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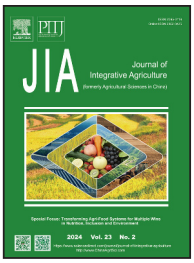

RESEARCH ARTICLE

The impact of demographic dynamics on food consumption and its environmental outcomes: Evidence from China

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Abstract

With increasing population and changing demographics, food consumption has experienced a significant transition in quantity and quality. However, a dearth of knowledge remains regarding its environmental impacts and how it responds to demographic dynamics, particularly in emerging economies like China. Using the two-stage Quadratic Almost Demand System (QUAIDS) model, this study empirically examines the impact of demographic dynamics on food consumption and its environmental outcomes based on the provincial data from 2000 to 2020 in China. Under various scenarios, according to changes in demographics, we extend our analysis to project the long-term trend of food consumption and its environmental impacts, including greenhouse gas (GHG) emissions, water footprint (WF), and land appropriation (LA). The results reveal that an increase in the proportion of senior people significantly decreases the consumption of grain and livestock meat and increases the consumption of poultry, egg, and aquatic products, particularly for urban residents. Moreover, an increase in the proportion of males in the population leads to higher consumption of poultry and aquatic products. Correspondingly, in the current scenario of an increased aging population and sex ratio, it is anticipated that GHG emissions, WF, and LA are likely to decrease by 1.37, 2.52, and 3.56%, respectively. More importantly, in the scenario adhering to the standards of nutritional intake according to the Dietary Guidelines for Chinese Residents in 2022, GHG emissions, WF, and LA in urban areas would increase by 12.78, 20.94, and 18.32%, respectively. Our findings suggest that changing demographics should be considered when designing policies to mitigate the diet-environment-health trilemma and achieve sustainable food consumption.

Keywords: demographic dynamics, food consumption, environmental impacts, nutrition intakes

1. Introduction

With economic development and urbanization, China has witnessed significant changes in food consumption in the last 20 years. The proportion of food expenditure in urban (rural) areas has reduced from 39.4% (49.1%) in 2000 to 29.2% (32.7%) in 2020 (NBSC 2001, 2021a), which is consistent with Engel's law. More importantly,

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the per capita consumption of grain decreased while the per capita consumption of animal-based food (including livestock, poultry, egg, aquatic products, and dairy products) increased (Ren *et al.* 2019; Yu *et al.* 2020). In particular, rural residents decreased their per capita consumption of grain from 250.23 kg in 2000 to 168.40 kg in 2020 but increased their per capita consumption of poultry (dairy products) from 2.81 (1.06) kg in 2000 to 12.40 (7.40) kg in 2020 (NBSC 2001, 2021a). Economic factors, such as income and price, are commonly believed to drive changes in food consumption patterns. However, demographics such as age and sex can not be ignored when studying food demand (Carter *et al.* 2009).

The impact of China's demographic dynamics on food consumption deserves more attention. There has been a significant change in the demographic structure of the population in China due to the one-child policy implemented in the 1980s and the longer life expectancy (Jiang *et al.* 2022). Although the government has allowed families to have a second or even a third child in recent years, it is an indisputable fact that the number of elderly people in this country is increasing rapidly (Peng 2011). According to the 7th National Population Census in China, there were 264 million people aged 60 and above in 2020, accounting for 18.70% of the population, an increase of 5.44% compared with 2010. It is estimated that by 2025 and 2050, China's population aging rate will reach 20 and 30%, respectively, which implies that China will have the largest elderly population in the world. In addition, the male population is 34.90 million more than the female population (NBSC 2021b), thereby indicating an imbalance in the sex ratio. Therefore, changes in demographic dynamics will inevitably affect future food demand in China (Seale *et al.* 2012). Unfortunately, although Ren *et al.* (2018) incorporated demographic variables into econometric models, the demand elasticities of demographic dynamics — that is, the impacts of demographics on food demand — are not calculated. Min *et al.* (2015) attempted to reveal the relationship between population aging and meat consumption in China, but their study could not accurately reflect the impact of population aging on other food items, which is not conducive to obtaining a good understanding of future changes in food demand in this country.

Changing food consumption patterns due to demographic dynamics may inevitably contribute to environmental changes, as various resources are involved in the entire food chain — from production to consumption (Tilman *et al.* 2001; Hu 2011). Food systems driven by consumption patterns are estimated to be responsible for 19–29% of greenhouse gas (GHG) emissions (Vermeulen *et al.* 2012), 70% of water consumption (Hoekstra *et al.* 2012), and 38% of land appropriation (LA) (Ranganathan 2013). Without technological changes and dedicated mitigation measures, the environmental impacts of the food system could reach and exceed the planetary boundaries that keep humans safe (Springmann *et al.* 2018). One possible approach is to reduce the consumption of animal-based foods (particularly red meat), which can both ease environmental pressure and reduce diet-related health risks (Aston *et al.* 2012). However, these findings are based mainly on developed countries, and studies that focus on developing countries like China are rare. Unlike Western countries, consumers in China consume more fruits and vegetables while less meat and milk but prefer pork rather than beef, which will likely lead to different conclusions (He *et al.* 2019). Meanwhile, a few important socio-economic factors, such as demographic dynamics, are missing in the existing evaluations of the relationship between food consumption and environmental outcomes.

Using the two-stage Quadratic Almost Demand System (QUAIDS) model, this study empirically examines the impact of demographic dynamics on food consumption and its environmental outcomes based on the provincial data from 2000 to 2020 in China. Then, considering the changes in demographics and the requirement for nutrition intake, we project future food demand and its environmental outcomes. Compared with previous research, this study makes the following contributions. First, we incorporate demographic dynamics into the elasticity calculation to reveal the impacts of demographics on food consumption, this helps to better understand the future changes in food demand due to the changes in demographics. Second, this study links diet with resource use and their environmental outcomes, making it possible to alleviate environmental pressure from the perspective of food consumption. Third, this study projects environmental outcomes of future food demand based on demographic changes to coordinate the relationship among population, diet, and environment, which is of great significance to ensure China's food security and sustainable food consumption.

The remainder of this study is organized in the following manner. In Section 2, we review the literature on the impact of demographic dynamics on food consumption and the environmental outcomes caused by food consumption. Section 3 briefly presents the two-stage QUAIDS model and corresponding environmental impact factors and describes the data used in this study; Section 4 estimates the demand elasticities with respect to demographic variables, predicts the future food demand and its environmental outcomes, and discusses these results; and Section 5 presents the conclusions.

2. Literature review

International evidence shows that demographic dynamics are important factors influencing food consumption. The first strand of literature highlights the importance of age in food consumption. Generally speaking, an increase in the proportion of the elderly and young population in the total population will reduce overall food consumption, but this does not mean that the demand for all foods will decrease (Riediger *et al.* 2008). Evidence shows that unhealthy food intake, including sugar and fast foods, decreases as age grows, while the demand for healthy food such as vegetables and fruits increases (Drewnowski *et al.* 2001). Therefore, changes in food consumption can be explained by changes in age structure in addition to economic income. It should be noted that age structure has no significant effect on food consumption in the UK, with race being the only important factor (Astbury *et al.* 2019). The second strand of literature explores the effects of sex on food choices and consumption behavior (Kim *et al.* 2009). In Finland, gender affects healthy food consumption because the diet of the female population is closer to the national nutrition recommendations (Adebayo *et al.* 2017). Based on 18,108 food frequency questionnaires, Brunin *et al.* (2022) suggested that young French women consume more plant-based and organic foods than other groups, which is consistent with the findings of Culliford *et al.* (2020). Regarding gender differences, men tend to eat more meat, eggs, milk, and sugary foods. Women, by contrast, eat more fruits and vegetables (Fraser *et al.* 2000). Similar to the above point, a food consumption survey in Canada shows that men consume 50% more food than women, yet they eat 30% less fruit and vegetables.

Many studies focus on the relationship between demographic dynamics and consumption in China (Modigliani *et al.* 2004; Han *et al.* 2022), while scant studies have addressed the effects of demographic dynamics on food demand. Huang (1999) pointed out that an increasing proportion of the elderly population is likely to reduce residents' demand for all food items. Different from this view, the aging population can increase the demand for certain foods, such as poultry and eggs (Gao *et al.* 2022). Based on the household survey data from 1991–2009, Zhong *et al.* (2012) constructed the index of the Adult Male Equivalent Scale and analyzed the effect of age structure on energy intake. However, the effect of age is not clearly revealed. Furthermore, Zheng *et al.* (2019) incorporated both age and sex structure into the econometric model, while they did not consider sex ratio when projecting future food demand. Existing studies do not reach a consensus, and there is a lack of empirical analysis of the relationship between demographic dynamics and food consumption.

Due to the changes in dietary patterns in China, the impact of food consumption on resources and the environment has also been a concern of scholars. It is an indisputable fact that the transformation of food consumption leads to increased pressure on resources and the environment, including greenhouse gas (GHG) emissions, water consumption, and land appropriation (Li *et al.* 2016; Zhu *et al.* 2023). For example, GHG emissions generated by food consumption among urban residents in Beijing increased from 2.15 kg/person/day in 1980 to 3.04 kg/person/day in 2017 due to the significant increase in animal-based food consumption (Xiong *et al.* 2020). Similarly, the water consumption caused by food consumption increased from 255 m^3/person/year in 1961 to 860 m^3/person/year in 2003 because of the increasing demand for meat foods (Liu *et al.* 2008). Based on this, it is the consensus to adjust the diet structure to achieve sustainable food consumption (Wang *et al.* 2020). Specifically, the main measures are to replace animal-based foods with plant-based foods and to recombine meat products (Wang *et al.* 2021). However, reducing meat consumption may have fewer environmental benefits, as residents may increase their consumption of other foods to obtain adequate nutrition (Song *et al.* 2017). Therefore, adjusting the dietary structure and relieving the pressure of resources and the environment can not be at the expense of reducing the nutritional needs of residents (He *et al.* 2018).

As mentioned, the existing studies still have the following limitations: First, there is insufficient knowledge regarding the impact of age and sex structure on food consumption in China, where the demographic structure is undergoing a huge shift. Second, existing studies do not consider demographic dynamics, food consumption, and environmental effects in the same analytical framework, which is not conducive to clearly revealing the internal relationship between socio-economic changes and the environment. Third, most of the studies focus on a single dimension and lack the quantitative analysis to take into account resource and environmental costs such as GHG emissions, water consumption, and land appropriation.

3. Data and methods

3.1. The two-stage QUAIDS model

Unlike existing literature that focuses on estimating income and price elasticities through a demand system, this study focuses on the demand elasticities of demographic variables. Generally, the almost ideal

demand system (AIDS) model derived by Deaton *et al.* (1980a) has been widely used in two-stage or multi-stage budgeting decisions (Edgerton 1997; Carpentier *et al.* 2001). However, the AIDS model is a two-rank model, and the Engel curve is a generalized linear. To characterize the impact of quadratic terms of expenditure on consumption share, Banks *et al.* (1997) proposed the QUAIDS model based on the AIDS model. Given that the rank of the demand system is 3, the QUAIDS model allows goods to change from luxuries to necessities as income rises (Cranfield *et al.* 2002, 2003; Yu *et al.* 2004; Seale Jr *et al.* 2006; Abler 2010). In addition, residents' food consumption can be divided into two stages: In the first stage, consumers allocate total expenditure to eight commodity groups; in the second stage, consumers allocate food expenditure to individual food items. Assuming that the total utility is weakly separable and the true cost-of-living index of the commodity group does not vary dramatically with the sub-utility level, the two-stage budgeting framework exists in approximation and can be used to investigate the determinants of food consumption (Deaton *et al.* 1980b). The general form of the QUAIDS model is given below:

$$w_{it}=\alpha_i+\sum_{j=1}^{n}\gamma_{ij}\ln(p_{jt})+\beta_i\ln\left[\frac{x_t}{a(p_t)}\right]+\frac{\lambda_i}{b(p_t)}\left\{\ln\left[\frac{x_t}{a(p_t)}\right]\right\}^2+\varepsilon_{it} \quad (1)$$

where the subscript i and j indicate the ith and jth goods, respectively; n represents the number of goods in the system; w_{it} represents the proportion of good i in year t; x_t is the total expenditure for the n goods in year t; p_{jt} is the price of good j in year t. α_i, γ_{ij}, β_i, and λ_i are the parameters to be estimated; when λ_i=0, the QUAIDS model degenerates to the AIDS model; ε_{it} is the error term. Further, $a(p_t)$ indicates the price index and can be described in the following manner:

$$\ln a(p_{jt})=\alpha_0+\sum_{i=1}^{n}\alpha_i\ln(p_{jt})+\frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\gamma_{ij}\ln(p_{it})\ln(p_{jt}) \quad (2)$$

and $b(p_t)$ is the Cobb-Douglas price aggregator:

$$b(p_{jt})=\prod_{i=1}^{n}p_{it}^{\beta_i} \quad (3)$$

According to the relevant translating approach (Pollak *et al.* 1978, 1981; Abdulai *et al.* 2004; Bopape *et al.* 2007), demographic variables, including the proportion of seniors and sex ratio, are added to the intercept term α_i. In addition, given that residents within the same region share similar preferences in terms of food consumption, all provinces are divided into seven groups — Northeast, North, Central, East, South, Northwest, and Southwest China. In addition, the time variable is also taken into account. Hence, six region dummies (D) and time trend terms (t) are incorporated into the intercept term in the QUAIDS model to capture the regional differences and changes in time. Then, α_i is presented in the following manner:

$$\alpha_i=\alpha_{i0}+\sum_{k=1}^{K}\alpha_{ik}Z_k+\beta_{i1}D_1+\beta_{i2}D_2+\beta_{i3}D_3+\beta_{i4}D_4+\beta_{i5}D_5+\beta_{i6}D_6+\beta_{i7}t \quad (4)$$

where α_{i0} and α_{ik} are parameters to be estimated, and Z_k denotes a set of K demographic variables. Three parametric restrictions must be imposed on the QUAIDS model for integrability (Moro *et al.* 2000; Gould *et al.* 2006). The adding-up restriction is given by:

$$\sum_{i=1}^{n}\alpha_{i0}=1,\ \sum_{i=1}^{n}\alpha_{ik}=0,\ \sum_{i=1}^{n}\gamma_{ij}=0,\ \sum_{i=1}^{n}\beta_i=0,\ \sum_{i=1}^{n}\lambda_i=0 \quad (5)$$

Further, homogeneity is imposed as:

$$\sum_{j=1}^{n}\gamma_{ij}=0 \quad (6)$$

Slutsky symmetry is expressed as:

$$\gamma_{ij}=\gamma_{ji},\ i\neq j \quad (7)$$

Based on Banks *et al.* (1997), the uncompensated (Marshallian) price elasticities are calculated in the following manner:

$$e_{ij}^{U}=\frac{\mu_{ij}}{w_i}-\delta_{ij} \quad (8)$$

where $\mu_{ij}=\frac{\partial w_i}{\partial \ln p_j}=\gamma_{ij}-\left[\beta_i+\frac{2\lambda_i}{b(p)}\ln\left(\frac{x}{a(p)}\right)\right]\left(\alpha_j+\sum_{k=1}^{n}\gamma_{ij}\,p_k\right)-\frac{\lambda_i\beta_i}{b(p)}\left[\ln\left(\frac{x}{a(p)}\right)\right]^2$; δ_{ij} is the Kronecker delta, which is 1 when $i=j$ and 0 otherwise.

The expenditure elasticities are expressed as:

$$e_i=1+\frac{u_i}{w_i} \quad (9)$$

where $u_i=\frac{\partial w_i}{\partial \ln m}=\left[\beta_i+\frac{2\lambda_i}{b(p)}\ln\left(\frac{x}{a(p)}\right)\right]$

Further, the demand elasticities of demographic variables are derived in the following manner:

$$e_{ik}^{Z}=\left\{\alpha_{ik}-\sum_{j=1}^{n}\alpha_{jk}\ln(p_{jt})\left[\beta_i+\frac{2\lambda_i}{b(p)}\ln\left(\frac{x}{a(p)}\right)\right]\right\}\times\frac{Z_k}{w_i} \quad (10)$$

Given that the dependent variable is budget share, one of the equations must be excluded to avoid a singular error-covariance matrix (Poi 2012). Further, Marshallian price elasticity and expenditure elasticity can be derived in accordance with eq. (11) (Yen *et al.* 2002; Yen *et al.* 2003):

$$\sum_{i=1}^{n}e_iw_i=1,\ \sum_{i=1}^{n}e_{ij}^{U}w_i=-w_j,\ \sum_{j=1}^{n}e_{ij}^{U}+e_i=0 \quad (11)$$

To explore future food consumption patterns due to demographic changes, we use the calculated elasticities of demographic variables to project the demand for each food item. Several assumptions must be made before making projections. First, the food consumption preferences of urban and rural residents remained unchanged during the period (2000–2020). Second, the

relative prices of various food items are held constant at 2020 levels. Third, income and income distribution also remain unchanged. Finally, market development is not considered. Hence, the changes in food demand are only related to changes in demographic factors. The formula for this is given below:

$$\Delta Q_i = \left(\frac{\Delta Demo}{Demo}\right) E_{Demo,\,i} q_i^0 \quad (12)$$

where ΔQ_i denotes the changes in the per capita consumption quantity of food i; $\Delta Demo/Demo$ is the percentage of changes in demographic factors; $E_{Demo,\,i}$ represents the demand elasticity of demographics for food i; q_i^0 denotes the current average consumption quantity of food i for every individual.

3.2. Measurement of environmental outcomes

To measure the environmental impact of each food item, this study considers three environmental outcomes as a result of food consumption, including GHG emissions, water footprint (WF), and LA. In line with the method based on the global life cycle assessment database with the inclusion of the whole food chain from production to consumption (Song *et al.* 2017), we construct the GHG emissions data, including CO_2, CH_4, and NO_2. The WF refers to the water resources for all services and commodities consumed by residents under a certain living standard (Hoekstra *et al.* 2002). Following the estimates by Song *et al.* (2015) and Xu *et al.* (2018), we construct the data on water footprint for different food items. In addition, we base the land appropriation data incorporated in this study on Meier *et al.* (2013). Three environmental outcomes are calculated in the following equation:

$$EO_i = \sum_{j=1}^{n} (EF_{ij} \times Q_j) \quad (13)$$

where EO_i denotes the ith environmental outcome, including GHG emissions, WF, and LA; EF_{ij} is the environmental impact factor of food j when we calculate the corresponding environmental outcomes; Q_j represents the quantity of food j consumed per year per capita; n is the number of food items. Table 1 presents the environmental impact factors of each food type.

3.3. Data

Since the available data regarding food consumption are taken from different sources for urban and rural residents and their statistical caliber is varied, we separately construct the data for urban and rural residents. For the demand analysis of urban residents, we used data from 31 provinces, autonomous regions and municipalities from 2000 to 2020 in China. In the first stage, total expenditure consists of eight commodity groups — food, clothing, housing, household equipment and services, health care, transport and communication, education and culture, and miscellaneous goods and services. The expenditure data of the eight commodity groups are obtained from the *Chinese Statistical Yearbook* (2001–2021), while the data on consumer price indexes are from the *China Price and Urban Household Income and Expenditure Survey Statistical Yearbook* (2001–2005), *China Urban Life and Price Yearbook* (2006–2012), and *China Price Statistical Yearbook* (2013–2021). With regard to the miscellaneous goods and services with missing values, we use the total consumer price index to replace them. Food expenditure in the first stage is equal to the sum of expenditure on individual food in the second stage. Based on the price of different individual foods, we can calculate Stone's price index and then convert it into the Laspeyres index as the price index of the food group.

There are nine individual food items in the second stage for urban residents — grains, edible oil, livestock meat (including pork, beef, and mutton), poultry meat, eggs, aquatic products, vegetables, fruits, and dairy products. The consumption of each food in 31 provinces, autonomous regions and municipalities during the period 2000–2020 is taken from the *Provincial Statistical Yearbook* (2001–2021) in China. The expenditure on nine major foods from 2000 to 2012 is obtained from the *China Urban Life and Price Yearbook* (2001–2013). In addition, we use expenditure and quantity data to calculate the unit value of different foods during the period 2000–2012; all prices of these food items from 2013 to 2020 are further extrapolated based on the data in 2012 and the corresponding urban price indexes from the *China Price Statistical Yearbook* (2013–2021). Therefore, the expenditure can be derived from price and quantity.

Table 1 Environmental impact factors of different foods

Food	GHG emissions[1)] (kg CO_2 e kg^{-1})	Water footprint (m^3 kg^{-1})	Land appropriation (m^2 kg^{-1})
Grains	1.52	1.49	1.78
Edible oil	3.43	6.25	4.14
Pork	4.22	5.99	8.91
Beef	21.30	15.41	25.44
Mutton	13.36	5.26	19.88
Poultry meat	3.92	4.33	6.24
Eggs	3.26	3.28	3.80
Aquatic products	3.85	1.22	0.17
Vegetables	0.87	0.27	0.45
Fruits	0.88	1.05	0.86
Dairy products	1.45	2.32	2.42

[1)] Greenhouse gas (GHG) emissions are measured as CO_2 equivalent.

For rural residents, we use panel data on 30 provinces, autonomous regions and municipalities (excluding Xizang) from 2000 to 2020 for demand analysis. The types of commodities in the first stage and their data sources are the same as those for urban areas. It should be noted that the missing data in Beijing, Tianjin, Shanghai, and Chongqing is replaced by the total consumer price index of rural residents. Similarly, the total food expenditure is also the sum of the costs of different individual food items in the second stage, and the Laspeyres index derived from Stone's price index based on individual foods is adapted to measure the price index of the entire food group.

Unlike urban residents, there are 11 individual food items for rural residents in the second stage, including grains, edible oil, pork, beef, mutton, poultry meat, eggs, aquatic products, vegetables, fruits, and dairy products. Per capita consumption of foods is taken from three sources: *China Yearbook of Rural Household Survey* (2001–2010), *China Yearbook of Household Survey* (2011–2021), and the *Provincial Statistical Yearbook* (2001–2021) in China. The prices for grains, edible oil, vegetables, fruits, pork, beef, mutton, poultry meat, eggs, and aquatic products during the period 2003–2015 are based on the farmer's market price from the *China Yearbook of Agricultural Price Survey* (2004–2016); price data for pork, beef, mutton, poultry meat, and eggs from 2016 to 2020 are taken from the *China Animal Husbandry Yearbook* (2016–2021). Further, the price for dairy products during the period 2000–2020 is from the *China Dairy Industry Yearbook* (2002–2020) and *China Animal Husbandry Yearbook* (2001–2021). The observations with missing values are calculated with price and corresponding rural price indexes on different food items. Last, we use price and quantity data to compute the expenditure for the 11 food items.

Following previous studies (Zhong *et al.* 2012; Zheng *et al.* 2019), two indicators for measuring demographic dynamics are considered in his study, including age composition and sex. However, as the number of seniors in the population continues to increase, China has entered a stage of a severely aging population. In addition, the sex ratio is unbalanced. Based on the actual situation and data availability, this study selects the proportion of seniors aged 65 and over and the sex ratio to explore the impacts of population dynamics on food consumption. These data are obtained from the *China Population and Employment Statistical Yearbook* (2001–2021).

4. Results and discussion

4.1. Statistical analysis

Trends of demographics and food consumption The demographic structure and food consumption in both urban and rural areas in China have undergone significant changes since the year 2000 (Table 2). According to Population Ageing and its Socio-economic Consequences, issued by the UN in 1956, an aging society is characterized by seniors aged 65 and over exceeding 7% of the total population within a country or region. First, China is characterized by an aging society with an unbalanced sex ratio. Specifically, the proportion of urban seniors aged 65 and over increased from 6.30% in 2000 to 11.11% in 2020, while the sex ratio shifted from "more female than male" to "more male than female" during the study period and showed obvious unbalanced characteristics. In contrast, there is a more severe problem in rural areas — that is, the aging of rural residents reached 10.06% in 2010 and 17.72% in 2020. Similarly, the sex ratio increased from 104.98 in 2000 to 107.91 in 2020, thereby indicating a clear upward trend.

Second, residents' food expenditure increases with the improvement of living standards. The reason for this is that residents could afford more food and meet their dietary energy requirements when household income increases. For example, the food expenditure of urban residents increased from 1,958.31 to 5,084.40 CNY per capita per year during 2000–2020, with an average annual growth rate of 4.89%, while rural residents have a higher growth rate of 6.15%. Nevertheless, the ratio of food expenditure to income gradually declined regardless of whether individuals lived in urban or rural areas, which is highly consistent with Engel's law.

Last, per capita consumption of animal-based food rapidly increases while grain consumption declines. Except for pork, the consumption of other animal-based foods (i.e., beef and mutton, poultry, aquatic products, egg, and dairy products) increased considerably during the study period. As shown in Table 2, the per capita consumption of poultry in the countryside increased from 2.81 kg in 2000 to 12.40 kg in 2020, but rural residents always consumed less animal-based food than their urban counterparts. In contrast, per capita consumption of grains in rural areas reduced from 250.23 in 2000 to 168.40 in 2020, with an average annual growth rate of –1.96%, which is still significantly higher than that of urban residents. In addition, the consumption of vegetables also shows a downward trend characterized by volatility.

Environmental outcomes of food consumption Increases in per capita food consumption lead to more demand for resources. As indicated in Table 3, the average annual growth rates of GHGs, WF, and LA of urban residents are 0.92, 1.03, and 1.16%, respectively, during the period 2000–2010. Further, the environmental impacts continue to increase after 2010. For example, WF increased from

600.22 m^3 in 2010 to 665.61 m^3 in 2020. Compared with urban areas, environmental outcomes caused by food consumption in rural areas show a downward trend from 2000 to 2010. The possible reason for the existence of opposite shifts between the two is that grain consumption of rural residents decreases sharply. Specifically, the substantial reduction in grain consumption offsets the pressure on resources and the environment caused by animal-based food consumption, which ultimately reduces GHG emissions, WF, and LA. However, the environmental outcomes of food consumption increased in both urban and rural areas during the period 2010–2020. Although the growth rate in rural areas is higher, the environmental outcomes of per capita food consumption are consistently smaller than those in urban areas. The reason is that urban residents consume more livestock meat, aquatic products, and dairy products, which increases resource consumption and aggravates the environmental burden.

With regard to the composition of environmental outcomes, there are both similarities and differences between urban and rural residents (Fig. 1). On the one hand, animal-based foods (i.e., pork, beef and mutton, poultry, eggs, aquatic products, and dairy products) play an increasingly important role in environmental outcomes, while plant-based foods (i.e., grains, edible oil, vegetables, and fruits) contribute less and less to this. On the other hand, given the different dietary structures in rural areas, plant-based food — particularly grain— has a significant environmental impact. For example, the contribution of grain consumption to GHGs, WF, and LA is 38.39, 39.08, and 38.75%, respectively, in 2020, while that in urban areas is 25.53, 26.90, and 26.36%, respectively, in 2020. In addition, the consumption of livestock and poultry meat has increasingly become the dominant factor affecting urban resources and the environment.

4.2. Empirical analysis

We use the iterated linear least-squares (ILLS) estimator to estimate the QUAIDS model to obtain a consistent and asymptotically normal estimator. It is worth noting that ILLS is a preferred alternative to nonlinear, seemingly

Table 2 Demographic structure and per capita food consumption in China from 2000 to 2020

Item[1)]	Urban					Rural				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Aging rate (%)	6.30	8.49	7.80	7.81	11.11	7.35	9.55	10.06	12.03	17.72
Sex ratio (%)	98.65	100.74	104.92	105.02	103.08	104.98	103.38	104.87	105.03	107.91
Engel (%)	39.40	36.70	35.70	29.70	29.20	49.10	45.50	41.10	33.00	32.70
Expenditure (CNY)	1,958.31	2,760.88	3,973.49	4,574.45	5,084.40	820.52	1,063.90	1,401.26	2,062.66	2,706.42
Grains (kg)	109.75	102.64	108.71	112.60	120.20	250.23	208.85	181.44	159.50	168.40
Edible oil (kg)	8.16	9.25	8.84	11.10	9.90	7.06	6.01	6.31	10.10	11.00
Pork (kg)	16.73	20.15	20.73	20.70	19.04	13.28	15.62	14.40	19.50	17.10
Beef & mutton (kg)	3.33	3.71	3.78	3.90	4.46	1.13	1.47	1.43	1.70	2.30
Poultry (kg)	5.44	8.97	10.21	9.40	13.00	2.81	3.67	4.17	7.10	12.40
Aquatic products (kg)	11.74	12.55	15.21	14.70	16.60	3.92	4.94	5.15	7.20	10.30
Eggs (kg)	11.21	10.40	10.00	10.50	13.50	4.77	4.71	5.12	8.30	11.80
Dairy products (kg)	9.94	17.92	13.98	17.10	17.30	1.06	2.86	3.55	6.30	7.40
Vegetables (kg)	114.74	118.58	116.11	104.40	109.80	106.74	102.28	93.28	90.30	95.80
Fruits (kg)	57.48	56.69	54.23	55.10	65.90	18.31	17.18	19.64	32.30	43.80

[1)] Aging rate denotes the proportion of seniors (age≥65); the sex ratio is calculated based on females (females=100); Engle denotes the Engle coefficient — that is, the proportion of food expenditure in total consumption expenditure; Expenditure represents the expenditure on food and is deflated by consumer price indexes for both urban and rural residents, with the price level in the year 2000 as the base; the grain consumption of urban residents is measured in reference to processed grains before 2013; however, due to the change in statistical caliber, we convert it into unprocessed grains (raw).

Sources: *China Statistical Yearbook* (2001–2021), *China Population and Employment Statistical Yearbook* (2001–2021).

Table 3 Environmental outcomes of per capita food consumption by urban and rural residents[1)]

Year	Urban			Rural		
	GHG emissions (kg CO_2 e)	WF (m^3)	LA (m^2)	GHG emissions (kg CO_2 e)	WF (m^3)	LA (m^2)
2000	593.64	541.57	659.17	637.73	594.21	724.13
2010	650.56	600.22	739.52	540.06	507.18	623.79
2020	715.50	665.61	811.43	666.66	641.86	773.42
$\Delta_{2000–2010}$	0.92%	1.03%	1.16%	–1.65%	–1.57%	–1.48%
$\Delta_{2010–2020}$	0.96%	1.04%	0.93%	2.13%	2.38%	2.17%

[1)] GHG, greenhouse gas; WF, water footprint; LA, land appropriation. The last two rows represent the average annual growth rate.

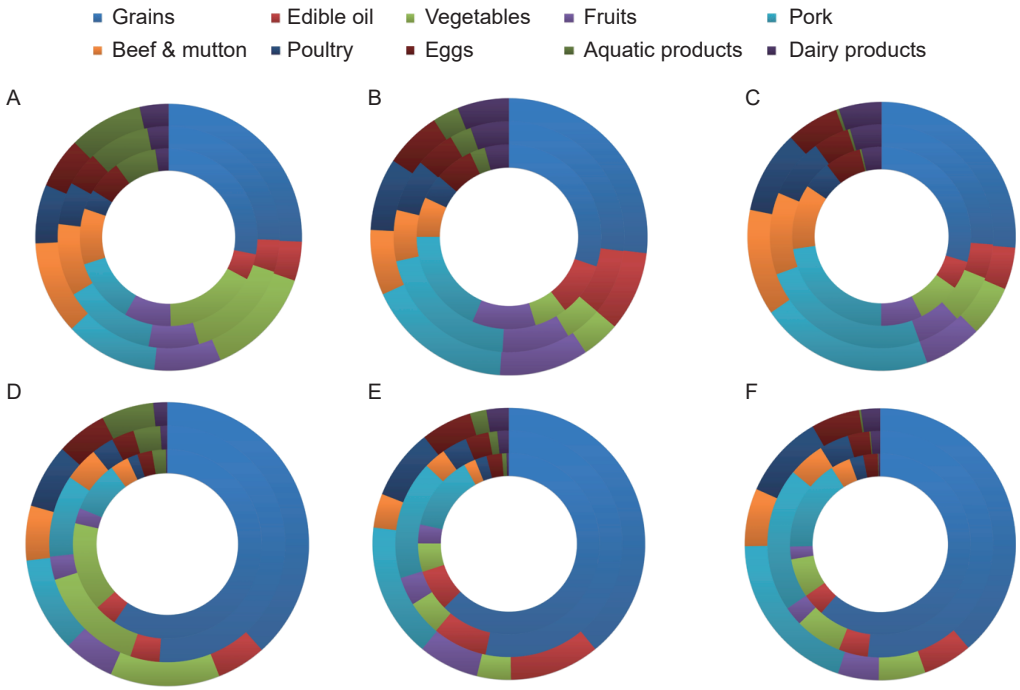

Fig. 1 The structure of food environmental outcomes. A and D denote the composition of greenhouse gas emissions in urban and rural areas, respectively; B and E represent the composition of the water footprint in urban and rural areas, respectively; while C and F refer to the composition of land appropriation in urban and rural areas, respectively. The doughnut chart represents the years 2000, 2010, and 2020, respectively, from the inside to the outside. Among 10 foods, the first four are plant-based foods, and the last six are animal-based foods.

unrelated regressions and nonlinear three-stage least squares for large demand systems (Lecocq *et al.* 2015). Further, the QUAIDS model satisfies the homogeneity and symmetry constraints, and one of the equations must be excluded to avoid a singular error-covariance matrix. The "miscellaneous goods and services" equation in Stage 1 and the "edible oil" equation in Stage 2 are omitted when executing the estimation. In particular, we calculate the demand elasticities for the entire food group in Stage 1 while reporting the demand elasticities for each food commodity in Stage 2. In addition, the estimation results for QUAIDS in Stage 2 are presented in Appendices A and B.

Demand elasticities for total food consumption Table 4 reports demand elasticities for eight commodities for urban and rural residents. Generally, the table indicates that own-price elasticity and expenditure elasticity are statistically significant for both urban and rural residents, while their magnitude is varying. As food is a necessity good, its demand has the smallest price, and expenditure elasticates among all expenditures for rural and urban residents. This indicates that with increasing expenditure, the demand for food does not change too much. Moreover, compared to urban residents, rural residents have higher price and expenditure elasticities, thereby suggesting that changing prices and expenditures would affect food consumption more for rural residents than for urban residents.

With regard to the demographic variables, for urban residents, the demand elasticity of aging is statistically significant, while the demand elasticity for the sex ratio is insignificant. Precisely, a 1% increase in aging would increase food expenditure by 0.082%. On the contrary, the demand elasticity of the sex ratio is significant for rural residents, but the demand elasticity of aging is insignificant. It should be noted that whether in urban or rural areas, the aging population has a positive impact on food consumption. The elderly in urban areas have higher income and dietary knowledge (Min *et al.* 2021), leading to a greater effect on food consumption. One interesting finding is that the sex ratio increases food consumption in rural areas but not in urban areas. Rural families have long favored sons over daughters, meaning the sex ratio is unbalanced in rural areas. The increase in the male population directly leads to more food consumption, which is consistent with the research of Morrison *et al.* (2011). Compared with rural residents, the sex ratio of urban residents is more reasonable and not highly variable, which is why the elasticity of the sex ratio is negative and not significant.

Table 4 Demand elasticities of family consumption for urban and rural residents

Item[1)]	Clothing	Housing	Food	Household equipment	Health care	Transport	Education & culture	Other[2)]
Urban								
Expenditure elasticities								
	1.018***	0.863***	0.524***	1.113***	0.884***	1.394***	1.226***	1.120***
	(0.028)	(0.061)	(0.029)	(0.030)	(0.025)	(0.026)	(0.025)	(0.052)
Own-price elasticities								
	–1.892***	–1.522***	–0.310***	–1.727***	–1.730***	–1.824***	–1.479***	–2.438***
	(0.052)	(0.164)	(0.043)	(0.080)	(0.052)	(0.072)	(0.057)	(0.374)
Demographic elasticities								
Aging rate	–0.382***	0.298***	0.082**	–0.042	0.276***	–0.214***	0.148***	–0.153***
	(0.039)	(0.050)	(0.038)	(0.029)	(0.031)	(0.029)	(0.034)	(0.054)
Sex ratio	–0.360**	0.152	–0.173	0.583***	0.089	–0.111	0.191	0.120
	(0.148)	(0.191)	(0.170)	(0.185)	(0.121)	(0.108)	(0.144)	(0.229)
Rural								
Expenditure elasticities								
	1.105***	1.171***	0.536***	1.214***	1.214***	1.238***	1.165***	1.278***
	(0.022)	(0.031)	(0.027)	(0.027)	(0.022)	(0.021)	(0.037)	(0.048)
Own-price elasticities								
	–2.172***	–1.584***	–0.683***	–1.527***	–1.963***	–2.323***	–1.279***	–1.490***
	(0.066)	(0.059)	(0.048)	(0.135)	(0.066)	(0.081)	(0.089)	(0.387)
Demographic elasticities								
Aging rate	0.043*	–0.073***	0.018	–0.033	–0.040*	–0.002	0.122***	–0.003
	(0.024)	(0.028)	(0.023)	(0.022)	(0.021)	(0.002)	(0.038)	(0.002)
Sex ratio	–0.050	–0.370**	0.490***	0.188	–0.218	–0.273**	–0.222	–0.450*
	(0.161)	(0.162)	(0.134)	(0.172)	(0.136)	(0.130)	(0.207)	(0.272)

[1)] Own-price elasticities are Marshallian own-price elasticities; aging rate is the proportion of seniors (age≥65); the sex ratio is calculated based on female (female=100).
[2)] Other indicates miscellaneous goods and services.
Standard errors are given in parentheses; *, P<0.1; **, P<0.05; ***, P<0.01.

To further examine whether demographic dynamics affect the patterns of food consumption, we conduct a QUAIDS estimation for each food commodity in the second stage.

Demand elasticities for different food commodities Table 5 reports the demand elasticities of different foods for urban and rural residents. As shown in Table 5, whether urban residents or rural residents, the price and expenditure elasticities of animal-based food are higher than that of plant-based food. For instance, the expenditure elasticity of grain for rural residents is 0.368, while that of aquatic products is 1.764, which shows that the consumption of aquatic products would fluctuate more with the change of expenditure than grain. In other words, total expenditure might not be a significant factor influencing grain consumption. Another interesting finding is that the price elasticities of animal-based food for rural residents are higher than those of urban residents, while the elasticities of plant-based food are lower than those for urban residents. As noted by Ren *et al.* (2018), rural households have more substitutional possibilities for animal-based food as the economy develops. Specifically, the own-price elasticities of egg and fruit for rural residents are –1.037 and –0.279, respectively, while those of urban residents are –0.742 and –0.544, respectively. This means that when prices rise, rural residents tend to consume less animal-based foods. In contrast, urban residents tend to reduce the consumption of plant-based foods. Therefore, even facing the same constraints, urban and rural residents will make different consumption decisions. However, the price elasticities of various foods for urban residents in our study are smaller than the findings of Zheng *et al.* (2010). Differences in price elasticities could be attributed to the time span of the data and whether the study used a two-stage demand system model.

As for demographic variables, most demand elasticities are significant at different levels, which means that demographic dynamics are important factors affecting the changes in food demand. Hence, projections of future food demand are undoubtedly biased without accounting for demographics (Zhong *et al.* 2012). Meanwhile, although population aging and gender imbalances are more severe in rural areas, demographic variables have stronger impacts on food demand in urban areas. For example, population aging has a significant impact on the consumption of various foods for urban residents but not on rural residents. As shown in Table 2, the consumption

Table 5 Demand elasticities of different food commodities for urban and rural residents

Item[1)]	Grains	Vegetables	Livestock			Poultry	Aquatic products	Eggs	Fruits	Dairy products	Edible oil
			Pork	Beef	Mutton						
Urban											
Expenditure elasticities											
	0.745***	0.579***		1.314***		1.660***	1.558***	0.751***	0.605***	0.847***	0.773***
	(0.052)	(0.053)		(0.051)		(0.093)	(0.158)	(0.066)	(0.088)	(0.105)	(0.210)
Marshallian own-price elasticities											
	–0.453***	–0.553***		–0.694***		–0.613***	0.113	–0.742***	–0.544***	–0.944***	–0.156**
	(0.037)	(0.042)		(0.030)		(0.048)	(0.084)	(0.062)	(0.052)	(0.040)	(0.077)
Demographic elasticities											
Aging rate	–0.347***	0.040*		–0.192***		0.147**	0.438***	0.127***	0.260***	0.046	–0.006
	(0.032)	(0.024)		(0.031)		(0.062)	(0.077)	(0.045)	(0.044)	(0.075)	(0.075)
Sex ratio	–0.148	–0.082		0.040		0.848***	0.793***	0.169	–0.082	–1.499***	–0.016
	(0.136)	(0.099)		(0.111)		(0.277)	(0.273)	(0.189)	(0.190)	(0.277)	(0.215)
Rural											
Expenditure elasticities											
	0.368***	1.003***	0.854***	1.877***	4.598***	1.480***	1.764***	0.427***	1.534***	0.808***	0.690***
	(0.053)	(0.066)	(0.081)	(0.360)	(0.988)	(0.095)	(0.142)	(0.091)	(0.141)	(0.186)	(0.090)
Marshallian own-price elasticities											
	–0.354***	–0.462***	–0.626***	–0.940**	0.665*	0.064	–0.329	–1.037***	–0.279**	–0.606***	–0.152*
	(0.064)	(0.069)	(0.056)	(0.426)	(0.342)	(0.076)	(0.208)	(0.111)	(0.117)	(0.217)	(0.083)
Demographic elasticities											
Aging rate	0.001	0.023	–0.083**	–0.208	0.348	0.066	–0.129	–0.044	0.122**	–0.102	–0.054
	(0.022)	(0.026)	(0.041)	(0.212)	(0.256)	(0.048)	(0.072)	(0.051)	(0.049)	(0.103)	(0.046)
Sex ratio	0.087	0.501***	–0.618***	–1.209	–1.189	–0.110	–1.304***	0.202	1.334***	–0.035	–0.332
	(0.167)	(0.135)	(0.224)	(1.005)	(1.604)	(0.274)	(0.491)	(0.318)	(0.339)	(0.736)	(0.267)

[1)] Aging rate is the proportion of seniors (age≥65); the sex ratio is calculated based on female (female=100).
Standard errors are given in parentheses; *, P<0.1; **, P<0.05; ***, P<0.01.

of other food items by urban residents is significantly higher than that by rural residents, except for grain. Furthermore, the gap between urban and rural populations will further widen with the advancement of urbanization (Huang *et al.* 1993; Rae 1998). Thus, it can be said that changes in the demographic characteristics of urban residents determine China's future food consumption patterns.

In terms of population aging, the traditional view is that lower metabolic rate and declined somatic function cause the elderly to have lower energy needs compared with younger people, which leads to a sharp reduction in food demand (Rolls 1993; Mendonca *et al.* 2016). However, our results do not support this view. For example, population aging among urban residents is shown to reduce the demands for grain and livestock meat while dramatically increasing the demands for vegetable, fruit, white meat (including poultry and aquatic products), and egg, which is consistent with the findings of Power *et al.* (2014). Similarly, population aging will prompt rural residents to increase the consumption of fruit (0.122) and decrease that of pork (–0.083). The above results show that this traditional view must be revised to better understand the impacts of an aging population on food demand. Further, different from Zheng *et al.* (2019), we argue that the sex ratio is also an important factor that affects food demand, particularly in urban areas. For instance, the increase in the sex ratio allows urban residents to consume more poultry and

aquatic products while reducing the consumption of dairy products, which is supported by Morrison *et al*. (2011). However, it should be noted that the sex ratio increases the consumption of vegetables and fruits for rural residents while reducing the consumption of pork and aquatic products. This finding doesn't match the common sense that males tend to consume more animal-based foods and less plant-based foods than females. The possible reason is that in rural households, women generally serve as food consumption decision-makers, so the demand for plant-based foods increases. In addition, low income and the lack of dietary knowledge are also important factors affecting the consumption of animal-based foods.

4.3. Projection of environmental outcomes

Another main purpose of this study is to explore the environmental outcomes of future changes in food demand due to demographics. Specifically, this section investigates the impact of changes in food demand on the environment in 2030, using the demand elasticities with respect to demographics. There are four scenarios: Scenarios 1 and 2 involve an increased rate of aging in the population and sex ratio, respectively, while keeping all other variables constant; scenario 3 involves an increased aging rate and sex ratio while keeping all other variables constant; scenario 4 involves an increase in the environmental pressure due to the recommended diet according to the Dietary Guidelines for Chinese Residents in 2022. The demographic variables and their changes are reported in Table 6.

Environmental impacts of the aging population An aging population leads to changes in food demand, which in turn have an effect on environmental outcomes (Table 7). Overall, an increase in the number of senior people will likely reduce the pressure on the environment due to changes in food demand, particularly in urban areas. For example, the changes in the age structure will likely reduce GHG emissions, WF, and LA from food consumption by 1.466, 2.464, and 3.519%, respectively. Notably, reduction in grain consumption contributes most to less environmental stress. However, for rural residents, population aging has little effect on alleviating environmental pressure. For example, the changes in the age structure will likely reduce GHG emissions, WF, and LA from food consumption by 0.584, 0.833, and 0.587%, respectively. In summary, aging could contribute to lower GHG emissions and resource use. We must acknowledge the fact that somatic function declines with age and that the elderly contribute less to social and economic development than younger groups. However, we can not treat older people as a burden on society in a narrow sense. Instead, the relationship between population aging, food consumption, and the environment should be viewed more positively from a sociological perspective (Rowe *et al.* 1987).

Environmental impacts of sex ratio Table 8 reports the changes in environmental outcomes caused by changes in the sex ratio both in urban and rural areas. Unlike population aging, the sex ratio does little to reduce the environmental consequences of food demand. For urban

Table 6 Demographic variables and their changes from 2020 to 2030

Demographics[1)]	Urban		Rural	
	2020	2030	2020	2030
Aging rate (%)	11.11	14.75	17.72	27.51
Δ	3.64		9.79	
Δ%	0.33		0.55	
Sex ratio (%)	103.08	105.37	107.91	109.41
Δ	2.29		1.50	
Δ%	0.022		0.014	

[1)] Aging rate is the proportion of seniors (age≥65); the sex ratio is calculated based on female (female=100).

Table 7 Environmental outcomes of the aging population in both urban and rural areas[1)]

Food	Urban			Rural		
	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)
Grains	–20.792	–20.382	–24.349	0.141	0.139	0.166
Edible oil	–0.067	–0.122	–0.081	–1.126	–2.052	–1.359
Livestock	–9.676	–10.261	–16.688	–3.974	–6.018	–7.035
Poultry	2.457	2.714	3.911	1.773	1.959	2.823
Aquatic products	9.181	2.909	0.405	–2.827	–0.896	–0.125
Eggs	1.833	1.844	2.137	–0.93	–0.941	–1.09
Dairy products	0.378	0.606	0.632	–0.605	–0.968	–1.010
Vegetables	1.253	0.389	0.648	1.060	0.329	0.548
Fruits	4.945	5.900	4.833	2.599	3.101	2.540
TotalΔ	–10.488	–16.403	–28.552	–3.895	–5.348	–4.543
TotalΔ%	–1.466	–2.464	–3.519	–0.584	–0.833	–0.587

[1)] GHG, greenhouse gas; WF, water footprint; LA, land appropriation.

residents, the sex ratio increases environmental pressure from livestock, poultry, aquatic products, and egg while reducing environmental pressure from other foods. For rural residents, the sex ratio is expected to increase environmental pressure from grain, vegetable, and fruit while decreasing the environmental pressure from other foods. However, GHG emissions in urban areas will likely increase by 0.092%, while WF and LA will decrease by 0.06 and 0.037%, respectively. In contrast, the decline is even lower for rural residents. Therefore, the mitigation of environmental pressure should give more consideration to population aging rather than sex ratio.

Environmental impacts of the aging population and sex ratio If the aging population and sex ratio hold the current growth rate constant, three environmental outcomes will undergo different changes (Table 9). Overall, the changes in demographic dynamics will reduce the pressure on the environment from the changes in food demand, especially in urban areas. Although demographic dynamics will put pressure on the environment due to the increase in demands for poultry, aquatic products, egg, and fruit, declines in grain and meat consumption would ultimately result in a 1.374, 2.524, and 3.556% reduction in GHG emissions, WF, and LA, respectively. In short, the co-movement of population aging and sex ratio will bring less environmental pressure.

Environmental impacts of recommended diet To ensure diet quality, we extend our analysis to examine how the environmental outcome would change when urban and rural residents would strictly follow the Dietary Guidelines for Chinese Residents in 2022. The estimation results are presented in Table 10. The results indicate that the standard nutrient intakes would place greater stress on the environment. For urban residents, the reduction in demand for grain, livestock meat, and poultry meat will likely reduce resource consumption and environmental pollution, while other food consumption will pose a threat to the environment, particularly dairy products. Ultimately, GHG emissions, WF, and LA will increase by 12.782, 20.939, and 10.211%, respectively. However, the overall increase in environmental outcomes for rural residents is significantly higher than for urban residents. More specifically, GHG emissions, WF, and LA will increase by 18.317, 24.203, and 12.964%. As indicated in the last three columns of Table 10, the increased demands for aquatic products, dairy products, vegetable, and fruit are

Table 8 Environmental outcomes of sex ratio in both urban and rural areas[1)]

Food	Urban			Rural		
	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)
Grain	–0.600	–0.589	–0.703	0.309	0.303	0.361
Edible oil	–0.0121	–0.022	–0.015	–0.174	–0.316	–0.210
Livestock	0.136	0.145	0.235	–0.618	–0.877	–1.305
Poultry	0.960	1.060	1.528	–0.074	–0.082	–0.118
Aquatic products	1.125	0.357	0.050	–0.717	–0.227	–0.032
Egg	0.165	0.166	0.193	0.108	0.108	0.126
Dairy products	–0.835	–1.336	–1.394	–0.005	–0.008	–0.009
Vegetable	–0.174	–0.054	–0.090	0.579	0.180	0.299
Fruit	–0.106	–0.126	–0.103	0.713	0.850	0.696
TotalΔ	0.660	–0.399	–0.299	0.120	–0.070	–0.190
TotalΔ%	0.092	–0.060	–0.037	0.018	–0.011	–0.025

[1)] GHG, greenhouse gas; WF, water footprint; LA, land appropriation.

Table 9 Environmental outcomes of an aging population and sex ratio in both urban and rural areas[1)]

Food	Urban			Rural		
	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)
Grain	–21.393	–20.971	–25.052	0.450	0.441	0.527
Edible oil	–0.079	–0.1434	–0.095	–1.300	–2.368	–1.569
Livestock	–9.540	–10.116	–16.453	–4.593	–6.895	–8.340
Poultry	3.416	3.774	5.438	1.699	1.877	2.705
Aquatic products	10.306	3.266	0.455	–3.544	–1.123	–0.156
Egg	1.998	2.011	2.329	–0.828	–0.833	–0.965
Dairy products	–0.457	–0.731	–0.762	–0.610	–0.976	–1.018
Vegetable	1.079	0.335	0.558	1.638	0.508	0.847
Fruit	4.839	5.774	4.729	3.312	3.951	3.236
TotalΔ	–9.829	–16.802	–28.852	–3.775	–5.418	–4.733
TotalΔ%	–1.374	–2.524	–3.556	–0.566	–0.844	–0.612

[1)] GHG, greenhouse gas; WF, water footprint; LA, land appropriation.

Table 10 Environmental outcomes of recommended diet in both urban and rural areas[1)]

Food	Urban			Rural		
	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)	ΔGHGs (kg CO_2 e)	ΔWF (m^3)	ΔLA (m^2)
Grains	–44.004	–43.136	–51.531	–117.268	–114.954	–137.327
Edible oil	0.472	0.859	0.569	–3.301	–6.016	–3.985
Livestock	–65.307	–69.253	–112.634	–38.521	–43.462	–69.829
Poultry	–21.658	–23.923	–34.476	–16.527	–18.256	–26.309
Aquatic products	16.892	5.35275	0.746	41.1469	13.0389	1.817
Eggs	9.5355	9.594	11.115	15.078	15.170	17.575
Dairy products	133.690	213.904	223.124	148.045	236.872	247.082
Vegetables	31.494	9.774	16.290	43.674	13.554	22.590
Fruits	30.338	36.199	29.649	49.786	59.404	48.655
TotalΔ	91.452	139.371	82.852	122.112	155.351	100.269
TotalΔ%	12.782	20.939	10.211	18.317	24.203	12.964

[1)] GHG, greenhouse gas; WF, water footprint; LA, land appropriation.

responsible for greater environmental pressures.

Therefore, a shift to a recommended diet is not necessarily as beneficial to the environment and resources as it is in developed countries (Macdiarmid *et al.* 2012; Grabs 2015). For example, in Germany, shifting from the current dietary pattern to the recommended diet proposed by the German Nutrition Society will result in a decrease of 11% in GHG emissions, 26% in WF, and 15% in LA (Meier and Christen 2013). Similarly, adopting a healthier diet could help US households reduce GHG emissions, LA, and energy consumption by 2, 24, and 4%, respectively (He *et al.* 2021). China is in the stage of economic transformation, and the consumption of most foods does not meet the requirements of the Dietary Guidelines for Chinese Residents in 2022, particularly dairy products, fruit, and vegetable. Improvements in the nutrition and health of residents come at the cost of increased GHG emissions, WF, and LA (He *et al.* 2019). Hence, there is a need to explore sustainable and nutritious dietary patterns in developing countries like China.

5. Conclusion

This study examines the impact of demographic dynamics on food consumption for urban and rural residents using a two-stage QUAIDS model and provincial data from 2000 to 2020 in China. Based on the estimated demand elasticities with respect to demographic variables, we project the responsiveness of environmental outcomes to changes in food demand under different scenarios. The major findings are presented below.

First, demographic variables, particularly population aging, significantly impact food demand. More specifically, population aging would increase the demands for egg, poultry, vegetable, fruit, and aquatic products, while reducing the demands for grain and livestock. Hence, the view that population aging will reduce food demand must be revised to better understand future food demand. A feasible way is that relevant departments should introduce relevant policies to increase support for producers of eggs, poultry, and milk to meet the demand for these foods due to future demographic dynamics.

Second, as population aging and sex ratio in urban China continue to grow at the current rate, GHG emissions, WF, and LA are expected to decrease by 1.37, 2.52, and 3.56%, respectively. In contrast, rural areas do not show a significant reduction in this aspect. Therefore, the Chinese government should further improve the current pension system and enhance the ability to transfer payments, which can not only meet the food needs of the population structure but also be conducive to the sustainability of resources and the environment.

Third, shifting to the recommended diet released by the Dietary Guidelines for Chinese Residents in 2022 would increase environmental pressure by 12.78% in GHG emissions, 20.94% in WF, and 10.21% in LA, different from the scenario in developed countries. More importantly, when rural residents follow the standard nutritional intake, they pose a more significant environment threat. Hence, while advocating the recommended diet, relevant departments should also be aware of its pressure on resources and the environment. Under the premise of ensuring adequate nutritional intake, more plant-based foods should be used instead of animal-based foods to achieve sustainable food consumption.

This study does have a few limitations. First, the data selected in this study are from 2000 to 2020, which spans a large period, so residents' food consumption preferences will likely change over time. However, we do not reveal the dynamic evolution of food preferences. Second, it is commonly held that technological progress is an important factor affecting the environment, thereby resulting in different environmental pollution and resource consumption.

Hence, environmental impact factors based on technological progress can be addressed in future research.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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