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How do regional and demographic differences in diets affect the health and environmental impact in China?

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ABSTRACT

A higher diet quality has been associated with lower environmental impacts, but not consistently. Considering the cultural diversity of dietary habits and the heterogeneity of socioeconomic development in China, we aimed to evaluate the association between diet quality and environmental impacts across demographic subgroups and regions. This study used dietary consumption data from the China Health Nutrition Survey 2011. Diet quality was measured with the Chinese Healthy Eating Index 2016 (CHEI2016). Diet-related environmental impact (Greenhouse Gas Emissions (GHGE), Total Water Use (TWU), and Land Use (LU)) were estimated using the Chinese Food Life Cycle Assessment Database. Multilevel regression models were used to quantify the association of the CHEI2016 score and the diet-related environmental impacts across heterogeneous population subgroups. A one-standard deviation increase in CHEI2016 score was associated with an increase of 9.7% in GHGE, 9.1% in TWU, and 6.4% in LU. This occurs because increasing the consumption of under-consumed foods (dairy products and fruit), partially offsets the environmental benefits of reduced meat consumption. Demographic subgroups characterized by either higher educated or a higher income exhibited a larger proportion of animal-based foods within their diet, consequently leading to higher diet-related environmental impacts. When expressed per standard deviation increase in CHEI2016, the dietary environmental impacts rose fastest in the Metropolitan area and slowest in the Northeast. Diets with higher CHEI2016 scores are associated with higher diet-related environmental impacts among Chinese adults but this varies per region. The development of sustainable diet strategies needs to account for potential trade-off between the health and environmental goals, and dietary habits of consumers in different regions and subpopulations.

1. Introduction

The Food and Agriculture Organization (FAO) defines sustainable diets as "*diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations*" (Burlingame et al., 2012). The FAO recommends incorporating sustainability into the development of food-based dietary guidelines and policies, while also recognizing the importance of research to reveal potential synergies and trade-offs among different sustainability dimensions (Ranganathan, 2019). Previous research has shown an inverse association between overall diet quality and diet-related environmental impacts (Rose et al., 2019b; Tilman and Clark, 2014). Reducing the consumption of animal-based products (especially red meat) can both reduce environmental impacts and benefit public health (Macdiarmid et al., 2012). Prior investigations have further demonstrated an inverse association between improved health outcomes, as indicated by reduced

Abbreviations: CHNS, **China Health Nutrition Survey**; NINH, **the National Institute of Nutrition and Health**; GHGE, **Greenhouse Gas Emissions**; TWU, **Total Water Use**; LU, **Land Use**; CHEI2016, **China Healthy Diet Index 2016**; FAO, **Food and Agriculture Organization**; HICs, **High-Income Countries**; LMICs, **Low and middle-income countries**; CFCT, **Chinese Food Composition Table**; SP, **Standard portions**; BMI, **Body Mass Index**; CFLCAD, **the Chinese Food Life Cycle Assessment Database**.

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simulated mortality rates, and decreased diet-related environmental impacts (Aleksandrowicz et al., 2016; Pollock et al., 2022). However, some studies showed positive or no associations between diet quality and diet-related environmental impact (Aleksandrowicz et al., 2019a; Vieux et al., 2013). Other modeling studies have explored whether the environmental impact would be reduced if consumers shifted to recommended healthy diets (Springmann et al., 2020; Willett et al., 2019). In contrast, results from low- and middle-income countries (LMIC) show that the environmental benefits of reducing red meat consumption did not compensate for the extra diet-related environmental impact brought by the recommended higher consumption of vegetables, fruit, and dairy products (Batlle-Bayer et al., 2020). Nevertheless, evidence of the association between the dietary quality and dietary environmental impacts is lacking for China, where dietary patterns are undergoing a rapid transition since the last decades (Fan et al., 2021b; Y. He et al., 2019b; Wang et al., 2018).

The Chinese food system is currently facing the dual challenge of providing healthy diets and reducing environmental impacts (Fan et al., 2021a). The main nutritional challenges in China are the risks of overweight, obesity, and diet-related chronic diseases such as hypertension (Report on the status of nutrition and chronic diseases of Chinese residents, 2015) and diabetes (Liu et al., 2019). The consumption of oil, salt, and red meat is much higher than the recommended amounts in the Chinese Dietary Guidelines, whereas those of fruits, vegetables, beans, and dairy products is insufficient (Y. He et al., 2019a). To meet the food demand of the growing population, intensive agricultural production has led to the degradation of soil, waste of water resources, and damage of ecosystems (Gitz et al., 2016). Agricultural GHG emissions in China increased from 600 million tons in 1990 to 710 million tons in 2018 (China and Global Food Policy Report, 2021). Therefore, achieving a environmental friendly and healthy diet for the Chinese population is warranted for both health and environment reasons.

As the dietary patterns vary among regions in China (Zhang et al., 2014), it is necessary to explore the heterogeneity of the association between diet quality and diet-related environment impacts across regions. These unique dietary patterns are determined by socioeconomic status and cultural preferences, which in turn affect the environmental impacts associated with diets (Heller et al., 2013a). Most studies on Chinese diets have focused on national averages, and the association between dietary quality and diet-related environmental impacts has not been thoroughly investigated at the regional level (Dong et al., 2021; Sheng et al., 2021; Sun et al., 2021; Xiong et al., 2022; Yin et al., 2020). National-level averages of food consumption ignore important socioeconomic heterogeneity in dietary patterns and diet-related environmental impacts, such as income, education level, and occupation (He et al., 2019c). Moreover, when calculating the environmental impacts of Chinese diets, most studies used LCA databases from food production systems in high income countries (HICs) (Lei and Shimokawa, 2020; Song et al., 2017). Environmental footprints determined using these databases do not reflect the actual environmental impacts of foods in China, as food production systems can vary according to geography and production methods (Heller et al., 2013b).

The aim of this study was to analyze the association between diet quality and diet-related environmental impacts. Secondly, socio demographic determinants for the heterogeneity of the association of dietary quality and the environmental impact of diets across regions were explored.

2. Data and methodology

2.1. Study population and dietary recall data

The study used individual food consumption data from the China Health Nutrition Survey 2011 (CHNS 2011), a long-term longitudinal cohort study conducted by the National Institute of Nutrition and Health (NINH) of the Chinese Centre for Disease Control and Prevention and the University of North Carolina, USA (Popkin et al., 2010a). A multi-stage stratified random cluster sampling method was used in the CHNS to select survey households in 9 provinces (Liaoning, Jiangsu, Shandong, Henan, Hubei, Hunan, Guangxi, Guizhou, and Heilongjiang) and metropolitan areas (Beijing, Shanghai, and Chongqing). Data on dietary, economic, physical activity, and health indicators were collected through questionnaires, physical measurements, and biochemical tests. The project was reviewed by the Ethics Committee of the NINH and all respondents signed an informed consent form. Trained interviewers recorded the consumption of all food items, including meals and snacks in residents' household for 3 consecutive days (two working days and one weekend day). Edible oils and condiments were weighed and recorded to estimate the consumed amounts (Popkin et al., 2010b). Conversion of food intake data into energy and nutrient intake data was carried out using the Chinese Food Composition Tables (FCT). From the overall dataset, adults aged 18–64 years were selected. Respondents younger than 18 or over 65 years (n = 4,651; 29.6 % of sample), pregnant and breastfeeding women (n = 89; 0.5 % of sample), as well as those with a z-score > 5 or < 5 for energy intake (n = 67; 0.4 % of sample), and those with only one day 24-h dietary recall available (n = 598; 3.8 % of sample) were excluded in this analysis. The final sample included 10,324 participants of the CHNS 2011.

2.2. Chinese healthy Eating Index 2016

The Chinese Healthy Eating Index 2016 (CHEI2016) was developed and based on the Chinese Dietary Guidelines (2016) combined with evidence from nutritional epidemiological studies related to health outcomes (Yuan et al., 2017). The index used standard portions (SP) of foods as the unit of dietary measurement, and one SP size in one food group should share consistent contents like same energy content and similar carbohydrate, and protein content. CHEI2016 evaluated the diet quality of overall dietary consumption in terms of adequacy (cereals, whole grains and mixed beans, tubers, total vegetables (excluding dark vegetables), dark vegetables, fruits, dairy, soybeans, fish and seafood, poultry, eggs, and seeds and nuts), and limitation (red meat, edible oils, sodium, added sugar and alcohol) in a total of 17 food groups (Supplementary Table 1). Scoring for the CHEI components is based on the energy density (as amounts per 1000 calories of intake). Recommended amounts for each food group-based component are converted and expressed in SP/1000 kcal, and cooking oils is expressed in gram/1000 kcal. The scores for each component were added together to calculate the total score, which ranges from 0 to 100, with higher scores representing better adherence to Chinese Dietary Guidelines 2016 for healthy diets.

2.3. Sociodemographic variables

Sociodemographic variables included age, gender, height, weight, work-related physical activity, educational level, degree of urbanization, annual household income per capita, dietary knowledge, proportion of animal-based foods in the diet, and regions. Weight and height were measured by trained technicians using standard methods. Body Mass Index (BMI) was calculated as weight (kg) divided by height-squared (m^2). The categories of work-related physical activity were light (e.g., sedentary job, office work, lab technician), moderate (e.g., driver, electrician) and heavy (e.g., farmer, steel worker, lumber worker, mason). Educational level was divided into three groups of low (below primary school (including not attending school)), medium (secondary school, including middle and high school), and high educational level (above high school, including undergraduate and graduate school). The degree of urbanization was categorized as living in urban or rural area. Household income was calculated as the total annual household income divided by the number of household members, and subsequently were divided into low (0–7,900 RMB), middle (7,916–17,237 RMB), and high-income groups (17,272–300,000 RMB). Dietary knowledge

Table 1
Description of basic demographic characteristics, CHEI2016 score and diet-related GHGE, TWU, LU, of participants in the China Health Nutrition Survey 2011, aged 18–64 years, stratified by region[1].

	Average n = 10,324		**Northeast n = 1,563**		**East n = 1,612**		**Central n = 2,528**		**Southwest n = 1,763**		**Metropolitan areas n = 2,858**	
Gender	N or mean	% or SD										
Male	4889	47.4 %	750	48.0 %	764	47.4 %	1180	46.7 %	863	49.0 %	1332	46.6 %
Female	5435	52.6 %	813	52.0 %	848	52.6 %	1348	53.3 %	900	51.0 %	1526	53.4 %
Age (years)	45.7	11.9	47.0	10.7	46.6	11.8	45.8	11.9	44.5	12.3	45.2	12.2
BMI (kg/m^2)	23.9	4.2	24.6	5.1	24.5	4.2	23.8	3.9	22.6	3.4	24.3	4.1
Educational level												
Primary school and below	3053	29.6 %	504	32.2 %	511	31.7 %	836	33.1 %	630	35.7 %	572	20.0 %
Secondary school	5106	49.5 %	761	48.7 %	849	52.7 %	1303	51.5 %	911	51.7 %	1282	44.9 %
High school and above	2165	21.0 %	298	19.1 %	252	15.6 %	389	15.4 %	222	12.6 %	1004	35.1 %
Activity level												
Low	6096	59.0 %	745	47.7 %	884	54.8 %	1386	54.8 %	798	45.3 %	2283	79.9 %
Medium	1666	16.1 %	175	11.2 %	369	22.9 %	396	15.7 %	374	21.2 %	352	12.3 %
High	2562	24.8 %	643	41.1 %	359	22.3 %	746	29.5 %	591	33.5 %	223	7.8 %
Dietary knowledge												
No	7358	71.3 %	962	61.6 %	1189	73.8 %	2091	82.7 %	1430	81.1 %	1687	59.1 %
Yes	2888	27.9 %	592	37.8 %	412	25.6 %	398	15.7 %	319	18.1 %	1166	40.8 %
Missing value	78	0.8 %	9	0.6 %	11	0.7 %	39	1.5 %	14	0.8 %	5	0.2 %
Income (1,000 RMB)	12.0	6.1, 20.9	12.8	6.8, 21.1	13.2	7.8, 20.6	9.1	4.2, 16.8	7.8	4.6, 12.8	18.1	9.6, 28.8
Degree of urbanization												
Urban	4253	41.2 %	502	32.1 %	497	30.8 %	911	36.0 %	661	37.5 %	1682	58.9 %
Rural	6071	58.8 %	1061	67.9 %	1115	69.2 %	1617	64.0 %	1102	62.5 %	1176	41.1 %
Dietary Energy intake (kcal)	1970	680.2	1968	640.3	2155	686.9	2142	759.8	2036	615.4	1673	548.5
Proportion of animal-based foods (%)	25.4	0.1	20.1	0.1	27.6	0.1	21.9	0.1	21.3	0.1	32.4	0.1
CHEI2016	51.9	10.5	54.6	10.9	52.5	9.6	48.9	9.5	49.2	8.6	54.4	11.4
GHGE (kg CO_2-eq/ 2000 kcal per person per day)	2.7	0.7	2.5	0.8	2.7	0.9	2.5	1.0	2.9	0.9	3.5	1.2
TWU (m^3/ 2000 kcal per person per day)	3.8	1.6	3.6	1.1	3.9	1.5	3.2	1.4	3.7	1.2	4.6	2.1
LU (m^2/ 2000 kcal per person per day)	3.3	1.3	3.0	1.1	3.0	1.1	2.8	1.2	3.3	1.2	4.0	1.5

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

referred to whether the respondents were aware of the Chinese Dietary Guidelines (simple Yes/No question). 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) in grams/ 2000 kcal by the total food consumption in grams/ 2000 kcal. Regions were divided based on geographical and cultural similarities into Northeast (Liaoning, Heilongjiang), East (Shandong, Jiangsu), Central (Henan, Hubei, Hunan), Southwest (Guizhou, Guangxi), and Metropolitan (Beijing, Shanghai, Chongqing) areas.

2.4. Environmental impact of diets

The environmental impacts of foods were linked to food consumption by using the Chinese Food Life Cycle Assessment Database (CFLCAD) (Cai et al., 2022). In summary, this database aggregates results from the LCA literature based on the Chinese context and provides each single food item an estimate of Greenhouse Gas Emissions (GHGE), Total Water Use (TWU), and Land Use (LU) per kg of food as consumed. The CHNS documented the consumption of prepared foods, such as cooked rice. Consequently, to calculate the environmental impact of each consumed food item, the system boundary of this study is defined from cradle to consumer. Apart from agricultural production, this includes contributions from storage, processing, packaging, transportation, and home preparation. Furthermore, food losses occurring within the food supply chain were also incorporated. In addition, the environmental impacts of fish did not include the fish stocks in oceans/ seas, and the system boundary of fish is from artificial fish farming to consumption. The appropriate conversion parameters have been acquired from literature and statistical yearbooks to calculate the environmental footprints of the post farm gate stage. Based on the food consumption data, daily impact on GHGE, TWU and LU were expressed as densities (per 2000 kcal), which is considered to compensate a large part of individual-level non-differential over- or underestimation of food consumption. The food codes in CFLCAD were referred to the Chinese FCT. This ensures that results in both the CHNS and CFLCAD are presented at the level of individual "food item", establishing a connective link between the two databases using the coding provided by the Chinese FCT. If no LCA data of a certain food was available, data from similar food groups were used as proxies.

2.5. Statistical analysis

All data collation and statistical analyses were conducted using Stata/se 13.1 (Stata Corp). Descriptive results were expressed as mean and standard deviation or median and interquartile range (IQR; 25th-75th percentile). All reported p-values were two-tailed, with a *p*-value < 0.05 considered statistically significant.

At first, the association between the CHEI2016 and diet-related environmental impacts was assessed using multiple linear regression. The model included either total diet-related GHGE (kg CO_2-eq/2000 kcal), TWU (m^3/2000 kcal), or LU (m^2/2000 kcal) as the dependent variable (logarithmic transformation), and the CHEI2016 score or its components as the independent variables, adjusted for age, gender and the proportion of animal-based food consumption. The regression coefficient was expressed as per standard deviation increase. Furthermore, this study applied general linear models with diet-related environmental impacts as dependent variables and quartiles of CHEI score, total energy intake, and sociodemographic variables as independent variables to calculate the adjusted mean environmental impact in each quintile of CHEI score and standardized the mean values to a total energy intake of 2000 kcal daily.

Secondly, the associations between diet related environmental impacts and dietary quality across regions and population subgroups were evaluated; a likelihood ratio (LR) test was used to assess statistical significance of the differential association between dietary quality and environmental impacts across regions. Multilevel regression models with random intercepts and random slopes were used to explain the heterogeneity of the association by region and population subgroup characteristics. The combined slope of each region consisted of fixed-effect slope plus random-effect slope. The models were fitted using two levels of variance: individuals (level 1, n = 13,072), and regions (level 2, n = 5). Thus, the slope and intercept of CHEI2016 were allowed to vary randomly across regions. Model 1 included diet-related environmental impacts per 2000 kcal (densities) as the dependent variable (logarithmic transformation) and CHEI2016 as the independent variable, and was adjusted for age and gender. Model 2 added dietary quality-related covariates as the fixed effect terms for degree of urbanization, educational level, income, dietary knowledge, and work-related physical activity.

3. Results

In the 10,324 participants of the CHNS 2011, about 53 % were female, with a mean age of 45.7 years (SD = 11.9), the median income was 12,040 RMB per year, and the mean BMI was 23.9 kg/m^2 (Table 1). Around 59 % of the participants lived in rural areas, 21 % had a high level of education, and 58 % worked in light physical activities. The CHEI2016 score was on average 51.9 points out of a maximum score of 100. The average daily energy intake was 1970 kcal/day, and the proportion of animal-based foods in diet consumption was 25.4 %. The average daily diet-related GHGE was 2.7 kg CO_2-eq/2000 kcal/day, TWU was 3.8 m^3/2000 kcal/day, and LU was 3.3 m^2/2000 kcal/day.

3.1. 3.1 CHEI2016 score and diet-related environmental impacts

In general energy-adjusted GHGE, TWU, and LU were higher in males and decreased with age (Table 3). After adjustments for age and sex, the CHEI2016 score was positively associated with GHGE, TWU, and LU (Fig. 1). Specifically, one standard deviation increased in CHEI2016 score (i.e., 10.5 points) was associated with increases of 10.6 % GHGE, 10.4 % TWU, and 7.5 % LU, respectively. Overall, a universal trend of a higher proportion of animal-based foods was found in higher diet-related environmental impacts diets within similar CHEI16 score.

For adequacy components, inverse significant associations were found between diet-related environmental impacts and cereals, whole grains, tubers, and seeds and nuts (Table 2). Thus, better adherence to these components of the CHEI2016 was associated with lower diet-related environmental impacts. Positive associations were found between diet-related environmental impacts and of fish and seafood, poultry, vegetables, dairy, dark vegetables, eggs, fruits, and soybeans. The coefficient of fish and seafood was the highest, with total diet-related GHGE, TWU, and LU increasing by 12.6 %, 10.3 %, and 10.8 % for each one standard deviation increase in the score (i.e., 2.2 points). For dietary components to be limited, only the red meat and sodium were negatively correlated with diet-related environmental impacts. Better adherence with components of meat, sodium and edible oils were associated with relatively lower diet-related environmental impacts. No association was found for the sugar and alcohol.

3.2. Diet-related environmental impacts across quartiles of CHEI2016 by different food groups

As the CHEI2016 score increases, an elevation is observed in dietary GHGE (2.51 kg CO2-eq/ 2000 kcal in Q1 vs. 3.23 kg CO2-eq/ 2000 kcal), TWU (3.30 m3/ 2000 kcal in Q1 vs. 4.23 m3/ 2000 kcal), and LU (3.02 m^2/ 2000 kcal in Q1 vs. 3.61 m^2/ 2000 kcal) (Fig. 2). When comparing the dietary group's contribution to the environmental impacts at the Q1 of the CHEI with the dietary group at the Q4 of the CHEI, it is evident that the Q4 group consumes a higher quantity of animal-based foods per 2000 kcal. Additionally, the proportion of cereal and vegetables in their diet shows a decreasing trend (GHGE: 43 % in Q1 vs. 50 % in Q4; TWU: 40 % in Q1 vs. 44 % in Q4; LU: 38 % in Q1 vs. 45 % in Q4) (Supplementary Table 2). In general, higher CHEI2016 score corresponded to increased diet-related environmental impacts, characterized by a higher proportion of animal-based foods in the diet.

3.3. Diet quality and diet-related environmental impacts across regions

Table 3 shows the results of multilevel regression analysis for diets in five regions of China. The CHEI2016 score was positively associated with diet-related environmental impacts in all models. As diet quality-related variables (BMI, income, educational level, work-related physical activity, and diet knowledge) were predictors of diet-related environmental impacts, including these variables in the model further explained the age and gender adjusted association, which attenuated the association between CHEI2016 and diet-related environmental impacts, but the positive association remained (model 2). Specifically, a one-standard deviation increase in CHEI2016 score was associated with

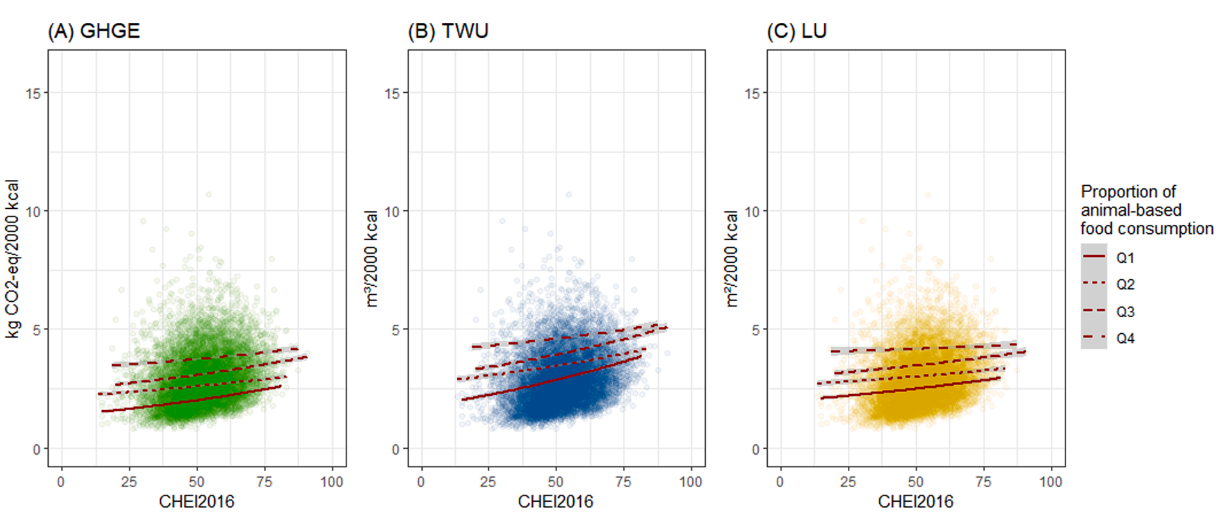

Fig. 1. The association between CHEI2016 and dietary environmental impacts of (A) GHGE, (B) TWU, and (C) LU across quartiles of proportion of animal-based food consumption for 10,324 participants derived from the Chinese Health Nutrition Survey 2011. Dots are the individual observation. Environmental impacts and regression lines are back-transformed from analysis on the log scale.

Table 2
Association between the total Chinese Healthy Eating Index 2016 score and its component scores with GHGE, TWU, and LU among 10,324 participants in the Chinese Health Nutrition Survey 2011[1].

	GHGE density		TWU density		LU density	
	Beta[2]	C.I.	Beta[2]	C.I.	Beta[2]	C.I.
Model 1. Total CHEI2016 score[1]	0.101***	(0.094, 0.107)	0.099***	(0.094, 0.106)	0.072***	(0.065, 0.078)
Model 2. CHEI2016 components[1] score						
Adequacy components						
Cereals	−0.049***	(-0.055, −0.043)	−0.073***	(-0.094, −0.08)	−0.064***	(-0.084, −0.069)
Whole grains and mixed beans	−0.027***	(-0.032, −0.021)	−0.022***	(-0.013, −0.008)	−0.016***	(-0.011, −0.005)
Tubers	−0.025***	(-0.031, −0.021)	−0.004	(-0.004, 0.001)	0.003	(-0.001, 0.004)
Seeds and nuts	−0.005	(-0.011, 0.001)	−0.011***	(-0.009, −0.003)	−0.014***	(-0.011, −0.004)
Soybeans	0.023***	(0.018, 0.028)	0.041***	(0.015, 0.021)	0.012*	(0.003, 0.008)
Fruits	0.037***	(0.031, 0.042)	0.055***	(0.012, 0.015)	0.046***	(0.011, 0.013)
Eggs	0.046***	(0.041, 0.051)	0.039***	(0.016, 0.022)	0.021***	(0.007, 0.013)
Dairy	0.049***	(0.045, 0.056)	0.034***	(0.017, 0.025)	0.042***	(0.022, 0.031)
Dark vegetables	0.051***	(0.050, 0.061)	0.036***	(0.016, 0.022)	0.038***	(0.017, 0.023)
Vegetables (excluding dark vegetables)	0.055***	(0.088, 0.099)	0.059***	(0.037, 0.044)	0.035***	(0.021, 0.028)
Poultry	0.094***	(0.113, 0.124)	0.056***	(0.022, 0.027)	0.052***	(0.021, 0.026)
Fish and seafood	0.119***	(-0.055, −0.043)	0.098***	(0.041, 0.046)	0.103***	(0.043, 0.049)
Limitation components[3]						
Red meats	−0.096***	(-0.102, −0.091)	−0.085***	(-0.051, −0.044)	−0.105***	(-0.062, −0.055)
Sodium	−0.011***	(-0.016, −0.006)	−0.014***	(-0.006, −0.002)	−0.023***	(-0.008, −0.005)
Edible oils	−0.007*	(-0.012, −0.001)	−0.004	(-0.004, 0.001)	−0.007*	(-0.005, 0.001)
Added sugars	0.001	(-0.005, 0.005)	0.002	(-0.018, 0.036)	0.003	(-0.042, 0.015)
Alcohol	0.003	(-0.003, 0.008)	0.008	(0.002, 0.011)	0.002	(-0.007, 0.003)

1 Models were adjusted for age (continuous), sex (male, female). The dependent variables are logarithmically transformed. Level of significance: *** <0.001, ** <0.01, * <0.05.
2 The regression coefficient was expressed as per standard deviation increase of the CHEI2016.
3 The components to be limited were inversely scored (lower consumption results in a higher score).

Table 3
Association of diet-related GHGE, TWU, and LU densities (per 2000 kcal) with CHEI2016 in five regions of China[1].

Variables	GHGE density		TWU density		LU density	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Fixed effect						
Level 2: regions						
CHEI2016[2]	0.087***	0.046***	0.081***	0.048***	0.055***	0.019*
Level 1: individuals						
Age (per 10 year)	−0.025***	−0.015***	−0.026***	−0.013***	−0.023***	−0.016***
Female (ref: male)	−0.023***	−0.017***	−0.011**	−0.006	−0.013***	−0.006
BMI (kg/m^2)		−0.001		−0.001		0.008**
Income (1,000 RMB/Y)		0.006*		0.007*		0.004
Educational level (ref: low)						
Medium		0.006		0.008		0.012
High		0.017*		0.033***		0.045***
Work-related physical activity (ref: light)						
Medium		−0.001		−0.004		−0.007
High		−0.064***		−0.064***		−0.054***
Urbanization (ref: urban)		−0.097***		−0.067***		−0.111***
Diet knowledge (ref: not aware)						
Aware		−0.042***		−0.038***		−0.038***
Proportion of animal-based foods		0.191***		0.145***		0.142***
Random effects						
Slope SD of CHEI2016[3]	0.003	0.002	0.003	0.002	0.003	0.002
Intercept SD of CHEI2016[4]	0.218	0.157	0.209	0.138	0.199	0.382
The likelihood ratio test statistic[5]	1620.6	554.9	1188.2	479.5	1423.9	556.4

1 In a multilevel model including the random slope of the regions, CHEI2016 was used as the independent variable and the diet related GHGE, TWU, and LU were used as dependent variables, respectively. The dependent variables are logarithmically transformed. Level of significance: *** <0.001, ** <0.01, * <0.05.
2 The regression coefficient was expressed per standard deviation increase.
3 SD of the random slope of CHEI2016 across regions.
4 SD of the random intercept of CHEI2016 across regions.
5 The likelihood ratio test was used to test whether the association between diet quality and environmental impacts of diets varies across regions. The likelihood ratio statistic follows a chi-square distribution. Chi-Square Probabilities 0.05 (4) = 9.48.

increases of 4.6 % GHGE, 4.3 % TWU, and 1.3 % LU, respectively. Those with higher diet-related environmental impacts tend to be in younger age groups, have a higher income, and lived in more urbanized areas (Table 3). The diet-related environmental impacts were lower for women and for those who were aware of the dietary guidelines. The proportion of animal-based food in diets showed a positive correlation with diet-related environmental impacts (Table 3). Education level and work-related physical activity level showed a positive association with

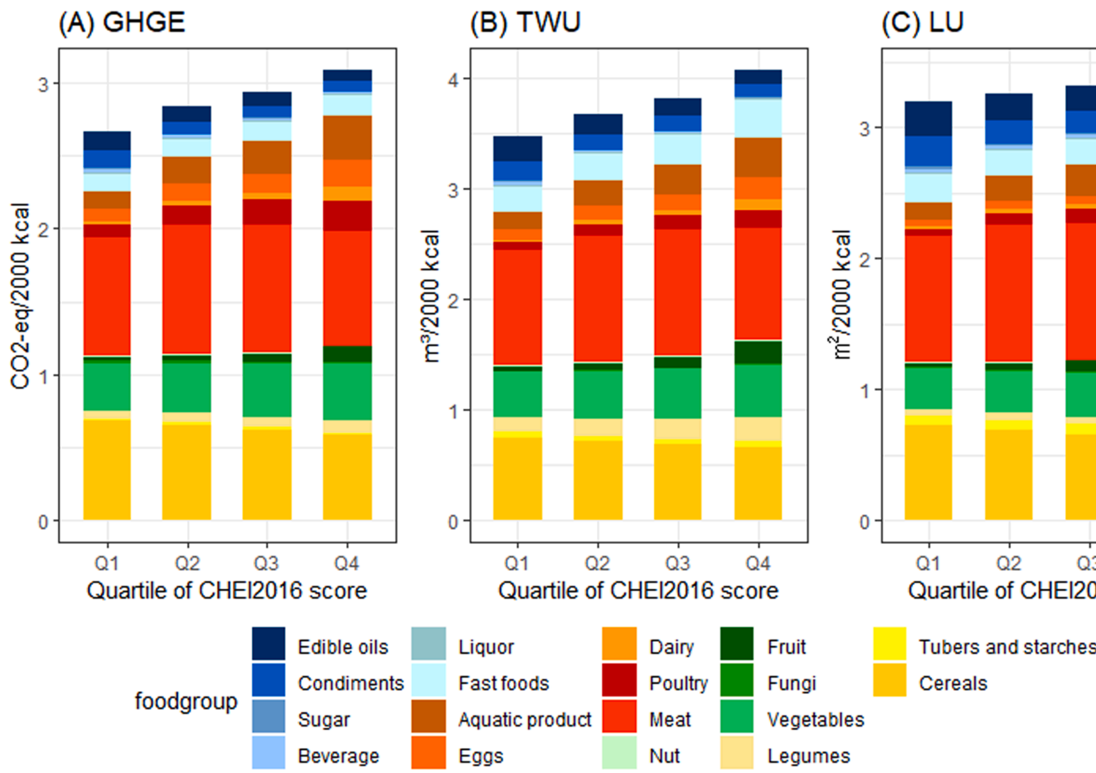

Fig. 2. GHGE (kg CO_2-eq/2000 kcal), TWU (M^3/2000 kcal), and LU (M^2/2000 kcal) across quartiles of the CHEI score by different food groups in the Chinese Health Nutrition Survey 2011*. *Values are adjusted means (95 % CI) estimated from general linear models with GHGE, TWU, and LU as dependent variables, respectively, and quartiles of CHEI score, total energy intake, and sociodemographic variables as independent variables.

dietary environmental impacts, and with higher education level and lower physical activity level, the dietary environmental impacts were higher (Fig. 3A&Fig. 3B, Supplementary Figure 2&3). The association between CHEI2016 and diet related GHGE, TWU, and LU differed significantly across regions (Likelihood ratio tests, Table 3). Fig. 3A&Fig. 3B presents the associations by region as obtained from model 2. In all regions, a higher CHEI2016 score was associated to higher diet-related environmental impact. Among the five regions, with one standard deviation increase in CHEI2016, the dietary environmental impacts rose fastest (GHGE: 4.9 %, TWU: 4.7 %, and LU: 1.5 %) in the Metropolitan area and slowest in the Northeast (GHGE: 4.0 %, TWU: 3.9 %, and LU: 0.5 %) (Supplementary Figure 1). Further, the proportion of animal-based food and dietary environmental impacts were highest of the residents with high education and low physical activity level in the Metropolitan areas, and lowest in the Northeast (Fig. 3A&B, Supplementary Figure 2&3). The proportion of animal-based food and dietary environmental impacts were higher for residents with high education level and low physical activity level than for those with low education level and high physical activity level in all five region (Table 4).

4. Discussion

In this study, dietary consumption in five regions of China was evaluated for diet quality and environmental impacts (GHGE, TWU, and LU). On average, diets with higher CHEI2016 scores had significantly higher diet-related environmental impacts than those with low CHEI2016 scores. A one standard deviation increase in CHEI2016 score was associated with increases in GHGE of 5.8 %, TWU of4.9 %, and LU of 2.2 %. This was mainly due to better adherence to the Chinese Dietary Guideline for adequate consumption of cereals, vegetables, fruits, dairy and fish, and lower consumption of red meat and sodium. At similar diet quality scores, the dietary environmental impacts were positively associated to the proportion of animal-based foods in the diet. Further, the multilevel regression model showed that both the level (intercept) and the strength (slope) of the positive association between dietary quality and environmental impact differed among regions. Therefore, the present study provides further evidence, based on self-selected diets, that reducing meat consumption and increasing plant-based food consumption may help to reduce diet-related environmental impacts and improve the dietary quality.

A large body of research has discussed whether improving diet quality improves environmental sustainability over the last decade, but mainly focused on HICs. A review of 29 studies in HICs showed that diets aligned with dietary guidelines, containing less meat and higher amounts of plant-derived foods (vegetables, pulses, fruit, wholegrains, nuts, seeds) would offer environmental benefits (20–50 % lower GHGE and LU) and improve population health (Steenson and Buttriss, 2021). Recent studies of scenario analyses have begun to examine the association between diet quality and diet-related environmental impacts in Low and middle-income countries (LMICs). In India, a shift towards healthy diets among those with dietary energy intakes below recommended guidelines would result in 28 % increase in GHGE, 18 % and 34 % increases in blue and green WU, respectively, and 41 % increase in LU (Aleksandrowicz et al., 2019b). In North Africa and the Middle East regions, for blue water and energy use, increased consumption of vegetables/legumes, nuts/seeds and fruit will outweigh the savings associated with reduced red meat consumption (Bahn et al., 2019). The findings of various studies suggested that to adhere to healthy dietary guidelines, HICs should reduce consumption of animal-based products, particularly meat, to a greater extent than LMICs. As a result, shifting to healthy dietary pattern in HICs would be a strategy to achieve both positive health outcomes and environmental sustainability (De Schutter et al., 2020; Eker et al., 2019). Conversely, meat overconsumption is not as prevalent in LMICs, whereas consumption of dairy products falls significantly below the recommended level (Lim et al., 2012). Increasing the consumption of under-consumed foods, such as dairy products and

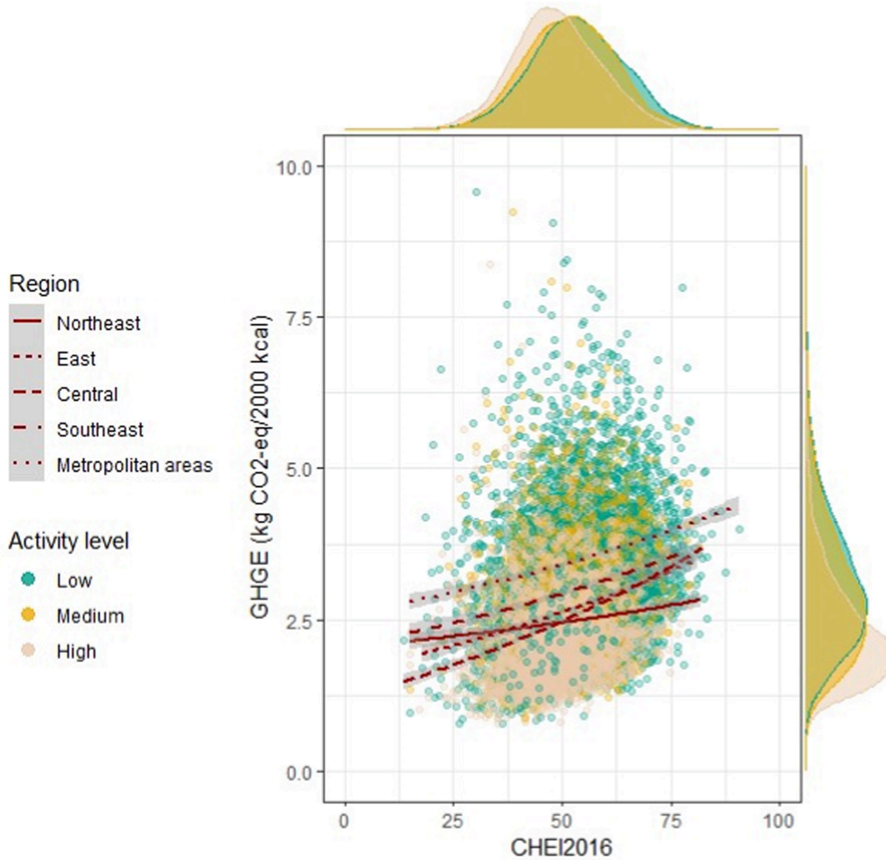

Fig. 3A. The association between CHEI2016 and diet-related GHGE in five different regions. Dots represent the individual observation, with different colors for the level of physical activity. Environmental impacts and regression lines are back transformed from analysis on the log scale.

fruit, partially offsets the environmental benefits of reduced meat consumption. Therefore, adhering to healthy dietary patterns consistent with dietary guidelines may not result in a reduction of diet-related environmental impacts in LMICs like observed in our study.

The inconsistency between the results of this study and studies from HIC can be attributed at least partly to differences in amount of animal-based food consumption. The per capita meat consumption in China is higher than recommended in the Chinese Dietary Guidelines (the average meat consumption per 2000 kcal in our study was 30 % higher than recommend), while other animal-based foods such as dairy and eggs were 90 % and 30 % lower than the recommended consumption, respectively. Similarly, the consumption of aquatic products, tubers, vegetables, and fruit of the Chinese population still felled short of the Chinese Dietary Guidelines' recommendations (Supplementary Table 4). The environmental benefits of reducing meat consumption were offset by the need to increase the consumption of fruit, vegetables, nuts, fish, and most importantly dairy to adhere to the Chinese Dietary Guidelines. It is noteworthy that the contribution of dietary environmental impacts from animal-based foods is lower in China (e.g. 43.2 % in this study) than in HICs (ranging from e.g. 55.7 % to 68.7 % (Hallström et al., 2015). In Spain (Batlle-Bayer et al., 2019) and the UK (Rippin et al., 2021), animal-based foods were the main contributors to dietary GHGE (meat: 33 % and 32 %; fish: 22 % and 8 %, and dairy products: 17 % and 14 %, respectively). In the present study, meat was the largest contributor to dietary environmental impacts (GHGE: 29.9 %, TWU:29.5 %, and LU:31.1 %), followed by cereals (GHGE:22.3 %, TWU:18.8 %, and LU:20.6 %), and vegetables (GHGE:12.1 %, TWU:11.8 %, and LU:9.8 %). In contrast, the contribution of dairy products (GHGE:1.5 %, TWU:1.2 %, and LU:1.4 %) was lower (Supplementary Table 4). A trade-off may exist between the diet quality and diet-related environmental impacts of the Chinese population, and a shift to a healthy diet may not necessarily be beneficial to environmental sustainability.

A novel aspect of this study is the exploration of quantitative and qualitative dimensions of inter-individual variability in diet-related environmental impacts. Our findings suggest that differences in the diet-related environmental impacts could be explained by differences in the proportion of animal-based food consumption. Within the same range of CHEI2016 score distribution, the higher the proportion of animal foods consumed, the greater the diet-related environmental impacts. In addition, food choices within the same food group can lead to large differences in total environmental impacts. For instance, for the consumption of red meat, the difference between the choice of pork (lower environmental impact) and beef (higher environmental impact) results in a difference in the environmental impact of the diet for a similar CHEI2016 score. Inconsistencies in the amounts of food consumed can also lead to differences in dietary environmental impacts. For example, consumption of 300 g of vegetables per day would result in a score of 10 for the vegetable component of the CHEI2016 score, while consumption of 400 g of vegetables would also result in a score of 10, but with much higher dietary environmental impacts.

Although numerous studies have been conducted on sustainable diets, comparative regional analysis of diets has not been explored from an environmental and health perspective. This study highlighted regional differences in the association between diet quality and diet-related environmental impacts. The results from Model 2 demonstrated that the association between diet quality and dietary environmental impacts is influenced by demographic factors, including education level, physical activity, animal food proportion in diets, and urbanization. Notably, the Metropolitan areas have the highest dietary environmental impacts compared to the other four regions studied. This is attributed to the proportion of highly-educated residents, a greater

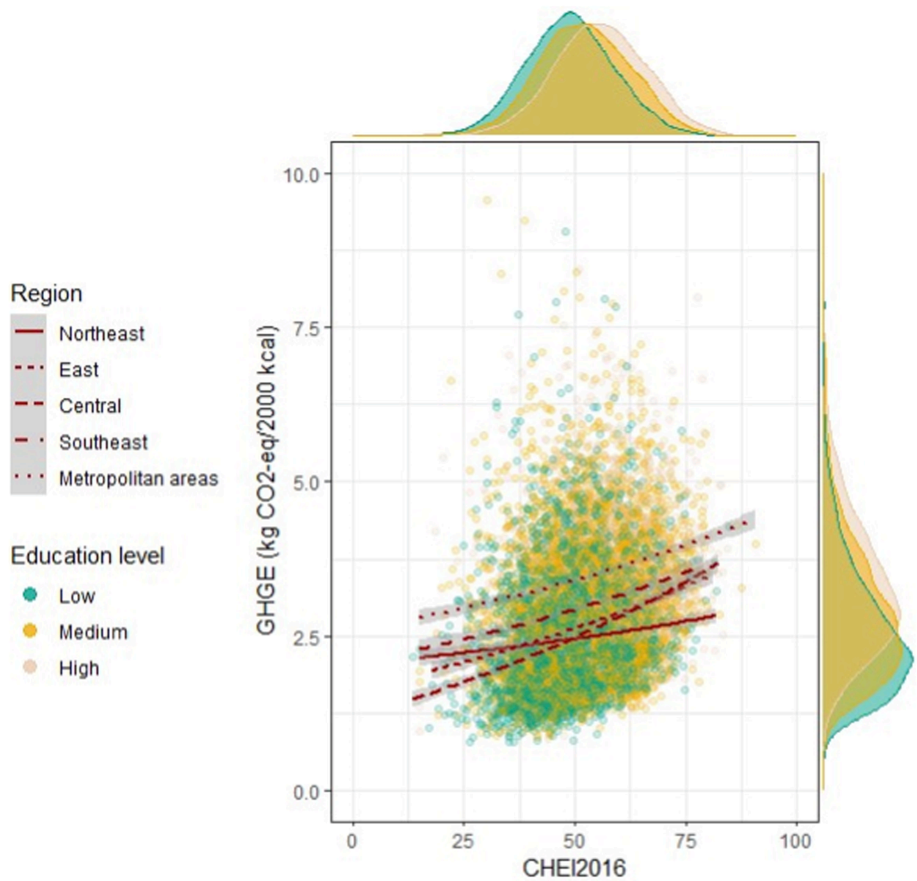

Fig. 3B. The association between CHEI2016 and diet related GHGE in five different regions. Dots represent the individual observation, with different colors for the level of education. Environmental impacts and regression lines are back transformed from analysis on the log scale.

Table 4
Dietary environmental impacts across education level, activity level, and proportion of animal based food of region in the Chinese Health Nutrition Survey 2011[1.]

	Northeast n = 1,563		East n = 1,612		Central n = 2,528		Southeast n = 1,763		Metropolitan areas n = 2,858	
	high education level & low activity level n = 269	*low education level & high activity level n = 322*	*high education level & low activity level n = 203*	*low education level & high activity level n = 214*	*high education level & low activity level n = 342*	*low education level & high activity level n = 360*	*high education level & low activity level n = 181*	*low education level & high activity level n = 310*	*high education level & low activity level n = 892*	*low education level & high activity level n = 149*
GHGE (kg CO_2-eq/ 2000 kcal)	2.84	2.21	3.26	2.19	2.97	1.89	3.11	2.61	3.71	2.69
TWU (m^3/2000 kcal)	3.86	3.24	4.34	3.23	3.89	2.48	3.98	3.33	4.71	3.38
LU (m^2/2000 kcal)	3.33	2.73	3.7	2.51	3.38	2.27	3.54	2.93	4.31	3.11
CHEI	54.58	53.26	55.74	48.55	52.48	45.21	51.52	46.59	58.09	43.05
Proportion of animal based food[2]	14.90 %	8.19 %	18.83 %	9.25 %	16.37 %	8.42 %	19.05 %	9.03 %	23.38 %	11.21 %

1 The detail of food group contribution were shown in Supplementary Table 3.
2 The percentage of animal based food consumption (grams).

prevalence of animal-based foods in dietary patterns, and a larger population with low levels of physical activity. This statement does not imply a direct relation between low physical activity or high educational level and increased environmental impacts. Instead, it highlights the interplay of the metropolitan context with lifestyle and diet choices that jointly contribute to higher diet-related environmental impacts. These factors include increased reliance on convenience foods, greater demand for resource-intensive food products, and higher rates of food waste. While lower physical activity may indeed result in lower individual energy requirements, the lifestyle and dietary patterns associated with metropolitan living can offset this effect. These findings demonstrate that demographic factors play a significant role in the association between diet quality and environmental impacts (Andreyeva et al., 2010), highlighting the importance of targeted interventions tailored to specific populations based on their unique demographic characteristics.

4.1. Advantages and limitations

The main advantage of this study is that food consumption data of each participant was obtained via a 3-days-24-hour dietary recall, an accurate method for determining the average consumption (Popkin et al., 2010c). Furthermore, this study used a food LCA database based on the Chinese context to assess the environmental impacts of diets to account for the heterogeneity (geographic location and production practices) among estimates of similar foods. For example, previous study used a globally representative food environment database (Barilla Center for Food and Nutrition (BCFN)) to calculate the CHNS 2011 dietary GHGE, with a result of 3.2 kg CO2-eq/2000 kcal, which is similar to the result of 2.7 kg CO2-eq/2000 kcal in this paper. When comparing the unit GHGE of specific foods, there are differences, e.g. the GHGE of beef in CFLCAD is 15.6 kg CO2-eq/kg compared to 20.7 kg CO2-eq/kg in BCFN.

In addition to some common weaknesses of observational studies, e.g., confounding from unknown factors, some other limitations also need to be considered. The CHNS 2011 data is not the most recent CHNS, and along with China's growing economy, dietary patterns have likely shifted. We acknowledge the importance of using the most up-to-date data to accurately reflect the current dietary trends in China. Unfortunately, the CHNS dietary data beyond 2011 are not accessible through open access channels. Therefore, we compared food consumption proportions between the China National Bureau of Statistics (2013–2021) and CHNS 2011 (Supplementary Table 5). The per capita food consumption data reveals an increasing trend in the proportion of animal-based foods over the past decade (9.1 % to 10.9 %). However, in 2021, the Chinese population still predominantly consumes plant-based foods (e.g., Cereal at 35 % and Vegetables and fungus at 26.6 %), with relatively low proportions of meat (8.0 %) and poultry (2.9 %), similar to the dietary pattern in CHNS 2011. In summary, our comparison suggests that the composition of food groups in the Chinese diet has remained largely consistent over the past decade. Therefore, it is unlikely that using the 2011 CHNS data has seriously affected the generalizability of our conclusions on associations between health and environmentally sustainability of Chinese diets.

Moreover, we acknowledge that the CHNS is not a representative sample of the population of China. The CHNS areas cover 47 % of China's population (according to the 2010 census), encompassing socio-economic diversity in rural regions, urban areas, and metropolitan areas, as well as variations in education and income. Therefore, the CHNS does represent the socio-economic diversity of China. Since the associations we studied rely on this socio-economic diversity rather than the representativeness of the CNHS, the lack of demographic representativeness does not impact our main results and conclusions. Additionally, in interpreting and applying CHNS data, it's crucial to remain aware of segments of China's population not represented, identifying areas requiring additional research and data collection for a more holistic understanding of the nation's dietary and health landscape. The environmental impacts of the actual diet consumption and the CHEI2016 score may be affected by misreporting. This study also assumed that all food is produced domestically (as is the case for most of the food consumed in China (FAOSTAT, 2023). For the environmental impacts of fish, this study did not include the fish stocks in the oceans/seas. Future analyses could thus be improved by using more accurate values of the dietary environmental impacts by combining international and domestic trade data. Moreover, the environmental impacts of the same food items in different areas will vary in fact. However, since the CHNS did not distinguish the origin of the foods, this study assumed that the environmental impacts of the same food items were identical for different regions. Furthermore, for the CHEI2016 scoring system, no decrease in score is given if the food consumption exceeds recommended range. For example, when participants consumed more than the recommended servings of cereals, their score remained at 10. Moreover, the CHEI, designed primarily for health assessment, lacks the capacity to distinguish between meats, particularly beef and pork, in terms of environmental impact. This limitation underscores the need to refine food groupings within the CHEI and similar indices for future studies on dietary sustainability. This improvement is vital for recognizing variations in nutritional quality and environmental impact among different food groups.

4.2. Policy implications

Based on the findings derived from this investigation, it is advisable to integrate environmental sustainability into the Chinese dietary recommendations (Rose et al., 2019a), taking into account the variations in economic and cultural factors across different regions. To effectively address the connection between dietary quality and environmental impacts, policymakers should consider the diverse socio-economic and regional dietary cultures. Therefore, it is crucial to promote healthy dietary patterns with minimal environmental footprints for specific subpopulations characterized by a high consumption of animal-based foods, ensuring the well-being of both the population and the planet. Moreover, dietary guidelines should consider further adjustments in the recommended consumption of animal-based foods, including dairy and red meat, considering regional variations, income levels, and health considerations. Striking a balance that aligns with both health and environmental objectives is essential. Additionally, the dietary guidelines should emphasize the reduction of food waste and endorse the consumption of seasonal, locally grown fruits and vegetables to diminish the resources required for processing, distribution, and storage. The integration of environmental sustainability into these guidelines necessitates the active participation and collaboration of sectors beyond the Ministry of Health. The inclusion of key stakeholders from various ministries and sectors influencing the food system (e.g., agriculture, trade) in the collaborative development of these guidelines can enhance support and policy coherence. Furthermore, it is essential to widely communicate the dietary guidelines to the general public. Employing diverse media channels, social media platforms, tools, applications, cookbooks, brochures, and events for targeted and repeated communication can effectively disseminate the guidelines and their recommendations. It is also crucial to establish linkages between the dietary guidelines and other food-related policies and interventions, such as food reformulation, initiatives to create healthier food environments, and regulations on food marketing and advertising.

5. Conclusion

This study revealed a trade-off between diet quality and diet-related environmental impacts in Chinese diets, which showed that a higher adherence to the Chinese Dietary Guidelines correspond to increased diet-related GHGE, TWU, and LU. This potentially counterintuitive result revealed the complex association between diet quality and environmental impacts in China. Regional heterogeneities can be explained by differences in dietary habits, and distributions in sociodemographic variables such as age, gender, educational level, income, and urbanization. The results should not discourage shifts towards healthier dietary patterns, but to urge policy makers and researchers in human health and agriculture to establish dietary recommendations that integrates both health and environmental goals, that are in line with local dietary culture and food supply.

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CRediT authorship contribution statement

Hongyi Cai: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Sander Biesbroek:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **Zhiyao Chang:** Data curation, Formal analysis, Methodology. **Xin Wen:** Formal analysis, Methodology, Writing – review & editing. **Shenggen Fan:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Pieter van 't Veer:** Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing – review & editing. **Elise F. Talsma:** Conceptualization, Formal analysis, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodpol.2024.102607.

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