007.

Note: The proportion of carbon emissions associated with each type of household expenditure compared to the total embodied emissions in 1992 and 2007 has been listed at the top of each histogram.

3.2. Carbon emissions embodied in household food consumption

Accompanying the rapid growth in household food expenditures per capita, the structure of the Chinese diet also changed significantly. In the UHEIS database, expenditures on food consumption covers eight major food types: Cereals, Oil, Vegetables, Meat, Egg, Fruit, Aquatic products and Milk. As depicted in Fig. 3, nearly all types of food consumption have increased in physical quantity except for cereals. Consumption of cereals decreased by approximately 9% from 37.42 to 34.15 kg per capita during 1992–2007. In contrast, food derived from animals, including meat, milk, egg and aquatic products, increased significantly. In particular, milk consumption increased approximately 2.86 times, jumping from 2.44 kg per capita in 1992 to 9.46 kg per capita in 2007. In terms of food expenditures, expenditures on animal-based food increased from ¥299.53 to ¥466.53/year per capita in constant 1990 prices. These results indicate that people in China increased their spending on food derived from animals. In other words, China transitioned to a more animal-based westernized diet between 1992 and 2007.

Despite the growth in household food expenditures, food related carbon emissions decreased by about 20.8%, from 0.548 tons/year per capita in 1992 to 0.434 tons/year per capita in 2007. This can be partly explained by the improvement of energy use efficiency in the food industry during this time period. According to Lin and Lei (2015), the energy intensity of the food industry decreased from 4 tce per ¥10,000 in 1992 to approximately 1 tce per ¥10,000 in 2007. Per capita carbon emissions embodied in each type of consumed food have also decreased to various degrees, with the exception of milk and fruit (See Fig. 4). From 1992 to 2007, emissions related to expenditures on milk and fruit increased 98.9% and 3.7%, respectively. Moreover, the contribution of animal-based food to total food-related carbon emissions decreased, while the ratio of plant-based food to the total carbon emissions embodied in food consumption increased. In 1992, food derived from animals, i.e., meat, aquatic products, milk and eggs, contributed 39.2% of total food-related emissions, while in 2007 this ratio had decreased to 35.8%. With the exception of emissions from milk, emissions from meat, aquatic products and egg have decreased 35.2%, 20.6% and 58.3%, respectively. At the same time, the percent of emissions from expenditures on plant-based foods – mainly cereals, fruits and vegetables – compared to total embodied emissions increased from 35.6% in 1992 to 37.3% in 2007.

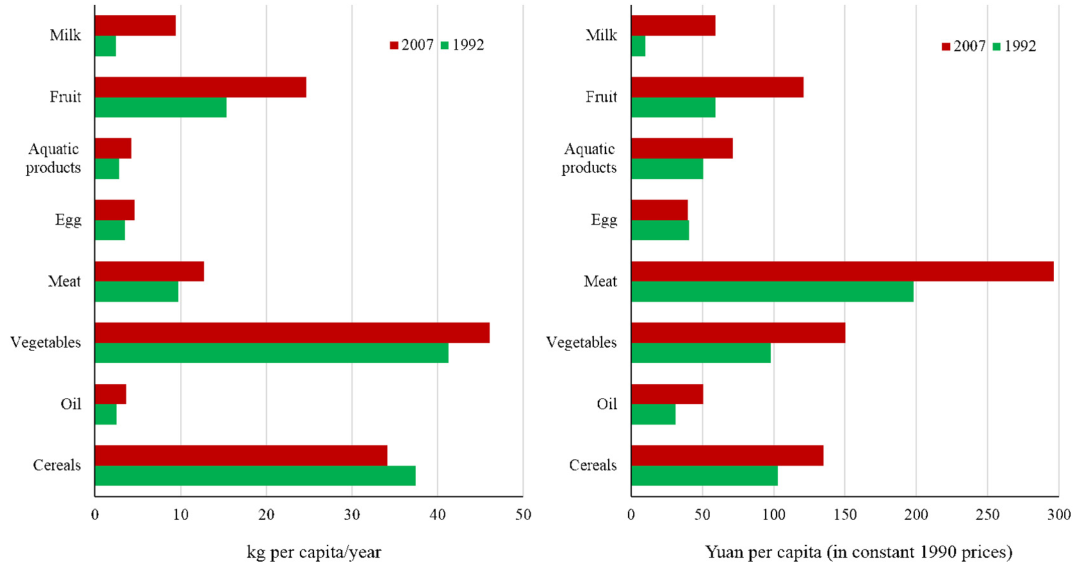

Fig. 3. Breakdown of household food consumption in China for 1992 and 2007.

3.3. Environmental Engel curves (EECs)

In conjunction with the rise of the average household income, per capita carbon emissions related to food in 2007 had decreased nearly 21% compared to 1992. Apart from energy efficiency improvements, how did household demographics affect household-level food-related emissions? To further parse the influence of income on carbon emissions embodied in household food expenditures, household-level environmental Engel curves in China have also been investigated for the years 1992 and 2007. Environmental Engel curves have been derived from the famous Engel curves, which have been widely used to represent how household food expenditures vary with household income. In a similar way, environmental Engel curves can effectively plot how household emissions embodied in expenditures on specific commodities and services vary with income (Levinson &

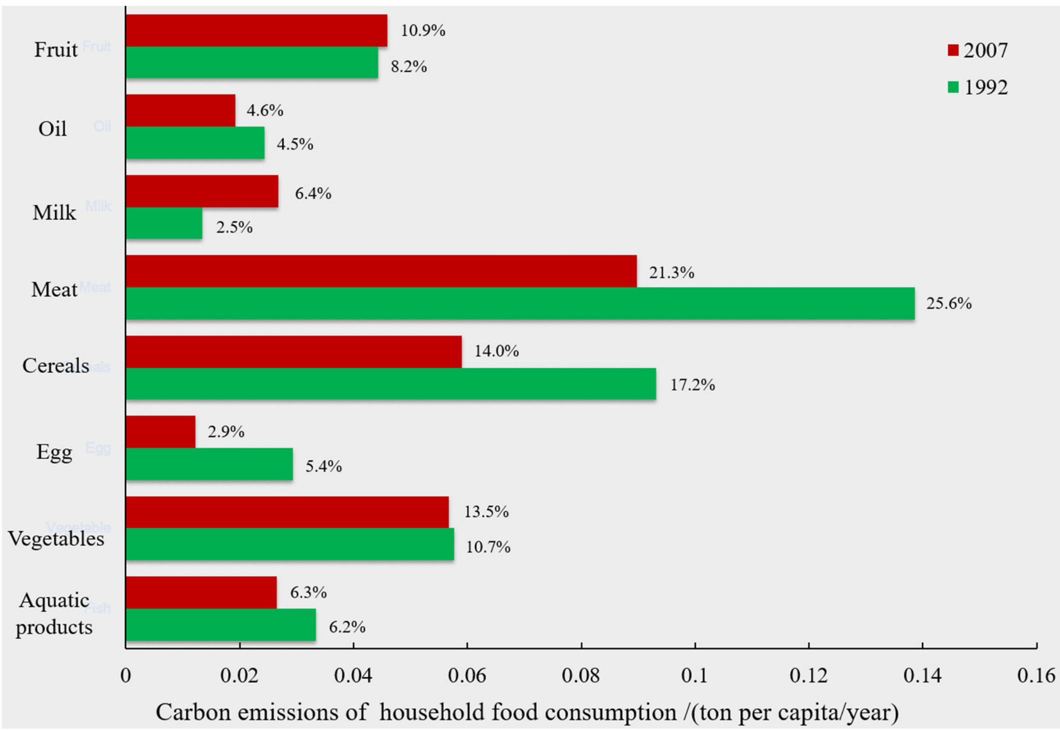

Fig. 4. Breakdown of carbon emissions embodied in household food consumption. Note: The proportion of carbon emissions associated with each type of household food expenditure compared to total food related emissions in 1992 and 2007 has been listed at the top of each histogram.

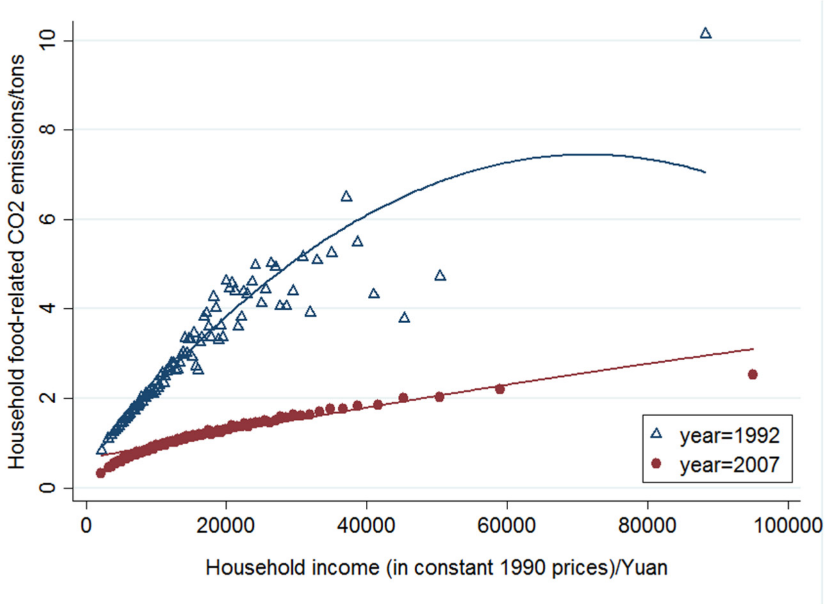

Fig. 5. The nonparametric environmental Engel curves for the years 1992 and 2007.

O'Brien, 2015). In this study, nonparametric estimates of environmental Engel curves have first been conducted to examine the shape of the Chinese environmental Engel curves, and parametric estimates of environmental Engel curves have also been applied using the ordinary least squares method (OLS). Finally, to further decompose the major influence factors on household food-related carbon emissions, the Oaxaca-Blinder decomposition has been provided.

Nonparametric estimates, i.e., simply plotting the data to examine the shape and structure of the EECs with only the considerations of income and food-related carbon emissions, were conducted first. In this paper, by dividing all the households in the UHIES database into 100 groups according to household income, the average household food-related carbon emissions within each income decile have been calculated. To observe the relationship between household income and food-related emissions over time, we have used household income on the horizontal axis and pollution on the vertical axis to generate nonparametric environmental Engel curves for the years 1992 and 2007, as shown in Fig. 5. In 1992, households in the 50th income decile (5660–5715 Yuan at constant 1990 prices) emitted 1.65 tons of carbon on average. In comparison, in 2007 households at the same level of income only contributed an average of 1.16 tons of carbon, nearly 30% less than their counterparts in 1992.

According to the characteristics of environmental Engel curves, three major phenomena can be observed. First, as shown in Fig. 5, the Chinese environmental Engel curves have shown an upward trend, indicating that households in higher income deciles contributed much more to food-related carbon emissions. The main reason is that the more affluent households spend much more on food consumption. In 1992, households in the top income decile spent more than twice the amount spent by the least affluent 10% of families, on average. Correspondingly, in an indirect way, the average food-related carbon emissions of the richest 10% of households are likely to be twice that of the poorest households. Second, as shown in Fig. 5, there are concave Chinese environmental Engel curves, which suggest that richer households tend to consume more emissions-intensive food. Third, by comparing the environmental Engel curves of 1992 and 2007, we can see that the curves are moving down over time, indicating that in the same constant 1990 prices, households in 2007 accounted for fewer carbon emissions than in 1992.

However, the non-parametric estimate cannot cover other household characteristics, which may make a difference in household food consumption and therefore in food-related carbon emissions. From 1992 to 2007, the average indirect carbon emissions associated with household food consumption decreased 32.25%, from 1.783 tons to 1.208 tons; however, household income nearly tripled. As households become much smaller and more educated, people may change their mode of food consumption. To further depict the impact of other household characteristics on food-related carbon emissions, a parametric estimate has also been employed.

In this study, the parametric model is an ordinary least square regression. By regressing for the years 1992 and 2007, we can obtain annual coefficients.

$$Y_t = \alpha_t x_t + \beta_t x_t^2 + \delta_t Z_t + \varepsilon_t \tag{3}$$

Y_t The food–related emissions for each household in year *t*.
x_t The income for each household in year *t*.

Table 1
Impact of household characteristics on household food-related carbon emissions.

Independent Variable	1992	2007	Coefficient change between 1992 and 2007
income	0.000194***	0.0000133***	−0.0001807***
	(2.59E-06)	(1.18E-07)	
Income squared	−1.38e-09***	−9.70e-12***	1.3703E-09***
	(6.14E-11)	(1.93E-13)	
Household size	0.0765***	0.0856***	0.0091***
	(0.0069725)	(0.0036646)	
Education level of household head	0.0678***	−0.0163***	−0.0841***
	(0.0039919)	(0.0019905)	
Constant	−0.0251	0.502***	0.5271***
	(0.0296835)	(0.0149497)	
Observations	9081	34,460	
R-squared	0.553	0.322	

Note: 1. ***$p < 0.001$. 2. Standard errors have been presented in parentheses.

Z_t Other factors influencing food-related emissions (control variables), including household size and the education level of the head of each household[2] in year *t*.
ε_t Random error term.

Table 1 shows the results of the OLS model. As can be seen from the table, household income, household size and the education level of the household head are all statistically significant on household food-related carbon emissions. In 1992, larger households were more likely to spend much more on food consumption and therefore emit much more carbon dioxide in an indirect way. Turning to 2007, the impact of household size still existed, but the emission increase was slower compared to that in 1992. As for the influence of the education level of the household head, household heads with higher levels of education generated much more carbon emissions in 1992. This can be explained by the fact that, among households with the same income, people with lower education may have lower expectations of future earnings and thus their consumption may be conservative relative to households with higher education levels at that time. With the increase in China's overall education level, people have come to realize the importance of a healthy diet and tend to consume food in a healthy way, other than eating much more and much better. Therefore, in 2007, households with more education contributed much less to food-related emissions compared to families with less education. By comparing the coefficients of income and income squared in 1992 and 2007, we can see that the environmental Engel curves have become lower and much less concave over the past 15 years, indicating that households are indirectly responsible for fewer carbon emissions in 2007 than households earning the same income in 1992 and that households in higher income deciles are more likely to consume less emission-intensive food.

To further investigate the extent of various factors affecting food-related emissions, the Oaxaca-Blinder decomposition (Blinder, 1973; Oaxaca, 1973) has been used to separate the impact of different influential components. First, we derived the average food-related carbon emissions in 1992 and 2007 from the OLS regression and the results in Table 1.

$$\overline{Y}_t = \alpha_t \overline{x}_t + \beta_t \overline{x_t^2} + \delta_t \overline{Z}_t \tag{4}$$

$\overline{Y_t}$ Average indirect emissions for year *t*.
$\overline{x_t}$ Average income for year *t*.
$\overline{x_t^2}$ Average income squared for year *t*.
$\overline{Z_t}$ Average of other included covariates for year *t*.

Then, based on Eq. (4), the change in the average level of food-related carbon emissions between 1992 and 2007 can be interpreted as:

$$\overline{Y_{2007}} - \overline{Y_{1992}} = \alpha_{2007}\overline{x_{2007}} + \beta_{2007}\overline{x_{2007}^2} + \delta_{2007}\overline{Z_{2007}} - \alpha_{1992}\overline{x_{1992}} - \beta_{1992}\overline{x_{1992}^2} - \delta_{1992}\overline{Z_{1992}} \tag{5}$$

[2] In the UHEIS dataset, the education level of the household head is a discontinuous variable. In the database, 1 represents that the head has never received any education, 2 means that the household head has attended literacy class. 3–9 indicates that the highest education the household head received is grade school, junior high school, senior high school, technical secondary school, junior college, undergraduate college and completed postgraduate, respectively. In this study, the education level of the household head has been turned into a continuous variable and we assumed that the bigger the number, the higher the educational level.

Table 2
Average values for selected variables in 1992 and 2007.

Variables	1992	2007	Mean Diff
Carbon emissions	1.783	1.208	0.575
Household income	6457	19,000	−1.3e + 04
Household income squared	5.400e + 07	5.900e + 08	−5.4e + 08
Household size	3.294	2.866	0.428
Education level of household head	3.980	5.490	−1.510

Finally, by adding and subtracting $\alpha_{1992}\overline{x_{2007}} + \beta_{1992}\overline{x^2_{2007}} + \delta_{1992}\overline{Z_{2007}}$, the change in average carbon emissions between 1992 and 2007 can be further grouped as:

$$\begin{aligned}\overline{Y_{2007}} - \overline{Y_{1992}} = {} & \alpha_{1992}(\overline{x_{2007}} - \overline{x_{1992}}) + \beta_{1992}\left(\overline{x^2_{2007}} - \overline{x^2_{1992}}\right) + (\alpha_{2007} - \alpha_{1992})\overline{x_{2007}} \\ & + (\beta_{2007} - \beta_{1992})\overline{x^2_{2007}} + (\delta_{2007} - \delta_{1992})\overline{Z_{2007}} + \left(\overline{Z_{2007}} - \overline{Z_{1992}}\right)\delta_{1992}\end{aligned} \quad (6)$$

By holding the 1992 OLS coefficients constant, the first two terms in Eq. (6) represent the effect of the change of income on household food-related carbon emissions. The second two terms account for the effect of different OLS coefficients on income and income squared in 2007 compared to 1992. Finally, the last two terms describe the changes in all other covariates, including household size, education level of household head and the corresponding coefficients. All the data are shown in Tables 1 and 2.

By grouping all the effects into effects due to income, effects due to other household demographics and effects due to other covariates, Table 3 provides the major results of the Oaxaca-Blinder decomposition. Between 1992 and 2007, the average level of carbon embodied in a household's food expenditure decreased by 0.575 tons (see Table 2). Variations in average income and income squared may lead to a hypothetical increase of 1.694 tons (2.433 increase from average income and 0.740 decrease from average income squared). Furthermore, changes in household demographics offset the increase in food-related emissions by 0.366 tons (0.007 and 0.359 tons from household size and the education level of the household head, respectively). The remaining 1.903 tons can be attributed to other differences, mainly environmental policy interventions and technology innovations over time.

4. Discussion

4.1. Contribution of technology innovation

Decomposition of the parametric estimates has indicated that income contributed most to the hypothetical increase in food-related carbon emissions, while the actual decrease in emissions can be significantly attributed to technology innovation. To further investigate the influence of technology innovation on carbon emissions from household food expenditure, we recalculated the food-related carbon emissions for 2007 using the emissions intensity of 1992. As shown in Fig. 6, we found that technology innovation exerted an important influence on household carbon emissions associated with food expenditures in 2007. Without technological progress, average household carbon emissions embodied in food in 2007 would have surged to 3.962 tons per household – >3 times the actual emissions in 2007. The hypothetical household emissions related to food expenditures in 2007 would have surpassed those of 1992. Moreover, technological improvement in carbon abatement over the past 15 years had a more significant impact on food derived from animals than on that from plants. In 2007, technological innovation actually brought an emissions reduction per household of approximately 1.078 tons and 0.992 tons for animal-based and plant-sourced food, respectively. In particular, the average household emissions associated with meat would have been 0.638 tons higher, which is nearly 1.4 times as high as the actual emissions from animal-based food in 2007.

Table 3
Decomposition of the parametric EECs for food-related carbon emissions in 1992 and 2007.

Variables	Increase in carbon emissions (tons)
Household income	2.433
Household income squared	−0.740
Household size	−0.007
Education level of household head	−0.359
Total change due to income	1.694
Total change due to other demographics	−0.366
Unexplained difference	−1.903

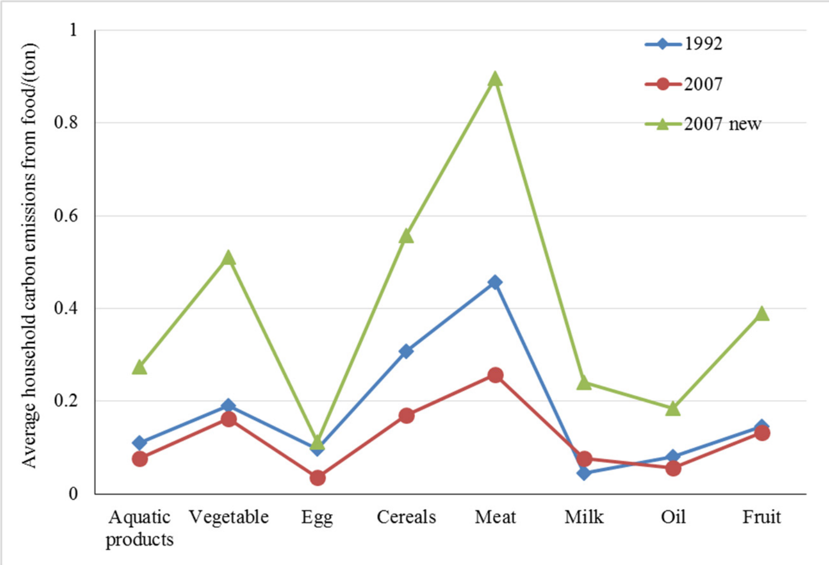

Fig. 6. Comparison of food-related carbon emissions in 1992 and 2007 Note: 2007 new indicates carbon emissions from household food consumption in 2007 using the emission intensity of 1992.

4.2. Sensitivity analysis

With respect to the influence of expenditures from eating out, we should note that FAFH is not well captured by the household surveys of the National Bureau of Statistics of China. According to the household survey conducted by Bai et al., (2013), pork consumed away from home as a proportion of total household expenditure was approximately 41% during 2007–2011, which is nearly 2 times (21%) the NBS statistics (Yu & Abler, 2014). Therefore, in this study, the ratio of two statistical discrepancies (denoted as the FAFH ratio), approximately 2, has been assumed as an adjusting factor to justify the potential statistical bias, as shown in Yu and Abler (2014). Sensitivity analysis has also been conducted in terms of the FAFH ratio with the low bound of 1.8 and the high bound of 2.2. To further examine the potential bias caused by the material cost ratio assumption, we also estimated the carbon dioxide emissions from each type of food consumption with the assumption that the ratio of the material expenditure to total expenditure of eating out would be 1/5 and 1/2, respectively.

Sensitivity analysis has indicated that the potential statistics bias may exert a great effect on the results. As shown in Table 4, assuming that the FAFH ratio is 1.8, 2 and 2.2, per capita carbon emissions from expenditures on food would increase 4.51%, 6.05%

Table 4
Sensitivity analysis of carbon emissions from household food consumption (kg per capita/year).

FAFH ratio	MC ratio	Year	Aquatic products	Vegetables	Egg	Cereals	Meat	Milk	Oil	Fruit	Sugar	Others	Food	Change VS base
1	1/3	1992	33.44	57.68	29.32	93.14	138.53	13.45	24.34	44.33	73.66	40.03	547.93	/
		2007	26.54	56.78	12.23	59.08	89.82	26.76	19.28	45.97	60.82	36.81	434.08	/
1.8	1/5	1992	36.04	60.29	31.41	98.45	148.70	13.98	25.94	47.40	69.68	37.77	569.65	3.96%
		2007	31.15	66.50	14.80	67.86	108.86	30.62	22.53	53.83	53.05	32.14	481.34	10.89%
	1/3	1992	36.07	59.95	31.34	98.64	148.79	14.17	25.94	47.54	71.45	38.77	572.65	4.51%
		2007	31.06	66.20	14.55	67.96	107.18	30.93	22.37	53.97	56.50	34.21	484.93	11.71%
	1/2	1992	36.10	59.51	31.25	98.88	148.90	14.41	25.95	47.72	73.66	40.03	576.41	5.20%
		2007	30.96	65.82	14.24	68.09	105.07	31.31	22.18	54.14	60.82	36.81	489.42	12.75%
2	1/5	1992	36.69	61.49	31.92	99.80	151.25	14.14	26.34	48.18	69.97	37.93	577.73	5.44%
		2007	32.29	68.88	15.41	70.07	113.39	31.63	23.32	55.82	53.63	32.48	496.92	14.48%
	1/3	1992	36.72	61.10	31.84	100.02	151.36	14.35	26.34	48.34	71.94	39.05	581.06	6.05%
		2007	32.19	68.55	15.13	70.18	111.51	31.97	23.15	55.97	57.46	34.79	500.91	15.39%
	1/2	1992	36.75	60.62	31.74	100.29	151.48	14.62	26.35	48.54	74.39	40.45	585.23	6.81%
		2007	32.07	68.14	14.78	70.32	109.17	32.39	22.93	56.16	62.26	37.68	505.90	16.54%
2.2	1/5	1992	37.35	62.69	32.43	101.16	153.81	14.30	26.74	48.97	70.27	38.10	585.81	6.91%
		2007	33.43	71.27	16.02	72.27	117.91	32.64	24.12	57.80	54.20	32.83	512.49	18.06%
	1/3	1992	37.38	62.26	32.34	101.39	153.92	14.53	26.74	49.14	72.43	39.33	589.47	7.58%
		2007	33.32	70.91	15.71	72.40	115.85	33.01	23.92	57.97	58.42	35.37	516.88	19.07%
	1/2	1992	37.41	61.73	32.24	101.69	154.06	14.82	26.75	49.36	75.13	40.87	594.06	8.42%
		2007	33.19	70.45	15.32	72.56	113.28	33.48	23.68	58.17	63.70	38.54	522.37	20.34%

Notes: In Table 4, FAFH ratio denotes the adjusting factor for justifying the potential statistical bias in UHEIS, MC ratio indicates the proportion of the material cost of the total expenditure on eating-out. 'Base' indicates the scenario when the material cost ratio is 1/3 and FAFH ratio is 1, and 'Change VS base' shows the change in carbon emissions associated with expenditures on household food consumption for each year in different scenarios.

and 7.58% in 1992, respectively, when the material cost occupied one third of the whole household eating-out expenditure. This gap would be even larger in 2007, with per capita carbon emissions increasing 11.71%, 15.39% and 19.07%, respectively. The huge discrepancies in emissions may highlight the importance of surveys on food consumption away from home. In terms of the assumption of the material cost ratio in eating out expenditures, the impact turned out to be insignificant. Supposing that the FAFH ratio is 1.8, changing the material ratio from 1/3 to 1/5 and 1/2 only changed the carbon emissions by 0.52% and 0.66% in 1992, respectively. The gap would be higher in 2007, but differences in carbon emissions were still <1%. This may be explained by the fact that emissions from expenditures on eating out have all been allocated to each type of food – both the emissions from the material cost and the service cost.

4.3. Limitations

It should also be noted that, in this study, only the indirect carbon dioxide emissions from the energy input throughout the entire food system have been evaluated; methane emissions from ruminants used for meat and nitrous oxide emissions from the crop growth stage have not been included due to data limitations. The addition of methane emissions and nitrous oxide emissions may increase the influence of food sourced from animals and plants to different degrees. To examine the impact of the exclusion of methane and nitrous oxide emissions, we calculated life cycle GHG emissions for 27 food groups in 2007, as shown in Song et al. (2015). We found that per capita GHG emissions from household food consumption are 1.11 tons, which is nearly 2.6 times as much as carbon dioxide emissions as reported in this paper. Moreover, in 1992, GHG emissions related to food derived from animals and plants were 0.281 and 0.640 ton per capita, respectively. Turning to 2007, the respective GHG emissions from animal- and plant- based food could be as high as 0.531 and 0.572 tons per capita. Compared to emissions from our IO model, animal-sourced food may exert an increasingly important role in climate change. Therefore, we must acknowledge that the exclusion of methane and nitrous oxide emissions may hugely underestimate the impact of food consumption on climate change. However, it should also be noted that applying the same life cycle emission factors might ignore the impact of technological innovation on emissions abatement from 1992 to 2007. Therefore, to accurately assess the impact of food consumption on climate change, the inclusion of CH_4 and N_2O emissions in the input-output model should be taken into account in future work.

5. Conclusions and policy implications

In this paper, an input-output model has been employed to assess the change in carbon emissions embodied in household food expenditures between 1992 and 2007. Over the past 15 years, although the physical volume of and the economic expenditure on food consumption increased by 20.7% and 35.9%, respectively, total carbon dioxide emissions embodied in food consumption showed a decreasing trend over the time. Between 1992 and 2007, income may have led to a hypothetical increase of 1.694 tons, while the change in household demographics offset the increase in food-related emissions by 0.366 tons. The decrease may be significantly attributable to technological innovation over time. Currently, there is still room for improvement in the energy use efficiency of the food industry. In China, the enterprise scale of the food industry is generally small, and these small-sized enterprises need much more capital investment to achieve technological innovation and improvements in energy use efficiency (Lin, Zhou, & Ma, 2010). Therefore, policy action should be taken to accelerate the food industry cluster so as to achieve a drop in energy intensity and the abatement of CO_2 emission.

Among all types of food, vegetables made the largest contribution to the carbon emissions embodied in food consumption in both 1992 and 2007. Over time, the quantity of vegetable consumption increased from 41.94 kg/y per capita in 1992 to 46.06 kg/y per capita in 2007. This increased vegetable consumption can be partly explained by the shopping basket program, aimed at solving the shortage of vegetables that had occurred since the late 1980s (Xu, 2014). With the support of this program, many provinces reached their goals of vegetable output. However, the excessive use of fertilizer for vegetable production became a very common phenomenon in China under the pressure to increase yields (Norse & Ju, 2015). Excessive fertilizer use for vegetable production led to unnecessary fertilizer production and related carbon emissions. Excessive fertilizer use also led to other environmental problems such as eutrophication of water bodies and soil hardness. As a result, we suggest that fertilizer applications should be controlled, especially for vegetables, to reduce the carbon emissions embodied in food consumption. In fact, the Chinese government noticed the excessive use of fertilizer and had issued the 2015 No. 1 Document for the construction of agriculture modernization, aiming at both food security and non-point pollution control in China (The State Council, 2015). The No. 1 Document was the most important policy for that year and beyond in China. In this national policy, soil testing for formulated fertilization and the application of biological organic fertilizer were proposed as the major solutions for the control of fertilizer application in China. These two fertilizer application methods should be used for vegetable production to reduce both fertilizer application and carbon emissions.

Although meat consumption increased with the rise in Chinese household income during the period 1992–2007, the contribution of meat consumption to the total emissions embodied in food consumption had decreased based on the input-output model. We should note that in this paper only carbon dioxide emissions have been included, direct methane emissions from the ruminants and indirect nitrous oxide emissions from the life cycle of animal feed may have more significant impacts on climate change. Moreover, the surge in meat consumption may also lead to health problems. In the past, China was considered to be one of the leanest populations, but China has caught up with the West in terms of the prevalence of overweight and obesity; about one fifth of the overweight and obese people in the world are Chinese. This was mainly caused by the shift to the diet structure of western developed countries, which is characterized by the consumption of more animal-based foods (Wu, 2006; Zhai et al., 2014). Previous studies have shown that a diet structure based on more plant-based foods should be adopted to promote health and GHG reduction. Whether such a change in consumption behavior is realistic is still a question, especially for China, which has been experiencing a shift from plant-based food to animal-based food. The control of animal-based food consumption requires policy intervention. The government could raise the price of animal-based food by direct taxation or by taxing its environmental impact, such as GHG emissions based on the production stage. The higher price of animal-based food would result in lower consumption, which is essential for both the population's health and for GHG emissions reduction (Westhoek et al., 2014).

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Appendix A

Table A1
The classification of economic sectors in the aggregated input-output tables.

Code	Economic sectors
Section 1	Crop cultivation
Section 2	Forestry
Section 3	Livestock and livestock products
Section 4	Fishery
Section 5	Other agricultural products
Section 6	Coal mining and processing
Section 7	Crude petroleum and Natural gas mining and processing
Section 8	Ferrous ore mining
Section 9	Non-ferrous ore mining
Section 10	Non-metal minerals and other mining
Section 11	Grain mill products, vegetable oil and forage
Section 12	Sugar refining
Section 13	Slaughtering, meat processing, eggs and dairy products
Section 14	Prepared fish and seafood
Section 15	Other food products
Section 16	Wines, spirits and liquors
Section 17	Other beverage
Section 18	Tobacco products
Section 19	Cotton, chemical fiber textile, and dyeing and finishing industry
Section 20	Wool textile and dyeing and finishing industry
Section 21	Hemp textiles, silk textiles and finishing industry
Section 22	Knitwear, woven goods, textile products manufacturing
Section 23	Wearing apparel
Section 24	Leather, furs, down and related products
Section 25	Wood processing and products of wood, bamboo, cane, palm, straw, etc.
Section 26	Furniture and products
Section 27	Paper and products
Section 28	Printing and record medium reproduction
Section 29	Cultural goods and other recreation products
Section 30	Petroleum refining and nuclear fuel processing
Section 31	Coking
Section 32	Raw chemical materials
Section 33	Chemical fertilizers
Section 34	Chemical pesticides
Section 35	Coatings, paints, inks and similar products manufacturing
Section 36	Chemical products for daily use
Section 37	Other chemical products
Section 38	Medical and pharmaceutical products
Section 39	Chemical fibers
Section 40	Rubber products
Section 41	Plastic products
Section 42	Cement and cement asbestos products
Section 43	Glass and glass products
Section 44	Pottery, china and earthenware
Section 45	Fireproof products
Section 46	Other non-metallic mineral products

Table A1 *(continued)*

Code	Economic sectors
Section 47	Primary iron and steel manufacturing
Section 48	Primary non-ferrous metals manufacturing
Section 49	Metal products
Section 50	Boiler, engines and turbine
Section 51	Metalworking machinery
Section 52	Agriculture, forestry, animal husbandry and fishing machinery
Section 53	Other special industrial equipment
Section 54	Other general industrial machinery
Section 55	Railroad transport equipment
Section 56	Motor vehicles and fittings
Section 57	Ship building
Section 58	Other transport machinery
Section 59	Generators
Section 60	Household electric appliances
Section 61	Other electric machinery and equipment
Section 62	Electronic computer
Section 63	Other electronic and communication equipment
Section 64	Instruments, meters and other measuring equipment
Section 65	Other manufacturing products
Section 66	Scrap waste
Section 67	Construction
Section 68	Railway transport
Section 69	Highway transport
Section 70	Water transport
Section 71	Air transport
Section 72	Other transport
Section 73	Post and Telecommunications
Section 74	Electricity and steam production and supply
Section 75	Gas production and supply
Section 76	Water production and supply
Section 77	Warehousing
Section 78	Wholesale and retail trade
Section 79	Eating and drinking places
Section 80	Real estate
Section 81	Finance
Section 82	Insurance
Section 83	Health services
Section 84	Sports
Section 85	Educational services
Section 86	Culture and arts, radio, film and television
Section 87	Social welfare
Section 88	Other Services

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