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Assessing the diet quality, environmental impact, and monetary costs of the dietary transition in China (1997–2011): Impact of urbanization

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Background: Increased urbanization has been linked to transitions in dietary patterns. However, evidence on the impacts of urbanization on diet quality, and environmental impact, and diet cost is limited. The aim of this study was to investigate the time trends of these three dietary sustainability in China over the period 1997–2011 and to examine their associations with urbanization.

Methods: Food consumption of 8,330 participants (18–64y) of the China Health and Nutrition Survey cohort (1997, 2000, 2004, 2006, 2009, and 2011) were examined and diet quality was assessed using the Chinese Healthy Eating Index 2016 (CHEI2016). Dietary related environmental impacts on Greenhouse Gas Emissions (GHGE), Total Water Use (TWU), and Land Use (LU) were estimated using the Chinese Food Life Cycle Assessment Database. Monetary cost of diet was calculated using the community market prices of food items. Multilevel mixed-effects models were used to estimate associations between the time trend of dietary sustainability indicators and degree of urbanization.

Results: From 1997 to 2011, the CHEI2016 score increased by 10.6%, GHGE by 23.8%, LU by 29.1%, and the inflation-corrected cost of diet by 80%. Urbanization was positively associated with these time trends, which remained after adjustment for sociodemographic and lifestyle factors (all $P < 0{\cdot}05$).

Conclusion: The rapid urbanization in China over the past two decades has been followed by an improvement in the overall dietary quality, but this has been accompanied by an increase in the environmental impacts and higher cost of the diet, especially in communities with lower urbanization index.

KEYWORDS

diet trends, sustainability, urbanization, China, diet quality, diet-related environmental impacts, cost of diet, multilevel model

Introduction

The current global food system is facing the challenges of a growing population and increasing environmental, health, and economic problems (FAO, 2022). These trends are associated with urbanization processes trend and diet shifts toward high consumption levels of animal products, cooking oils, salt, and sugar, which is increasing the prevalence of overweight, obesity, and hypertension (Afshin et al., 2019). In the context of population growth, these dietary transitions are having an increasingly negative impact on climate change, water resources, land availability, and ecosystems (Johnston et al., 2014; Tilman and Clark, 2014). Additionally, 3 billion people are currently unable to afford a healthy diet (Herforth et al., 2020).

China has the highest growth rate of urbanization in the world over the past four decades (18% in 1978 to 65% in 2021) (Yang, 2013), the increasing urbanization indicates a growing modernized living environment with improved food environment, health care, communication, infrastructure, etc. (Fong et al., 2019). Dietary patterns are shifting from a grain and vegetable-based diet to a diet high in red meat and processed foods (Du et al., 2004), consequently affecting human health and the environment (Xiong et al., 2022). Moreover, the increase in overweight in rural areas of China was 64.5% higher compared to urban areas in 2000–2020 (Huang et al., 2021). Although the diet-related greenhouse gas emissions (GHGE) of rural residents in China are lower than those of urban residents, this gap is narrowing (He et al., 2018).

A sustainable diet, which considers the role of dietary patterns for sustainable development, posts a positive effect on public health (reduction of diet-related chronic diseases, etc.), environmental sustainability (reduction of greenhouse gas emissions, water and land use), and economic sustainability (increased affordability of diets) (FAO and WHO, 2019). To alleviate the resource constraints and food insecurity caused by rapid urbanization, it is necessary to redefine dietary patterns from a health, environmental, and economic perspective (Clark et al., 2019). Most studies focus their analysis and interpretation on a single dimension of sustainability, e.g. the nutritional dimension, or several environmental indicators (mainly GHGE). Few studies have focused on these sustainability dimensions simultaneously (Macdiarmid, 2013; Willett et al., 2019; Hirvonen et al., 2020). Furthermore, there is limited empirical evidence on changes in urbanization as related to dietary quality, diet-related environmental impacts and cost of diet in China.

Therefore, this study attempts to answer the questions: What are the trends of diet quality, diet-related environmental impacts, and cost of diets during the period from 1997 to 2011, and does the changes depend on the level of urbanization?

Data and methodology

Study population and dietary data

The China Health and Nutrition Survey (CHNS) is an ongoing longitudinal and international cohort project. The CHNS collect individual-level data of the health, nutrition, and the community-level as well as household-level data of family planning policies and programs implemented by national and local governments (China Health and Nutrition Survey, 2014). The current research is based on the data of wave 1997, 2000, 2004, 2006, 2009, and 2011 and is drawn from the 9 provinces or autonomous cities/districts, including Guangxi, Guizhou, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Liaoning, and Shandong. The dietary assessment is based on a combination of data collected at the individual level with 3 consecutive 24-h dietary recalls and a food inventory taken at the household level over the same 3-day period. To collect individual dietary data, every household member (aged 12 years or older) was asked to report all food consumed over the previous 24 h for each of the 3 days.

Diets of adults aged 18–64 years were evaluated. Exclusion of the records in the dataset was based on the following criteria: children (<18y, n = 2,469, 14.6% of sample) and elderly (>65y, n = 2,768, 17.7% of sample), lactating and pregnant women (n = 417, 0.38% of sample), as well as those with a Z-score >5 for energy intake (n = 524; 0.42% of sample). The final sample included 8,330 in 1997, 7,453 in 2000, 6,078 in 2004, 5,767 in 2006, 5,230 in 2009, and 4,756 in 2011. All the adult participants have reliable dietary intake and with non-missing values on key demographic and behavioral variables for this analysis.

Chinese Healthy Eating Index 2016

The Chinese Healthy Eating Index 2016 (CHEI2016) was used to assess the quality of the diet as a dietary sustainability indicator of health (Yuan et al., 2017). The index used standard portion of foods as the unit of dietary measurement, and standard portion is defined as a food that contains the same amount of energy and has similar carbohydrate, fat and protein content within the same food group (Supplementary Table 1). The CHEI2016 consists of 12 food components in terms of adequacy (cereals, whole grains and mixed beans, tubers, total vegetables (exclude dark vegetables), dark vegetables, fruits, dairy, soybeans, fish and seafood, poultry, eggs, and seeds and nuts) and 5 food components in terms of limitation (red meat, edible oils, sodium, added sugar and alcohol). Most food components were rated on a scale from 0 to 5, except for fruit, cooking oil and salt, which were rated on a scale from 0 to 10, with higher scores indicating a higher quality diet. The minimum and maximum cut-off values for each food component were based on the recommendations of the Chinese Dietary Guidelines 2016, and the scores were distributed linearly between the minimum and maximum cut-off values. The total CHEI2016 score is the sum of the 17 food component scores, ranging from 0 to 100, with 100 representing the highest dietary quality.

Environmental impact of diets

The environmental impact of foods in the CHNS samples was evaluated by linking them to the Chinese Food Life Cycle Assessment Database (CFLCAD). Details of the CFLCAD can be found elsewhere (Cai et al., 2022). In the database, Greenhouse Gas Emissions (GHGE) for 80 food items, Total Water Use (TWU) for 93 food items, and Land Use (LU) for 50 food items were collected, as the dietary sustainability indicators of diet-related environmental impacts. When no LCA data of a certain food were available, data from food groups with similar nutritional composition or cultivation condition were used as proxies. To harmonize the system boundaries, the database covers the 6 life cycle stages of all foods in the CHNS: production, processing, storage, packaging, transportation, food preparation stages, as well as the loss rates in the food chain.

Costs of diets

The cost of diets was evaluated as the dietary sustainability indicator from the economic perspective of the consumers. The CHNS conducted a detailed community survey consisting of food market information such as infrastructure, services, and organization, as well as the prices of foods at the community level (Guo et al., 1999, 2000). The food groups collected in CHNS consist of 13 food categories: cereals and tubers, legumes, vegetables, fruit and nuts, meat, poultry, dairy, eggs, aquatic products, beverages and fast food, liquor and alcohol, fats and oils, and condiment (vinegar, soy sauce). For all food categories, we use the least free market prices by default, and substitute with lowest retail prices wherever free market prices are missing. Using a free market price for each specific food commodity from CHNS, total daily monetary costs were calculated by multiplying the cost per g (RMB/g) of each food item by the reported daily quantity consumed through the 3 day 24 h dietary recall survey. Inflation adjustment is accomplished by multiplying the cost of diet by the Consumer Price Index of 2011.

Urbanization index

The CHNS used the urbanization index as a multidimensional measure to determine the level of urbanization of the respective community. This index consists of 12 community indicators, namely population density, economic activity, traditional markets, modern markets, transportation and health infrastructure, sanitation, communication, social services, diversity and housing. The 12 components were calculated based on the amount of infrastructure present in the community, the percentage of households in the community, and a maximum score of 10 for each indicator (with a range of 0–10, Supplementary Table 2). The detailed construction procedure, scale scoring algorithms, cut-off values and the dataset of the index are available in the supplementary material of the work of Jones-Smith and Popkin (2010).

Covariates

Sociodemographic and behavior data obtained using the CHNS questionnaire included age (in years), sex (male or female), height, weight, work-related physical activity, educational level, and dietary knowledge. The Body Mass Index was calculated using self-reported height and weight. The categories of work-related physical activity were light (e.g., sedentary job, office work, watch repairers, counter salesperson, lab technician), moderate (e.g., driver, electrician) and heavy (e.g., farmer, athlete, dancer, steel worker, lumber worker, mason). CHNS classified education level as follows: no school (0 year), primary school (1–6 years), junior middle school (1–3 years), senior middle school (1–3 years), middle technical or vocational school (1–2 years), college (3–4 years in college/university), and graduate school (over 4 years in college/university). Educational level was then divided into three categories of low (no school; primary school; junior middle school); medium (senior middle school; middle technical or vocational school), and high educational level (college; graduate school). Proportion of animal-based foods (%) in the diet was determined by dividing the animal-based food consumption (including: meat, poultry, dairy, egg and aquatic products) (g) by the total food consumption (g).

Statistical analysis

The mean and standard deviation (SD) of the dietary sustainability indicators (CHEI2016, environmental impacts, and cost of diet) of all participants were described. Energy intake was highly correlated with diet quality and diet-related environmental impacts and cost of diet, thus dietary sustainable indicators were recalculated per 2,000 kcal/d.

The crude secular trends of variables were statistically evaluated by the Jonckheere–Terpstra test in the cohort study (Vock and Balakrishnan, 2010). The participants were categorized into quartiles of urbanicity index and tested for differences in diet-related GHGE, TWU, LU, CHEI2016, and cost of diet across the quartiles of urbanicity index using one-way analysis of variance (ANOVA). The mediation analyses was conducted for urbanization index (predictor variable) and each dietary sustainability indicator (dependent variable), with the proportion of animal-based food consumption (mediator) and demographic characteristics (covariates) using the Sobel-Goodman mediation test.

Likelihood ratio tests were used to compare the fit of nested models (Random intercept models as well as multilevel random slope and intercept regression models) for effect measure modifiers and goodness of fit, and the results showed that the fit of multilevel random slope and intercept regression model was better (Supplementary Table 3). The longitudinal tracking data in CHNS violated the assumptions of data independence and homogeneity of variance because of the nested structure. Therefore, a two-level random slope and intercept regression model with individuals (level 1) nested within community (level 2) was used to estimate the association between sustainable indicators of diet and urbanization index.

The main analysis was replicated in two multilevel analyses: Model 1 included one of the three dietary sustainability indicators and the urbanization index with adjustments for individual-level explanatory variables (age, gender, BMI, education level, activity level, income, and dietary knowledge). In Model 2, the urbanization index was deconstructed into its 12 subcomponents and the individual-level variables were the same as in Model 1. In each model, the intra-class coefficient of correlation (ICC) was calculated as the ratio of between-community variance to total variance of dietary sustainability indicators (Snijders and Bosker,

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TABLE 1 Cross-sectional univariate descriptive of participants in the CHNS 1997-2011, aged 18–64 years[a].

	1997 ($n = 8,330$)		2000 ($n = 7,453$)		2004 ($n = 6,078$)		2006 ($n = 5,767$)		2009 ($n = 5,230$)		2011 ($n = 4,756$)		p-trend[b]
Gender													
Male	4,131	49.6%	3,641	48.9%	2,948	48.5%	2,767	48.0%	2,531	48.4%	2,265	47.6%	0.016*
Female	4,199	50.4%	3,812	51.1%	3,130	51.5%	3,000	52.0%	2,699	51.6%	2,491	52.4%	0.017*
Age (years)	39.4	12.5	43.5	11.9	48.4	11.4	50.5	11.2	53.3	11.3	55.4	11.1	<0.001***
Resident place													
Urban area	2,755	33.1%	2,400	32.2%	1,862	30.6%	1,733	29.1%	1,491	28.5%	1,288	27.1%	0.272
Rural area	5,575	66.9%	5,053	67.8%	4,216	69.4%	4,216	70.9%	3,739	71.5%	3,468	72.9%	0.278
BMI (kg/m^2)	22.3	3.1	22.9	3.2	23.2	3.3	23.3	3.6	23.5	3.4	23.9	4.9	<0.001***
Educational level													
Below primary school	6,632	79.6%	5,833	78.3%	4,784	78.7%	4,488	75.4%	4,285	81.9%	3,901	82.0%	0.712
Secondary school	1,492	17.9%	1,351	18.1%	1,101	18.1%	1,055	17.7%	789	15.1%	666	14.0%	0.851
Above high school	206	2.5%	269	3.6%	193	3.2%	224	3.8%	156	3.0%	189	4.0%	0.033*
Activity level													
Low	3,175	38.1%	2,764	37.1%	2,493	41.0%	2,401	40.4%	2,424	46.3%	2,288	48.1%	0.003**
Medium	1,337	16.1%	1,090	14.6%	978	16.1%	872	14.7%	690	13.2%	686	14.4%	0.587
High	3,818	45.8%	3,599	48.3%	2,607	42.9%	2,494	41.9%	2,116	40.5%	1,782	37.5%	0.029*
Dietary knowledge													
No	Not measured		Not measured		5,547	93.8%	5132	89.9%	4,600	88.7%	3,829	81.2%	0.042*
Yes	Not measured		Not measured		369	6.2%	576	10.1%	588	11.3%	889	18.8%	0.041*
Income (1,000 RMB/Y, inflated to 2011)	2,520.6	1,387.4–4,159.1	2,984.1	1,504.6–5,018.5	3,565.6	1,835.1–6,666.7	3,999.1	1,920.1–7,716.6	7,000.1	3,605.1–12,766.6	9,025.1	4,651.6–16,400.1	<0.001***
Dietary Energy (kcal/d)	2,368	714	2,297	650	2,239	669	2,211	675	2,167	678	2,050	972	<0.001***
Proportion of animal-based foods (%)	11.3	0.1	12.7	0.1	12.2	0.1	12.9	0.1	13.1	0.1	12.1	0.1	<0.001***
Urbanization index	52.6	18.1	58.1	18.1	60.3	20.1	61.9	19.8	64.5	18.6	64.5	18.2	<0.001***

[a]Continuous variables were expressed by means and SD (except income variable was expressed by median and IQR). Categorical variables were expressed by number and percentage.

[b]p-value for the trend was determined by the Jonckheere–Terpstra test. For categorical variables, this study examined trends in percentages by years. Jonckheere-Terpstra test is a rank-based nonparametric test that is used to determine if there is a statistically significant trend between an ordinal independent variable and a continuous or ordinal dependent variable. The ∗ symbol indicates the P-value for significance <0.001. The ∗∗ symbol indicates the P-value for significance <0.01 and ∗ ∗ ∗ symbol indicates the P-value for significance < 0.05.

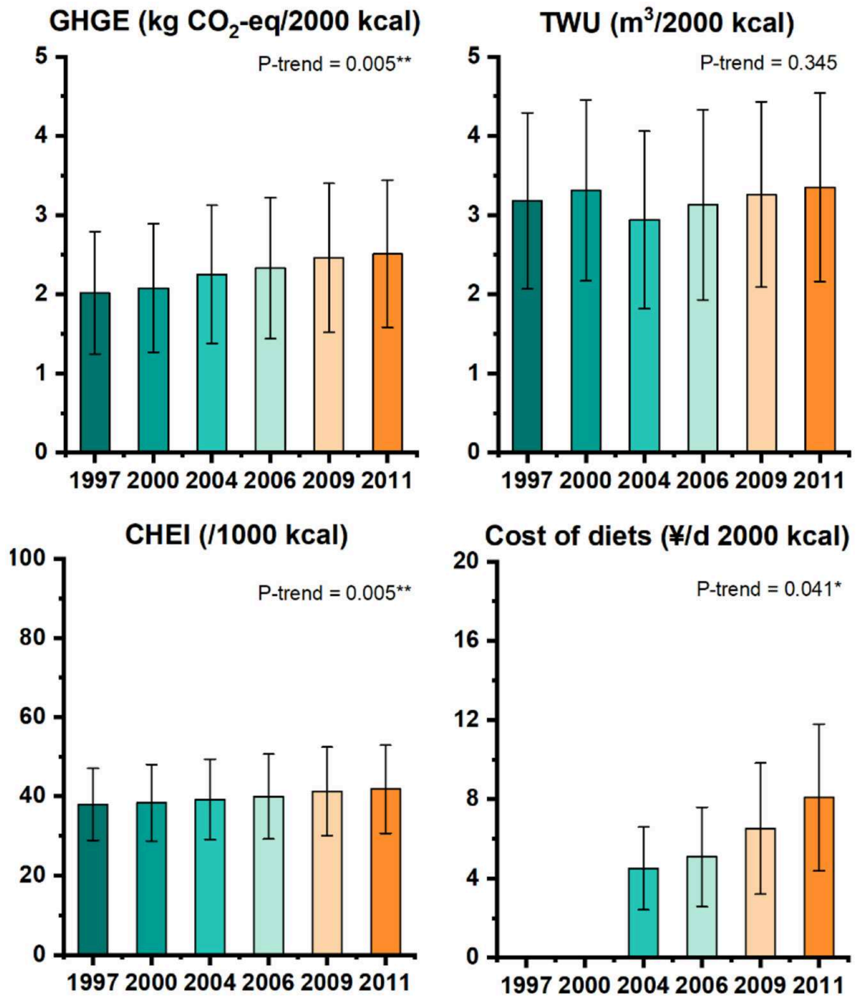

FIGURE 1
Mean and standard deviation of the diet-related GHGE, TWU, LU, CHEI2016, and cost of diet in the CHNS 1997–2011[a]. [a]Food price data is available from 2004 onwards. p-trend = 0.005** for GHGE, P-trend = 0.345 for TWU, P-trend = 0.002** for LU, p-trend = 0.005** for CHEI2016, p-trend = 0.041* for cost of diet. The p-trend was based on Jonckheere–Terpstra test.

2011). The closer ICC to 1, the larger the proportion of the variance that can be attributed to community level characteristics rather than individual characteristics (Raudenbush and Bryk, 2002). To assess the goodness of fit of these models Akaike's Information Criterion (AIC) was used (Akaike, 1974). The interaction between urbanization index and survey year was tested to evaluate whether the time trend of the dietary sustainability indicators differs by the degree of urbanization.

All data collation and statistical analyses were performed with Stata/se 13.1 (Stata Corp). All reported p-values were two-tailed, with a P-value < 0.05 considered statistically significant.

Results

The cohort study consisted of 8,330 people at baseline and reduced over the years to 4,756 in the final round (Table 1). From 1997 to 2011, activity levels and energy intake of participants decreased while BMI, per capita income, and educational level increased. The mean urbanization index increased as well from 52.6 (±18.1 SD, 1997) to 64.5 (±18.2 SD, 2011).

Between 1997–2011, a significant increasing time trend was observed for the CHEI2016 ($p = 0.005$), dietary GHGE ($p = 0.005$), LU ($P = 0.002$), and dietary cost ($p = 0.041$), while the TWU ($p = 0.345$) fluctuated during the same period (Figure 1 and Supplementary Table 4). The CHEI2016 score was 37.9 in 1997 and increased to 41.9 in 2011 (+ 10.6%). Dietary GHGE progressively increased by 23.8% (0.6 kg CO_2-eq/2000 kcal/d per person) and LU increased by 29.1% (0.7 m^2/2,000 kcal/d per person) respectively. Dietary TWU was 3.2 in 1997 and 3.4 m^3/2,000 kcal in 2011. Similarly, the inflation-corrected diet cost rose by 80.0% from 4.5 RMB/d/2,000 kcal in 2004 to 8.1 RMB/d/2,000 kcal in 2011.

A higher degree of urbanization was associated with higher diet-related CHEI2016, GHGE, TWU, LU, and cost of diet from 1997 to 2011 (Figure 2). Also during the past two decades, the increase of indicators was larger in the lowest as compared to highest quartiles of urbanization. CHEI2016 in the lowest vs. highest urbanization quartile increased by 18.1% compared to 7.4%, diet-related GHGE increased by 86.9% compared to 17.8%, TWU increased by 38.4% compared to −0.9%, LU increased by 57.8 vs. 13.1%, and cost of diet increased by 124.4% compared to 64.7% from 2004 to 2011.

Dietary sustainability indicators were positively associated with the urbanization index (P-for trend <0.05) in Model 1 after adjustment for individual-level covariates and survey year (Table 2). An increase of 0.241 kg CO_2-eq/2,000 kcal (GHGE), 0.289 m^3/2,000 kcal (TWU), 0.198 m^2/2,000 kcal (LU), 2.843 per 1000 kcal (CHEI2016), and 1.108 RMB/d/2,000 kcal (cost of diet) for highest vs. lowest quartile of urbanization index (Q4 vs. Q1). The ICC coefficient for Model 1 all exceeded 0.7, indicating there was substantial inter-community heterogeneity in dietary sustainable indicators. The proportion of animal-based food in diet consumption showed a positive correlation with CHEI2016, diet-related environmental impacts (GHGE, TWU, and LU), and cost of diet, respectively ($p<0.001$). The interaction between urbanization index and survey year was significant ($p<0.001$). Model 2 further performed multilevel analyses of the 12 sub scores of the urbanization index: "Communication", Economic activity, Housing infrastructure, and Sanitation were significantly positively associated with each of the environmental impact indicators, while Education was negatively associated. Health infrastructure was positively associated with GHGE and TWU but had no association with LU. In terms of the health indicator, Population density, Housing infrastructure, and Education showed a positive association with CHEI2016. Moreover, cost of diet was positively associated with Housing infrastructure, Traditional markets, and Sanitation. The proportion of animal-based foods in the diet might be an intermediary factor between urbanization and dietary sustainability outcomes as Mediation analysis showed that animal-based foods could explain 24.5% (CHEI2016), 9.2% (GHGE), 13.8% (TWU), 11.3% (LU) and 38.1% (cost of diet) of the overall association between urbanization and these sustainability outcomes (Sobel-Goodman mediation test, all $p<0.001$; see Supplementary Table 5).

Discussion

This study showed that while diet quality increased 10.6% as indicated by the CHEI2016, also the dietary GHGE increased 23.8%, LU increased 29.1% during the period 1997 to 2011, and dietary costs increased by 80% between 2004 to 2011. These time trends were more pronounced in the lowest quartile of urbanization as compared to the highest: CHEI2016 in the lowest vs. highest quartile of urbanization increased by 18.1% compared to 7.4%, diet-related GHGE increased by 86.9% compared to 17.8%, TWU increased by 38.4% compared to −0.9%, LU increased by 57.8% compared to 13.1%, and cost of diet increased by 124.4% compared to 64.7%. Mediation analysis indicates that these associations are mediated by the consumption of animal-based foods. Between-community differences explained over 70% of this population's total variability in dietary sustainable indicators, suggesting that community-level variables are essential factors that are driving these trends.

As a low- and middle-income country (LMIC) China is in the midst of rapid urbanization and therefore provides a suitable context to study the role of urbanization on the sustainability of diets. This study showed that all indicators were highest in highly urbanized areas. In line with this, an almost tenfold increase of animal sourced food consumption in China was reported, correlating with a rapidly growing degree of urbanization and modernization from 1961 to 2000 (FAO., 2005). Previous studies compared sustainable diets in rural and urban areas in LMICs (Auestad and Fulgoni, 2015; Downs et al., 2017; Batis et al., 2021; Castellanos-Gutiérrez et al., 2021), and the results of these studies suggest that the better dietary quality in more urbanized areas goes along with increased environmental impacts and higher cost of diet (United Nations Department of Economics Social Affairs, 2012). Therefore, for higher urbanized areas, it is necessary to promote a dietary pattern that is healthy, low in diet-related environmental impacts, and at an affordable cost to ensure the health of the planet and the population. The multilevel analysis of this study suggested that the sustainability indicators in low urbanized areas are catching up with higher urbanized areas. An important challenge lies in accompanying the continued growth of urbanization and modernization in less urbanized areas, which means diets in these areas would follow the changes toward more animal-based foods as higher urbanized areas have already been undergoing. Moreover, as the proportion of animal-based food was a intermediator of this association, the results suggested that urbanization may have shaped the context for a diet shift toward a high intake of red meats, poultry, and eggs, with associated diet costs and subsequent environmental impacts. These results underpin the close interrelationship between economic development, agricultural supply, and demand for more expensive animal foods. Therefore, to reduce the adverse environmental impacts of this economic development, not only increase the public awareness about the health, environmental impacts, and cost of diets need to be increased that can promote more sustainable dietary choices, but also require interrelated changes in supply and demand. Consequently, promoting more sustainable dietary choices for consumers.

Using population size and density alone as a measure of urbanization is biased (Ng et al., 2009). Indeed, the concept of urbanization in this study tends to represent the degree of modernization beyond the population size and density. Modernization has an impact on the dietary transition in terms of transportation, health service, and social services (Zhou et al., 2015). The associations observed in the analysis suggest that the impact of urbanization on sustainable indicators might vary depending on various aspects of urbanization. When this study decomposed the overall urbanization index into its sub-scores (while controlling for the other sub-scores), population density was associated to the CHEI2016 only and not to the environmental indicators or diet costs. The components of Communication, Economic activity, Housing infrastructure, and Sanitation were significantly associated with dietary environmental impacts. A previous study concluded that the higher the per capita income of a household and the more urbanized the area, the more likely the population is to consume more sugar, fat, and highly processed and packaged foods (Colozza and Avendano, 2019). The increasing complexity of food processing has increased the environmental footprint of food. These conclusions were in line with present study which demonstrated that the component of Economic

TABLE 2 Coefficients from two-level mixed effect models for dietary environmental impacts, CHEI2016, and cost of diet among adults aged 18–64 years, CHNS 1997–2011[a].

		GHG emissions (kg CO_2-eq/2,000 kcal)		Total water use (m^3/2,000 kcal)		Land use (m^2/2,000 kcal)		CHEI2016 (/1,000 kcal)		Cost of diet (RMB/d/2,000 kcal)	
	Effects	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Fixed effects											
Level-1 (Individual level variables)											
Survey year (ref. =1997)[b]											
	2000	0.086***	0.105***	0.167***	0.185***	0.075***	0.083***	−0.656***	−0.724***	Not measured	
	2004	0.231***	0.215***	−0.256***	−0.274***	0.152***	0.119***	0.563**	0.391	Not measured	
	2006	0.304***	0.267***	−0.065**	−0.108***	0.245***	0.183***	1.225***	0.999***	0.537***	0.505***
	2009	0.417***	0.362***	0.044	−0.033	0.337***	0.251***	2.364***	2.177***	1.921***	1.861***
	2011	0.501***	0.435***	0.169***	0.088*	0.491***	0.388***	3.112***	2.823***	3.423***	3.338***
Proportion of animal-based foods (per 10%)		0.548***	0.549***	0.546***	0.548***	0.538***	0.541***	2.472***	2.481***	0.228***	0.228***
Age (per 10 years)		−0.041***	−0.040***	−0.051***	−0.061***	−0.041***	−0.051***	−0.441***	−0.441***	−0.031	−0.031
Gender (ref. = female)		0.021**	0.021**	0.075***	0.071***	0.044***	0.044***	−2.081***	−2.081***	0.057	0.056
BMI (kg/m^2)		0.004***	0.004***	0.005**	0.002	0.006**	0.005***	0.031*	−0.031*	0.011**	0.011**
Income (1,000 RMB/Y, inflated to 2011)		0.004***	0.004***	0.005***	0.005***	0.005***	0.004***	0.063***	0.062***	0.003	0.003
Education level (ref. = Below primary school)											
	Secondary school	0.075***	0.076***	0.087**	0.079***	0.105***	0.106***	0.891***	0.872***	0.146**	0.148***
	Above high school	0.107***	0.115***	0.107**	0.129**	0.118***	0.121***	0.716*	0.667*	0.183*	0.187*
Activity level (ref. = Low)											
	Medium	−0.024	−0.026*	−0.041*	−0.058**	−0.044*	−0.044*	0.701	0.072	−0.081	−0.077
	High	−0.165***	−0.163***	−0.193***	−0.186***	−0.195***	−0.191***	−0.327*	−0.306*	−0.167***	−0.161***
Level-2 (Community variables)											
Urbanization index (per Q4 vs. Q1)[c]		0.241 **		0.289*		0.198***		2.843**		1.108*	
Interaction: Urbanization index*Survey year		−0.001***		−0.001***		−0.001*		−0.004*		−0.002*	
Urbanization components (per SD)											
General sub scores											
	Population density		−0.001		−0.041		−0.001		0.745***		0.008
	Education		−0.077***		−0.061*		−0.052*		0.571**		−0.109
	Economic activity		0.044***		0.051***		0.044***		0.197		0.025

(Continued)

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TABLE 2 (Continued)

	Effects	GHG emissions (kg CO_2-eq/2,000 kcal)		Total water use (m^3/2,000 kcal)		Land use (m^2/2,000 kcal)		CHEI2016 (/1,000 kcal)		Cost of diet (RMB/d/2,000 kcal)	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	Transportation infrastructure		0.007		0.026*		0.005		0.103		0.002
	Social services		−0.002		−0.008		−0.002		0.002		0.067
	Education and income diversity		0.014		0.038		0.023		−0.019		0.083
Sub scores with relevance to health and food domain											
	Housing infrastructure		0.049**		0.072***		0.063***		0.367*		0.144**
	Sanitation		0.039**		0.042*		0.057***		0.189		0.311***
	Communication		0.021**		0.054***		0.027***		0.064		0.001
	Health infrastructure		0.017*		0.041***		0.007		0.002		0.015
	Traditional markets		−0.004		−0.014		0.014		−0.094		0.177***
	Modern markets		−0.003		−0.012		−0.015		0.539		0.015
Random effects											
Variance of slope		0.001	0.001	0.001	0.001	0.001	0.001	0.073	0.071	0.018	0.019
Variance of intercept		1.953	1.918	4.159	3.9476	2.553	2.467	236.804	233.753	66.101	71.961
Variance of residual		0.536	0.535	1.099	1.097	0.971	0.969	75.271	75.198	4.396	4.382
ICC[d]		0.784	0.781	0.791	0.784	0.724	0.718	0.758	0.748	0.937	0.942
AIC		77,660	77,619	102,345	102,547	97,891	97,868	247,796	247,764	89,944	89,916

[a]Model 1: included individual and community variables; Model 2: added urbanization components instead of urbanization index in community level from Model 1.
[b]For the cost of diet, the survey year is referenced to 2004.
[c]Unit was based on the mean of quintile 4 minus quintile 1.
[d]The inter-class correlation coefficient (ICC) is a ratio of between-community variance to total variance in dietary sustainability indicators.
The * symbol indicates the P-value for significance <0.001. The ** symbol indicates the P-value for significance <0.01 and *** symbol indicates the P-value for significance < 0.05.

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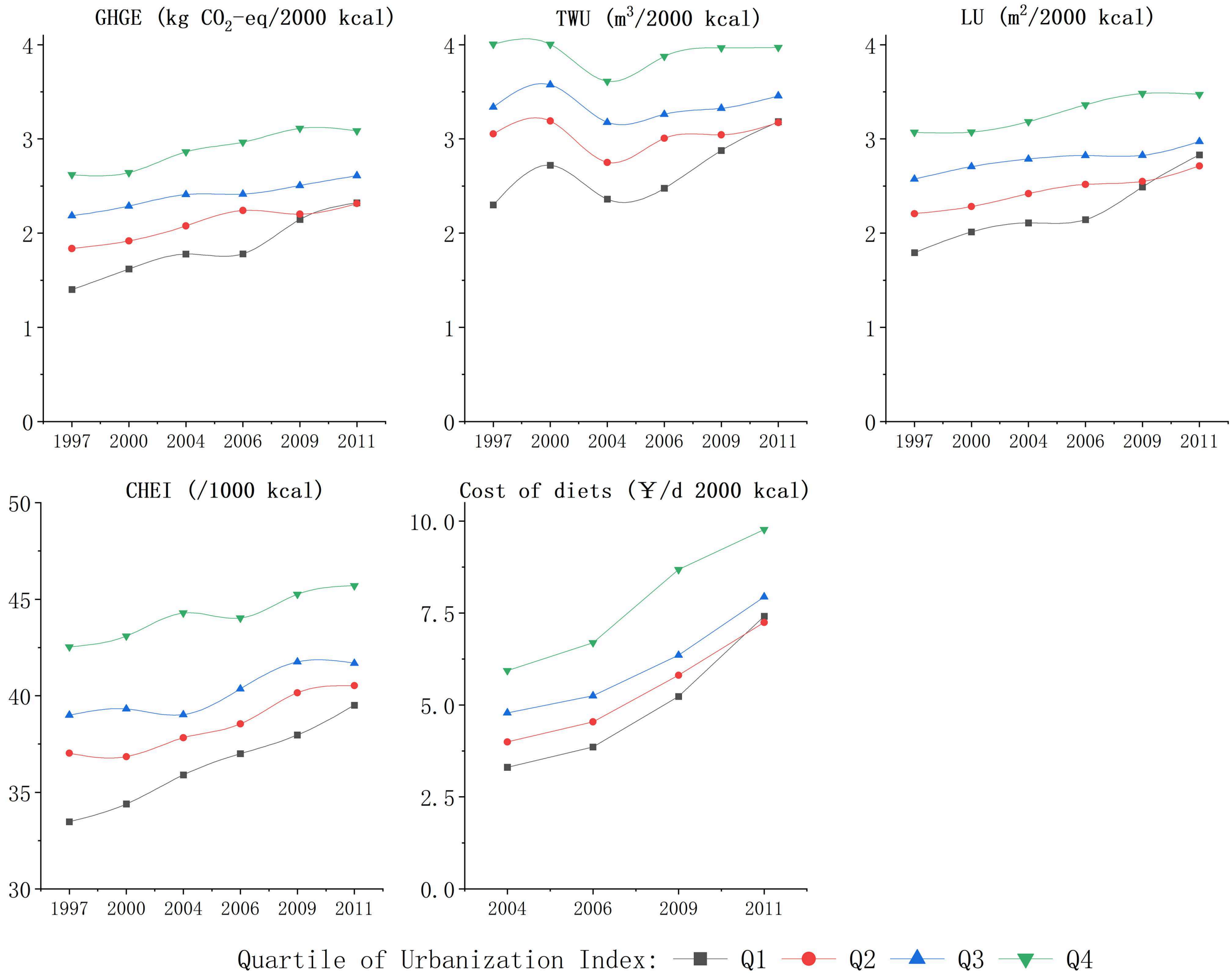

FIGURE 2
Diet-related GHGE, TWU, LU, CHEI2016, and cost of diet by quartiles of the urbanization index in the CHNS 1997-2011.

activity was positively associated with the diet-related GHGE, TWU, and LU, respectively. Furthermore, due to the increased accessibility of communication devices, residents are able to receive advertisements for dairy products, snacks, convenience foods, and fast food outlets on television, the internet, and mobile phones (Huang et al., 2015), thus potentially increasing the frequency of consumption of these foods. This is similar to the results in Model 2, GHGE, TWU, and LU was increased with the growth of the component of communication. The components of Health infrastructure, Housing infrastructure, Traditional markets and Sanitation are positively associated with the cost of diet. Traditional markets can be found in almost all Chinese cities and villages. Animal foods such as meat, dairy products and fish can be accessed directly by the consumers (Zhai et al., 2014). This change in the community environment was associated with a high-fat, high-energy dietary pattern, thus increasing the costs of diets.

Considerable heterogeneity was observed in the association between individual-level variables (such as education and income) and dietary sustainability indicators of Chinese consumers in present study and similar result from the previous study (Su et al., 2020), suggesting that trends in dietary sustainability indicators are not fully explained by community-level variables. Diet-related GHGE, TWU, LU, CHEI2016, and cost of diet showed a strong association with educational levels, respectively. Previous studies have shown that higher educational levels directly influence consumers' concerns about nutrition adequacy, which resulted in improved quality of the diets (Hotz and Gibson, 2005). In addition, education level also influenced consumers' choice of the proportion of animal- and plant-based food, indirectly driving changes in the environmental impacts of food consumption and dietary costs (Aggarwal et al., 2011; Van Bussel et al., 2020). Moreover, as income levels rise, consumers tended to improve the quality of diets. A previous study concluded that the higher the income level of a household, the more likely it is to consume more refined and highly processed and packaged foods (Reynolds et al., 2019). However, the increasing complexity of food processing has also increased the environmental impacts of food.

This current research has several strengths. First, this study benefited from a large sample size and a 15-year follow-up period. Only the individuals with 3-day 24-h recall data were included in this prospective study, which minimizes bias and provides stronger evidence for causality (Kandola et al., 2020). Secondly, this research uses a multilevel mixed effects model to distinguish between community and individual impacts on dietary sustainability indicators. Thirdly, for each community surveyed, the contextual variable urbanization in this study consists of 12 different dimensions of infrastructure, economic, and demographic items. This greatly improves the ability to distinguish the impact of urbanization on the commonly used urban-rural dichotomy (Jones-Smith and Popkin, 2010). This dichotomy not only assumes homogeneity within the "urban" and "rural" categories, but it also ignores change over time. Moreover, the environmental impacts in this study were based on the Chinese Food LCA Database, without using impact estimates from High-Income Countries that would lead to an overestimation of those impacts.

However, some limitations should be mentioned. Given that China has undergone significant changes in recent years in terms of urbanization and dietary transition, however, this study covered only the survey period 1997–2011. Secondly, regional heterogeneity of urbanization can lead to differences in food consumption and its associated sustainability indicators that deserve future attention. This heterogeneity highlights the need for region-specific dietary adjustment strategies. A deeper understanding of the complex associated mechanisms will be of great value for future research.

Conclusions

The present study demonstrated that the rapid urbanization in China over the past two decades has been accompanied by an improvement in overall diet quality, however, also by an increase in the diet-related environmental impacts and cost of the diet. Of special concern was the observed trend that people from the lower urbanization levels are rapidly adopting similar diet-transitions as the highest urbanization quartile. Halting and reversing these dietary trends that are increasing health at the expense of environmental impacts and increased dietary cost is a key challenge for policy makers and nutrition researchers.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Available upon reasonable request from the National Institute for Nutrition and Food Safety, China Center for Disease Control and Prevention. Requests to access these datasets should be directed to chns@unc.edu.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Committees from the University of North Carolina at Chapel Hill and the National Institute for Nutrition and Food Safety, China Center for Disease Control and Prevention approved the survey protocols and instruments and the process for obtaining informed consent for the survey. The patients/participants provided their written informed consent to participate in this study.

Author contributions

ET, PV, and SB designed the research. ZC and HC conducted the analyses and wrote the paper. All authors provided feedback on the manuscript and approved of the final version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1111361/full#supplementary-material

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