HEALTHY PLATES FOR A HEALTHY PLANET:

identifying opportunities and challenges for China

Hongyi Cai

Propositions

1. Achieving a healthy dietary transformation in China requires consuming more animal-based foods.
   (this thesis)

2. To achieve sustainable diets, health outcomes are most important in Low- or Middle-Income Countries whereas environmental outcomes are in High Income Countries.
   (this thesis)

3. Carbon emission trading does not contribute to its reduction.

4. Although prevention is more cost-effective, most resources go to treatment of diseases.

5. Businesses can increase productivity by standardizing working hours.

6. Interests of research communities hinder open-access to data.

Propositions belonging to the thesis, entitled

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CONTENTS

CHAPTER 1

1

General introduction

1 Challenges for transforming the food system

The current global food system is facing challenges of malnutrition, diet-related non-communicable diseases, climate change, and related economic and social inequalities (**Figure 1.1**)(1). Acute malnutrition and escalating hunger coexist with an unprecedented surge in overweight, obesity, and diet-related noncommunicable diseases, primarily attributable to unhealthy diets (2). It is estimated that over 122 million more people are facing hunger in the world since 2019, with 2.4 billion people experiencing micronutrient deficiencies(3) and 670 million adults dealing with obesity(4). Additionally, nearly 3.1 billion people will be unable to afford a nutritious diet, marking an increase of 112 million people from the previous year. Unhealthy dietary patterns constitute the largest global burden of disease, posing substantial risks to morbidity and mortality(5).

Food systems play a crucial role in providing essential nutrients but this comes with certain environmental costs(6). Globally, agriculture utilizes 40% of the planet's arable land, accounting for 70% of freshwater withdrawals, and contributing significantly to terrestrial acidification and eutrophication(7). The global food system is a major contributor to greenhouse gas emissions (GHGE), accounting for about 30% of the total global emissions(8). Agricultural land expansion drives 90% of global deforestation(9). Meanwhile the exploitation of food system directly threatens biodiversity on land and in water, posing a threat to 24,000 species (86%)(10). Approximately 34% of the world's marine fish stocks are overfished, while 60% are fully exploited(11). Additionally, about one third of all food produced for human consumption is lost or wasted, carrying substantial environmental, economic, and societal implications(12).

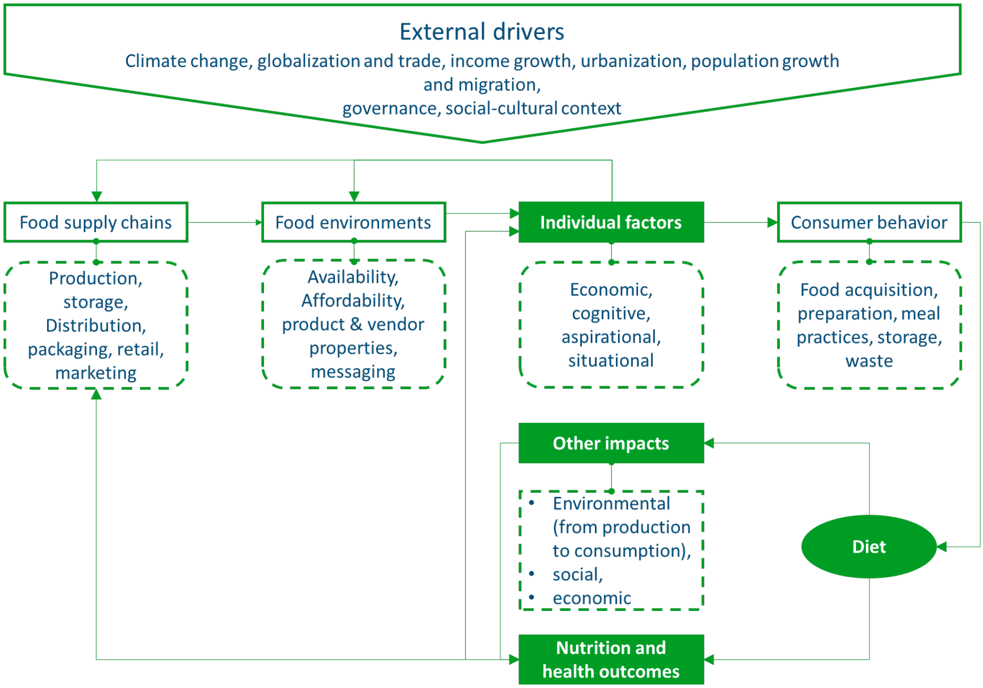

Figure 1.1. Conceptual framework for the links between food systems, food production, food environments, diet quality, and dietary environmental impacts(13). Components in green represent the focus of this thesis.

2 Sustainable diets for population and environmental health

A shift towards more sustainable diets is essential to harmonize food production and consumption with both population and planetary health(14). Emerging evidence highlights how current food production and consumption contribute to nutritional and health issues, surpassing planetary boundaries for a safe operating space for humanity(15). Projections indicate that if current dietary patterns continue, health costs related to mortality and non-communicable diseases (NCDs) will surpass USD 1.3 trillion annually by 2030(3). While technological advancements in food production may mitigate some environmental impacts, these measures have limitations and do not adequately address health issues associated with the food system(16). Substantial evidence emphasizes the need for significant changes in food consumption and food waste management to decrease the overall environmental impact of the current and future food systems(17).

In this context, global efforts to promote sustainable and healthy eating are increasingly focused on comprehensive strategies that address food systems, food environments, and their effects on diets, nutrition, and overall health(18). The 2014 Rome Declaration on Nutrition, the 2015 Sustainable Development Goals (SDGs), and the 2021 United Nations Food Systems Summit(19) collectively aim to eliminate all forms of malnutrition by 2030(20). These initiatives also emphasize the need for a transformation of food systems to safeguard both human and planetary health(21). Sustainable healthy diets are characterized by accessibility, affordability, safety, equity, and cultural acceptability(22). Therefore, sustainable dietary patterns not only promote health but should also exhibit a lower environmental impact(23).

Shifting the focus to China, a country with over a billion people and the world's second-largest economy, presents a complex challenge. China has successfully reduced hunger and malnutrition with heightened agricultural productivity and rising income levels(24). Meanwhile, dietary patterns are changing significantly, with increased consumption of fruits, refined grain, and animal-based foods(25). This poses complex challenges to nutritional health, environmental sustainability, and resource management(26). In the context of China's rapid urbanization and economic growth, understanding the shift in dietary patterns is crucial for devising sustainable solutions(27).

2.1 The impacts of dietary transition on public health in China

Numerous studies emphasize that dietary diversity in China is increasing(28). However, challenges include the widespread excessive consumption of refined grains, salt, and oil, as well as inadequate consumption of dairy products and fruit(29). Consumption of fruits and vegetables falls below the recommended values in the Chinese dietary guidelines (24.5% and 75.4% of the recommended values, respectively)(30). Simultaneously, this dietary transition has resulted in adverse health outcomes, encompassing issues of overnutrition and related NCDs(31). In China, the number of deaths related to diet was 2.0 million in 2019, an increase of 77.6% compared to 1.1 million in 1990(32). From 1990 to 2016, all-age prevalence of diabetes rose from 3.7% to 6.6%(33). Cardiovascular diseases increased to 330 million cases in 2019(34). Obesity prevalence among those aged 18 and older reached 34% in 2019, up from 4% in 1992 (35).

2.2 Environmental impacts of food systems in China

The dietary transition in China has dual consequences, affecting both nutritional security and exacerbating environmental impacts(36). With the increase in household income and the growth of the middle class, China has become the world's largest consumer of meat (in absolute terms) and has also become the world's largest emitter of food-related GHGE. According to the Food and Agriculture Organization (FAO), China's GHGE from the food system reached 1.9 billion tons in 2020, constituting 14% of China's total emissions(37). Changes in dietary patterns have increased the cost of arable land and water resources, revealing a significant insufficiency in China's resources to provide food for its large population. China's irrigation water increased by 17% from 1982 to 2015, yet per capita fresh water availability is only 25% of the global average(38). Per capita arable land within China is approximately 0.08 ha, significantly below the world average of 0.22 ha(39). As China faces these challenges, there is an urgent need for comprehensive strategies that address both the nutritional needs of the population and the sustainability of its food systems.

3 Challenges in achieving sustainable diet in China

As the complexity of China's ongoing dietary transition becomes increasingly apparent, there is still a research gap in understanding the impacts on public health and environmental sustainability. Most studies on dietary shifts focus on sustainable diets in high-income countries (HICs). However, China is undergoing a distinct phase of both dietary and socioeconomic transitions. Therefore, findings from HICs may not necessarily be directly applicable to China. This thesis aims to address this knowledge gap by exploring the unique dynamics of China's dietary transition and its implications for public health and environmental sustainability. Given China's vast territory, notable regional economic disparities, and diverse dietary cultures, studying sustainable diets in China and formulating policy recommendations for both health and environmental sustainability can offer valuable insights applicable to other regions worldwide.

3.1 Local environmental impact assessment of foods

The existing knowledge gap in understanding the local environmental impact of food items in China is primarily attributed to the widespread reliance on global databases in current studies. Presently, research on the environmental impact of diets in China heavily depends on parameters extracted from global datasets, such as those featured in studies like Tilman's(40), IPCC reports(41), and data from the Barilla Food and Nutrition Centre(42). Disparities in resource availability, including water and arable land, contribute to variations in the environmental impacts of food production across different regions of the globe. Therefore, the environmental impact parameters of food items sourced from global databases may not adequately account for the intricacies of local agricultural practices and diverse food production systems prevalent across China(43). Moreover, the majority of existing studies predominantly focus on the dietary GHGE, overlooking crucial environmental impact indicators such as water and land resource utilization that have more local importance(44). To narrow this gap, it is necessary to establish a database of environmental impact indicators for Chinese food items. Incorporating additional indicators to assess the environmental impacts of dietary choices is essential for accurate evaluation of the comprehensive effects on the environment across various regions in China.

3.2 Challenges in defining sustainable diets in China

The existing body of research on sustainable diets in China has made considerable improvements in unraveling the intricacies of dietary patterns and their corresponding environmental impacts(45). A significant hurdle arises from the absence of a standardized, universally accepted definition of a sustainable diet within the Chinese context. There is currently a lack of interdisciplinary research addressing sustainable diets in China(46). Many studies narrowly focus on isolated impacts, such as health implications, environmental effects, or economic costs during dietary transitions(47). This approach fails to acknowledge the interconnected nature of these factors within the broader context of sustainability. For instance, while a diet relatively high in certain animal products might have health benefits, it could also contribute significantly to environmental degradation and associated economic costs(48).

Furthermore, the existing body of knowledge concerning the environmental impacts or economic costs of diets predominantly relies on per capita data at the national or regional level, and can therefore not incorporate detailed information of dietary patterns in population subgroups or at the individual level(49). This dominant approach hinders the exploration of their association with individual socio-demographic characteristics, which is crucial for developing targeted interventions and policies to address specific dietary challenges within diverse population groups(50).

Diet modeling approaches have emerged as valuable tools in the exploration of identifying dietary patterns that align with both health and environmental sustainability(51). However, these models encounter persistent challenges, particularly in their ability to integrate cultural dimensions into their frameworks(52). Factors such as accessibility, acceptability, and affordability, which play a role in shaping individuals' dietary choices, are often overlooked in the optimization process(53). As a result, the dietary patterns generated by these models may not reflect the lived experiences and realities of diverse populations, undermining their practical applicability.

3.3 Sustainability assessment of dietary transition in China

Rapid economic development and urbanization have promoted an unprecedented social transformation in China, concurrently leading to changes in residents' dietary patterns(56). Moreover, urbanization can lead to resource scarcity and environmental pollution, thereby affecting food supply and health(57). To address the resource constraints and food insecurity arising from rapid urbanization, it is necessary to reevaluate existing dietary patterns from health, environmental, and economic perspectives(58). Empirical evidence regarding the association between China's urbanization, changes in dietary quality, environmental impacts related to diet, and dietary costs is limited. Furthermore, the existing literature acknowledges the general association between urbanization and dietary shifts but falls short of offering an exploration of specific aspects of urbanization, such as infrastructure development, cultural changes, and socioeconomic factors, that contribute to changes in dietary patterns(59).

Another knowledge gap that requires attention is the examination of the socio-demographic factors influencing individual food choices within the urban context. While previous studies acknowledged the role of socioeconomic factors(60), further exploration could involve investigating how age, education, and occupation intersect with urbanization dynamics to shape dietary preferences(61). For instance, understanding how the preferences of younger urban populations differ from those of older generations or how educational backgrounds influence awareness and adherence to sustainable dietary practices could provide valuable insights for crafting tailored interventions.

3.4 Gaps in understanding the impacts of shifting to sustainable diets in China

In HICs, numerous studies have explored the idea that diets following the Food-Based Dietary Guidelines (FBDG) can reduce GHGE and enhance land carrying capacity(62). However, concurrently, many studies in low- and middle- income countries (LMIC) indicate that a shift towards a healthier diet rich in fruits and vegetables may increase agricultural water use, energy inputs, as well as greenhouse gas emissions(63). Additionally, transitioning to a health-oriented sustainable dietary pattern, while reducing the risk of non-communicable chronic diseases, seems to come with higher dietary costs, making it challenging for low-income populations to afford(64).

Currently, there are knowledge gaps in understanding the dietary, environmental, and economic impacts of China's transition toward dietary guidelines or sustainable diets(65). Furthermore, due to uneven economic development within China, there exists a significant income disparity among regions. Combined with factors such as dietary culture, this has led to varying degrees of dietary transitions in different regions(66). However, currently, there is no research exploring the trade-off or synergistic between the shift towards recommended healthy diets and the sustainability indicators of diets in different regions of China. A more in-depth description of the environmental and economic dimensions is crucial to guide policymakers to develop strategies that promote sustainable dietary choices, ensuring the harmonization of environmental, health, and economic goals within China's food system.

4 Aim and outline of this thesis

Existing research underscores that the adoption of healthy diets in high-income nations can yield positive environmental consequences(67). As the world faces the complexities of sustainable development, a profound understanding of the dynamics underlying dietary choices becomes increasingly vital, especially within populous and diverse nations like China. However, there remains a significant knowledge gap, particularly in LMICs, where the dynamics of dietary patterns remain are insufficiently explored(68). Therefore, this thesis aims to evaluate how dietary shifts in China can improve health outcomes and reduce the environmental impact associated with dietary choices. Firstly, this thesis analyzed the impact of China's dietary transition on dietary quality, environmental impact, and dietary costs. Secondly, based on the current dietary patterns, it identified sustainable dietary patterns in China that could improve dietary quality, reduce environmental impact, and lower dietary costs. Moreover, it studied the effects of Chinese residents shifting to recommended diets on health outcomes, environmental impact, and dietary costs. The following are the specific research objectives of this thesis (**Figure 1.2**):

Objective 1: To analyze changes in dietary quality, environmental impacts, and dietary costs of the dietary transition in China

- How to assess the environmental impact of diets in China and what are the indicators for assessing the environmental impact of diets? (chapter 2)
- What are the changes in dietary quality, dietary environmental impacts, and dietary costs of dietary transition in China? (chapter 3)

Objective 2: To identify Chinese sustainable dietary patterns that improve diet quality, environmental impact, and dietary cost based on current diets

- How to identify Chinese dietary patterns that meets health, environmental sustainability, and considers economic costs? (chapter 4)

Objective 3: To analyze changes in health outcome, environmental impacts, and dietary costs of dietary shifts to recommended diets for the Chinese population

- How would the environmental impact of diets change if the diets of the Chinese population shifted to the Chinese Dietary Guidelines? (chapter 5)
- How would health outcomes, environmental impact of diets and dietary costs change if the Chinese population shifted to the EAT-Lancet diet? (chapter 6)

Chapters 2 and 3 elaborate on the first objective. In Chapter 2, we establish the CFLCAD, compiling GHGE, WU, and LU data for various food items. The CFLCAD provides a tool to link individual-level food consumption data with nutrition surveys for estimations of dietary environmental impacts.

Chapter 3 investigates the food consumption patterns within the China Health and Nutrition Survey (CHNS) cohort from 1997 to 2011. It evaluates the quality and cost of diets, including environmental impacts in terms of GHGE, TWU, and LU. This chapter further explores the association between time trends in dietary sustainability indicators and the level of urbanization.

Chapter 4 outlines Objective 2, which involves the identification of sustainable dietary patterns within current diet in populations. This chapter aims to identify dietary patterns that align with sustainability indicators, encompassing dietary quality, environmental impact, and cost considerations.

Chapters 5 and 6 provide in-depth exploration of Objective 3. Chapter 5 focuses on evaluating the trade-offs or synergies between dietary quality and environmental impacts across diverse population subgroups and regions, utilizing dietary consumption data from the 2011 China Healthy Nutrition Survey. In contrast, Chapter 6 employs CHNS data from 1997 to 2015, to prospectively assess the associations between EAT-Lancet diets and outcomes such as mortality, cardiovascular disease (CVD) and diabetes risk, as well as exploring dietary costs and diet-related environmental impacts in China.

Chapter 7 will explain the primary discoveries presented in this thesis, offering insights into the potential rationales behind the conclusions. This chapter will also explore methodological considerations and provide policy recommendations aimed at facilitating the future realization of a sustainable dietary transition in China. **Figure 1.2** illustrates the research framework of this paper and the connections between chapters.

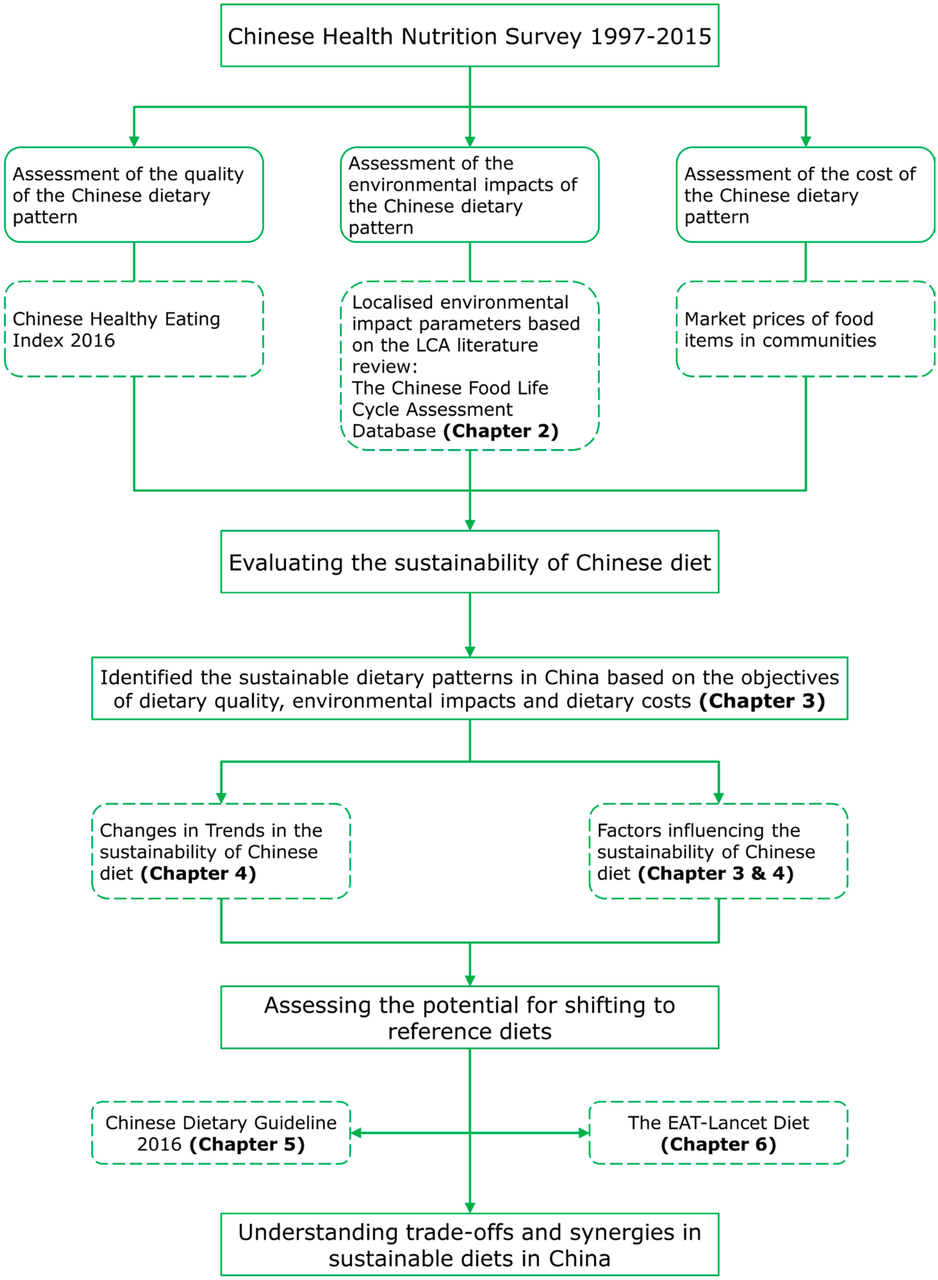

Figure 1.2. Research framework of this thesis

This thesis uses a comprehensive exploration of dietary sustainability within the Chinese population, utilizing data spanning from 1997 to 2011 obtained from the CHNS(69). The CHNS dataset serves as a robust foundation, offering a longitudinal perspective that enables an in-depth analysis of the evolving dietary landscape and its implications. Through a multidimensional lens, the ensuing chapters seek to contribute nuanced insights into the sustainability of diets in China, addressing key facets such as environmental impact, nutritional health, dietary quality, and economic considerations. A description of the CHNS dataset can be found in Box 1.

Box.1 Objectives and design of Chinese Health Nutrition Survey in this thesis*(70)*.

The China Health and Nutrition Survey is a nationally representative, longitudinal survey that has played a pivotal role in advancing our understanding of health, nutrition, and lifestyle patterns in the Chinese population. The CHNS has been conducted collaboratively by several institutions, including the University of North Carolina at Chapel Hill and the National Institute for Nutrition and Health at the Chinese Center for Disease Control and Prevention.

Objectives of CHNS

The primary objective of the CHNS is to comprehensively examine the health and nutrition status of the Chinese population across diverse demographic and geographic contexts. The survey employs a multistage, random cluster sampling strategy to select participants, covering both urban and rural areas in several provinces. By collecting detailed information on individuals and households, the CHNS captures a wide range of variables, including dietary habits, physical activity, healthcare utilization, socioeconomic status, and anthropometric measurements.

Researchers and policymakers widely utilize the CHNS data to address a spectrum of health-related research questions, including those related to nutrition, chronic diseases, and the impact of social and economic factors on health outcomes. Overall, the CHNS stands as a foundational resource for advancing public health knowledge in the Chinese context and beyond.

Design of CHNS

One distinctive feature of the CHNS is its longitudinal design, which allows researchers to track changes and trends over time. With waves of data collected at regular intervals, typically every 2-4 years, the CHNS enables the investigation of evolving patterns in health and nutrition-related factors. Since 1997, if there are fewer participants from the community (less than 20 households), new participants are recruited as replenishment samples. The survey's longitudinal nature is invaluable for understanding how dietary habits, lifestyle choices, and health outcomes may be influenced by social, economic, and environmental changes.

The dietary component of the CHNS involves detailed assessments of food consumption at both individual and household levels. These assessments include information on the types and quantities of foods consumed, cooking methods, and sources of food. This wealth of dietary data makes the CHNS particularly valuable for studying the complex relationship between dietary patterns and various health outcomes.

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CHAPTER 2

Environmental footprints of Chinese foods and beverages: Literature-based construction of an LCA database

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Abstract

Abstract

To accurately estimate and model the impact of food consumption and potential dietary changes on environment and climate change, the need for country specific data is evident. This study developed a Chinese Food Life Cycle Analysis Database (CFLCAD) in which 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 through a literature review. To estimate the environmental footprints of food from production to consumption, the study applied conversion factors for the edible portion of food, food loss ratio and processing, storage, packaging, transportation, and food preparation stages. In addition, when no LCA data of a certain food was available, data from food groups with similar nutritional composition or cultivation condition were used as proxies. The database covered 17 food groups and each food item was referenced to the Chinese Food Composition Table and has a unique food code. The CFLCAD can be used to link individual-level food consumption data with nutrition survey in China, to allow for a more accurate estimation of the environmental footprints of Chinese diets.

Keywords: Greenhouse gas emission; Land use; Total water use; Life cycle analyses; Chinese food and drink; Diet

Specifications table

Subject	Environmental Engineering
Specific subject area	Diet-related environmental sustainability
Type of data	Figures and tables
How the data were acquired	Data on the environmental footprints of all life cycle stages of food items have been extracted from literature and compiled into Microsoft Excel.
Data format	Analysed data and descriptive statistics
Description of data collection	• Data on the environmental footprints by means of life cycle analysis of food were collected through a literature review in the Chinese National Knowledge Infrastructure (CNKI) and Google Scholar. • Articles and reports written in English or Chinese and published in the years 2005-2020 were identified. • The types of environmental footprints included were Greenhouse gas emission (GHGE), Total Water use (TWU) and Land use (LU). • Articles were excluded if: studies are not available in English or Chinese, or no system boundaries were considered.
Data source location	Food items included in the Chinese Food Life Cycle Analysis Database were based on the Chinese Food Composition Table, resulting in 17 food groups and each food items coded with a unique food code.
Data accessibility	Estimates of environmental footprints of food are available on a data repository with the following https://doi.org/10.17026/dans-zyw-efav. Data users need to first register an account on the website and then submit a request to use the data to download the raw data. Contact point for further use is prof Pieter van 't Veer at the Division of Human Nutrition and Health, Wageningen University (pieter.vantveer@wur.nl). Reproduction and translation for non-commercial purposes are authorised, provided the source is acknowledged and the publisher is given prior notice and sent a copy.

Value of the data

- This database contains environmental footprint indicators for GHGE, TWU and LU of 17 food groups commonly consumed in China.
- The database can be linked to the population dietary intake data to calculate the environmental footprints of individual level food consumption.
- With this dataset a comprehensive assessment of the sustainability of Chinese diets can be done, by including dietary quality, consumer dietary preference choices, and affordability of diets.

1 Data description

The Chinese Food Life Cycle Analysis Database (CFLCAD) provides for each single food item an estimate on Greenhouse gas emissions (GHGE), Total Water Use (TWU) and Land Use (LU) per kg of food as consumed. The food groups in CFLCAD are based on the Chinese Food Composition Table[1], and each food item has a unique food code. **Figure 2.1** shows the literature search strategy of this study. **Table 2.1** provides summary statistics for GHGE (kg CO_2-eq/kg food as consumed), TWU (m^3/kg food as consumed), and LU (m^2/kg food as consumed) from literature for the different food groups in CFLCAD. For this study the GHGE values found in literature were converted to the system boundary off cradle to the post farm gate, and includes the production, storage, processing, packaging, transportation, and preparation at home stages. **Table 2.2** illustrates the GHGE conversion parameters for food groups collected. **Table 2.3** shows the proportion of losses for food groups along the whole food supply chain. The life cycle inventory data source that was utilized to calculate the environmental footprints for each food group can be found in **Table 2.4**. Processed foods and mixed dishes were disaggregated into their basic components and cooked food portions were translated into raw quantities. **Table 2.5** shows the conversion factors for the environmental footprint of food groups of boneless weight of animal-based food.

2 Experimental design, materials, and methods

2.1 Literature review

2.1.1 Search strategy and data sources

The CFLCAD was developed based on a literature review using the China National Knowledge Infrastructure (CNKI) for journals in Chinese and Google Scholar databases for journals in English. The searching keywords were "LCA" or "life cycle analysis", "China or Chinese", "food" and "food name". Studies were selected when any of the types of environmental footprint namely GHGE, TWU, and LU was reported and when the articles and reports were published between 2005 to 2020. We realized that potential biases exist in studies with different life cycle analysis methods. One study analyzed impacts on global warming, energy demand and consumptive water use from meat processing of chicken, pork, sheep and beef. They compared LCA methodologies between process based, EIO, and hybrid methodologies [2], with results generally remaining within a similar range. Therefore, we can accept errors within a certain range through the method of literature review. The literature review strategy is shown in **Figure 2.1**.

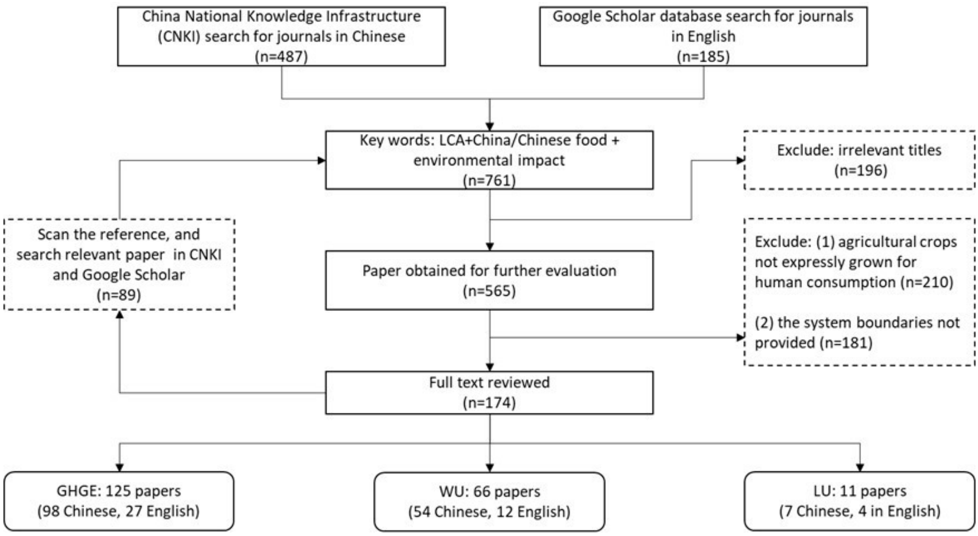

Figure 2.1. Literature review process

2.1.2 Inclusion and exclusion of literature

Articles were included when the system boundary of the LCA studies includes at least "cradle to farm-gate" and when the functional unit of GHGE, TWU and LU values were reported in kg CO_2-eq/kg, m^3/kg, and m^2/kg, respectively. Articles were excluded when the agricultural crops studied were not grown for human consumption (e.g., for biofuels, timber, fibers, cotton) or when the system boundary was not specified. After full text screening, for GHGE, this resulted in a total of 125 papers, of which 98 in Chinese and 27 in English. For TWU, this resulted in a total of 66 papers, of which 54 in Chinese and 12 in English. For LU, this resulted in a total of 11 papers, 7 in Chinese and 4 in English. The average values of GHGE, WU and LU from literature are presented in **Table 2.1.**

Table 2.1. Environmental footprints values from literature for food groups in the CFLCAD

Food group	# Food items	# LCA studies	# GHGE values	Mean (kg CO_2-eq/kg)	Stdev
Greenhouse gas emissions, GHGE					
Vegetables	20	22	133	0.266	0.292
Cereals	15	60	490	1.016	0.806
Fast foods	2	2	3	1.334	1.616
Aquatic products	6	10	16	7.029	6.358
Fruits	9	18	64	0.353	0.246
Legumes	4	7	14	0.832	0.681
Meat	4	23	122	5.134	2.350
Sugars and preserves	2	3	4	0.689	0.479
Beverages	4	3	4	0.931	0.815
Liquor and alcohol	2	3	4	0.726	0.454
Poultry	2	11	21	3.784	2.128
Dairy	3	21	67	1.297	0.404
Eggs	1	13	22	2.890	1.215
Nuts and seeds	1	2	2	0.695	0.290
Tubers, starches	3	6	7	0.291	0.367
Fungi and algae	1	1	1	0.930	--
Fats and oils	1	3	5	1.822	1.404
Total	**80**	**208**	**979**		
Total Water Use, TWU					
Vegetables	23	26	111	0.491	0.775
Cereals	8	39	468	1.290	0.856
Fast foods	2	2	3	0.813	0.076
Aquatic products	17	16	41	3.235	1.881
Fruits	8	18	53	0.574	0.445
Legumes	4	15	49	2.512	0.944
Meat	7	28	61	8.970	6.204
Sugars and preserves	1	6	7	0.797	0.559
Beverages	3	3	4	5.228	4.735
Liquor and alcohol	2	6	9	0.803	0.998
Poultry	5	15	19	3.030	1.105
Dairy	1	13	14	1.609	0.614
Eggs	1	15	17	3.257	0.176
Nuts and seeds	2	7	23	1.400	0.345
Tubers, starches	4	13	41	0.926	0.516
Fungi and algae	1	1	1	0.270	--
Fats and oils	3	12	19	4.475	1.626
Total	**93**	**235**	**940**		

Food group	# Food items	# LCA studies	# GHGE values	Mean (kg CO_2-eq/kg)	Stdev
Land Use, LU					
Vegetables	4	4	8	0.402	0.552
Cereals	8	6	33	1.538	0.950
Fast foods	4	1	3	1.920	1.106
Aquatic products	5	1	10	2.356	2.317
Fruits	1	1	1	0.640	--
Legumes	4	1	1	0.810	--
Meat	8	3	12	13.179	10.197
Sugars and preserves	3	1	2	1.615	0.955
Beverages	1	1	1	1.480	
Liquor and alcohol	2	1	2	1.075	1.223
Poultry	4	1	4	2.035	0.595
Dairy	4	2	12	2.911	2.945
Eggs	1	1	2	1.360	0.156
Nuts and seeds	--	--	--	--	--
Tubers, starches	--	--	--	--	--
Fungi and algae	--	--	--	--	--
Fats and oils	1	1	3	5.210	0.292
Total	**50**	**17**	**94**		

2.2 Environmental footprints from production to consumption

Most LCA studies used the farm gate or production phase as system boundaries and excluded the preparation, consumption, and waste management phases. Especially, for GHGE, this results in an underestimation of the actual environmental footprints of food products. To resolve the data gap, the environmental footprints values in this study were converted to the system boundary from cradle to the post farm gate, by using conversion factors on production, storage, processing, packaging, transportation, preparation at home stages, as well as the food losses along the food supply chain from literature. The appropriate conversion parameters were acquired from literature data and statistical yearbooks to calculate the environmental footprints of the post farm gate stage. It was found that no significant increases in TWU and LU were detected in the post-farm gate phase[3–5]. For the system boundaries of TWU and LU, this study did not include the storage, transportation, packaging, and preparation at home stages. GHGE conversion parameters of food groups in each post farm gate stage are shown in **Table 2.2**, and the calculation of post-farm gate of GHGE are shown in section 2.2.1 to 2.2.4. Furthermore, for all three environmental footprints indicators, pot-farm gate losses were considered and shown in section 2.2.5.

Table 2.2. GHGE parameters of food groups in subsequent post farm gate stages (kg CO_2-eq/kg as produced)*

Food type	Processing	Storage	Transportation	Package	Preparation at home	Total
Vegetables and fungi	—	0.005	0.040	0.023	0.005	0.081
Cereals	0.007	0.005	0.040	0.023	0.109	0.184
Fruits and nuts	—	0.004	0.040	0.023	0.0003	0.075
Legumes	0.156	0.005	0.040	0.023	0.006	0.230
Tubers, starches	—	0.002	0.025	—	0.005	0.032
Aquatic products	—	0.026	0.010	0.023	0.082	0.350
Meat	—	0.015	0.087	0.023	0.175	0.603
Dairy	0.045	0.015	0.087	0.023	0.016	0.186
Poultry	—	0.015	0.044	0.023	0.136	0.521
Eggs	—	0.015	0.087	0.023	0.055	0.180
Beverages	—	0.002	0.022	0.064	—	0.049
Sugars and preserves	0.133	0.005	0.040	0.023	0.005	0.081
Liquor and alcohol	—	0.002	0.022	0.064	—	0.049
Fats and oils	0.034	—	0.040	—	0.654	0.728

**A version of Table 2.2 with references is available in the Supplementary*

2.2.1 GHGE of different food groups during the processing stage

For cereals, vegetable oils and pulses, processing is concerned with primary processing of agricultural by-products. Grain was assumed to be processed by medium-sized grain milling machine, with main parameters including capacity of 4.5 t/h, and power of 41 kW. The main parameters of vegetable oil processing machinery were assumed as capacity of 210 kg/h, power of 7.5 kW. Soybean was assumed to be mainly processed to tofu by machinery with capacity of 30 kg/h and power of 5.5 kW [6]. Table 2.2 shows the GHGE per unit mass of energy consumed in the processing. Dairy products need cooling and sterilization before selling as foods and beverages and therefore the GHGE parameters of the work of Gan et al. (2019) for dairy processing were applied [7]. The calculation of GHGE for processed foods were derived from different sources and can be found in **Supplementary Table 2.1**.

2.2.2 GHGE of different food groups during the storage stage

In the storage stage, the distribution center is normally equipped with large-scale cold storage and other refrigeration facilities to ensure that the fresh food remains fresh before distribution[8,9]. This refrigeration system requires a large amount of energy and therefore the storage volume of food and the storage time of the food in the cold storage are the main factors affecting GHGE. The GHGE of food products during the storage stage were shown in **Table 2.2**, and the parameters were derived from different sources and can be found in **Supplementary Table 2.1**.

2.2.3 GHGE of different food groups during the transportation stage

GHGE of food during the transportation stage includes energy used by refrigerating agents and vehicles in the transportation process (international and national). At the time of this study, 90% of the food consumed in China was produced domestically (**Supplementary Table 2.2**). For two food items these were not the case, i.e., barley and oil crops, of which more than 50% of the available food was imported. However, because these food items comprised a small amount of the total diet by weight, GHGE, WU, and LU were quantified using China-specific production data. For national transportation, transport distances by truck to wholesalers and retailers were assumed to be 400 km and 100 km, respectively [10, 11]. The GHGE of food products during the transportation stage were shown in **Table 2.2**, and the parameters from different sources can be found in **Supplementary Table 2.1**.

2.2.4 GHGE of different food groups during the package stage

The GHGE of food during packaging stage were obtained from the research results of Kuai et al. (2013) [12]. Kuai et al. (2013) conducted research on GHGE of five shopping bags commonly used by Chinese consumers, namely high-density polyethylene (HDPE) plastic bags, low-density polyethylene (LDPE) plastic bags, paper shopping bags, non-woven shopping bags and cotton shopping bags. The specifications of the five types of shopping bags are shown in **Supplementary Table 2.3**, and the parameters can be found in **Supplementary Table 2.1**.

Table 2.3. Loss proportion of food groups in the food supply chain*,1

Food group	Production	Postharvest handling	Storage	Processing	Transportation	Total
Vegetables and fungi	12.15%	19.40%	15.00%	--	5.13%	51.67%
Cereals						
Rice	3.47%	2.66%	6.17%	2.18%	0.74%	15.22%
Wheat	3.12%	0.77%	6.91%	2.38%	0.24%	13.42%
Corn	2.17%	1.12%	6.49%	2.27%	0.19%	12.23%
Fruits and nuts	9.58%	0.92%	5.36%	--	5.50%	21.36%
Legumes	6.00%	3.00%	--	5.00%	1.00%	15.00%
Tubers, starches	4.41%	--	17.13%	0.04%	0.01%	21.59%
Aquatic products	2.00%	--	4.00%	4.00%	3.20%	13.2%
Meat						
Pork	11.00%	2.33%	0.89%	0.40%	0.24%	14.86%
Beef	10.18%	4.45%	1.04%	0.40%	0.86%	16.93%
Mutton	4.15%	2.28%	0.35%	0.40%	0.83%	8.01%
Dairy	3.50%	1.00%	--	1.20%	0.50%	6.20%
Poultry	8.75%	2.86%	3.24%	0.40%	0.62%	15.87%
Eggs	--	--	--	--	--	10.5%
Beverages	--	--	--	--	--	5.00%
Sugars and preserves	12.15%	19.40%	15.00%	--	5.13%	51.67%
Liquor and alcohol	--	--	--	--	--	5.00%
Fats and oils	6.00%	3.00%	--	5.00%	1.00%	15.00%

**The dash means that we did not find a relevant coefficient in the literature and therefore the total food loss proportion is underestimated.*
[1]A version of Table 2 with references is available in the Supplementary

2.2.5 GHGE of different food groups during preparation at home stage

The GHGE of preparation at home stage were derived from Huang et al. (2021)[13] (**Supplementary Table 2.1**). For vegetables and legumes we assumed they needed to be cooked for 2 minutes per 500 grams, meat for 40 minutes per 500 grams, aquatic products for 20 minutes per 1 kilogram, eggs for 10 minutes per 200 grams, and poultry for 20 minutes per 1 kilogram. At present, most residents in China use natural gas for cooking, and the average consumption of natural gas is 0.4 m^3/h. The electricity consumption for rice cooking was calculated assuming that for 500 grams or rice, a rice cooker of 900W would take 35 minutes.

2.2.6 Food loss proportion of food groups

Food losses are an important factor in estimating environmental footprints of diets as foods produced but not consumed also contribute to the overall system impact. Food losses in this study included losses during storage, processing, packaging, transportation, retailing, and preparation at home. Percentages of food losses were estimated at the level of food groups. **Table 2.3** shows the food loss proportions in the whole food chain of the food that is frequently consumed in China based on weight that were used to calculate the GHGE, WU and LU. The food loss proportions were derived from different sources and can be found in **Supplementary Table 2.4**.

Table 2.4. Number of food items for which LCA data were estimated via different procedures

Food groups	Number of food item in CFLCAD				
	From literature	Via direct mapping[1]	Via processing[2]	Via recipes[3]	Total
Greenhouse gas emissions, GHGE					
Vegetables	20	181	--	--	201
Cereals	15	76	2	--	93
Fruits	9	61	--	--	70
Legumes	4	64	1	--	69
Tubers, starches	3	22	--	--	25
Nuts and seeds	1	40	--	--	41
Fungi and algae	1	3	--	--	4
Aquatic products	6	108	--	--	114
Meat	4	126	--	--	130
Dairy	3	44	1	--	48
Poultry	2	40	--	--	42
Eggs	1	22	--	--	23
Beverages	4	47	--	--	51
Fast foods	2	103	2	7	114
Sugars and preserves	2	21	--	--	23
Liquor and alcohol	2	44	--	--	46
Fats and oils	1	6	--	--	7
Total	80	1008	6	7	1101[4]
Total Water Use, TWU					
Vegetables	25	240		--	265
Cereals	12	78		--	91
Fruits	9	75		--	84
Legumes	5	63		--	69
Tubers, starches	4	21		--	25
Nuts and seeds	3	37		--	40
Fungi and algae	1	1		--	2
Aquatic products	30	78		--	108
Meat	8	123		--	131
Dairy	1	38		--	40
Poultry	6	42		--	48
Eggs	1	22		--	23
Beverages	7	35		--	42
Fast foods	3	100		6	112
Sugars and preserves	2	21		--	23
Liquor and alcohol	3	49		--	52
Fats and oils	4	3		--	7
Total	124	1026		6	1156[4]
Land Use, LU					
Vegetables	4	133		--	137
Cereals	8	76		--	84

Food groups	Number of food item in CFLCAD				
	From literature	Via direct mapping[1]	Via processing[2]	Via recipes[3]	Total
Fruits	1	22		--	23
Legumes	4	66		--	70
Tubers, starches	0	0		--	0
Nuts and seeds	0	0		--	0
Fungi and algae	0	0		--	0
Aquatic products	5	95		--	100
Meat	8	122		--	130
Dairy	4	44		--	49
Poultry	4	22		--	26
Eggs	1	22		--	23
Beverages	1	28		--	29
Fast foods	4	97		6	108
Sugars and preserves	3	20		--	23
Liquor and alcohol	2	44		--	46
Fats and oils	1	6		--	7
Total	50	797		6	853[4]

[1] *The environmental impact value was directly mapping to the same food irrespective of the form (i.e., raw, boiled, dried, steamed, or graded, branded).*

[2] *The GHGE for processed foods was calculated by reference to the processing factors in Table 2.2.*

[3] *Recipe foods were disaggregated into basic components and cooked food portions were translated into raw quantities, and recipes were taken from the Chinese Food Composition Table or the first hit on internet.*

[4] *The total number of the three indicators varies due to the different amounts of literature on the GHGE, WU and LU of food.*

2.3 Matching environmental footprints of food groups to the Chinese Food Composition Table

2.3.1 Matching to the single food items

The environmental footprints value was directly assigned to the same food irrespective of the form (i.e., raw, boiled, dried, steamed, or graded, branded). For example, GHGE value for "wheat flour" was assigned as same to both "wheat flour, refined, special grade 1" and "wheat flour, refined, special grade 2". When no LCA data of a certain food was available, data from similar food groups were used as proxies (**Table 2.4**). Data on land use for nuts, fungi, and tubers were not found in our literature search. However, these food groups comprise a very small amount of the total diet by weight and therefore fungi and tubers were based on the average of vegetables, while values for nuts were based on fruits based on similarity of cultivation condition.

2.3.2 Matching to the recipe

For recipes, a break-down into ingredients was needed before linking these to their corresponding primary food items. To integrate the dietary intake data with the GHGE data, processed foods and mixed dishes were disaggregated into their basic components and cooked food portions were translated into raw quantities. Furthermore, recipes taken from the Chinese Food Composition Table were used to break down composite foods into their ingredients, but if recipes from food composition table were not available, the first hit on internet was used. All recipes for composite foods were assumed to be homogenous across China (**Supplementary Table 2.5 & 2.6**). Food groups of CFLCAD and their corresponding life cycle inventory data source used for quantifying environmental footprints are shown in **Table 2.4**.

2.3.3 Conversion to edible portion

For the edible part of the food, the environmental footprints for animal-base foods were converted to a common functional unit in per kg boneless weight. The conversion ratios were derived from the literature as shown in **Table 2.5**. In LCA studies of plant-based foods, the weight basis is the form in which it is delivered or purchased (e.g., whole apples, bananas with peels)[14]. To reconcile this inconsistency, the conversion factors of edible portion were drawn from the Chinese Food Composition Table.

Table 2.5. The conversion ratios of boneless weight of animal-based food

	Sheep	Chicken	Beef	Pork	Fish
Ratio boneless weight: live weight	33%[15,16]	65%[17]	46%[18]	43%[19,20]	54%[1]
Ratio boneless weight: carcass weight	67%[15,16]	75%[17]	83%[18]	62%[19,20]	--

2.4 Calculations of the tabulated values of GHGE, WU and LU

The total GHGE, TWU and LU per kg of food as consumed were calculated using the following formula, respectively:

- Total GHGE = GHGE from cradle to farm gate * (1/edible portion parameter) * (1/losses and waste parameter) + GHGE during storage + GHGE during transportation + GHGE during packaging + GHGE during preparation at home
- Total TWU = TWU from cradle to farm gate * (1/edible portion parameter) * (1/losses and waste parameter)
- Total LU = LU from cradle to farm gate * (1/edible portion parameter) * (1/losses and waste parameter)

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Supplementary material

Supplementary Table 2.1. GHGE parameters of food groups in subsequent post farm gate stages (kg CO_2-eq/kg as produced)

Food type	Processing	Storage	Transportation	Package	Preparation at home	Total
Vegetables and fungi	—	0.005[1,2]	0.040[1,2]	0.023[3,4]	0.005[5]	0.081
Cereals	0.007[6]	0.005[1,2]	0.040[1,2]	0.023[3,4]	0.109[5]	0.184
Fruits and nuts	—	0.004[1,2,7]	0.040[1,2]	0.023[3,4]	0.0003[5]	0.075
Legumes	0.156[6]	0.005[1,2]	0.040[1,2]	0.023[3,4]	0.006[5]	0.230
Tubers, starches	—	0.002[8]	0.025[8]	—	0.005[5]	0.032
Aquatic products	—	0.026[9]	0.010[9]	0.023[3,4]	0.082[5]	0.350
Meat	—	0.015[10]	0.087[10]	0.023[3,4]	0.175[5]	0.603
Dairy	0.045[11]	0.015[10]	0.087[10]	0.023[3,4]	0.016[5]	0.186
Poultry	—	0.015[10]	0.044[12]	0.023[3,4]	0.136[5]	0.521
Eggs	—	0.015[10]	0.087[10]	0.023[3,4]	0.055[5]	0.180
Beverages	—	0.002[13–15]	0.022[13–16]	0.064[13–15]	—	0.049
Sugars and preserves	0.133[17]	0.005[1,2]	0.040[1,2]	0.023[3,4]	0.005[5]	0.081
Liquor and alcohol	—	0.002[13–15]	0.022[13–16]	0.064[13–15]	—	0.049
Fats and oils	0.034[6]	—	0.040[1,2]	—	0.654[5]	0.728

Supplementary Table 2.2. Overview of Chinese domestic food production and imports, 2016 (ten thousand tons, %)

Food items	Domestic net production	Total import	Domestic net production (%)	Total import (%)
Cereals	48399.6	2167.1	95.7%	4.3%
Wheat and products	12121.8	757.2	94.1%	5.9%
Rice and products	13630.8	271.4	98.0%	2.0%
Barley and products	108.4	252.8	30.0%	70.0%
Corn and products	21837.2	740.7	96.7%	3.3%
Sorghum and products	287.8	119.8	70.6%	29.4%
Starchy roots	17234	3167.1	84.5%	15.5%
Sugar crops	13810.6	92.9	99.3%	0.7%
Sugar and sweetener	1506.6	569.4	72.6%	27.4%
Beans (excluding soybeans)	364.1	118.1	75.5%	24.5%
Tree nuts	324.8	58.1	84.8%	15.2%
Oil crops	5709.9	7037.1	44.8%	55.2%
Soybeans	1167.4	6556.4	15.1%	84.9%
Vegetable oil	2175.7	1167.3	65.1%	34.9%
Palm oil	15.8	709.8	2.2%	97.8%
Vegetables	57040.9	167.4	99.7%	0.3%
Fruits	14638.4	570	96.3%	3.7%
Fast food	146.9	43.8	77.0%	23.0%
Spices	43.8	2.8	94.0%	6.0%
Alcoholic beverages	6512.3	115.4	98.3%	1.7%
Meat	8322.1	442.2	95.0%	5.0%
Animal fat	401.5	66.3	85.8%	14.2%
Eggs	2902.7	12.6	99.6%	0.4%
Milk (without butter)	4033.7	978	80.5%	19.5%
Fish and sea food	6358.2	1126.7	84.9%	15.1%

Data source: FAOSTAT[18]

Supplementary Table 2.3. Specifications and GHGE of five shopping bags

	HDPE plastic bags	LDPE plastic bags	Paper bags	Non-woven bags	Cotton bags
Volume(L)	18.1	17.8	18.2	18	18.5
Length*width*height (cm)	37*12*40	33*13*42	35*13*40	40*10*45	35*12*44
Single bag weight (g)	5.68	10.45	23.8	60.0	130.0
GHGE (kg CO_2-eq/kg)	0.023	0.034	0.092	0.31	3.12

Data source: Kuai, et al. (2013) [3], Luo, et al. (2021) [4]

Supplementary Table 2.4. Loss proportion of food groups in the food supply chain*

Food group	Production	Postharvest handling	Storage	Processing	Transportation	Total
Vegetables and fungi	12.15%[19–23]	19.40%[19,20]	15.00%[19,20]	--	5.13%[19,20]	51.67%[19,20]
Cereals						
Rice	3.47%[19–23]	2.66%[19–23]	6.17%[19–23]	2.18%[19–23]	0.74%[19–23]	15.22%[19–23]
Wheat	3.12%[19–23]	0.77%[19–23]	6.91%[19–23]	2.38%[19–23]	0.24%[19–23]	13.42%[19–23]
Corn	2.17%[19–23]	1.12%[19–23]	6.49%[19–23]	2.27%[19–23]	0.19%[19–23]	12.23%[19–23]
Fruits and nuts	9.58%[19–23]	0.92%[19–23]	5.36%[19–23]	--	5.50%[19–23]	21.36%[19–23]
Legumes	6.00%[19]	3.00%[19]	--	5.00%[19]	1.00%[19]	15.00%[19]
Tubers, starches	4.41%[19]	--	17.13%[19]	0.04%[19]	0.01%[19]	21.59%[19]
Aquatic products	2.00%[19,24]	--	4.00%[19,24]	4.00%[19,24]	3.20%[19,24]	13.2%[19,24]
Meat						
Pork	11.00%[19,24]	2.33%[19,24]	0.89%[19,24]	0.40%[19,24]	0.24%[19,24]	14.86%[19,24]
Beef	10.18%[19,24]	4.45%[19,24]	1.04%[19,24]	0.40%[19,24]	0.86%[19,24]	16.93%[19,24]
Mutton	4.15%[19,24]	2.28%[19,24]	0.35%[19,24]	0.40%[19,24]	0.83%[19,24]	8.01%[19,24]
Dairy	3.50%[19]	1.00%[19]	--	1.20%[19]	0.50%[19]	6.20%[19]
Poultry	8.75%[19,24]	2.86%[19,24]	3.24%[19,24]	0.40%[19,24]	0.62%[19,24]	15.87%[19,24]
Eggs	--	--	--	--	--	10.5%[25]
Beverages	--	--	--	--	--	5.00%[14]
Sugars and preserves	12.15%[19,20]	19.40%[19,20]	15.00%[19,20]	--	5.13%[19,20]	51.67%[19,20]
Liquor and alcohol	--	--	--	--	--	5.00%[14]
Fats and oils	6.00%[19]	3.00%[19]	--	5.00%[19]	1.00%[19]	15.00%[19]

**The dash means that we did not find a relevant coefficient in the literature and therefore the total food loss proportion is underestimated.*

2

Supplementary Table 2.5. Calculation of the GHGE of high-frequency consumed processed food in the Chinese Food Composition Table based on weight*

Food groups	Food items	Data sources (kg CO_2-eq/ kg)		
		GHGE of agricultural activity	GHGE of post farm gate	Total
Cereals	Noodle Steamed bread Dried noodles You Tiao Pancake Rice flour Flat rice-noodles	0.978	0.007	0.985
	Rice flour Flat rice-noodles	1.21	0.007	1.217
Ethnic foods and cakes	Bread	0.978	0.007	0.985
Dried legumes and legume products	Tofu	0.792	0.156	0.948

Recipes taken from the Chinese Food Composition Table are used to break-down composite foods into its ingredients, if the food composition table is not available, the first hit on internet will be referred.

Supplementary Table 2.6. Calculation of the high-frequency consumed recipe in Chinese Food Composition Table based on weight*

Food group	Food sub-groups	Food items	Data of GHGE sources (kg CO_2-eq/ kg)	The proportion of ingredients used in the food recipe table[1]	Total (kg CO_2-eq/ kg)
Ethnic foods and cakes	Convenience food	Steamed Bun (Pork Filling)	Pork (fat and lean)	62.5%	2.963
			Wheat flour (standard flour)	37.5%	
		Dumplings (pork and cabbage stuffing)	Pork (fat and lean)	70%	2.6852
			Cabbage	10%	
			Wheat flour (standard flour)	20%	
		Biscuits	Egg	1/3	1.552
			Wheat flour (standard flour)	2/3	
	Cake	Cake	Egg	60%	2.196
			Milk	20%	
			Wheat flour (standard flour)	20%	

Recipes taken from the Chinese Food Composition Table are used to break-down composite foods into its ingredients, if the food composition table is not available, the first hit on internet will be referred.

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CHAPTER 3

Aligning Health, Environment, and Cost Aspects of Diets: Identifying Sustainable Dietary Patterns in China

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Abstract

Considering the adverse effects of agricultural-food systems on both human health and the environment, this research aimed to identify sustainable diets, which are nutritious, culturally acceptable, affordable, and have low environmental impacts, based on self-reported diets in China. Dietary data was collected with a 3-day 24-hour dietary recall and weight food record combined method among 10,324 subjects aged 18-64 year, who participated in the China Health Nutrition Survey 2011. Diet quality was assessed by the Chinese Healthy Eating Index 2016 (CHEI2016). Environmental impact was measured by greenhouse gas emissions (GHGE), total water use (TWU), and land use (LU), and diet costs were calculated using market prices of community surveys. Reduced rank regression derived dietary patterns with 34 food groups as predictor variables, and used CHEI2016 score, dietary greenhouse gas emissions (GHGE), total water use (TWU), land use (LU), and cost of the diet as response variables. Four dietary patterns were identified. Participants with the highest adherence (decile 10) to the "High animal-based food" pattern showed higher dietary GHGE (+57%), TWU (+51%), and LU (+54%) and dietary costs (+64%), compared to the average population's diets. The diet in decile 10 for the "High fruit, low ruminant meat" pattern displayed a 21% higher CHEI2016 score, and higher dietary environmental impact (GHGE +17%; TWU +22%; LU +19%) and dietary costs (+46%) than the average diets. Diets of participants who followed the "High fish, low beverages" pattern showed higher environmental impact (GHGE +39%; TWU +32%; LU +28%) and dietary costs (+19%), but the CHEI2016 score was similar (+0.1%). Finally, the "High wheat, low pork" pattern demonstrated lower environmental impacts (GHGE -17%, TWU -12%, LU -2%) and lower cost of the diet (-2%) but also lower CHEI2016 score (-1%) compared to average population. This study reveals the complex trade-offs between diet quality, environmental sustainability, and dietary costs of current dietary patterns. None of the four patterns achieved the desirable combination of high CHEI2016 scores, reduced environmental impact, and reduced dietary costs. The findings offer insights into sustainable diet choices within the current food system, suggesting dietary guidelines should consider environmental sustainability and cost-effectiveness.

Keywords: sustainable diets; dietary pattern; reduced rank regression; dietary quality; dietary environmental impacts; cost of diet

1 Introduction

Adopting sustainable diets has the potential to achieve multiple benefits, including the reduction of environmental impacts of the food system, such as greenhouse gas emissions (GHGE) and land occupation, as well as increasing nutritional health, and the prevention of diet-related chronic diseases(1). Food production, processing, storage, and transportation are responsible for significant contributions to global land use (LU) (38%)(2), total water use (TWU) (70%)(3), and GHGE (19-29%)(4). Unhealthy dietary patterns, characterized by high consumption of sugar, salt, and saturated fatty acids, have led to increasing obesity rates(5) and non-communicable diseases(6). Given the interdependence between dietary patterns, nutritional health, and environmental impacts, the Food and Agriculture Organization (FAO) has recommended sustainable diets that are "nutritionally adequate, safe, healthy, culturally acceptable, and economically accessible, and that have low environmental impacts and contribute to food and nutrition security for present and future generations"(7).

Along with the growing economy, the dietary patterns of Chinese residents have shifted from plant-based to mixed diets that include a larger proportion of animal-based foods(8). The nutritional quality of Chinese has been improving year by year, with a decreasing trend in stunted growth and malnutrition(9). From 2002 to 2012, the prevalence of malnutrition decreased from 15% to 11.4%(10). However, concurrently, the excessive intake of energy, added sugars, and fats increased along with the risk of health problems, including obesity, diabetes, and cardiovascular diseases(11). By 2022, the percentage of overweight adults in China has risen to 50%, and obesity increased by 37% since 2012, reaching a prevalence of 16%(12). Moreover, the prevalence of type II diabetes had increased from less than 5% in 2000 to 11% in 2015(13). The GHGE of the food system in China has increased due to the rise in red meat consumption, the use of fertilizers, and food waste(14). In 2020, the food system in China emitted 1.9 billion tons of carbon dioxide equivalents, accounting for 14% of total national emissions(15), and 43% of Chinese water withdrawals for irrigation(16).

There has been a growing interest in diet modelling as an approach to identify healthy and environmentally sustainable dietary patterns. However, as such models have difficulty to incorporate the cultural dimensions of accessibility, acceptability and affordability, the optimized dietary patterns can be far from realistic(17). Moreover, many studies have been limited to GHGE as the environmental indicator(18), with little consideration to land use and water use(19). Moreover, previous research largely focused on high-income countries (HIC), and there remains a lack of understanding the intricate trade-offs between dietary patterns and sustainable indicators in Low- and Middle-Income Countries (LMIC) (20). In China, dietary patterns have previously been characterized using principal component analysis and factor analysis, subsequently linked to disease risk estimates and environmental impacts (21,22). These a posteriori analysis methods identify dietary pattern in the data but are not primarily aimed to derive patterns that have associations with environmental impact(23). In this study, our aim was to identify dietary patterns that not only promote health but also align with environmental sustainability goals, while taking into account the economic costs of diets in China. Furthermore, we explored the associations between sociodemographic characteristics and derived dietary patterns. Our study contributes to the literature in four main aspects: (1) Comprehensive consideration of the sustainability dimensions of diets by including diet quality, environmental impact, and economic costs-and analyzed the trade-offs and synergies among them. (2) We have considered not only GHG emissions but also the use of water and land. (3) Consideration of the acceptability of dietary patterns: The identified dietary patterns are based on real dietary data from Chinese residents, making them culturally realistic within the socio-cultural context of China. (4) Exploration of group heterogeneity: We quantified the associations between various population subgroups and dietary patterns, exploring the transition pathways toward sustainable diets for different population subgroups.

2 Methods and data

2.1 Study Design and Population

This study utilized cross-sectional data from the 2011 China Health and Nutrition Survey (CHNS), a longitudinal study conducted since 1989 in nine provinces across China, to investigate sustainable dietary patterns among Chinese adults(24). The survey collected comprehensive data on socio-demographic, dietary, lifestyle, and health-related factors from a sample of individuals from urban and rural areas, providing a rich database for studying household situations in China. The study protocol was approved by the Institutional Review Boards of the University of North Carolina at Chapel Hill, the National Institute of Nutrition and Food Safety, and the China Center for Disease Control and Prevention, ensuring the ethical conduct of the research.

For this study, we included individuals aged between 18 and 64 years who participated in the 2011 CHNS with a least two days of dietary consumption data. We excluded participants who were either younger than 18 or older than 65 years of age, pregnant and breastfeeding women, those with a z-score above 5 or below -5 for energy intake. Following the application of these exclusionary criteria, the resulting sample size comprised 10,324 participants from the CHNS 2011.

2.2 Dietary Assessment

To collect dietary consumption data, this study utilized a 3-day 24h dietary recall and weight food record combined method. Participants were instructed to record all food and beverages consumed over three consecutive days, including two weekdays and one weekend day. Trained interviewers visited participants' homes to review the food record and gather additional information on portion sizes and cooking methods. The CHNS 2011 covered 1,950 food items, which were coded according to the Chinese Food Composition Table (CFCT). All the food items were combined into 34 categories, namely Rice, Wheat, Corn, Other cereals, Tubers & starches, Soybean, Other legumes, Nuts & seeds, Fungi & algae, Light vegetables, Dark vegetables, Fruit, Pork, Beef, Lamb, Other meat, Chicken, Duck, Other poultry, Fish, Crab, Other aquatic products, Shrimp, Cheese, Milk, Yogurt, Other dairy, Eggs, Tea, Liquor & alcohol, Other beverages, Sweets, Fast foods, Animal oil, Vegetable oil, Condiment. The estimation of energy intake for the recorded food items was accomplished through the utilization of the CFCT. To mitigate variations attributable to age and gender, consumption values were standardized to g/2000 kcal. Furthermore, the proportion of animal-based foods (%) in the diet was calculated by dividing the consumption of animal-based foods (including meat, poultry, dairy, eggs, and aquatic products) in grams per 2000 kcal by the total food consumption in grams per 2000 kcal.

2.3 Sociodemographic variables

This study considered various sociodemographic variables, such as age, gender, height, weight, work-related physical activity, educational attainment, degree of urbanization, annual household income per capita, dietary knowledge, smoking status, proportion of animal-based foods in the diet, and geographic regions. Trained technicians utilized standardized methods to measure weight and height. Body Mass Index (BMI) was calculated by dividing weight (in kilograms) by the square of height (in meters). This Work-related physical activity was categorized as 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 classified into three groups: low (below primary school, including those who did not attend school), medium (secondary school, including middle and high school), and high (above high school, including undergraduate and graduate school). The place of residence was categorized as urban or rural areas, and is constructed from the original sampling-unit variables. Household income was determined by dividing the total annual household income by the number of household members and further categorized into low (0-7,900 CNY), middle (7,916-17,237 CNY), and high-income groups (17,272-300,000 CNY). Dietary knowledge was assessed based on respondents' awareness of the Chinese Dietary Guidelines, with a simple Yes/No question. Smoking status was divided into three groups: non-smoker, current smoker, and ex-smoker.

2.4 Chinese Health Eating Index

To evaluate the daily dietary quality of Chinese individuals, the Chinese Healthy Eating Index (CHEI) was used, which applies the updated Dietary Guidelines for Chinese 2016(25). Dietary consumption recorded in the survey was averaged and then used to calculate the CHEI. The CHEI evaluates the overall adherence to the guidelines through the scoring of seventeen components. A higher total score, ranging from 0 to 100, indicates better adherence to Dietary Guidelines for Chinese recommendations. The CHEI2016 encompasses 12 food components evaluating 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 5 food components assessing limitation (red meat, edible oils, sodium, added sugar, and alcohol). The scoring system generally ranged from 0 to 5 for most food components, while fruit, cooking oil, and salt were rated on a scale from 0 to 10. The index used standardized portions (SP) to quantify dietary consumption, ensuring consistent across food groups in terms of energy content, and comparable levels of carbohydrates, and protein. The CHEI accounts for total energy intake, by quantifying the contribution of each of its components by the density method (as amounts per 1,000 calories of intake), except for sugar (percentage of energy) and alcohol (absolute consumption). The recommended quantities for each component derived from different food groups are standardized and presented in SP/1000 kcal, while cooking oils are expressed in grams/1000 kcal. Detailed information on the CHEI's validity and reliability is provided in **Supplementary Table 1**.

2.5 Diet related environmental impacts

In this study, the environmental impact of food consumption was evaluated using the China Food Life Cycle Assessment Database (CFLCAD)(26), which integrates over 1,000 literature-based LCAs from the Chinese context. The CFLCAD provides estimates of GHGE, TWU, and LU per kilogram of food for each food item. The cradle-to-table system boundary was considered, which encompasses storage, processing, packaging, transportation, and household stages of food preparation, while accounting for food losses throughout the supply chain. To calculate the environmental impacts of individual diets, each food item reported in the dietary recall (in grams) is multiplied by the corresponding environmental impact factors from the CFLCAD (**Supplementary Table 5**). When LCA data were not available, data from similar food groups were used as a proxy, with food codes from the CFCT used to reference the CFLCAD database. The total environmental impacts per day from the diet were determined by summing the dietary GHGE, TWU, and LU and expressed as density (per 2,000 kcal) to account for variation in energy intake. The adjustment was made to enable unbiased comparisons between the environmental impacts of participants' diets. Food items within the CFLCAD were cross-referenced with entries contained in the Chinese Food Composition Tables (FCT). This matching process guarantees that outcomes derived from both the CHNS and CFLCAD are at the specific level of individual "food items."

2.6 The cost of diet

In the CHNS, the community food price data encompassed the prices of food items from various markets in the community, including state stores and free markets (food price unit: Chinese Yuan, CNY). It was found that free market prices were the most influential in shaping consumption decisions, and as such, these prices were utilized in the analysis. The food price database included 13 food categories, i.e., 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 condiments such as vinegar and soy sauce. Within each food group, the lowest free market price was used as the default, given a number of different types of foods available. If free market prices were not available, the lowest retail prices were used as a substitute. To determine an individual's total dietary cost, the unit cost of each food item was calculated by dividing the price of each item by its unit (e.g., grams or liters), and this was then multiplied by the amount of each energy adjusted food item consumed by the individual to obtain the cost of each item. Finally, the costs of all energy adjusted foods consumed were combined to obtain the overall cost of an individual's diet (CNY/2000 kcal).

3

2.7 Statistical Analysis

Utilizing data from the Chinese Health and Nutrition Survey, this study applied the reduced rank regression (RRR) method in the PROC PLS procedure in SAS 9.4 to establish dietary patterns. The RRR is a multivariate technique that maximizes the correlation of explanatory variables (e.g. food groups) with a set of predefined response variables, usually biomarkers linked to a disease outcome (27). The diet-related environmental impacts, including GHGE, TWU, and LU per 2000 kcal, the CHEI2016 score, and the cost of the diet per 2000 kcal, were selected as response variables. The RRR will identify an equivalent number of dietary patterns corresponding to the number of response variables. The factor loadings (FL) of all 34 food groups for each dietary pattern were obtained as the regression results. The FL exceeding 0.20 or below -0.20 indicate a relatively strong association between the corresponding food group and the response variable and were used to describe the pattern. Scores for each participant's adherence to each dietary pattern were calculated based on the factor loadings of the food groups. Participants' dietary pattern scores were divided into ten groups (decile 1 to decile 10), representing increasing adherence to that pattern in order (decile 1 indicating least adherence, decile 10 indicating most adherence). This study assessed the Pearson correlation coefficient (r) between dietary pattern scores and consumption of each food group and sustainability indicators, respectively. Kruskal–Wallis test were employed to determine the statistical significance of the differences in the sustainable indicators between decile 1 and decile 10 of dietary patterns. To investigate associations between socio-demographic characteristics and the derived dietary pattern, generalized linear models were applied to estimate the association of socio-demographic characteristics across dietary patterns with 95% CIs. The variables age, gender, BMI, physical activity, household income, educational level, residence location, dietary knowledge, smoking habits were added as covariates to the model. Data analysis was performed using SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA) and STATA 17.0 (Stata Corporation, College Station). A two-sided p value of <0.05 was considered statistically significant.

3 Results

3.1 Population Characteristics and Food Consumption

The study population included a total of 10,324 participants from the CHNS, with 52.6% being female (**Table 3.1**). The participants mean age was 45.7 years (standard deviation (SD): 11.9), and their men daily energy intake was 1970 kcal/day (SD: 680). The average body mass index (BMI) was 23.6 kg/m^2, with approximately 25% of the population being current smokers, and around one-fifth of participants having attained a university-level education or higher. Additionally, 60% of the participants reported a low level of physical activity. The proportion of animal-based foods in the diet of the population was 15.1%, and 28% of individuals reported familiarity with the Chinese Dietary Guidelines. The average score on the CHEI2011 was 51.9 (SD: 10.5), out of a maximum score of 100. In terms of dietary environmental impact, the average dietary GHGE were 2.9 CO_2-eq/2000 kcal (SD: 1.1), with a TWU of 3.7 m^3/2000 kcal (SD: 1.3) and LU of 3.3 m^2/2000 kcal (SD: 1.3). The average dietary cost was 11.9 CNY/2000 kcal (SD:4.9).

Table 3.1. Sociodemographic characteristics and food group consumption (g/2000 kcal) of participants in the China Health Nutrition Survey 2011 (n = 10,324), and diets in decile 1 and decile 10 of dietary pattern derived by the Reduced Rank Regression[1].

	Average population in CHNS	**High animal-based food**		**High fruit, low ruminant meat**		**High fish, low beverages**		**High wheat, low pork**	
		Decile 1	**Decile 10**	**Decile 1**	**Decile 10**	**Decile 1**	**Decile 10**	**Decile 1**	**Decile 10**
Participants (n)	10,324	1,033	1,033	1,033	1,033	1,033	1,033	1,033	1,033
Gender (n, %)									
Male	4889, 47.4	504, 48.8	453, 43.9	515, 49.9	331, 32.0	558, 54.0	445, 43.1	503, 48.7	470, 45.5
Female	5435, 52.6	529, 51.2	580, 56.1	518, 50.1	702, 68.0	475, 46.0	588, 56.9	530, 51.3	563, 54.5
Age (mean years, ±SD)	45.7±11.9	45.8±12.0	44.5±12.4	46.2±11.7	44.7±12.4	45.3±12.5	46.1±11.4	45.5±11.8	45.1±12.4
BMI (mean kg/m^2, ±SD)	23.6±4.2	24.6±4.7	23.5±3.6	23.6±4.0	24.1±4.3	24.2±4.0	23.7±3.7	23.8±4.4	24.5±4.2
Income (median 1,000 CNY, interquartile range)	12.1, 6.1-20.9	5.7, 2.2-11.7	13.7, 7.0-23.1	9.7, 5.1-16.3	18.4, 9.4-29.1	10.7, 5.0-21.0	12.0, 6.0-19.8	10.6, 5.6-18.0	7.4, 2.6-14.4
Dietary Energy intake (mean kcal/d, ±SD)	1970±680	2074±776	1568±547	1920±685	1760±546	2098±785	1539±514	1871±607	1866±629
Degree of urbanization (n, %)									
Urban	4253, 41.2	220, 21.3	690, 66.8	353, 34.2	601, 58.2	382, 37.0	607, 58.8	395, 38.2	279, 27.0
Rural	6071, 58.8	813, 78.7	343, 33.2	680, 65.8	432, 41.8	651, 63.0	426, 41.2	638, 61.8	754, 73.0
Dietary knowledge[2] (n, %)									
No	7437, 72.0	862, 83.4	719, 69.6	824, 79.8	563, 54.5	717, 69.4	813, 78.7	806, 78.0	776, 75.1
Yes	2887, 28.0	171, 16.6	314, 30.4	209, 20.2	470, 45.5	316, 30.6	220, 21.3	227, 22.0	257, 24.9
Educational level (n, %)									

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	Average population in CHNS	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
		Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10
Primary school and below	3053, 29.6	415, 40.2	256, 24.8	410, 39.7	169, 16.4	313, 30.3	339, 32.8	392, 37.9	341, 33.0
Secondary school	5106, 49.5	529, 51.2	477, 46.2	496, 48.0	498, 48.2	495, 47.9	507, 49.1	488, 47.2	548, 53.0
High school and above	2165, 21.1	89, 8.6	300, 29.0	127, 12.3	366, 35.4	225, 21.8	187, 18.1	153, 14.8	144, 13.9
Activity level (n, %)									
Low	6096, 59.0	413, 71.1	666, 66.0	487, 47.1	759, 73.5	551, 53.3	606, 58.7	525, 50.8	483,46.8
Medium	1666, 16.1	168, 28.9	201, 19.9	220, 21.3	126, 12.2	178, 17.2	238, 23.0	221, 21.4	151, 14.6
High	2562, 24.8	452, 72.9	166, 15.7	326, 31.6	148, 14.3	304, 29.4	189, 18.3	287, 27.8	399, 38.6
Smoking status (n, %)									
Non-smoker	7190, 69.6	694, 68.9	732, 70.7	725, 70.2	834, 80.7	647, 62.6	737, 71.3	714, 69.1	728, 70.5
Current smoker	2792, 27.1	313, 31.1	266, 25.7	275, 26.6	163, 15.8	333, 32.2	265, 25.7	280, 27.1	271, 26.2
Ex-smoker	342, 3.3	26, 7.7	35, 3.3	33, 3.2	36, 3.5	53, 5.1	31, 3.0	39, 3.8	34, 3.3
Animal-based food(mean grams/2000 kcal, ±SD)									
Pork	79.4±53.6	36.0±23.3	111.0±69.3	99.5±57.2	60.2±42.2	51.3±39.9	113.1±66.3	101.0±57.2	36.4±24.5
Beef	42.3±35.4	29.9±16.5	57.1±42.0	43.9±40.1	41.1±32.3	44.4±42.9	45.1±32.0	35.9±24.0	68.8±66.4
Lamb	48.3±39	26.0±17.5	67.1±40.9	45.1±33.5	53.4±35.3	54.4±53.2	55.1±30.0	42.7±32.4	45.2±48.2
Other meat (include donkey, horse)	50.7±36.8	52.7±54.6	49.0±29.0	58.0±17.3	41.8±32.1	54.2±49.6	53.0±44.4	79.0±25.5	59.3±45.6
Chicken	44.8±32.1	37.2±22.6	53.9±38.9	43.3±30.4	49.4±34.4	39.3±32.2	55.5±37.6	46.3±29.6	42.6±22.9
Duck	43±32.5	35.1±19.9	50.4±37.6	41.7±38.1	39.5±21.6	36.4±25.8	53.4±39.9	46.6±39.6	39.9±24.4
Other poultry (include goose, turkey)	35.8±30.8	87.0±71.1	28.7±19.0	27.9±30.1	37.8±24.6	24.2±2.3	37.7±28.3	22.0±11.7	40.7±0
Milk	168.3±110.8	122.8±60.9	241.3±151.1	111.4±48.1	202.5±139.1	183.7±151.6	162.2±91.7	172.5±101.7	166.6±111.4

	Average population in CHNS	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
		Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10
Other dairy (include milk powder, butter)	55.5±63.8	118.4±39.1	6.6±0.4	28.6±24.1	65.7±62.0	79.7±84.2	14.7±11.6	21.9±27.2	43.7±37.0
Yogurt	117.1±79.9	76.7±40.3	161.0±101.7	222.8±122.9	151.2±93.3	142.9±84.1	130.6±83.3	99.2±55.9	155.2±109.5
Cheese	33.7±35.6	54.4±9.1	0±0	0±0	91.2±73.9	77.7±65.8	0±0	0±0	32.8±2.5
Eggs	45.9±34.7	41.3±30.6	58.9±42.6	38.1±29.9	62.6±44.6	40.9±29.5	58.5±46.0	42.9±33.7	52.7±40.4
Fish	53.4±40.6	32.3±21.9	77.4±53.3	52.4±41.2	55.6±38.8	39.7±28.5	84.7±55.2	53.0±36.9	50.1±39.2
Shrimp	32.1±30.3	18.0±16.8	44.6±35.4	37.4±36.5	30.1±28.0	22.3±22.3	46.1±43.6	44.9±42.2	17.8±19.9
Crab	36.5±25.7	31.2±28.6	43.1±32.3	28.8±15.0	40.4±31.8	46.3±36.6	42.0±29.6	34.4±19.9	17.9±15.3
Other fish (include Sea Cucumber & Cuttlefish)	27.4±20.3	26.6±11.0	25.7±16.6	21.1±22.1	32.6±21.4	23.6±13.0	22.7±13.1	26.7±16.6	30.3±22.5
Plant-based foods (mean grams/2000 kcal, ±SD)									
Wheat	162.5±127.9	369.0±148.6	90.4±59.6	109.1±77.3	162.3±103.2	217.9±150.5	112.2±81.9	95.9±57.4	384.2±149.0
Rice	270.4±188.8	82.6±77.1	458.0±324.4	377.2±212.6	197.6±140.5	168.0±133.5	451.1±276.3	381.8±217.2	97.9±110.9
Other cereals (include Corn, Sorghum)	66.9±75.6	81.6±105.7	76.4±72.4	46.9±40.4	83.0±99.5	75.7±88.1	76.5±66.8	48.8±48.8	104.3±119.6
Tubers & starches	73.3±67.3	86.8±85.3	70.2±73.1	73.9±66.8	78.7±89.2	102.7±99.9	61.4±52.9	78.8±71.9	92.1±93.0
Other legumes (include cowpeas & mung beans)	37.4±33.2	30.2±26.6	26.5±30.6	44.4±36.1	35.6±36.4	27.3±30.6	39.8±32.4	42.5±35.9	30.2±33.2
Soybean	85±83.1	66.9±61.5	113.0±122.6	64.1±55.3	125.7±121.3	57.2±50.2	143.1±146.4	76.5±72.4	100.2±93.7
Vegetables	305±164.8	201.3±110.3	489.5±231.1	321.3±174.8	308.7±169.0	172.5±100.0	569.0±208.7	351.9±193.7	252.0±144.8
Fungi and algae	32.9±29.1	26.2±22.4	41.9±42.7	27.6±22.4	35.7±31.0	26.8±21.8	43.0±45.1	31.2±26.6	32.3±30.8
Fruit	140.2±110.8	78.1±48.0	251.5±172.5	65.3±45.0	277.0±142.9	193.7±158.0	131.1±95.2	117.1±83.6	206.4±174.7
Nut	26.9±22.1	23.1±20.9	24.8±22.2	24.2±16.6	29.6±28.3	28.2±26.1	28.4±21.5	26.6±17.7	27.5±23.6

	Average population in CHNS	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
		Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10
Beverages (mean grams/2000 kcal, ±SD)									
Tea	530.7±636.4	8.5±7.4	920.4±882.5	325.3±244.1	558.3±413.7	786.3±828.7	370.6±190.7	607.6±1033.6	584.0±326.1
Liquor	109.1±193.4	93.3±74.7	200.3±366.1	51.9±105.4	209.8±406.2	269.5±324.2	31.2±67.5	173.0±297.1	66.2±93.8
Other beverages (include soft drinks, fruit juice)	169.1±294.2	87.4±37.7	310.8±555.4	154.2±147.5	250.7±534.8	310.2±527.4	82.2±70.4	156.6±136.0	155.8±181.7
Miscellaneous (mean grams/2000 kcal, ±SD)									
Fast foods	111 ±88.1	144.3 ±110.1	96.8 ±73.0	87.8 ±73.1	120.8 ±89.1	132.0 ±106.4	91.9 ±66.8	99.9 ±88.2	115.1 ±84.9
Sweets	7.4±16.5	16.8±54.1	7.4±14.5	7.1±21.4	6.1±7.9	10.6±34.8	7.9±14.0	5.9±6.9	5.9±6.8
Animal oil	21±17.6	40.7±38.7	17.8±14.3	22.4±17.1	12.9±9.8	24.5±25.5	19.6±14.5	21.0±15.8	21.8±8.8
Vegetable oil	33.1±21.4	38.6±27.6	27.3±17.2	37.7±23.3	28.0±17.2	36.0±27.8	32.6±19.5	32.3±19.4	30.7±18.1
Condiment	30.5±31	31.5±31.2	34.4±34.5	37.6±44.1	30.6±27.3	35.0±38.6	31.7±30.4	31.8±35.5	30.9±27.1
Proportion of animal-based foods (mean %, ±SD)	15.1±9.8	6.4±6.2	19.0±11.3	14.8±9.0	17.2±11.1	12.0±10.7	15.9±9.0	15.7±9.4	8.6±8.6
GHGE (mean CO_2-eq/2000 kcal, ±SD)	2.9±1.1	1.7±0.5	4.5±1.1	2.9±1.1	3.4±1.1	2.5±1.1	3.9±1.1	3.2±1.1	2.4±1.2
TWU (mean m^3/2000 kcal, ±SD)	3.7±1.3	2.4±0.7	5.6±1.4	3.6±1.3	4.6±1.3	3.6±1.4	4.9±1.4	3.9±1.4	3.3±1.5
LU (mean m^2/2000 kcal, ±SD)	3.3±1.3	2.2±0.6	5.1±1.4	3.2±1.2	3.9±1.4	3.3±1.5	4.2±1.3	3.4±1.2	3.2±2.1
CHEI2016 score (mean, ±SD)	51.9±10.5	45.5±8.9	57.8±10.5	44.5±7.9	63.1±9.1	51.2±11.4	51.9±9.8	48.8±9.4	51.3±11.4
Cost of diets (mean CNY/2000 kcal, ±SD)	11.9±4.9	7.2±2.5	19.6±6.1	10.4±3.8	17.4±6.1	13.6±6.6	13.8±4.1	12.1±5.5	11.6±6.9

[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).
[2] Dietary knowledge indicated whether participants were familiar with the Chinese dietary guidelines.

3.2 Dietary Patterns Derived by RRR

RRR initially identified five distinct dietary patterns (**Supplementary Table 3.2**), corresponding to the number of response variables examined. The "High animal-based food" dietary pattern accounted for 66.3% of the variance in dietary GHGE, TWU, LU, CHEI2016, and cost of the diet, as well as 4.6% of the variation in food consumption. The "High fruit, low ruminant meat" pattern emerged as an influential dietary pattern that explained 9.1% of the variation in both the dependent and predictor variables. The "High fish, low beverages" pattern accounted for 2.4% and 2.9% of the variance in the dependent and predictor variables, respectively. Similarly, the "High wheat, low pork" pattern" explained 3.5% of the variance in the dependent variables and 1.5% in the predictor variables. In contrast, the fifth dietary pattern demonstrated minimal impact on the dependent variables (<0.50%) and was not considered in further analysis.

The "High animal-based food" dietary pattern was characterized by high consumption of beef (factor loading (FL): 0.38), pork (FL: 0.37), fish (FL: 0.31), lamb (FL: 0.24), milk (FL: 0.22), and chicken (FL: 0.20), while displaying a low consumption of wheat (FL: –0.24) (**Figure 3.1**). Within this group, the D10 of population exhibited a higher average consumption of animal-based foods, accounting for 19.0% of dietary consumption, with pork contributing 111.0 grams. Conversely, the "High fruit, low ruminant meat" pattern had high consumption of fruit (FL: 0.55), eggs (FL: 0.28), nuts and seeds (FL: 0.26), and milk (FL: 0.23), alongside a low consumption of pork (FL: –0.25), beef (FL: –0.24), and rice (FL: -0.22). In this pattern, the proportion of animal-based foods in diet was approximately 17.2%. While their consumption of ruminant meat was low, they had a notable milk and egg consumption, averaging 202 grams and 62.6 grams compared to the average of 168.3 grams and 45.9 grams, respectively. Furthermore, the "High fish, low beverages" pattern were characterized by a high consumption of fish (FL: 0.33) and eggs (FL: 0.22), while exhibiting a low consumption of alcohol (FL: -0.43), fast foods (FL: -0.42), tea (FL: -0.33), and tubers (FL: -0.31). The proportion of animal-based foods in their diet accounted for approximately 15.9%, with pork consumption averaging 113.1 grams. Additionally, their rice consumption was high, reaching 451.1 grams, compared to the overall mean of 270.4 grams. Lastly, the "High wheat, low pork" patterns displayed a higher consumption of beef (factor loading (FL): 0.57), wheat (FL: 0.22), fruit (FL: 0.19), and other cereals (FL: 0.19), and a low consumption of pork (FL: -0.48), rice (FL: –0.25), liquor and alcohol (FL: -0.19). Even though "beef" was the dominant factor, the beef consumption in the D10 diet increased from 35.9 grams in D1 to 68.8 grams in D10. In contrast, pork consumption decreased significantly from 101.0 grams in D1 to 36.4 grams in D10. Consequently, the proportion of animal-based food in this diet pattern was low at 8.6%.

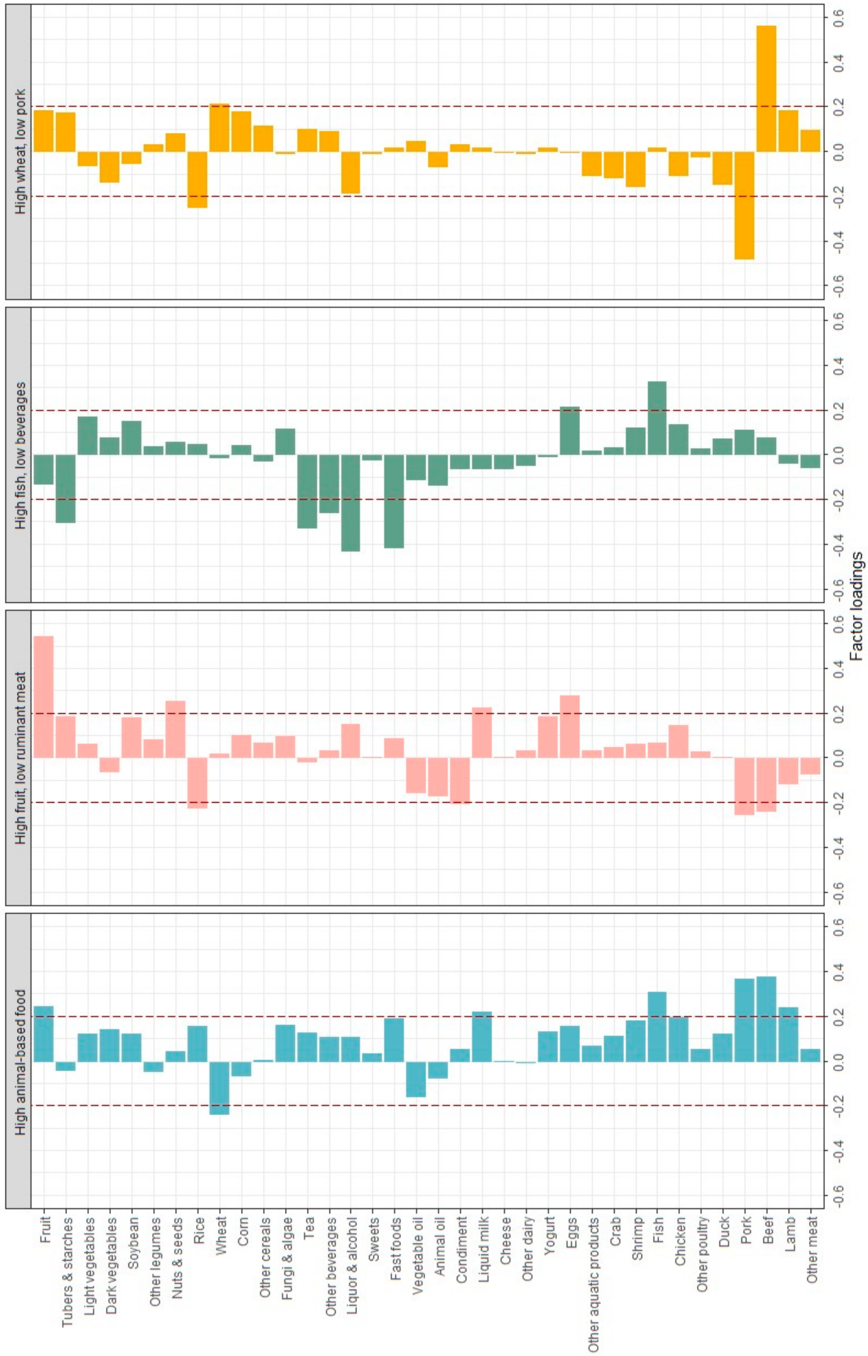

Figure 3.1. Factor loadings of the food groups on dietary patterns derived by reduced rank regression explaining the variation in the sustainable indicators. Factor loadings >|0.20| were considered important contributors to a dietary pattern.

3.3 Sustainability of the Dietary Patterns

Environmental impacts (GHGE, TWU, LU), diet quality (CHEI2016), and cost of the diet were positively correlated between the "High animal-based food" pattern and the "High fruit, low ruminant meat" pattern (**Table 3.2**). Specifically, the "High animal-based food" pattern displayed a strong positive association with dietary environmental impacts (r=0.765 for GHGE, r=0.715 for TWU, and r=0.647 for LU). Particularly, the "High fruit, low ruminant meat" pattern demonstrated a strong positive association with CHEI2016 (r=0.507), it also exhibited a positive correlation with the cost of the diet (r=0.462). While the "High fish, low beverages" pattern was weakly positively associated with dietary costs (r=0.021), and was negatively associated with CHEI2016 (r=-0.013) and strongly positively associated with dietary GHGE, TWU and LU. Lastly, the "High wheat, low pork" pattern exhibited a negative correlation with environmental impact indicators (GHGE, r=-0.156; TWU, r=-0.106; LU, r=-0.031) and cost of diet (r=-0.057), while exhibited a positive correlation with the CHEI2016 score (r=0.072).

3

The mean energy-adjusted dietary GHGE were calculated to be 2.87 (SD: 1.09) kg CO_2-eq/2000 kcal, while the TWU was estimated at 3.75 (SD: 1.35) m^3/2000 kcal, and LU at 3.30 (SD: 1.32) m^2/2000 kcal. The mean CHEI2016 score was 51.9, and the mean cost of the diet amounted 11.92 (SD: 4.98) CNY/2000 kcal within the sample of CHNS 2011 participants (**Table 3.1**). Among the dietary patterns, the adherents in highest-scoring diet in decile 10 for the "High animal-based food" pattern demonstrated notable differences compared to the average population's diets (**Supplementary Figure 3.1**). It exhibited a 11.4% higher CHEI2016 score, 56.9% higher dietary greenhouse gas emissions (GHGE), 50.9% higher total water use (TWU), 53.7% higher land use (LU), and a 64.5% higher cost of the diet (**Figure 3.2**). Similarly, the diet in decile 10 for the "High fruit, low ruminant meat" pattern displayed a 21.4% higher CHEI2016 score than the average population's diets. Moreover, it had higher dietary environmental impacts (GHGE +16.8%; TWU +21.7%; LU +18.8%) and cost (+45.9%) compared to the average population. In contrast, the diet in decile 10 for the "High fish, low beverages" pattern exhibited higher dietary environmental impacts (GHGE +39.1%; TWU +31.9%; LU +28.4%) and cost (+16.2%) compared to the average population but had a slightly lower CHEI2016 score (+0.1%). Notably, the "High wheat, low pork" pattern in decile 10 demonstrated lower environmental impacts compared to other dietary patterns. Participants adhering to this pattern had the lowest cost of the diet. Increasing adherence to the "High wheat, low pork" pattern resulted in a 16.6% lower dietary GHGE, 12.5% lower dietary TWU, 2.1% lower dietary LU, and 2.3% lower cost of the diet compared to the average CHNS population's diets. Furthermore, diets in decile 10 of the pattern scores for the "High wheat, low pork" pattern had a 1.1% lower CHEI2016 score compared to the average population diets.

Table 3.2. Pearson correlation of sustainable indicators with dietary pattern derived by Reduced Rank Regression (extracted from n =10,324)[1].

Pearson's correlation coefficient (r)	High animal-based food	High fruit, low ruminant meat	High fish, low beverages	High wheat, low pork
GHGE (kg CO_2-eq/2000 kcal)	0.765***	0.141***	0.404***	-0.156***
TWU (m^3/2000 kcal)	0.715***	0.226***	0.313***	-0.106***
LU (m^2/2000 kcal)	0.647***	0.164***	0.227***	-0.031*
CHEI2016 score	0.332**	0.507***	-0.013	0.072***
Cost of diet (CNY/2000 kcal)	0.724***	0.462***	0.021*	-0.057***

[1] Level of significance: *** <0.001, ** <0.01, * <0.05.

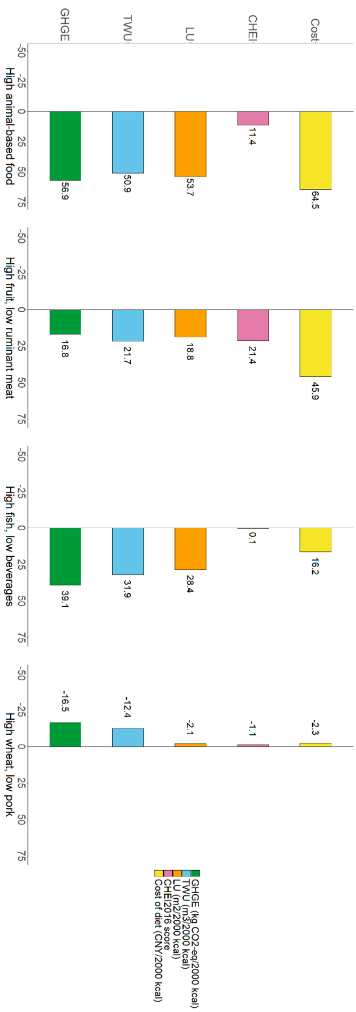

Figure 3.2. Comparison of mean sustainability indicators for Decile 10 of adherence of the dietary patterns derived with Reduced Rank Regression with the average CHNS population

Table 3.3. Associations between the socio-demographic characteristics of participant and the five derived dietary patterns in the 2011 CHNS. (n = 10,324)[1].

Participants (n)	**High animal-based food**		**High fruit, low ruminant meat**		**High fish, low beverages**		**High wheat, low pork**	
	Coefficient*	95% CI	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI
Gender (female vs male ref, category)	5.57*	(1.17, 9.98)	17.98***	(13.83, 22.14)	1.07	(-1.31, 3.46)	4.26***	(2.32, 6.21)
Age (per 10 years)	-3.42***	(-4.97, -1.86)	-0.69	(-2.17, 0.77)	0.68	(-0.16, 1.53)	-0.63	(-1.32, 0.05)
BMI (kg/m^2)	-1.44***	(-1.84, -1.05)	0.41*	(0.03, 0.78)	-0.36***	(-0.57, -0.14)	0.61***	(0.44, 0.79)
Household income (per 1,000 CHY/year)	0.48***	(0.38, 0.58)	0.35***	(0.25, 0.44)	-0.08**	(-0.13, -0.03)	-0.08***	(-0.12, -0.03)
Degree of urbanization (rural vs urban area)	-39.84***	(-43.51, -36.17)	-14.12***	(-17.58, -10.65)	-7.24***	(-9.23, -5.26)	1.33	(-0.28, 2.95)
Dietary knowledge (Being aware of the dietary guidelines, vs not)	1.93	(-1.91, 5.78)	23.37***	(19.73, 27.01)	-6.88***	(-8.96, -4.81)	5.41***	(3.71, 7.11)
Educational level								
Secondary school, vs primary school or below	2.33	(-1.83, 6.51)	14.67***	(10.73, 18.61)	-2.23	(-4.48, 0.02)	3.05***	(1.21, 4.91)
High school and above, vs primary school or below	16.93***	(11.07, 22.79)	27.41***	(21.87, 32.94)	-7.56***	(-10.73, -4.39)	5.67***	(3.09, 8.26)
Activity level								
Medium, vs low	-1.97	(-5.12, 4.67)	-6.26**	(-10.89, -1.63)	3.19*	(0.53, 5.84)	-1.52	(-3.68, 0.64)
High, vs low	-17.89***	(-22.41, -13.37)	1.23	(-5.49, 3.03)	-3.87***	(-6.31, -1.43)	6.72***	(4.73, 8.72)
Smoking status								
Current smoker vs non-smoker	1.97	(-2.87, 6.82)	-4.61	(-9.19, -0.02)	-1.27	(-3.89, 1.35)	-0.35	(-2.49, 1.79)
Ex-smoker, vs non-smoker	7.84	(-1.81, 17.49)	12.81	(3.71, 21.93)	-2.73	(-7.95, 2.48)	1.77	(-2.48, 6.03)

[1] Level of significance: *** <0.001, ** <0.01, * <0.05.
* The coefficients in the model represent the absolute values of the dietary scores. The score averages 51.9 and ranges from 13.4 to 90.8.

3

3.4 Characteristics of Adherents of the Dietary Patterns

Distinct socio-demographic profiles emerge among adherents to different dietary patterns. Adherents to the "High animal-based food" pattern were characterized by higher education levels, greater income, lower physical activity, and urban residence (**Table 3.3**). Similarly, those following the "High fruit, low ruminant meat" pattern exhibited characteristics of being female, a significant proportion displaying knowledge about dietary guidelines, higher education levels, and residing in urban areas. In contrast, those following the "High fish, low beverages" pattern had less familiarity with healthy dietary guidelines and lower education level. Distinct from other patterns, the adherents to the "High wheat, low pork" pattern had higher education levels and activity levels. Remarkably, in all models, no significant association was observed between smoking status and dietary patterns.

4 Discussion

We derived four distinctive dietary patterns in the 2011 Chinese Health Nutrition Survey by using the hybrid RRR approach, namely the "High fruit, low ruminant meat," "High animal-based food," "High wheat, low pork," and "High fish, low beverage". These patterns were derived using the explained variance of diet quality, dietary environmental impacts, and dietary costs. Among them, the "High fruit, low ruminant meat" pattern exhibited the strongest correlation with diet quality (r=0.507). However, it tended to be more costly (r=0.462) while displaying a lesser connection to dietary environmental impacts, with modest correlations observed for GHGE (r=0.141), TWU (r=0.226), and LU (r=0.164). Conversely, the "High animal-based food" pattern displayed a weaker association with diet quality (r=0.332) and manifested high dietary environmental impacts, exhibiting substantial correlations with GHGE (r=0.765), TWU (r=0.715), and LU (r=0.647). This pattern also ranked as the most expensive among the dietary patterns identified. The "High wheat, low pork" pattern emerged as a distinctive dietary choice, contributing positively to all outcome measures. It demonstrated a weak correlation with diet quality (r=0.072) and displayed slightly lower dietary environmental impacts, indicated by negative correlations for GHGE (r=-0.156), TWU (r=-0.106), and LU (r=-0.031). Additionally, it incurred slightly lower dietary costs (r=-0.057). Meanwhile, the "High fish, low beverage" pattern was associated with a reduction in diet quality (r=-0.013), an increase in dietary costs (r=0.021), and similarly elevated dietary environmental impacts, with positive correlations observed for GHGE (r=0.404), TWU (r=0.313), and LU (r=0.227). In terms of the goals of reducing dietary environmental impacts and diet costs, the "High wheat, low pork" pattern emerges as the most environmentally sustainable and cost-effective choice of the current dietary patterns, although this pattern would not increase population health. Conversely, the "High animal-based food" pattern ranks as the most expensive with the highest environmental impacts.

Previous studies have extensively documented the significant contributions of animal-based foods to diet-related environmental impacts(28,29). Furthermore, some research has highlighted the potential cost benefits associated with reducing animal-based foods in the diet(30). However, the healthy and environmental sustainable EAT-Lancet diet was associated with increased cost(31). In line with our study, diets adhering to the "High animal-based food" pattern exhibited significantly higher levels of diet-related environmental impacts and dietary costs compared to the average population. Conversely, the derived "High wheat, low pork" pattern exhibits reduced dietary environmental impact and dietary costs compared to the average Chinese diets, primarily attributable to its limited incorporation of animal-based foods. However, it is essential to note that for dietary quality, the CHEI2016 score associated with the "High wheat, low pork" pattern slightly falls below the observed score in the average population (51.3 vs. 51.9 points) (**Supplementary Table 3**). This can be attributed to the fact that adherents of the "High wheat, low pork" pattern consumed less chicken and fish with elevated consumption of fruits and whole grains compared to the average population (**Supplementary Table 3**). Moreover, in the "High wheat, low pork" pattern, beef contributes a large part of the variation; adherents of this pattern replace pork with a small portion of beef. Despite the relatively increased beef consumption, the overall meat consumption in adherents of the "High wheat, low pork" pattern maintains a modest share at 8.6%, notably falling below the average population of 15.1%. Specifically, those with low adherence to the "High wheat, low pork" pattern showed a high pork consumption level of 101.0 grams. Conversely, individuals with high adherence to the "High wheat, low pork" pattern exhibited a decrease in pork consumption to 36.4 grams. Simultaneously, beef consumption experienced an increase from 35.9 grams in the low adherents to 68.8 grams in the high adherents (**Table 3.1**). Within the most adherents of the "High wheat, low pork" pattern, there exists a trade-off relationship between beef and pork consumption. Conversely, the proportion of animal-based food in the diet of decile 10 of the "High animal-based food" pattern was 19.0%, the highest among the four derived dietary patterns. Although increasing the consumption of beef is not recommended from the perspective of environmental or nutritional health (32), this association reflects the inverse association between beef and other types of animal protein sources in current Chinese diets.

When comparing the dietary patterns to those of other countries, several similarities and differences emerge. A study conducted in the Dutch EPIC-NL cohort applied the RRR approach with the DHD15-index of diet quality and diet-related GHGE as dependent variables and concluded that the "plant-based diet" exhibited greater health benefits and an inverse relation to GHGE (33). This is not consistent with the "High wheat, low pork" model derived in this study, which may be due to the different response variables used. Land use, water use, and affordability issues were not addressed in the Dutch cohort study. In an investigation conducted using data from the 2012-2016 Dutch National Food Consumption Survey(33), a dietary pattern characterized as 'high dairy, low fruit juices' was identified. This dietary pattern was found to be healthier while exhibiting higher dietary GHGE, aligning with the findings from our "High animal-based food" pattern. A recent systematic review emphasized that a shift towards reducing red meat and alcoholic beverage consumption, coupled with an increase in the consumption of fish, fruits, and vegetables, constitutes a pivotal factor for environmental enhancement, particularly in terms of reducing dietary GHGE and land use(34). This is in line with the "High wheat, low pork" dietary pattern identified in our study. Another study conducted in five European countries applied energy-adjusted factor analysis to identify dietary clusters based on nutrient intake and GHGE as variables(35). In line with our results, clusters with the lowest dietary GHGE had the poorest nutritional quality. In this study, the adherents of the "High wheat, low pork" pattern had the lowest diet cost among the different dietary patterns, but also no increase in dietary quality. A study assessing the affordability of healthy and sustainable diets across various income groups on a global scale revealed a notable increase in the cost associated with procuring a food basket that aligns with both health and sustainability objectives. These findings bear a resemblance to the outcomes observed in the "High fruit, low ruminant meat" dietary patterns identified in our current study(36).

The transition to healthy diets can lead to varying trade-offs and synergies with environmental impacts, depending on the proportion of animal-based foods in dietary patterns (37,38). In low- and middle-income countries (LMIC), the EAT-Lancet diet may lead to a 25% to 75% rise of per capita water use (39), and a 3-8% increase of GHGE (40). This can be attributed to an increased consumption of vegetables, fruits, nuts, legumes, and various animal-based foods compared to current dietary patterns in LMIC. Conversely, high-income countries transitioning to the EAT-Lancet diet witness a decrease in per capita dietary GHGE by 40%-50% (41), TWU by 25%-50%(42), which can be attributed to the high consumption of resource-intensive meat products in typical diets in high-income countries(43).

4.1 Policy implications

This study applied dietary environmental impact, dietary health index, and dietary cost as the response variables, thereby the factor loadings reflect combinations of food groups and the trade-offs between them. None of the derived dietary patterns exhibited a combination of the highest CHEI2016 score, the lowest dietary environmental impacts, and reduced or similar cost of the diet. Although the "Low wheat, high pork" pattern has a low environmental impact and low cost, it is not an improvement in terms of dietary quality relative to the average current diet. Given that the dietary patterns are derived from the food consumption data of the Chinese population, it can be inferred that these patterns may be socially acceptable for a significant portion of the population. Consequently, this model offers insights into the pursuit of sustainable diets: the challenge of enhancing dietary quality while maintaining environmental and cost considerations at a minimum. In comparison to the EAT-Lancet Health Reference Diet, the "Low wheat, high pork" pattern shows deficiencies in vegetable and milk consumption, while the consumption of red meat and cereals needs to be further reduced. The results of this study indicate that young individuals, urban residents, and those engaged in low-intensity labor are more inclined to follow the "High animal-based food" pattern. Conversely, individuals with higher levels of education, rural residents, and those involved in labor-intensive work tend to adhere to the "High wheat, low pork" pattern. Education campaigns, especially those targeted at young people, can play a crucial role in promoting healthy and sustainable dietary pattern(44). These education campaigns may encourage the adoption of sustainable eating habits, such as increased consumption of fruits and vegetables and reduced food waste, from an early age(45). Certainly, the reduction of meat consumption has been established as a pivotal factor in promoting both dietary sustainability and environmental well-being(46,47). Previous studies revealed that foods with similar nutritional profiles can exhibit substantial differences in GHGE(48). Individuals who habitually consume a significant proportion of animal-based foods, as indicated by their adherence to "High animal-based food" pattern, may derive benefits from incorporating plant-based alternatives, like legumes, nuts and seeds or food products with innovative protein sources as substitutes for meat products (49,50). Therefore, through the dietary choices mentioned above, individuals within the "High animal-based food" pattern can effectively mitigate dietary environmental impacts and lower dietary costs, facilitating a transition towards more sustainable diets. Similarly, consumers adhering to the "High wheat, low pork" pattern should choose foods with high nutritional quality, low environmental impacts, and lower cost, thereby improving diet quality and maintaining low dietary environmental impacts.

Our findings indicate that dietary patterns that adhere more closely to the Chinese Dietary Guidelines (higher CHEI scores) were associated with increased dietary costs. The dietary guidelines are typically designed with a primary focus on promoting health and may not inherently consider linkages to environmental sustainability and affordability(51). In a comprehensive review encompassing 83 countries' national food-based dietary guidelines(52), it was revealed that only four countries, namely Brazil, Sweden, Qatar, and Germany, had incorporated specific sustainability considerations into their guidelines, while affordability was not mentioned at all. Studies indicate that health-conscious and environmentally sustainable diets tend to be less affordable(31), a trend that is particularly pronounced in lower- to middle-income countries and among individuals from lower SES groups(53). To mitigate the cost of diets, governmental efforts should prioritize agricultural policies and public food procurement strategies aimed at enhancing food productivity and diversity(54). Concurrently, there is a need to improve market infrastructure and supply chains, facilitating the accessibility of a wide range of nutritious foods in the market(55). This emphasis should particularly encompass fruits, vegetables, and legumes(56).

In addition, the government can provide agricultural subsidies for plant-based agricultural products such as vegetables and fruits to encourage sustainable dietary transitions transition(57). Furthermore, discouraging the consumption of foods with minimal nutritional value, such as sugar-sweetened beverages, cakes, and cookies – often associated with a higher environmental impacts(58) – can be achieved through appropriate policies and clear food labeling, aiding consumers in making informed choices. The interrelationships between diet quality, diet costs, and environmental impact also highlight the importance of their trade-offs and synergies when designing dietary guidelines that respect the planetary boundaries(59). This requires an interdisciplinary and multistakeholder perspective to balance interests from politics, civil society, and the private sector(60).

4.2 Strengths and limitation

The innovation of this study bridges this gap by applying the Reduced rank regression method, to identify dietary patterns that not only promote health but also align with environmental sustainability and reduced dietary costs. The conventional diet models often struggle to capture the realistic aspects of cultural considerations, making the optimized patterns less applicable. Moreover, this study is unique in its integration of diverse dimensions, moving beyond a singular focus on greenhouse gas emissions to include land use, water use and cost of diet. By applying RRR to the Chinese Health and Nutrition Survey, this study provides insights for decision-making by policymakers in low- and middle-income countries, where such methods have been less explored.

Nevertheless, several limitations need to be considered as well. Firstly, memory-based 24-hour dietary recalls are susceptible to recall bias and underreporting (61), such day-patterns should be used less frequently in the population, which was accounted for by standardizing food consumption to 2,000 kcal/day. Additionally, the response variables in this study were limited to encompass indicators of environmental impacts, dietary costs, and the CHEI2016. Future studies should strive to incorporate a broader range of response variables that capture the multifaceted dimensions of sustainability. Potential examples include measuring food availability in the food environment, pesticides and biodiversity, as well as evaluating the cultural acceptance of specific dietary practices in specific cultural contexts. While using the lowest free market price may not fully capture the typical economic impact of dietary patterns, focusing primarily on the most cost-effective options available(62), it's essential to acknowledge that employing the lowest cost estimate is a common practice in estimating the cost of healthy diets. However, its practicality may vary, as visiting numerous stores is often impractical. Despite its limitations, this approach is widely utilized in the field(63), and future research could improve accuracy by recording unit prices for each consumed food item during dietary surveys. In addition, a validated 2022 Chinese Healthy Diet Index is not available yet. However, both the 2016 and 2022 Chinese Dietary Guideline promote a higher consumption of dairy products while reducing recommendations for grains (**Supplementary Table 6**), with recommendations for other food groups remaining unchanged. It can be inferred that the more closely the 2022 Dietary Guideline are followed, the greater the environmental impact of the diet. Therefore, even if the 2022 Chinese Dietary Guideline was adopted, it would not alter the conclusion reached in this study that there is still a trade-off between dietary quality and environmental impacts. We understand the importance of incorporating the latest data to accurately capture the current dietary pattern in China. To assess individual-level regional variations, cultural practices, and dietary preferences, we used CHNS dietary data of 2011, as more recent CHNS data are not accessible through open access channels. Although major changes in the Chinese diet composition have occurred in the period 1960-2010, the consumption of the major food groups seem to have stabilized thereafter(64). Despites differences in methodology of data collection, individual-level CHNS 2011 data and per capita data from the China National Bureau of Statistics 2013-2021, show that the dietary pattern of China remains predominantly plant-based (**Supplementary Table 4**). In the CHNS 2011, the consumption proportions of plant-based foods were 35.3% for cereals, 27.3% for vegetables, and 5.9% for fruits. According to the China National Bureau of Statistics data (2021), the consumption proportions were similar for cereals (35.0%) and vegetables (26.6%) while fruits were somewhat higher(14.7%). Consequently, the statistical data suggest that tome trends have stabilized and that dietary composition is largely similar according top per capita data. It is therefore unlikely that the use of CHNS 2011 data has significantly impact the generalizability of our conclusions regarding the associations between health and environmental sustainability in Chinese dietary pattern.

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.

5. Conclusion

In this study, reduced rank regression was applied to identify sustainable dietary patterns within the participants of the Chinese Health Nutrition Survey 2011. The study used a comprehensive array of indicators, including dietary quality, environmental impact, and affordability. Four dietary patterns were identified: "High animal-based food", "High fruit, low ruminant meat", "High fish, low beverages", and "High wheat, low pork". None exhibited the desired combination of increased CHEI2016 scores, reduced dietary environmental impact, and reduced dietary costs. These outcomes highlight trade-offs between these dimensions of the dietary pattern. Nevertheless, the "High wheat, low pork" diet exhibited noteworthy reductions in dietary greenhouse gas emissions by 21.7%, total water use by 16.5%, and land use by 10.4%. Additionally, this pattern demonstrated 13.4% lower costs while maintaining a similar CHEI2016 score. The "High wheat, low pork" pattern suggests the feasibility of adopting lower cost and environmentally sustainable diets without compromising current dietary quality. The observed associations between dietary patterns and socio-demographic factors underscore the need for targeted educational campaigns to promote sustainable and healthy eating habits, particularly among young individuals and urban populations. It is recommended that dietary guidelines include explicit recommendations regarding environmental sustainability and affordability.

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Supplementary material

Supplementary Table 3.1. Chinese Healthy Eating Index 2016 (CHEI2016) components and standard for scoring.

Component	Score		
	0	5	10
Adequacy for food consumption			
Cereals	0	≥2.5 SP/1000 kcal	
Whole grains and mixed beans	0	≥0.6 SP/1000 kcal	
Tubers	0	≥0.3 SP/1000 kcal	
Total vegetables (excluding dark vegetables)	0	≥1.9 SP/1000 kcal	
Dark vegetables	0	≥0.9 SP/1000 kcal	
Fruits	0		≥1.1 SP/1000 kcal
Dairy	0	≥0.5 SP/1000 kcal	
Soybeans	0	≥0.4 SP/1000 kcal	
Fish and seafood	0	≥0.6 SP/1000 kcal	
Poultry	0	≥0.3 SP/1000 kcal	
Eggs	0	≥0.5 SP/1000 kcal	
Seeds and nuts	0	≥0.4 SP/1000 kcal	
Limitation for food consumption			
Red meat	≥3.5 SP/1000 kcal	≤0.4 SP/1000 kcal	
Edible oils	≥32.6 g/1000 kcal		≤15.6 g/1000 kcal
Sodium	≥3608 mg/1000 kcal		≤1,000 mg/1000 kcal
Added sugars	≥20% of energy	≤10% of energy	
Alcohol	≥25 g (men)/ 15 g (women)	≤60 g (men)/40 g (women)	

Supplementary Table 3.2. Explained variation in the consumption of food groups and sustainable indicators accounted for by Reduced Rank Regression dietary patterns (extracted from n =10,324).

	High animal-based food	High fruit, low ruminant meat	High fish, low beverages	High wheat, low pork	Dietary Pattern 5
Explained variation in sustainable indicators (%)	66.29%	9.14%	2.38%	1.48%	0.46%
Explained variation in food groups[1] (%)	4.63%	3.74%	2.95%	2.37%	2.03%

[1]Food groups were adjusted for total energy intake (2000 kcal/d)

Supplementary Table 3.3. Total CHEI2016 score and components of participants in the China Health Nutrition Survey 2011 (n = 10,324), and in decile 1 and decile 10 of dietary pattern derived by the Reduced Rank Regression[1].

Components of CHEI score	Average CHNS	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
		Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10
Cereals	4.6	4.9	4.2	4.9	4.0	4.0	4.8	4.8	4.6
Whole grains and mixed beans	1.5	2.5	0.9	0.9	1.9	1.9	0.9	0.9	2.6
Tubers	2.0	2.6	1.6	1.2	2.5	2.8	1.2	1.4	2.7
Total vegetables (excluding dark vegetables)	3.1	2.7	3.7	3.2	3.1	2.0	4.4	3.3	2.6
Dark vegetables	2.7	1.9	3.5	2.9	2.9	1.9	3.6	3.0	2.2
Fruits	3.4	1.2	6.6	0.5	9.5	4.4	2.0	2.1	4.8
Dairy	0.7	0.1	1.6	0.1	2.0	1.1	0.4	0.4	0.7
Soybeans	2.7	2.0	2.7	2.2	3.1	2.3	3.0	2.4	2.1
Fish and seafood	1.9	0.5	3.2	1.6	2.3	1.2	3.4	2.1	0.9
Poultry	1.6	0.7	2.3	1.5	1.8	1.2	1.8	1.8	0.8
Eggs	2.6	2.2	2.8	1.7	3.6	2.5	2.9	2.1	2.7
Seeds and nuts	0.8	0.5	0.8	0.4	1.2	1.0	0.6	0.6	0.7
Red meat	2.2	2.3	1.6	1.7	2.7	2.5	1.7	1.8	2.1
Sodium	7.7	7.3	7.6	7.7	7.8	7.5	7.4	7.8	7.5
Edible oils	9.1	9.0	9.4	8.9	9.4	9.1	9.0	9.1	9.3
Alcohol	0.3	0.2	0.5	0.1	0.4	0.7	0.1	0.3	0.1
Added sugars	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Total CHEI2016 score	51.9	45.5	57.8	44.5	63.0	51.2	51.9	48.9	51.3

Supplementary Table 3.4. Proportion of Food consumption (%) in China from National Bureau of Statistics 2013-2021[1] and in CHNS 2011

Food group	CHNS 2011	2013	2014	2015	2016	2017	2018	2019	2020	2021
Cereal	35.3	41.0	39.4	37.8	36.8	36.1	35.5	34.9	36.2	35.0
Edible oils	2.9	3.0	2.8	3.1	3.0	2.8	2.8	2.7	2.6	2.7
Vegetable and fungus	27.3	27.0	27.1	27.5	27.7	27.5	26.8	26.6	26.7	26.6
Meat	6.8	7.2	7.3	7.3	7.2	7.5	8.4	7.3	6.4	8.0
Poultry	1.5	1.9	2.2	2.2	2.5	2.5	2.5	3.0	3.3	2.9
Aquatic products	2.4	2.8	3.1	3.1	3.0	3.3	3.1	3.8	3.6	3.4
Eggs	2.8	2.2	2.5	2.8	2.8	2.8	2.8	3.0	3.3	3.1
Milk	2.5	3.3	3.6	3.4	3.3	3.3	3.4	3.5	3.3	3.4
Fruit	5.9	11.3	11.7	12.6	13.3	13.9	14.5	15.1	14.4	14.7
Sugar	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2

[1] National Bureau of Statistics of China. https://data.stats.gov.cn/easyquery.htm?cn=C01

Supplementary Table 3.5. Environmental footprints values from literature for food groups in the CFLCAD*

	Greenhouse gas emissions (GHGE)			Total Water Use (WU)			Land Use (LU)		
Food group	**# GHGE values**	**Mean (kg CO_2-eq/kg)**	**Stdev**	**# TWU values**	**Mean (M^3/kg)**	**Stdev**	**# LU values**	**Mean (M^2/kg)**	**Stdev**
Vegetables	133	0.266	0.292	111	0.491	0.775	8	0.402	0.552
Cereals	490	1.016	0.806	468	1.290	0.856	33	1.538	0.950
Fast foods	3	1.334	1.616	3	0.813	0.076	3	1.920	1.106
Aquatic products	16	7.029	6.358	41	3.235	1.881	10	2.356	2.317
Fruit	64	0.353	0.246	53	0.574	0.445	1	0.640	--
Legumes	14	0.832	0.681	49	2.512	0.944	1	0.810	--
Meat	122	5.134	2.350	61	8.970	6.204	12	13.179	10.197
Sugars and preserves	4	0.689	0.479	7	0.797	0.559	2	1.615	0.955
Beverages	4	0.931	0.815	4	5.228	4.735	1	1.480	
Liquor and alcohol	4	0.726	0.454	9	0.803	0.998	2	1.075	1.223
Poultry	21	3.784	2.128	19	3.030	1.105	4	2.035	0.595
Dairy	67	1.297	0.404	14	1.609	0.614	12	2.911	2.945
Eggs	22	2.890	1.215	17	3.257	0.176	2	1.360	0.156
Nuts and seeds	2	0.695	0.290	23	1.400	0.345	--	--	--
Tubers, starches	7	0.291	0.367	41	0.926	0.516	--	--	--
Fungi and algae	1	0.930	--	1	0.270	--	--	--	--
Fats and oils	5	1.822	1.404	19	4.475	1.626	3	5.210	0.292
Total	979			940			94		

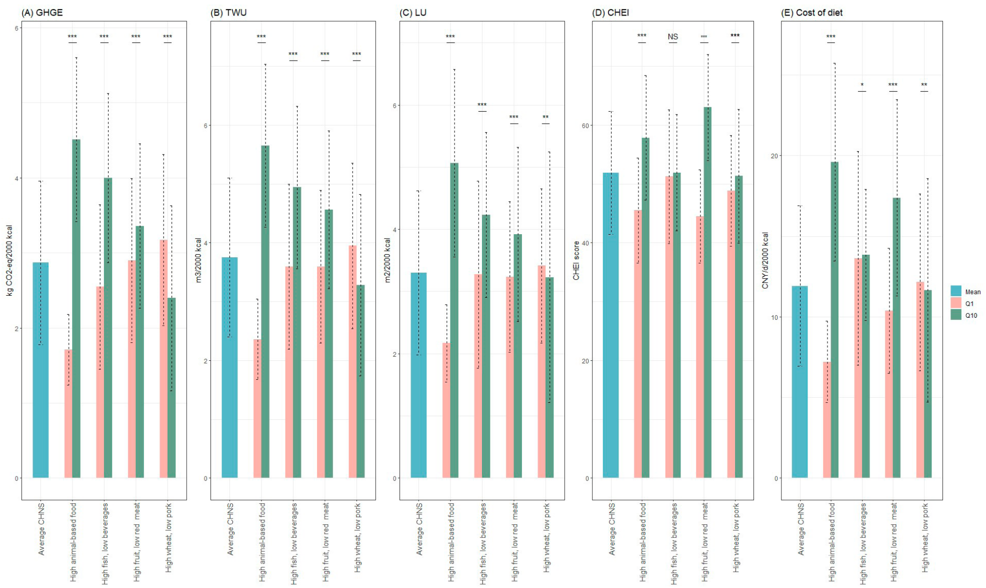
*The detail of environmental impacts of food items can be found: https://data.mendeley.com/datasets/37jnjbt454/3

3

Supplementary Table 3.6. Comparing the Chinese Dietary Guidelines of 2016[1] and 2022[2].

Food group	2016 (grams)	2022 (grams)
Salt	< 6	< 5
Edible oils	25-30	25-30
Milk and dairy products	300	300-500
Soybean and nuts	25-35	25-35
Meat and poultry	40-75	
Aquatic product	40-75	Animal-based food 120-200g (aquatic products at least 2 times a week; one egg per day)
Eggs	40-75	
Vegetables	300-500	300-500
Fruits	200-350	200-350
Cereals and tubers	250-400	200-300
Whole grains and mixed beans	50-150	50-150
Tubers	50-100	50-100

[1] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5018612/
[2] https://en.chinacdc.cn/health_topics/nutrition_health/202206/t20220622_259773.html



Supplementary Figure 3.1. Mean sustainable indicators (with standard deviation) of the highest and lowest quartile of adherence of the dietary patterns derived with Reduced Rank Regression compared to the CHNS mean[1].

[1] *p*-value was determined by Kruskal–Wallis test. The number of stars indicate the *p*-value: * *p*-value <0.05, ** *p*-value <0.01, and *** *p*-value <0.001.

CHAPTER 4

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

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Abstract

Increased urbanization has been linked to transitions in dietary patterns. However, evidence on the impacts of urbanization on dietary quality, 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. 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. 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 $P < 0{\cdot}05$). 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 quality; Diet-related environmental impacts; Cost of diet; Sustainable diet; Urbanization; Multilevel model;

1 Introduction

The current global food system is facing the challenges of a growing population and increasing environmental, health, and economic problems (1). These trends are associated with urbanization processes trend and diet shifts towards high consumption levels of animal products, cooking oils, salt, and sugar, which is increasing the prevalence of overweight, obesity, and hypertension(2). In the context of population growth, these dietary transitions are having an increasingly negative impact on climate change, water resources, land availability, and ecosystems(3,4). Additionally, 3 billion people are currently unable to afford a healthy diet (5).

China has the highest rate of urbanization in the world over the past four decades (18% in 1978 to 65% in 2021)(6), the increasing urbanization indicates a growing modernized living environment with improved food environment, health care, communication, infrastructure, etc(7). Dietary patterns are shifting from a grain and vegetable-based diet to a diet high in red meat and processed foods (8), consequently affecting human health and diet-related environmental impacts (9). Moreover, the increase in overweight in rural areas of China was 64.5% higher compared to urban areas in 2000-2020 (10). Although the diet-related greenhouse gas emissions (GHGE) of rural residents in China are lower than those of urban residents, this gap is narrowing (11).

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)(12). 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(13). 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(14–16). 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?

2 Data and methodology

2.1 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(17). 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 hours for each of the three 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.

2.2 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(18). 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 4.1**). 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.

2.3 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). Additional details of CFLCAD can be found elsewhere (19). 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.

2.4 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 (20,21). 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 hours dietary recall survey. Inflation adjustment is accomplished by multiplying the cost of diet by the Consumer Price Index of 2011.

2.5 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 4.2**). 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 Jessica C. et al.(22).

2.6 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).

2.7 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 2000 kcal/d.

The crude secular trends of variables were statistically evaluated by the Jonckheere–Terpstra test in the cohort study(23). 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 4.3).** 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 (24). The closer ICC to 1, the larger the proportion of the variance that can be attributed to community level characteristics rather than individual characteristics(25). To assess the goodness of fit of these models Akaike's Information Criterion (AIC) was used(26). 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.

3 Results

The cohort study consisted of 8,330 people at baseline and reduced over the years to 4,756 in the final round (**Table 4.1**). 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 4.1** & **Supplementary Table 4.4**). 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^2/2000 kcal/d per person) respectively. Dietary TWU was 3.2 in 1997 and 3.4 m^3/2000 kcal in 2011. Similarly, the inflation-corrected diet cost rose by 80.0% from 4.5 RMB/d/2000 kcal in 2004 to 8.1 RMB/d/2000 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 4.2**). 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.

Table 4.1. Cross-sectional univariate descriptive of participants in the CHNS 1997-2011, aged 18–64 years[1]

	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[2]
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***

[1] 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.

[2] *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.

4

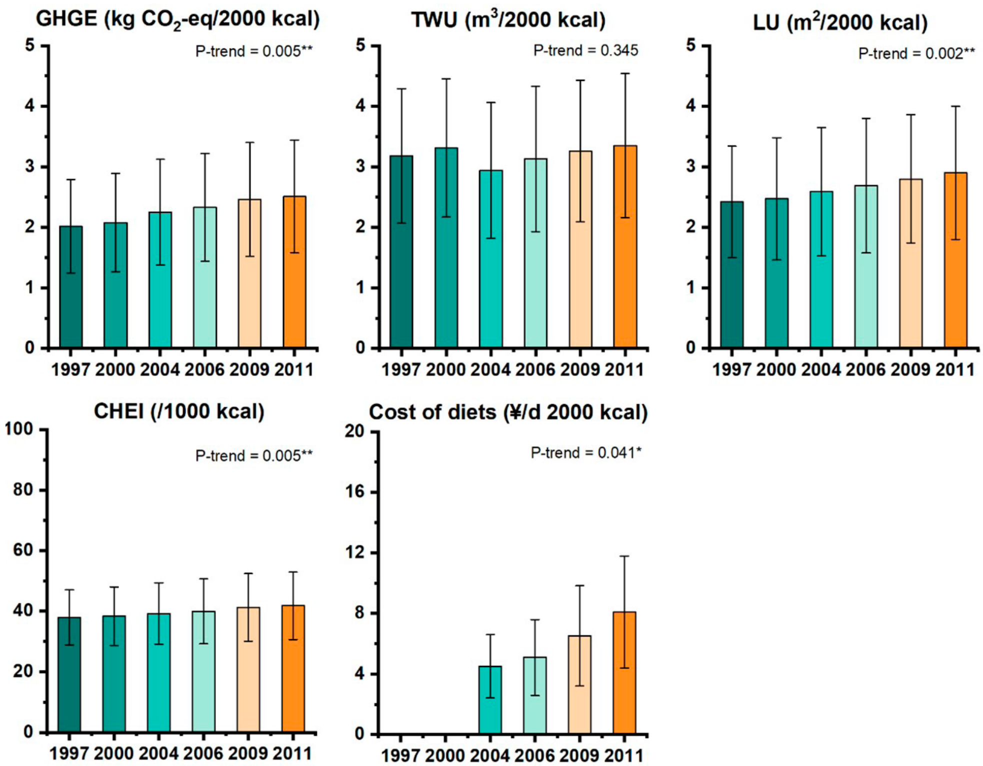

Figure 4.1. Mean and standard deviation of the diet-related GHGE, TWU, LU, CHEI2016, and cost of diet in the CHNS 1997-2011[1]

[1]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.

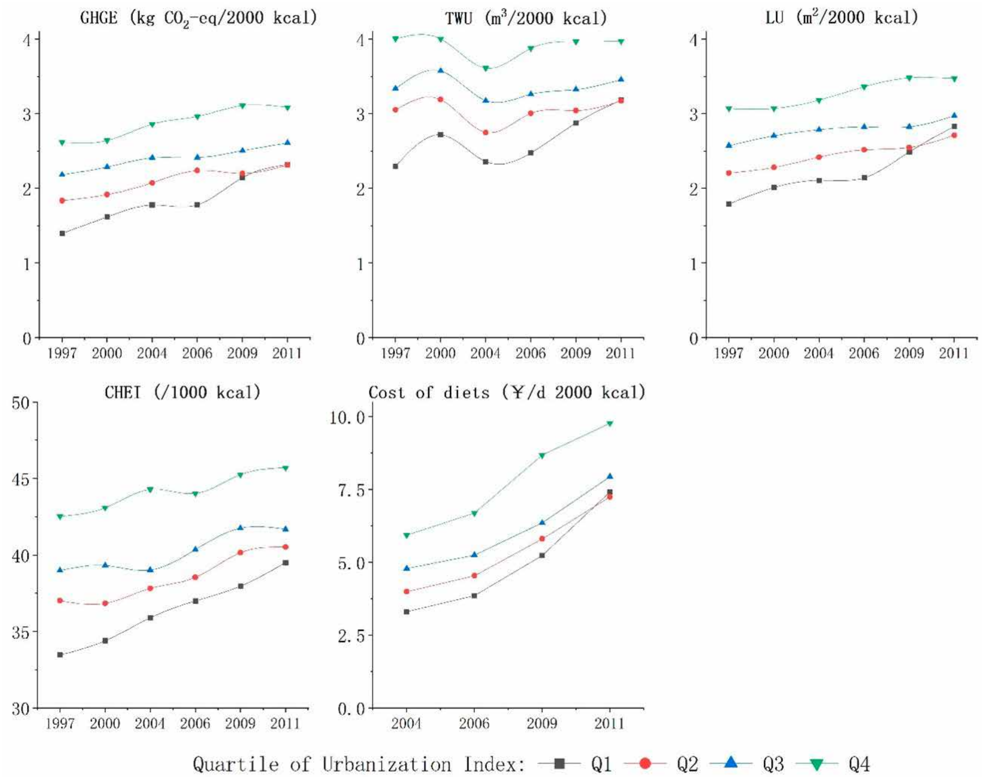

Figure 4.2. Diet-related GHGE, TWU, LU, CHEI2016, and cost of diet by quartiles of the urbanization index in the CHNS 1997-2011.

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 4.2**). An increase of 0.241 kg CO_2-eq/2000 kcal (GHGE), 0.289 m^3/2000 kcal (TWU), 0.198 m^2/2000 kcal (LU), 2.843 per 1000 kcal (CHEI2016), and 1.108 RMB/d/2000 kcal (cost of diet) for highest versus 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 4.5**).

Table 4.2. 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[1]

	GHG Emissions (kg CO_2-eq/2000 kcal)		Total Water Use (m^3/2000 kcal)		Land Use (m^2/2000 kcal)		CHEI2016 (/1000 kcal)		Cost of diet (RMB/d/2000 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)[2]										
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	v	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 Q4vsQ1)[3]	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)										

	GHG Emissions (kg CO_2-eq/2000 kcal)		Total Water Use (m^3/2000 kcal)		Land Use (m^2/2000 kcal)		CHEI2016 (/1000 kcal)		Cost of diet (RMB/d/2000 kcal)	
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
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 & 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[4]	0.784	0.781	0.791	0.784	0.724	0.718	0.758	0.748	0.937	0.942
AIC	77660	77619	102345	102547	97891	97868	247796	247764	89944	89916

[1] Model 1: included individual and community variables; Model 2: added urbanization components instead of urbanization index in community level from Model 1.

[2] For the cost of diet, the survey year is referenced to 2004.

[3] Unit was based on the mean of quintile 4 minus quintile 1.

[4] The inter-class correlation coefficient (ICC) is a ratio of between-community variance to total variance in dietary sustainability indicators.

4 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 versus 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 1961-2000(27). Previous studies compared sustainable diets in rural and urban areas in LMICs(28–31), 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. 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 towards 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 towards 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, reducing the adverse environmental impacts of this economic development and/or diet costs will also require interrelated changes in supply and demand.

Using population size and density alone as a measure of urbanization is biased(33). 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(34). 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(35). 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 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(36), 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 (37). 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 (38), 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(39). 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(40,41). 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(42). 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-hour recall data were included in this prospective study, which minimizes bias and provides stronger evidence for causality(43). 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(22). 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 to 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.

5 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.

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Supplementary material

Supplementary Table 4.1. Chinese Healthy Eating Index 2016 (CHEI2016) components and standard for scoring.

Component	Score		
	0	5	10
Adequacy for food intake			
Cereals	0	≥2.5 SP/1000 kcal[a]	
Whole grains and mixed beans	0	≥0.6 SP/1000 kcal	
Tubers	0	≥0.3 SP/1000 kcal	
Total vegetables (exclude dark vegetables)	0	≥1.9 SP/1000 kcal	
Dark vegetables	0	≥0.9 SP/1000 kcal	
Fruits	0		≥1.1 SP/1000 kcal
Dairy	0	≥0.5 SP/1000 kcal	
Soybeans	0	≥0.4 SP/1000 kcal	
Fish and seafood	0	≥0.6 SP/1000 kcal	
Poultry	0	≥0.3 SP/1000 kcal	
Eggs	0	≥0.5 SP/1000 kcal	
Seeds and nuts	0	≥0.4 SP/1000 kcal	
Limitation for food intake			
Red meat	≥3.5 SP/1000 kcal	≤0.4 SP/1000 kcal	
Edible oils	≥32.6 g/1000 kcal		≤15.6 g/1000 kcal
Sodium	≥3608 mg/1000 kcal		≤1000 mg/1000 kcal
Added sugars	≥20% of energy	≤10% of energy	
Alcohol	≥25g (men)/ 15g (women)	≤60g (men)/40g (women)	

[a]Stand portion (SP) 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.

4

Supplementary Table 4.2. Description of urbanization index and its components

Index Components	Description
Population density	Higher population densities indicate higher levels of urbanization.
Social services	Greater access to health insurance and childcare facilities indicates greater urbanization.
Health infrastructure	The better the access to health facilities, the more urbanization is indicated.
Modern markets	The greater the number of supermarkets, cafes, internet cafes, restaurants and fast food outlets in the community, the greater the degree of urbanization.
Traditional markets	The greater the number of farmers' markets in a community and the longer they are open, the greater the degree of urbanization.
Transportation infrastructure	The greater the number of roads, buses and train stations in a community, the greater the degree of urbanization.
Communication	The higher the percentage of households with a TV, television or mobile phone, the more cinemas, newsagents and telephone services there are in the community, indicating a higher level of urbanization.
Housing infrastructure	The higher the percentage of households with indoor running water, flushing toilets and gas stoves, and the more hours of electricity per week, the more urbanization is indicated.
Sanitation	The higher the percentage of households with treated water and no excreta in the home, the higher the level of urbanization.
Economic activity	The higher the general wage for male workers and the lower the percentage of the population working in non-agricultural jobs, the higher the degree of urbanization.
Education	The average educational attainment of adults aged 21 and over in the community, with higher average educational attainment indicating greater urbanization.
Education and income diversity	The greater the difference between the average educational attainment and household income of adults in the community, the greater the degree of urbanization.

Supplementary Table 4.3. Consumption of different food groups (g/2000 kcal) in the China Health Nutrition Survey 1997-2011.

Food group	1997		2000		2004		2006		2009		2011	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Animal-based food												
Meat	55.9	59.8	62.2	66.5	58.5	61.2	65.2	62.3	66.8	62.2	63.3	59.7
Poultry	10.5	29.8	10.8	29.0	11.3	31.9	10.9	31.2	15.0	34.9	15.1	33.6
Dairy	2.2	19.2	5.6	32.4	10.7	47.3	9.4	46.3	8.0	40.5	8.1	44.4
Eggs	20.4	31.1	22.6	35.1	23.0	34.9	26.2	36.2	27.6	35.1	29.2	36.4
Aquatic products	23.2	41.8	24.0	45.8	26.2	49.4	28.8	52.6	31.9	55.5	29.1	52.0
Plant-based food												
Cereals	414.8	118.3	386.1	120.4	400.8	133.4	380.5	123.2	391.5	152.4	434.5	197.7
Tubers	29.5	61.2	27.6	57.5	39.2	76.8	40.9	75.8	39.2	65.0	39.8	65.8
Legumes	64.1	59.7	78.7	75.1	45.0	65.3	47.7	71.1	52.4	69.4	53.1	72.4
Vegetables	267.8	142.8	270.4	161.2	330.7	182.3	327.2	178.8	328.0	177.4	326.8	187.0
Fungi	3.7	14.8	3.2	12.9	3.5	14.8	3.0	12.7	5.1	17.8	5.9	18.0
Fruit	9.5	40.2	13.6	57.9	21.2	72.7	48.7	151.5	50.4	108.8	71.7	129.1
Nut	2.0	8.7	2.8	11.3	2.6	11.3	2.8	13.8	3.6	16.5	4.3	14.7
Other foods												
Fast foods	2.1	13.4	2.6	13.6	10.0	38.1	19.1	50.7	22.7	55.2	31.4	67.8
Beverages	0.4	6.5	0.3	9.0	0.8	12.9	1.9	20.3	3.4	48.0	5.0	39.7
Liquor	10.0	57.9	11.0	65.6	14.1	70.5	18.2	97.4	15.4	79.4	15.7	79.1
Sugar	2.9	10.6	3.2	12.5	1.3	5.8	1.2	5.7	2.0	8.3	2.0	7.0
Edible oils	27.6	19.0	28.6	19.2	29.3	19.2	29.5	19.7	32.0	22.4	35.7	24.1
Condiments	27.3	23.6	27.4	23.9	31.6	31.5	31.2	38.2	38.4	35.9	36.8	31.4

Supplementary Table 4.4. The fit of the multilevel random intercept model and multilevel random slope and intercept model for diet-related GHGE, TWU, LU, CHEI2016, and cost of diet based on likelihood ratio test.

Models		GHG Emissions	Total Water Use	Land Use	CHEI2016	Cost of diet
Multilevel random intercept Model[1]	Urbanization index	0.012***	0.018***	0.147***	0.125***	0.124***
	Intercept	1.778***	2.237***	2.027***	33.048***	-1.203***
	Log likelihood	-30276.2	-37982.7	-37787.9	-92103.7	-70976.8
	AIC	60560.3	75973.5	75583.9	184215.5	141961.7
Multilevel random slope and intercept Model[2]	Urbanization index	0.011***	0.016***	0.014***	0.109***	0.163***
	Intercept	1.775***	2.267***	2.024***	33.843***	-2.933
	Log likelihood	-29978.5	-37708.8	-37605.7	-91935.3	-69887.4
	AIC	59969	75429	75223	183882	139787

[1] Testing for random intercept: a likelihood ratio test was carried out to compare the multilevel random intercept model with a normal linear regression model. Chi-Square Probabilities 0.05 (2)=5.991
[2] Testing for random slopes: a likelihood ratio test was used to test whether the urbanization index varies across communities. Chi-Square Probabilities 0.05 (2)=5.991

Supplementary Table 4.5. Diet-related GHGE, TWU, LU, CHEI2016, and cost of diet during the dietary transition in the CHNS 1997-20111

	1997	2000	2004	2006	2009	2011	P-trend[2]
GHGE (kg CO_2-eq/2000 kcal)	2.0±0.9	2.1±0.9	2.3±0.9	2.4±0.9	2.5±1.1	2.6±1.1	0.005**
TWU (m^3/2000 kcal)	3.2±1.3	3.4±1.4	3.1±1.1	3.2±1.3	3.3±1.2	3.4±1.3	0.345
LU (m^2/2000 kcal)	2.4±1.1	2.5±1.2	2.6±1.1	2.7±1.2	2.8±1.1	3.1±1.2	0.002**
CHEI2016	37.9±9.1	38.4±9.7	39.3±10.1	40±10.7	41.3±11.2	41.9±11.1	0.005**
Cost of diets (¥/d/2000 kcal)	Not measured		4.5±2.1	5.1±2.5	6.5±3.3	8.1±3.7	0.041*

[1] Values are means ± SD.
[2] The Jonckheere–Terpstra test was used to evaluate trends of sustainable indicators by years.

Supplementary Table 4.6. The Sobel-Goodman mediation test in the impact of proportion of animal-based foods to CHEI2016, dietary environmental impacts, and cost of diet1

Dietary sustainability indicators	The Sobel-Goodman mediation test			
	Coefficients	**Z**	**p value**	**Proportion of mediation effect**
CHEI 2016	8.1	28.8	<0.001	24.5%
GHGE	0.6	30.1	<0.001	9.2%
TWU	0.9	30.3	<0.001	13.8%
LU	0.7 25.2		<0.001	11.3%
Cost of diet	3.4	32.5	<0.001	38.1%

[1] The Sobel-Goodman mediation test was conducted with the dietary sustainability indicators (predictor variable), proportion of animal food consumption (mediator), urbanization index (dependent variable), demographic characteristics (covariate).

CHAPTER 5

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.

Keywords: Diet quality; Diet-related environmental impacts; Sustainable diet; Multilevel model; Regions

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 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 socio-economic heterogeneity in dietary patterns and diet-related environmental impacts, such as income, education level, and occupation(P. He et al., 2019). 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 5.1). 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.

5

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 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 5.1). 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.

Table 5.1. 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

	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	
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).

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 5.3). After adjustments for age and sex, the CHEI2016 score was positively associated with GHGE, TWU, and LU (Figure 5.1). 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 5.2). 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.

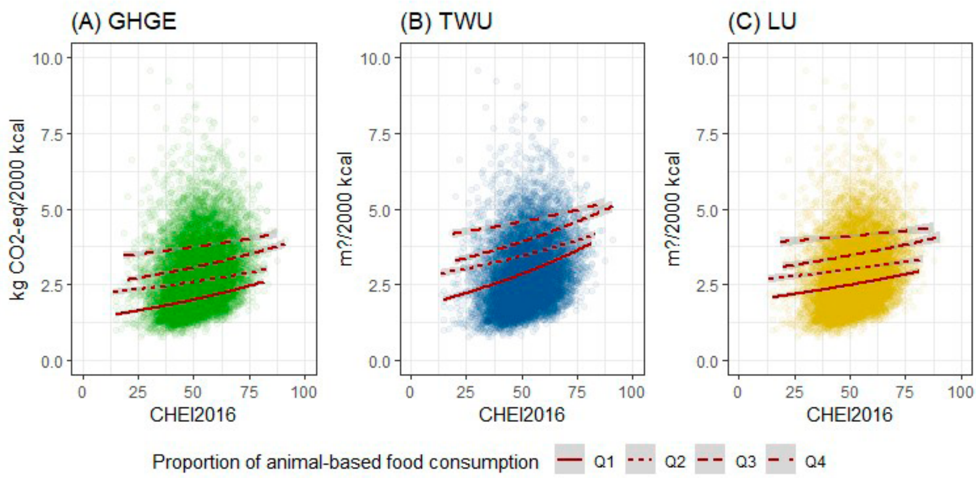

Figure 5.1. The association between CHEI2016 and dietary environmental impacts of (A) GHGE, (B) TWU, and (C) LU across quartiles of proportion of animal-based food consumption for 10,324 participants derived from the Chinese Health Nutrition Survey 2011. Dots are the individual observation. Environmental impacts and regression lines are back-transformed from analysis on the log scale.

Table 5.2. 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).

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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 CO_2-eq/ 2000 kcal in Q1 vs. 3.23 kg CO_2-eq/ 2000 kcal), TWU (3.30 m^3/ 2000 kcal in Q1 vs. 4.23 m^3/ 2000 kcal), and LU (3.02 m^2/ 2000 kcal in Q1 vs. 3.61 m^2/ 2000 kcal) (Figure 5.2). 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 5.2). In general, higher CHEI2016 score corresponded to increased diet-related environmental impacts, characterized by a higher proportion of animal-based foods in the diet.

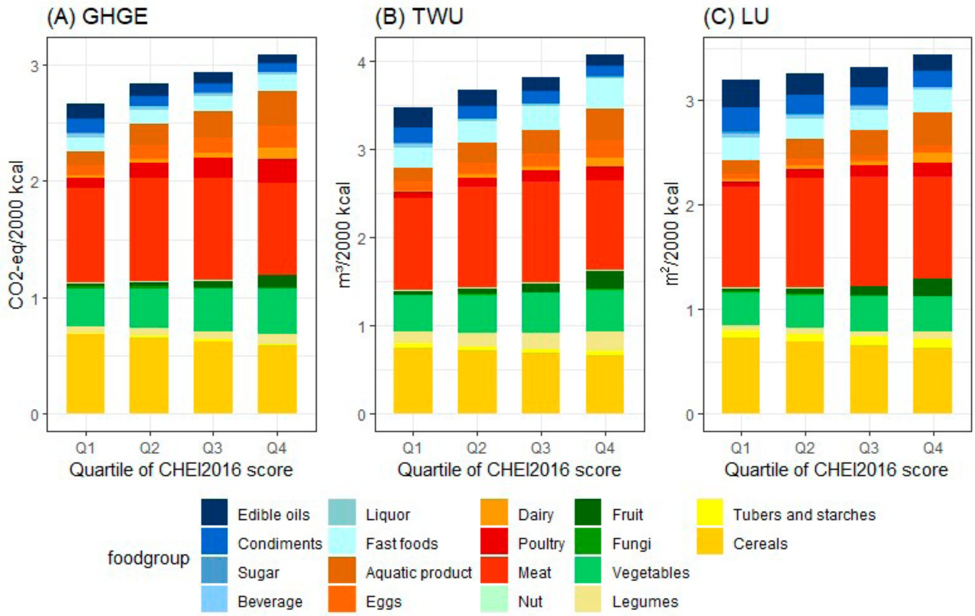

Figure 5.2. GHGE (kg CO_2-eq/2000 kcal), TWU (M^3/2000 kcal), and LU (M^2/2000 kcal) across quartiles of the CHEI score by different food groups in the Chinese Health Nutrition Survey 2011*.

*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.

3.3 Diet quality and diet-related environmental impacts across regions

Table 5.3 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 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 5.3). 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 5.3). Education level and work-related physical activity level showed a positive association with dietary environmental impacts, and with higher education level and lower physical activity level, the dietary environmental impacts were higher (Figure 5.3A&B, Supplementary Figure 5.2&3). The association between CHEI2016 and diet related GHGE, TWU, and LU differed significantly across regions (Likelihood ratio tests, Table 5.3). Figure 5.3A&B 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 5.1). 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 (Figure 5.3A&B, Supplementary Figure 5.2&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 5.4).

Table 5.3. 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

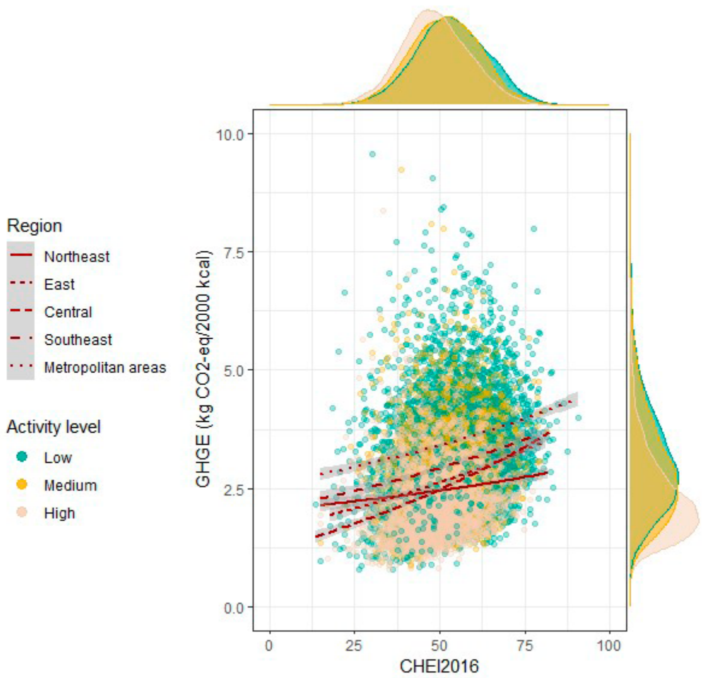

Figure 5.3A. The association between CHEI2016 and diet-related GHGE in five different regions. Dots represent the individual observation, with different colors for the level of physical activity. Environmental impacts and regression lines are back transformed from analysis on the log scale.

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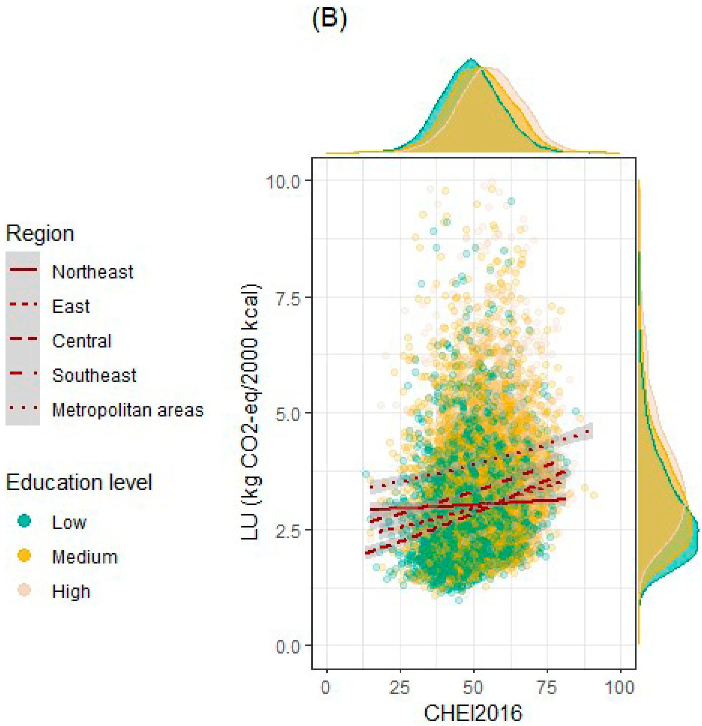

Figure 5.3B. The association between CHEI2016 and diet related GHGE in five different regions. Dots represent the individual observation, with different colors for the level of education. Environmental impacts and regression lines are back transformed from analysis on the log scale.

Table 5.4. 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 5.3.
2 The percentage of animal based food consumption (grams).

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 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 5.4). 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 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 CO_2-eq/2000 kcal, which is similar to the result of 2.7 kg CO_2-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 CO_2-eq/kg compared to 20.7 kg CO_2-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 5.5). 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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Supplementary Material

Supplementary Table 5.1. Chinese Healthy Eating Index 2016 (CHEI2016) components and standard for scoring.

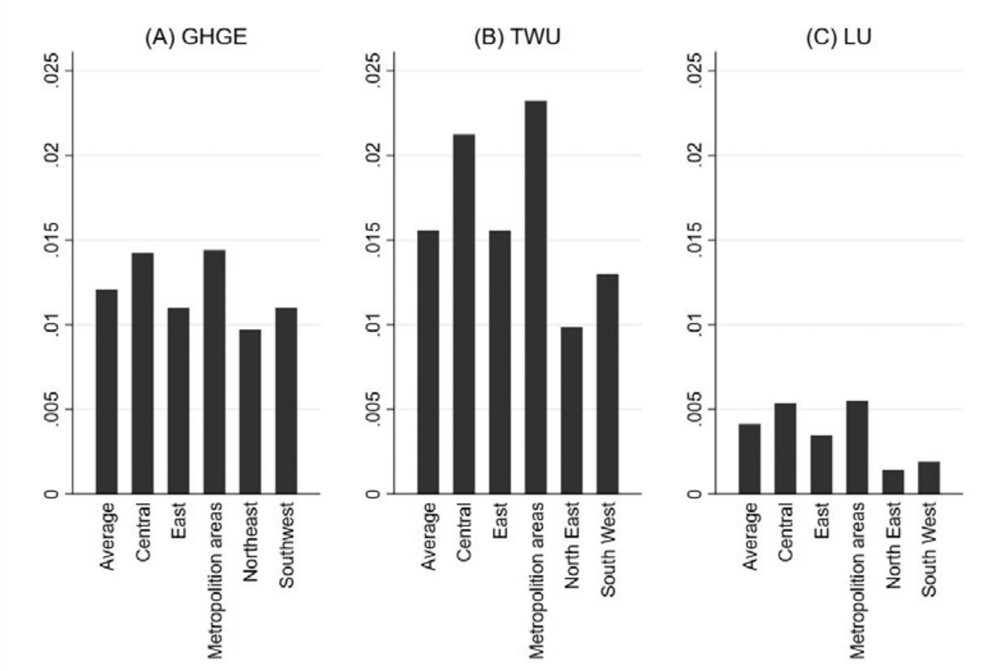
Component	Score		
	0	**5**	**10**
Adequacy for food consumption			
Cereals	0	≥2.5 SP/1000 kcal	
Whole grains and mixed beans	0	≥0.6 SP/1000 kcal	
Tubers	0	≥0.3 SP/1000 kcal	
Total vegetables (excluding dark vegetables)	0	≥1.9 SP/1000 kcal	
Dark vegetables	0	≥0.9 SP/1000 kcal	
Fruits	0		≥1.1 SP/1000 kcal
Dairy	0	≥0.5 SP/1000 kcal	
Soybeans	0	≥0.4 SP/1000 kcal	
Fish and seafood	0	≥0.6 SP/1000 kcal	
Poultry	0	≥0.3 SP/1000 kcal	
Eggs	0	≥0.5 SP/1000 kcal	
Seeds and nuts	0	≥0.4 SP/1000 kcal	
Limitation for food consumption			
Red meat	≥3.5 SP/1000 kcal	≤0.4 SP/1000 kcal	
Edible oils	≥32.6 g/1000 kcal		≤15.6 g/1000 kcal
Sodium	≥3608 mg/1000 kcal		≤1,000 mg/1000 kcal
Added sugars	≥20% of energy	≤10% of energy	
Alcohol	≥25 g (men)/ 15 g (women)	≤60 g (men)/40 g (women)	

Supplementary Table 5.2. Food group contribution (%) by dietary environmental impacts groups across quartile of the CHEI2016 in the Chinese Health Nutrition Survey 2011[1]

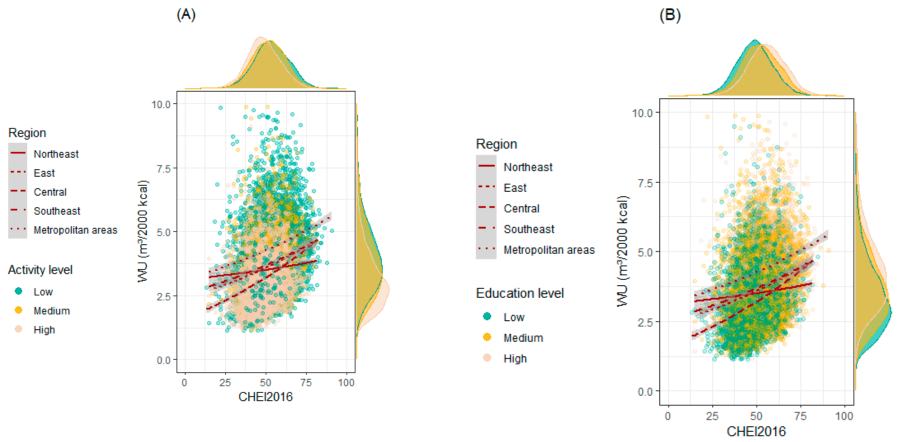
Food group contribution (%)	GHGE Q1[2] (n=2581)	GHGE Q2[2] (n=2581)	GHGE Q3[2] (n=2581)	GHGE Q4[2] (n=2581)	GHGE P-trend[3]	TWU Q1[2] (n=2581)	TWU Q2[2] (n=2581)	TWU Q3[2] (n=2581)	TWU Q4[2] (n=2581)	TWU P-trend[3]	LU Q1[2] (n=2581)	LU Q2[2] (n=2581)	LU Q3[2] (n=2581)	LU Q4[2] (n=2581)	LU P-trend[3]
Cereals	27.0%	23.5%	21.1%	18.5%	<0.001***	22.8%	20.0%	18.1%	15.9%	<0.001***	24.0%	21.6%	19.7%	17.7%	<0.004***
Tubers and starche	0.4%	0.4%	0.5%	0.5%	<0.001***	1.2%	1.1%	1.2%	1.4%	0.101	2.3%	2.2%	2.4%	2.7%	<0.006**
Legumes	1.8%	2.2%	2.4%	2.9%	<0.001***	3.4%	4.2%	4.7%	5.4%	<0.001***	1.2%	1.5%	1.7%	2.1%	<0.003***
Vegetables	12.5%	12.2%	12.2%	12.3%	0.231	12.2%	11.7%	11.8%	11.5%	0.058	9.9%	10.0%	10.0%	9.7%	0.121
Fungi and algae	0.3%	0.4%	0.5%	0.6%	<0.001***	0.1%	0.1%	0.1%	0.1%	0.021*	0.2%	0.2%	0.3%	0.4%	<0.004***
Fruit	0.5%	1.2%	2.0%	3.7%	<0.001***	0.7%	1.6%	2.8%	5.1%	<0.001***	0.6%	1.4%	2.5%	4.8%	0.245
Nuts and seeds	0.1%	0.2%	0.3%	0.4%	<0.001***	0.2%	0.2%	0.4%	0.6%	<0.001***	0.1%	0.1%	0.2%	0.3%	<0.008***
Meat	32.1%	32.0%	29.8%	24.9%	<0.001***	31.7%	31.9%	29.5%	24.5%	0.133	31.5%	32.8%	31.3%	27.7%	0.075
Poultry	3.1%	4.6%	5.8%	6.4%	<0.001***	1.8%	2.7%	3.4%	3.6%	<0.001***	1.7%	2.7%	3.3%	3.7%	0.005***
Dairy	0.5%	0.9%	1.4%	3.4%	<0.001***	0.4%	0.8%	1.1%	2.7%	<0.001***	0.4%	0.9%	1.3%	3.1%	<0.006***
Eggs	3.1%	4.3%	4.8%	6.0%	<0.001***	2.5%	3.5%	3.9%	4.8%	<0.001***	1.2%	1.6%	1.9%	2.4%	<0.004***
Aquatic products	4.4%	6.4%	7.7%	9.6%	<0.001***	4.2%	6.3%	7.1%	8.8%	<0.001***	3.9%	5.9%	7.1%	8.9%	<0.003***
Fast foods	4.3%	4.1%	4.3%	4.6%	0.912	6.8%	6.6%	7.1%	8.2%	0.371	6.5%	5.8%	5.8%	6.0%	0.423
Beverages	0.4%	0.3%	0.5%	0.5%	0.681	0.3%	0.2%	0.3%	0.3%	0.551	0.6%	0.6%	0.9%	0.9%	<0.004***
Liquor and alcohol	0.2%	0.4%	0.6%	0.6%	<0.001***	0.2%	0.4%	0.5%	0.5%	<0.001***	0.1%	0.3%	0.4%	0.4%	<0.007***
Sugar, preserves and honeys	0.1%	0.1%	0.1%	0.1%	<0.001***	0.1%	0.1%	0.1%	0.1%	<0.001***	0.2%	0.2%	0.2%	0.2%	<0.056*
Edible oils	4.9%	3.7%	3.2%	2.5%	<0.001***	6.3%	4.7%	4.2%	3.2%	<0.001***	8.4%	6.5%	5.8%	4.6%	<0.003***
Condiments	4.2%	3.1%	2.9%	2.5%	<0.001***	5.1%	3.9%	3.5%	3.1%	<0.001***	7.2%	5.6%	5.2%	4.6%	0.235
Total	100%	100%	100%	100%		100%	100%	100%	100%		100%	100%	100%	100%	

[1] Analyses were adjusted for dietary energy (g/2000 kcal/d). The scores of the Chinese Healthy Diet Index were divided into quartiles (1st the lowest and the 4th the highest).

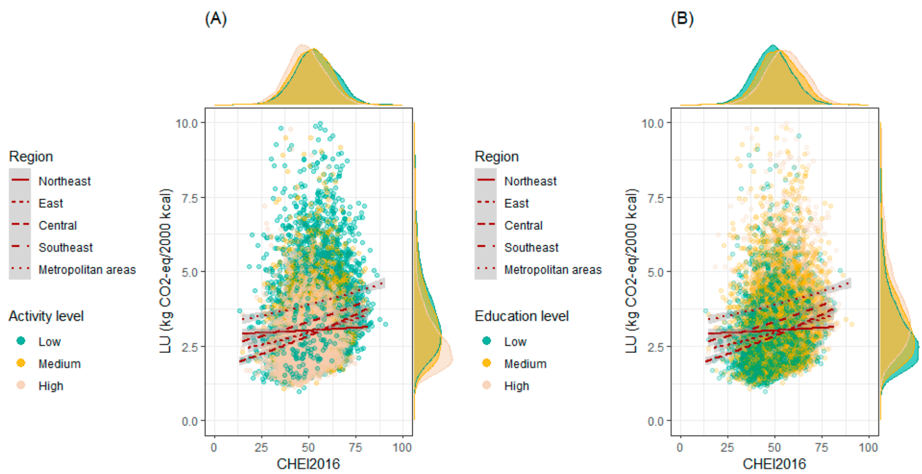
[2] Based on linear regression with quartiles of each food group treated as group linear variable.



Supplementary Figure 5.1. Chang in dietary environmental impacts of (A) GHGE, (B) TWU, and (C) LU with one standard deviation increase of the CHEI2016 score.



Supplementary Figure 5.2. The association between CHEI2016 and diet-related TWU in five different regions. Dots represent the individual observation, with different colors for the level of physical activity (A) and the level of education (B). Environmental impacts and regression lines are back transformed from analysis on the log scale.



Supplementary Figure 5.3. The association between CHEI2016 and diet-related LU in five different regions. Dots represent the individual observation, with different colors for the level of physical activity (A) and the level of education (B). Environmental impacts and regression lines are back transformed from analysis on the log scale.

Supplementary Table 5.3A. Food group contribution by dietary GHGE across education level & activity level of region in the Chinese Health Nutrition Survey 20111

	Northeast (n=1,563)		East (n=1,612)		Central (n=2,528)		Southeast (n=1,763)		Metropolitan areas (n=2,858)	
Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level
	n=269	n=322	n=203	n=214	n=342	n=360	n=181	n=310	n=892	n=149
Cereals	0.65 (22.91%)	0.75 (34.24%)	0.53 (16.32%)	0.71 (31.79%)	0.55 (18.51%	0.62 (32.91%	0.65 (21.06%)	0.89 (33.92%)	0.51 (13.48%)	0.75 (28.06%)
Tubers	0.02 (0.60%)	0.03 (1.35%)	0.01 (0.26%)	0.01 (0.49%)	0.02 (0.51%	0.01 (0.57%	0.01 (0.29%)	0.01 (0.37%)	0.01 (0.37%)	0.02 (0.89%)
Legumes	0.11 (3.99%)	0.07 (3.13%)	0.08 (2.48%)	0.06 (2.90%)	0.07 (2.48%	0.04 (1.88%	0.06 (1.81%)	0.07 (2.79%)	0.08 (2.28%)	0.03 (1.05%)
Vegetables	0.25 (8.90%)	0.26 (11.91%)	0.36 (11.15%)	0.31 (14.02%)	0.38 (12.83%	0.31 (16.23%	0.32 (10.19%)	0.39 (14.78%)	0.39 (10.55%)	0.4 (14.86%)
Fungi	0.02 (0.54%)	0.01 (0.53%)	0.02 (0.52%)	0.01 (0.17%)	0.02 (0.53%	0.01 (0.17%	0.01 (0.36%)	0.01 (0.10%)	0.03 (0.68%)	0.01 (0.29%)
Fruit	0.08 (2.77%)	0.06 (2.82%)	0.07 (2.26%)	0.02 (0.90%)	0.06 (2.15%	0.02 (1.14%	0.07 (2.15%)	0.04 (1.59%)	0.1 (2.69%)	0.01 (0.35%)
Nut	0.01 (0.34%)	0.01 (0.17%)	0.01 (0.20%)	0.01 (0.21%)	0.01 (0.23%	0.01 (0.35%	0.01 (0.19%)	0.01 (0.18%)	0.02 (0.47%)	0.01 (0.16%)
Meat	0.82 (28.73%)	0.37 (16.91%)	0.94 (28.73%)	0.38 (17.17%	0.96 (32.28%	0.38 (19.93%	1.29 (41.71%)	0.77 (29.39%)	1.19 (32.14%)	0.91 (33.75%)
Poultry	0.06 (2.17%)	0.04 (1.89%)	0.21 (6.16%)	0.11 (4.35%	0.14 (4.81%	0.06 (3.30%	0.18 (5.92%)	0.12 (4.46%)	0.22 (5.90%)	0.06 (2.29%)
Dairy	0.06 (2.11%)	0.01 (0.48%)	0.07 (2.02%)	0.01 (0.07%	0.03 (1.03%	0.01 (0.04%	0.06 (1.97%)	0.01 (0.00%)	0.17 (4.59%)	0.01 (0.24%)

	Northeast (n=1,563)		East (n=1,612)		Central (n=2,528)		Southeast (n=1,763)		Metropolitan areas (n=2,858)	
Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level
Eggs	0.17 (5.88%)	0.16 (7.04%)	0.19 (5.91%)	0.11 (5.22%	0.13 (4.48%	0.08 (4.41%	0.08 (2.74%)	0.05 (1.90%)	0.2 (5.27%)	0.09 (3.30%)
Aquatic	0.19 (6.54%)	0.12 (5.59%)	0.33 (10.02%)	0.15 (6.98%	0.26 (8.61%	0.11 (5.99%	0.11 (3.64%)	0.04 (1.49%)	0.33 (8.89%)	0.07 (2.51%)
Fast food	0.17 (5.95%)	0.07 (3.24%)	0.26 (7.86%)	0.14 (6.28%	0.15 (4.90%	0.06 (3.11%	0.07 (2.10%)	0.01 (0.38%)	0.24 (6.49%)	0.02 (0.85%)
Beverages	0.01 (0.09%)	0.01 (0.09%)	0.02 (0.60%)	0.01 (0.09%	0.01 (0.33%	0.01 (0.02%	0.01 (0.19%)	0.01 (0.12%)	0.05 (1.27%)	0.01 (0.05%)
Liquor	0.02 (0.85%)	0.02 (0.77%)	0.01 (0.45%)	0.02 (0.74%	0.01 (0.23%	0.01 (0.24%	0.01 (0.14%)	0.01 (0.44%)	0.01 (0.24%)	0.02 (0.71%)
Sugar	0.01 (0.08%)	0.01 (0.06%)	0.01 (0.11%)	0.01 (0.08%	0.01 (0.06%	0.01 (0.07%	0.01 (0.07%)	0.01 (0.03%)	0.01 (0.21%)	0.01 (0.25%)
Fats	0.11 (3.73%)	0.11 (4.96%)	0.08 (2.53%)	0.09 (4.11%	0.11 (3.76%	0.11 (6.02%	0.11 (3.29%)	0.11 (4.01%)	0.07 (2.00%)	0.16 (5.79%)
Condiment	0.11 (3.83%)	0.11 (4.83%)	0.08 (2.42%)	0.11 (4.42%	0.07 (2.27%	0.07 (3.61%	0.07 (2.17%)	0.11 (4.04%)	0.09 (2.49%)	0.12 (4.59%)
Total GHGE	2.84 (100%)	2.2 (100%)	3.26 (100%)	2.19 (100%	2.97 (100%	1.89 (100%	3.11 (100%)	2.61 (100%)	3.71 (100%)	2.69 (100%)
CHEI	54.58	53.26	55.73	48.56	52.48	45.21	51.52	46.59	58.09	43.05
Proportion of animal based food[2]	14.93%	8.19%	18.83%	9.25%	16.37%	8.42%	19.05%	9.03%	23.38%	11.21%

1 The percentage (%) contribution of food groups to dietary LU (m^2/2000 kcal) is shown in parentheses.
2 The percentage of animal based food consumption (grams).

Supplementary Table 5.3B. Food group contribution by dietary TWU across education level & activity level of region in the Chinese Health Nutrition Survey 20111

	Northeast (n=1,563)		**East (n=1,612)**		**Central (n=2,528)**		**Southeast (n=1,763)**		**Metropolitan areas (n=2,858)**	
Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level
	n=269	n=322	n=203	n=214	n=342		n=269	n=322	n=203	n=214
Cereals	0.71 (18.33%)	0.84 (25.95%)	0.57 (13.09%)	0.85 (26.31%)	0.59 (15.07%)	0.71 (28.76%)	0.68 (17.06%)	0.94 (28.37%)	0.6 (12.76%)	0.81 (23.91%)
Tubers	0.07 (1.72%)	0.13 (4.11%)	0.03 (0.75%)	0.04 (1.37%)	0.03 (0.78%)	0.04 (1.54%)	0.03 (0.66%)	0.04 (1.24%)	0.04 (0.77%)	0.08 (2.36%)
Legumes	0.28 (7.22%)	0.17 (5.24%)	0.2 (4.66%)	0.16 (4.95%)	0.18 (4.7%)	0.09 (3.68%)	0.14 (3.54%)	0.18 (5.48%)	0.21 (4.43%)	0.07 (2.12%)
Vegetables	0.4 (10.43%)	0.59 (18.23%)	0.49 (11.32%)	0.53 (16.25%)	0.41 (10.46%)	0.38 (15.5%)	0.41 (10.27%)	0.51 (15.21%)	0.39 (8.2%)	0.41 (12.16%)
Fungi	0 (0.11%)	0 (0.11%)	0.01 (0.13%)	0 (0.04%)	0 (0.12%)	0 (0.04%)	0 (0.08%)	0 (0.02%)	0.01 (0.16%)	0 (0.06%)
Fruit	0.15 (3.87%)	0.13 (4.06%)	0.14 (3.17%)	0.03 (0.97%)	0.11 (2.89%)	0.04 (1.63%)	0.12 (3.07%)	0.09 (2.56%)	0.17 (3.66%)	0.02 (0.59%)
Nut	0.02 (0.48%)	0.01 (0.2%)	0.01 (0.32%)	0.01 (0.25%)	0.01 (0.35%)	0.01 (0.47%)	0.01 (0.28%)	0.01 (0.23%)	0.03 (0.72%)	0.01 (0.22%)
Meat	1.06 (27.36%)	0.48 (14.8%)	1.21 (27.88%)	0.49 (15.05%)	1.23 (31.61%)	0.48 (19.56%)	1.67 (42.04%)	0.98 (29.6%)	1.54 (32.72%)	1.17 (34.65%)
Poultry	0.04 (1.13%)	0.03 (0.89%)	0.15 (3.42%)	0.07 (2.18%)	0.11 (2.7%)	0.05 (1.89%)	0.14 (3.62%)	0.09 (2.83%)	0.17 (3.54%)	0.05 (1.45%)
Dairy	0.07 (1.7%)	0.01 (0.37%)	0.07 (1.51%)	0 (0.05%)	0.03 (0.75%)	0 (0.04%)	0.07 (1.68%)	0 (0%)	0.17 (3.7%)	0.01 (0.22%)
Eggs	0.18 (4.58%)	0.16 (5.08%)	0.2 (4.71%)	0.12 (3.76%)	0.14 (3.63%)	0.09 (3.58%)	0.09 (2.26%)	0.05 (1.58%)	0.21 (4.41%)	0.09 (2.78%)

	Northeast (n=1,563)		**East (n=1,612)**		**Central (n=2,528)**		**Southeast (n=1,763)**		**Metropolitan areas (n=2,858)**	
Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level
	n=269	n=322	n=203	n=214	n=342		n=269	n=322	n=203	n=214
Aquatic	0.2 (5.2%)	0.14 (4.26%)	0.45 (10.45%)	0.16 (4.95%)	0.35 (9.12%)	0.15 (6.03%)	0.15 (3.88%)	0.05 (1.47%)	0.38 (8.13%)	0.08 (2.37%)
Fast food	0.29 (7.51%)	0.16 (4.94%)	0.52 (11.95%)	0.44 (13.52%)	0.37 (9.59%)	0.12 (4.78%)	0.16 (3.9%)	0.01 (0.36%)	0.48 (10.17%)	0.08 (2.39%)
Beverages	0.02 (0.46%)	0 (0.07%)	0 (0.07%)	0 (0.1%)	0.01 (0.32%)	0 (0.05%)	0.02 (0.45%)	0.01 (0.2%)	0.02 (0.45%)	0 (0.03%)
Liquor	0.03 (0.73%)	0.02 (0.72%)	0.02 (0.42%)	0.02 (0.69%)	0.01 (0.23%)	0.01 (0.28%)	0 (0.12%)	0.01 (0.38%)	0.01 (0.2%)	0.02 (0.56%)
Sugar	0 (0.09%)	0 (0.06%)	0.01 (0.12%)	0 (0.08%)	0 (0.06%)	0 (0.06%)	0 (0.07%)	0 (0.04%)	0.01 (0.21%)	0.01 (0.27%)
Fats	0.18 (4.6%)	0.18 (5.68%)	0.14 (3.14%)	0.15 (4.66%)	0.19 (4.85%)	0.19 (7.7%)	0.17 (4.31%)	0.18 (5.35%)	0.12 (2.61%)	0.27 (8.01%)
Condiment	0.17 (4.5%)	0.17 (5.26%)	0.13 (2.91%)	0.16 (4.81%)	0.11 (2.77%)	0.11 (4.42%)	0.11 (2.71%)	0.17 (5.08%)	0.15 (3.16%)	0.2 (5.85%)
Total TWU	3.86 (100%)	3.24 (100%)	4.34 (100%)	3.23 (100%)	3.89 (100%)	2.48 (100%)	3.98 (100%)	3.33 (100%)	4.7 (100%)	3.38 (100%)
CHEI	54.58	53.26	55.73	48.56	52.48	45.21	51.52	46.59	58.09	43.05
Proportion of animal based food[2]	14.93%	8.19%	18.83%	9.25%	16.37%	8.42%	19.05%	9.03%	23.38%	11.21%

1 The percentage (%) contribution of food groups to dietary LU (m^2/2000 kcal) is shown in parentheses.
2 The percentage of animal based food consumption (grams).

Supplementary Table 5.3C. Food group contribution by dietary LU across education level & activity level of region in the Chinese Health Nutrition Survey 20111

	Northeast (n=1,563)		**East (n=1,612)**		**Central (n=2,528)**		**Southeast (n=1,763)**		**Metropolitan areas (n=2,858)**	
Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level
	n=269	n=322	n=203	n=214	n=342		n=269	n=322	n=203	n=214
Cereals	0.7 (20.94%)	0.82 (30.05%)	0.53 (14.32%)	0.68 (27.1%)	0.58 (17.1%)	0.71 (31.11%)	0.66 (18.67%)	0.92 (31.36%)	0.55 (12.81%)	0.79 (25.49%)
Tubers	0.11 (3.36%)	0.22 (8.17%)	0.05 (1.45%)	0.07 (2.96%)	0.05 (1.59%)	0.06 (2.82%)	0.04 (1.23%)	0.07 (2.35%)	0.06 (1.5%)	0.16 (5.17%)
Legumes	0.09 (2.7%)	0.05 (2%)	0.07 (1.77%)	0.05 (2.06%)	0.06 (1.75%)	0.03 (1.29%)	0.05 (1.28%)	0.06 (2%)	0.07 (1.57%)	0.02 (0.76%)
Vegetables	0.24 (7.27%)	0.26 (9.61%)	0.33 (8.96%)	0.29 (11.7%)	0.34 (9.93%)	0.3 (13.34%)	0.32 (9.01%)	0.41 (13.87%)	0.32 (7.36%)	0.37 (12.07%)
Fungi	0.01 (0.29%)	0.01 (0.31%)	0.02 (0.43%)	0 (0.14%)	0.01 (0.35%)	0 (0.1%)	0.01 (0.2%)	0 (0.07%)	0.02 (0.41%)	0 (0.16%)
Fruit	0.12 (3.6%)	0.12 (4.45%)	0.1 (2.72%)	0.03 (1.04%)	0.09 (2.55%)	0.03 (1.39%)	0.09 (2.58%)	0.06 (2%)	0.13 (3.07%)	0.01 (0.46%)
Nut	0.01 (0.19%)	0 (0.07%)	0 (0.11%)	0 (0.12%)	0.01 (0.18%)	0 (0.19%)	0 (0.13%)	0 (0.09%)	0.01 (0.24%)	0 (0.08%)
Meat	1.03 (30.93%)	0.41 (14.83%)	1.16 (31.3%)	0.43 (17.22%)	1.19 (35.25%)	0.41 (18.1%)	1.52 (42.85%)	0.8 (27.36%)	1.56 (36.2%)	0.93 (30.02%)
Poultry	0.04 (1.11%)	0.03 (0.96%)	0.13 (3.55%)	0.07 (2.63%)	0.09 (2.54%)	0.04 (1.84%)	0.12 (3.52%)	0.08 (2.62%)	0.14 (3.24%)	0.04 (1.32%)
Dairy	0.07 (1.99%)	0.01 (0.47%)	0.06 (1.68%)	0 (0.07%)	0.03 (0.8%)	0 (0.04%)	0.06 (1.78%)	0 (0%)	0.17 (4.02%)	0.01 (0.23%)
Eggs	0.07 (2.22%)	0.07 (2.51%)	0.09 (2.31%)	0.05 (2.02%)	0.06 (1.74%)	0.04 (1.63%)	0.04 (1.06%)	0.02 (0.75%)	0.09 (2.01%)	0.04 (1.27%)

5

	Northeast (n=1,563)		East (n=1,612)		Central (n=2,528)		Southeast (n=1,763)		Metropolitan areas (n=2,858)	
Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level	high education level & low activity level	Food group	high education level & low activity level	low education level & high activity level	high education level & low activity level	low education level & high activity level
	n=269	n=322	n=203	n=214	n=342		n=269	n=322	n=203	n=214
Aquatic	0.18 (5.38%)	0.14 (5.26%)	0.32 (8.57%)	0.16 (6.3%)	0.29 (8.5%)	0.13 (5.74%)	0.14 (3.82%)	0.05 (1.58%)	0.32 (7.52%)	0.08 (2.52%)
Fast food	0.2 (6.06%)	0.12 (4.37%)	0.46 (12.39%)	0.26 (10.47%)	0.21 (6.08%)	0.13 (5.6%)	0.12 (3.51%)	0.02 (0.75%)	0.39 (9.08%)	0.03 (1.12%)
Beverages	0.01 (0.17%)	0 (0.17%)	0.04 (1.02%)	0 (0.15%)	0.02 (0.52%)	0 (0.04%)	0.01 (0.39%)	0.01 (0.17%)	0.11 (2.55%)	0 (0.09%)
Liquor	0.01 (0.43%)	0.01 (0.54%)	0.01 (0.31%)	0.02 (0.64%)	0.01 (0.19%)	0.01 (0.23%)	0 (0.09%)	0.01 (0.32%)	0.01 (0.13%)	0.01 (0.38%)
Sugar	0.01 (0.18%)	0 (0.14%)	0.01 (0.22%)	0 (0.15%)	0 (0.11%)	0 (0.11%)	0 (0.11%)	0 (0.05%)	0.02 (0.39%)	0.01 (0.42%)
Fats	0.22 (6.5%)	0.22 (8.16%)	0.17 (4.55%)	0.18 (7.35%)	0.23 (6.75%)	0.23 (10.27%)	0.21 (5.89%)	0.21 (7.28%)	0.15 (3.51%)	0.32 (10.29%)
Condiment	0.22 (6.67%)	0.22 (7.95%)	0.16 (4.36%)	0.2 (7.91%)	0.14 (4.07%)	0.14 (6.16%)	0.14 (3.88%)	0.22 (7.35%)	0.19 (4.39%)	0.25 (8.15%)
Total LU	3.33 (100%)	2.73 (100%)	3.7 (100%)	2.51 (100%)	3.38 (100%)	2.27 (100%)	3.54 (100%)	2.93 (100%)	4.31 (100%)	3.1 (100%)
CHEI	54.58	53.26	55.73	48.56	52.48	45.21	51.52	46.59	58.09	43.05
Proportion of animal based food[2]	14.93%	8.19%	18.83%	9.25%	16.37%	8.42%	19.05%	9.03%	23.38%	11.21%

1 The percentage (%) contribution of food groups to dietary LU (m^2/2000 kcal) is shown in parentheses.
2 The percentage of animal based food consumption (grams).

Supplementary Table 5.4. Contribution (%) of different food groups to GHGE, TWU, and LU from diet across regions in the China Health Nutrition Survey 2011.

Food group	Northeast	East	Central	Southwest	Metropolitan areas	Average
GHGE						
Cereals	28.9	22.1	23.9	27.4	16.0	22.2
Tubers	1.1	0.4	0.5	0.2	0.4	0.5
Legumes	3.4	2.8	2.2	1.9	2.1	2.4
Vegetables	10.9	12.6	14.4	11.5	11.8	12.3
Fungi	0.6	0.4	0.4	0.2	0.6	0.5
Fruit	2.9	1.7	1.5	1.7	2.1	1.9
Nut	0.3	0.2	0.3	0.1	0.4	0.3
Meat	21.2	24.3	28.4	35.6	32.4	29.4
Poultry	2.3	5.7	3.9	6.8	5.8	5.1
Dairy	1.0	1.0	0.5	0.5	3.5	1.7
Eggs	6.6	5.7	4.7	2.3	4.5	4.6
Aquatic products	7.1	8.5	7.5	3.8	8.3	7.2
Fast foods	4.1	6.8	4.1	1.1	5.2	4.3
Beverages	0.2	0.4	0.2	0.2	0.8	0.4
Liquor	0.8	0.8	0.3	0.3	0.4	0.5
Sugar	0.1	0.1	0.0	0.1	0.2	0.1
Fats	4.1	3.4	4.6	3.3	2.7	3.5
Condiments	4.4	3.2	2.8	3.0	2.8	3.1
TWU						
Cereals	22.6	18.3	20.3	23.1	14.7	19.0
Tubers	3.1	1.1	1.0	0.8	0.9	1.2
Legumes	6.0	5.2	4.2	3.7	4.1	4.5
Vegetables	15.0	13.3	12.5	12.0	9.2	11.8
Fungi	0.1	0.1	0.1	0.0	0.1	0.1
Fruit	4.1	2.1	2.0	2.5	2.9	2.7
Nut	0.3	0.3	0.4	0.2	0.5	0.4
Meat	19.3	22.8	28	36.6	33.3	29.2
Poultry	1.1	3.1	2.2	4.2	3.5	2.9
Dairy	0.8	0.7	0.4	0.5	2.9	1.3
Eggs	5.0	4.5	3.8	2.0	3.8	3.8
Aquatic products	5.5	7.7	7.8	4.1	7.6	6.7
Fast foods	5.9	11.9	7.4	1.6	8.4	7.2
Beverages	0.5	0.1	0.2	0.3	0.3	0.3
Liquor	0.7	0.7	0.3	0.3	0.3	0.4

Food group	Northeast	East	Central	Southwest	Metropolitan areas	Average
Sugar	0.1	0.1	0.0	0.1	0.2	0.1
Fats	4.9	4.2	6.0	4.4	3.6	4.5
Condiments	5.0	3.8	3.4	3.8	3.6	3.8
LU						
Cereals	25.9	19.6	22.8	25.0	15.2	20.6
Tubers	6.1	2.2	1.9	1.4	1.8	2.4
Legumes	2.2	2.0	1.5	1.3	1.5	1.7
Vegetables	8.7	10.4	11.4	10.9	8.6	9.9
Fungi	0.3	0.3	0.3	0.1	0.4	0.3
Fruit	4.2	2.0	1.8	2.1	2.5	2.4
Nut	0.1	0.1	0.2	0.1	0.2	0.1
Meat	10.8	14	11.7	9.4	15.5	12.8
Poultry	5.0	10.6	5.3	1.6	7.2	6.0
Dairy	0.4	0.7	0.3	0.4	1.5	0.8
Eggs	0.4	0.6	0.2	0.2	0.2	0.3
Aquatic products	0.2	0.2	0.1	0.1	0.3	0.2
Fast foods	6.9	6.3	8.2	6.0	4.9	6.2
Beverages	7.4	5.9	4.9	5.4	5.1	5.6
Liquor	6.2	5.8	8.5	8.4	10.1	8.3
Sugar	13.6	17.9	19.5	26.6	20.6	20.0
Fats	1.1	1.1	1.2	0.5	4.3	2.1
Condiments	0.2	0.3	0.2	0.3	0.5	0.3

Supplementary Table 5.5. Proportion of Food consumption (%) in China from National Bureau of Statistics, 2013-2021[1] and in CHNS 2011

Food group	CHNS 2011	2013	2014	2015	2016	2017	2018	2019	2020	2021
Cereal	35.3	41.0	39.4	37.8	36.8	36.1	35.5	34.9	36.2	35.0
Edible oils	2.9	3.0	2.8	3.1	3.0	2.8	2.8	2.7	2.6	2.7
Vegetable and fungus	27.3	27.0	27.1	27.5	27.7	27.5	26.8	26.6	26.7	26.6
Red meat	6.8	7.2	7.3	7.3	7.2	7.5	8.4	7.3	6.4	8.0
Poultry	1.5	1.9	2.2	2.2	2.5	2.5	2.5	3.0	3.3	2.9
Aquatic products	2.4	2.8	3.1	3.1	3.0	3.3	3.1	3.8	3.6	3.4
Eggs	2.8	2.2	2.5	2.8	2.8	2.8	2.8	3.0	3.3	3.1
Milk	2.5	3.3	3.6	3.4	3.3	3.3	3.4	3.5	3.3	3.4
Fruit	5.9	11.3	11.7	12.6	13.3	13.9	14.5	15.1	14.4	14.7
Sugar	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2

[1] National Bureau of Statistics of China. https://data.stats.gov.cn/easyquery.htm?cn=C01

CHAPTER 6

Health outcomes, Environmental Impacts, and Diet Costs of Adherence to the EAT-Lancet Diet in the China Health and Nutrition Survey 1997–2015

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ABSTRACT

In 2019, the EAT-Lancet commission proposed a global reference dietary pattern. While research on its associations with mortality, cardiovascular disease (CVD), type 2 diabetes (T2D), dietary environmental impacts, or diet costs increases, studies in low- and middle-income countries are limited. This study examines health outcomes, environmental impacts, and costs of following the EAT-Lancet diet in China. It involved 16,029 participants from the China Health and Nutrition Survey (1997–2015). Adherence to the diet was associated with decreased mortality (8% per standard deviation increase, 95% CI: 2.2%-14.1%), CVD (16.1% decrease, 95% CI: 9.2%-20.3%), and T2D (25.3% decrease, 95% CI: 19.5%-28.4%). In addition, it led to reduced Greenhouse Gas Emissions (-2.1% per 10-point increase, 95% CI:1.9% - 2.4%) and Land Use (-2.2%, 95% CI: 1.8% -2.6%), but increased diet costs by 2.7% (95% CI: 2.3% to 3.1%). Integrating sustainable indicators into Chinese Dietary Guidelines and implementing policies like agricultural subsidies for fruits and vegetables, and carbon taxes on red meat, are recommended to enhance diet sustainability in China.

1 Introduction

Producing nutritious and equitable diets for the global population poses challenges to public health and environmental sustainability(1). Simultaneously mitigating environmental impacts stands as one of the foremost imperatives in the transformation of our food systems today(2). For the period 1990 to 2017, the Global Burden of Disease study showed an increase from 8 million to 11 million deaths attributed to dietary habits(2). Among these diet-related deaths, cardiovascular diseases (CVD) and type 2 diabetes (T2D) emerge as the leading causes(3). Moreover, the shift toward Westernized diets contributes to environmental degradation, as food systems contribute to 30% of global greenhouse gas emissions (GHGE)(4), utilize 70% of freshwater(5), and occupy 40% of available arable land(6). Furthermore, as healthy diets are economically inaccessible for approximately 3 billion individuals globally(7), and diet costs need to be considered in the quest for sustainable and healthy diets(8).

Over the past 20 years, dietary patterns in China have transitioned from a traditional plant-based diet to high intake of refined grains and meat driven by increased agricultural productivity and rising income(9). Non-communicable diseases, including cardiovascular and cerebrovascular diseases, cancers, chronic respiratory diseases, and diabetes, account for 88% of all deaths in China in 2018(10). Further, the intensification of agricultural production, driven by the growing food demand of the population, results in soil degradation, inefficient use of water resources, and damage to ecosystems(11). Agricultural GHGE in China have increased from 600 million tons in 1990 to 710 million tons in 2018(12). Furthermore, research indicates that in 2021, the dietary expenditures of at least 182 million urban households in China did not meet the recommended standards of the Chinese Dietary Guideline(13).

Therefore, it is importance to address the dual challenge of reducing the environmental impact of diets while simultaneously enhancing diet quality(14). In 2019, the EAT-Lancet Commission introduced recommendations for a "Healthy Reference Diet" (the EAT-Lancet reference diet), which advocates for a predominantly plant-based diet with limited consumption of animal-based foods, added sugars, refined grains, and processed foods(15). The EAT-Lancet report projected that adopting the EAT-Lancet reference diet could potentially avert a portion of premature adult deaths, estimated between 19.0% to 23.6%, while ensuring that these dietary changes remain within acceptable environmental limits according to theoretical models(16).

While the daily recommendations of the EAT-Lancet reference diet were derived from both extensive literature on foods, dietary patterns, and health outcomes, and the environmental impact of food groups(17). To date, only a limited number of cohort studies have examined the association between the EAT-Lancet Diet and the incidence of health outcomes (18,19), yielding inconclusive results. A prospective cohort study from Brazil has indicated positive effects of the EAT-Lancet reference diet on mortality and the risk of cardiometabolic diseases(20). Similarly, a prospective study in the UK observed a reduction in diabetes risk associated with adherence to the EAT-Lancet reference diet, which was largely mediated by BMI(21). However, in one prospective cohort of the EPIC-Oxford study, the EAT-Lancet reference diet demonstrated no correlation with stroke and did not show a statistically significant association with mortality(22). Furthermore, the environmental impact and dietary costs associated with the EAT-Lancet reference diet have not been empirically evaluated in specific regions, particularly in low- and middle-income countries (LMICs).

The EAT-Lancet reference diet, recognized as the world's first sustainable dietary guideline that considers both public and planetary health, requires further investigation to determine its applicability to specific regions. More specifically, it is important to understand how adherence to the EAT-Lancet Diet affects the health status, environmental impact and diet costs in the large Chinese population. Therefore, we estimated the association between adherence to the EAT-Lancet Diet and the risk of mortality, CVD, and T2D, as well as to the diet-related environmental impact and costs of the diet in a large prospective cohort of Chinese adults.

2 Methods and data

2.1 Study Design and Participants

The CHNS is a nationally representative long-term-follow-up survey project(23). The content of the survey includes general demographics, lifestyle, health status, diet, etc. Since its establishment in 1989, CHNS has been used to collect 10 rounds of data in 1989, 1991, 1993, 1997, 2000, 2004, 2006, 2009, 2011, and 2015, and has been used to survey cumulatively from 12 provinces and three megacities in China (three new cities were added in 2011, and three new provinces were added in 2015). These areas vary in levels of economic development, public resources, geographic location, and citizen health. A multistage random-cluster sampling method was used to obtain research samples in each province or city for representativeness.

Detailed information of dietary assessment has been documented in other sources(24). In summary, during the baseline survey, researchers conducted face-to-face interviews to collect individual dietary data. These data were procured through a process involving repeated assessments of individual dietary habits across three distinct 24-hour periods. Participants were requested to provide a comprehensive list of consumed foods and beverages over the span of 24 hours. The food types and quantities of items were documented with visual representations, complemented by standardized measurements (utilizing household containers and packaging-indicated grams). A random selection process allocated three consecutive days (including two weekdays and one weekend day) during the week for dietary assessment. This allocation aimed for a near equilibrium of sampling units across all seven days of the week. The computation of dietary energy and food categories including cereals, legumes, vegetables, and fruits were relied on the Chinese Food Composition Table (2009 edition). Notably, the study did not encompass an evaluation of supplement consumption. In instances where participants took part in solely one of the survey years, the dietary intake of the current year was utilized as the foundational baseline assessment. The methodology employed in this research is also evidenced in other sources(25).

This study included adults who participated in at least one dietary recall during the CHNS from 1997 to 2015. The data recorded until the 2015 survey were used to determine the survival status and times of the subjects we included. The exclusion criteria in this specific study were missing information about food consumption, only one day of 3-day 24 hours recall of food consumption and missing data on date of birth. Adolescents (age < 18y) and elderly (age > 65y) were also excluded. In addition, participants with a Z-score >5 for energy intake, who were pregnant or breast-feeding in each round were further excluded. A total of 16,029 participants (7,617 men and 8,412 women) were included in the final analysis.

2.2 EAT-Lancet Diet Index (ELDI) Score

For this study, we applied the EAT-Lancet Diet Index (ELDI) score, indicating adherence to the EAT-Lancet Diet, using the methodology outlined from Colizzi et al. (26) (Supplementary Table 6.1). To assess adherence to the EAT-Lancet Diet scores, the dietary guidelines outlined in the EAT-Lancet report were adjusted proportionally according to the actual dietary intake of individuals. Subsequently, the dietary recommendations from the EAT-Lancet report were recalibrated to correspond to a standardized daily energy intake of 2,000 kcal/day for women and 2,500 kcal/day for men (Supplementary Table 6.1). Each participant received proportional scores on a scale of 0 to 10 for each of the 14 dietary recommendations stipulated in the EAT-Lancet Diet. These individual scores were then aggregated, yielding a comprehensive adherence score spanning from 0 (indicating no adherence) to 140 (representing full adherence). Within the EAT-Lancet Diet score, every food group fell into distinct scoring components: adequacy (encompassing whole grains, vegetables, fruits, legumes, and soy foods), moderation (encompassing beef, lamb, pork, and sweeteners), optimum (encompassing potatoes, dairy, chicken, eggs, fish, and nuts), and ratio (focused on the unsaturated to saturated fats ratio).

Participants were awarded 10 points for adhering to the recommended intake levels for adequacy components. Conversely, they received 0 points if they did not consume any of these components. For intake levels falling between 0 and the recommended thresholds, participants were assigned proportional scores. Regarding moderation components, participants received 0 points if their intake exceeded the reference values, while those who adhered to or consumed less than the reference intake were awarded 10 points. For intakes falling between 0 and the recommended levels, proportional scores were assigned. In the case of optimum components, participants who maintained their intake within the specified optimum range received a full score of 10 points. Those with intake levels below or above the optimum range were graded proportionally, with scores varying from 0 to 10 and vice versa. Participants who did not consume items from these components were assigned 0 points. When it came to added fats, individuals who did not consume unsaturated fats or achieved an unsaturated to saturated fats ratio lower than 0.6 received 0 points. Conversely, those who did not consume saturated fats or attained an unsaturated to saturated fats ratio exceeding 13 were allocated 10 points. Ratios falling within these extremes were assigned scores proportionally based on their specific values.

2.3 Dietary-related environmental impact assessment

Within the context of evaluating environmental impacts based on the planetary boundaries framework, the primary environmental concerns linked to food production encompass climate change, land system changes, and freshwater usage. Thus, this study employed three environmental indicators to evaluate the environmental impacts of the EAT-Lancet Diet, encompassing Greenhouse Gas Emissions (GHGE, measured in kg CO_2-eq/kg), Total Water Use (TWU, measured in m^3/kg), and Land Use (LU, measured in m^2/kg). The environmental impacts of foods were linked to food consumption by using the Chinese Food Life Cycle Assessment Database (CFLCAD) (27). Essentially, this database collects findings from Life Cycle Assessment (LCA) studies tailored to the Chinese context, offering estimates of GHGE, TWU, and LU per kilogram of consumed food. The environmental impacts considered in this study encompassed the entire food supply chain, from production and storage to processing, packaging, transportation, and home preparation, while also accounting for food losses along this chain. For fish, the environmental impacts were assessed from artificial fish farming to consumption, excluding considerations of fish stocks in oceans and seas. Conversion parameters pertinent to the post-farm gate stage were obtained from literature sources and statistical yearbooks. To reflect daily environmental impacts per 2,000 kcal food consumption, densities for GHGE, TWU, and LU were derived based on the food consumption data. This approach was adopted to address potential individual-level variations in food consumption and compensate for over- or underestimations. When specific LCA data for certain food items were unavailable, data from analogous food groups were used as proxies, ensuring a comprehensive assessment of environmental impact of the EAT-Lancet Diet. Food items listed in the CFLCAD were cross-referenced with entries in the Chinese Food Composition Tables (FCT). This matching process ensures that results obtained from both the CHNS and CFLCAD are aligned at the level of individual "food items".

2.4 Outcome measures

In the CHNS study, information regarding all-cause mortality status was obtained through household data collected during each survey wave. In instances where a death was reported more than once, the earliest reported date of death was utilized for analysis. There was no information of cause of death from specific disease in CHNS, and was only reported in the 1991 survey. For each study participant, the baseline time was defined as the date of their initial participation, provided they had complete dietary data since 1997. Individual follow-up person-years for each participant were calculated from this baseline date until one of the following events occurred: the date of death, the last survey wave prior to their departure from the study, or the conclusion of the last survey conducted in 2015, whichever event came first.

The identification of T2D in the CHNS study was based on self-reports of a prior T2D diagnosis, fasting blood glucose levels equal to or exceeding 7.0 mmol/l, HbA1c levels equal to or exceeding 40 mmol/mol (6.5%), or receiving treatment for T2D. This treatment encompassed various approaches, including (1) adherence to a special diet, (2) weight management efforts, (3) oral medication, (4) insulin injections, (5) the use of Chinese traditional medicine, and (6) home remedies. Data concerning the incidence of self-reported T2D were initially collected in 1997 and subsequently during follow-up survey waves in 2000, 2004, 2006, 2009, 2011, and 2015. In the 2009 survey, incident T2D cases were also identified using fasting blood glucose and HbA1c levels. A total of 767 new cases of T2D were recorded. Additionally, the study examined the concordance between diagnoses based on participant questionnaires and those based on HbA1c or glycemia levels among the 8202 participants surveyed in 2009. Among the 247 participants who self-reported a physician diagnosed T2D in the 2009 survey, 182 individuals (74%) had fasting glucose levels ≥7.0 mmol/L or HbA1c levels ≥6.5%. The remaining 65 participants, while not meeting these criteria, were found to be receiving glucose-lowering treatment, which can maintain fasting glucose and HbA1c at relatively normal levels. The follow-up period was defined as the time from the date of initial T2D diagnosis, the date of death, or the last survey date minus the date of first entry into the cohort, whichever occurred first.

The other outcome variable under consideration was the occurrence of CVD during the follow-up period. On-site investigators conducted interviews with participants, specifically inquiring whether they had received a diagnosis of myocardial infarction or stroke from a doctor at a public hospital at or above the county level. Responses were categorized as "no," "yes," or "unknown." The CVD was defined as a self-reported physician diagnosis of myocardial infarction or stroke during the follow-up period, supported by the provision of a certificate confirming the diagnosis of stroke and/or myocardial infarction. In cases where participants provided inconsistent answers during follow-up, the first recorded stroke event was considered to minimize potential recall bias. Similar to the T2D analysis, the follow-up period for CVD was determined as the time from the date of the initial diagnosis of CVD, the date of death, or the last survey date minus the date of first entry into the cohort, whichever occurred first.

2.5 Costs of diets

The assessment of diet costs served as an indicator of dietary sustainability from a consumer's economic perspective. In the CHNS study, a comprehensive community survey was conducted, encompassing information about food markets, including infrastructure, services, and organization, as well as the pricing of food items at the community level(28). The food groups covered in the CHNS dataset comprised 13 distinct categories: cereals and tubers, legumes, vegetables, fruits and nuts, meat, poultry, dairy, eggs, aquatic products, beverages and fast food, liquor and alcohol, fats and oils, and condiments (such as vinegar and soy sauce). To calculate the daily monetary expenses associated with dietary choices, the study primarily utilized the average market prices. This was done for each specific food item within all food categories. The total daily cost was computed by multiplying the cost per gram (in Chinese Yuan per gram, CNY/g) for each food item by the reported daily quantity consumed, as obtained from the 3-day 24-hour dietary recall survey. To account for inflation, the cost of the diet was adjusted by multiplying it by the Consumer Price Index for the year 2015.

2.6 Lifestyle and anthropometric variables

Several participant variables were considered as potential confounding factors in the analysis of the association between EAT-Lancet Diet scores and health outcomes. These included sociodemographic information, i.e., Age, Gender, BMI (Body Mass Index) in kg/m^2, Residence location (urban or rural), Education level categorized as low (illiterate/primary school), medium (junior middle school), and high (high middle school or higher); Work-Related Physical Activity Categories (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)), Per Capita Annual Family Income (Recoded into tertiles as low, medium, and high), Dietary Knowledge (Referring to whether respondents were aware of the Chinese Dietary Guidelines, assessed with a simple Yes/No question); Lifestyle Variables, i.e., Smoking status categorized as nonsmokers, ex-smokers, and current smokers based on self-reported history and current smoking status. Alcohol consumption categorized as yes or no based on the question "Did you drink beer or any other alcoholic beverage during the last year?"; Health-Related Variables, i.e., Waist circumference measured midway between the lowest rib margin and the iliac crest(29,30);

Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP) measurements taken on the right arm, using mercury sphygmomanometers after a ten-minute seated rest(31). These variables were considered as potential confounding factors to control for their influence on the association between EAT-Lancet Diet scores and various health outcomes.

2.7 Statistical analysis

Baseline characteristics were reported across quartiles of the ELDI. Normally distributed continuous variables are presented as means with SDs. Categorical variables are presented as frequency and percentages. The crude trends of variables were statistically evaluated by the Jonckheere–Terpstra test across quartiles of the ELDI(32).

This study used Cox proportional hazards regression model with time-varying covariates to estimate the hazard ratios (HRs) and 95% confidence intervals (95% CI) of the EAT-Lancet score associated with the all-cause mortality, CVD, and T2D. The years of follow-up were used as the underlying time variable. The participants were divided into 4 groups according to their summed ELDI scores and compared the HRs with Quartile1 as the reference group. Multiple covariates were selected and adjusted in two models for all-cause mortality, CVD, and T2D: Model 1 (basic model) was adjusted for age, gender; Model 2 was adjusted for the covariates included in model 1 plus BMI, dietary energy, physical activity, household income, educational level, residence location, dietary knowledge, smoking habits and alcohol consumption. The fully adjusted model (Model 2) was used as the main model, and the results below are based on this model unless otherwise stated. The covariates included in the model were identified from the literature to indicate potential confounding of diet-disease associations. This study used a Cox proportional hazards model and the "survival" package in R software, version 4.0.2 (R Project for Statistical Computing).

We conducted tests of linear trend (likelihood ratio test) by assigning the median of each quartile to the ELDI, and used the resulting variable in models equivalent to those just described. The proportional hazards assumption was checked using the Schoenfeld test, with no violations observed. Further, the study estimated the risk of healthy outcome for each standard deviation (1 SD) increase in dietary index by treating the scores as continuous variables. Moreover, to test whether there was a non-linear association between the EAT-Lancet diet score and the health outcomes, adjusted linear regression models were run using restricted cubic splines with 3 knots and the median of EAT-Lancet diet score as a reference point.

Several sensitivity analyses were performed to test the robustness of our findings as follows and educe the possibility of spurious association due to reverse causation. First, this study repeated all analyses after excluding all participants diagnosed with cancer, hypertension, or T2D during the first 2 y of follow-up and participants with <2 y of follow-up. Additionally, stratified analyses were conducted by age, sex, and educational level, adjusted for the same confounders as Model 2, to test whether the association with health outcomes differed per subgroup. The model structures for the sensitivity analyses were the same as those for the main analyses.

This study used Multilevel mixed-effects linear regression models to estimate the association between diet score and each environmental indicators (GHGE, TWU, and LU) and costs of diet, the exposure was the diet score, and the outcome were the environmental indicator and costs of diet (all logarithmic transformation). The models take into account both intra- and inter-individual variations in response variable (ELDI score) over time, and are particularly appropriate for analysis of longitudinal data with repeated measurements. Random effect of the model included intercept and slope for time, and other covariates were fitted as fixed effects. Unstandardized β-coefficients were obtained from the mixed-effects linear models using maximum-likelihood estimation. Model 1 (basic model) was adjusted for age, gender; Model 2 was adjusted for the covariates included in model 1 plus BMI, dietary energy, physical activity, household income, educational level, residence location, dietary knowledge, smoking habits and alcohol consumption. We used Akaike information criterion (AIC) and Bayesian information criterion (BIC) for model fit. The general linear models were employed to calculate the energy-adjusted mean environmental impacts (GHGE, TWU, and LU) of food groups in each quartile of the ELDI score. These models used the environmental impacts of each food group as the dependent variables and incorporated quartiles of the ELDI score, total energy intake, and sociodemographic variables as independent variables. The mean values of environmental impacts were standardized to a daily total energy intake of 2000 kcal. All tests were 2-sided, and $P < 0.05$ was considered statistically significant. Statistical analyses were performed using STATA 15.0 and R version 4.0.4 (R Foundation).

Results

The median follow-up time in the cohort was 9.86 years, and 908 cases of all-cause mortality, 803 cases of T2D, and 563 cases of CVD were identified (Table 1). The principal sample at baseline was composed of 52.5% females and the mean ± SD age was 43.8 ± 14.6 y. ELDI scores ranged from 9.4 to 110.8 points and the average value was 57.3 ± 12.8 points. Adherence to the EAT-Lancet diet remained relatively consistent over the years. The mean ELDI score (±SD) showed a modest increase from 55.3 ± 11.8 to 59.1 ± 12.8 between 1997 and 2011. There were higher proportions of females (53.2%) and high-income group in the highest ELDI score quartiles (most adherence to the EAT-Lancet diet). As the ELDI score increased to group Q4, the proportion of people with low physical activity (62.4%), urban residents (51.2%), those with above secondary education (39%), and those who knew the Chinese dietary guidelines (16.5%) increased. From the 15 EAT-Lancet reference diet food groups, the recommendations were met by average consumption for only 5 groups in the baseline: Whole Grains, Vegetables, Soy foods, Chicken and other poultry, and Fish (Supplementary Table 2).

Table 6.1. Description of anthropometric, sociodemographic, and lifestyle characteristics at baseline, overall and by ELDI score quartile, CHNS, 1997–20151.[1]

	All (n=16,029)	Quartile of ELDI score Q1 (n=4,008)	Q2 (n=4,007)	Q3 (n=4,007)	Q4 (n=4,007)	P-trend value[2]
ELDI score (mean years, ±SD)	57.3 (12.8)	41.7 (5.6)	52.4 (2.6)	60.7 (2.3)	74.2 (7.2)	<0.001***
Gender (n,%)						
Male	7617 (47.5)	1923 (48.0)	1925 (48.0)	1892 (47.2)	1877 (46.8)	0.52
Female	8412 (52.5)	2085 (52.0)	2082 (52.0)	2115 (52.8)	2130 (53.2)	0.52
Age (mean years, ±SD)	43.8 (14.6)	43.7 (14.9)	43.8 (14.5)	43.6 (14.6)	44.2 (14.5)	0.15
Dietary energy (kcal/day)	2210 (810)	2184 (863)	2172 (781)	2235 (791)	2251 (801)	<0.001***
Resident place (n,%)						
Urban area	6185 (38.6)	1244 (31.0)	1337 (33.4)	1551 (38.7)	2053 (51.2)	<0.001***
Rural area	9844 (61.4)	2764 (69.0)	2670 (66.6)	2456 (61.3)	1954 (48.8)	<0.001***
Educational level (n,%)						
Primary school or below	11683 (72.9)	3202 (79.9)	3096 (77.3)	2940 (73.4)	2445 (61.0)	<0.001***
Secondary school	3262 (20.4)	665 (16.6)	720 (18.0)	820 (20.5)	1057 (26.4)	<0.001***
High school and above	1084 (6.8)	141 (3.5)	191 (4.8)	247 (6.2)	505 (12.6)	<0.001***
Activity level (n,%)						
Low	8238 (51.4)	1819 (45.4)	1871 (46.7)	2049 (51.1)	2499 (62.4)	<0.001***
Medium	2287 (14.3)	619 (14.0)	534 (13.3)	591 (14.7)	543 (13.6)	0.81
High	5504 (34.3)	1570 (39.2)	1602 (40.0)	1367 (34.1)	965 (24.1)	0.56
BMI (mean kg/m^2, ±SD)	23.0 (3.4)	22.5 (3.2)	22.8 (3.3)	23.1 (3.4)	23.5 (3.4)	0.005**
Income (median 1,000 RMB/Y, interquartile range)	7.6 (3.4-15.4)	6.4 (2.8-11.7)	6.7 (2.9-13.5)	7.6 (3.4-15.6)	10.9 (4.8-20.7)	<0.001***
Dietary knowledge (n,%)						
No	14647 (91.4)	3849 (96.0)	3761 (93.9)	3693 (92.2)	3344 (83.5)	<0.001***
Yes	1382 (8.6)	159 (4.0)	246 (6.1)	314 (7.8)	663 (16.5)	<0.001***
Alcohol consumption (mean g/day, ±SD)	21.5 (109.1)	20.1 (110.7)	18.9 (105.1)	22.6 (112.1)	24.5 (108.4)	0.26
Smoking[3] (n,%)						
Non-smokers	10945 (68.3)	2695 (67.2)	2707 (68.1)	2742 (68.4)	2801 (69.9)	0.11
Ex-smokers	330 (2.1)	69 (1.7)	80 (0.9)	78 (1.9)	103 (2.6)	0.38
current smokers	4754 (29.7)	1244 (31.0)	1220 (31)	1187 (29.6)	1103 (27.5)	0.88
GHGE (mean kg CO_2-eq/2000 kcal, ±SD)	2.39±1.07	2.43±1.09	2.33±1.04	2.36±1.09	2.45±1.07	0.628
TWU (mean m^3/2000 kcal, ±SD)	2.40±1.27	3.38±1.27	3.33±1.23	3.37±1.29	3.51±1.28	0.211
LU (mean m^2/2000 kcal, ±SD)	2.74±1.24	2.80±1.19	2.68±1.17	2.69±1.22	2.79±1.24	0.584
Cost of diet (mean RMB/day, ±SD)	11.7±7.6	10.6±7.4	10.6±6.9	11.5±7.6	13.2±7.9	0.005**

[1] *n* = 16,029. Values are mean (SD) for quantitative variables and percentages for qualitative variables. ELD-I, EAT-Lancet Diet Index; Q, quintile.
[2] *P* value for the trend was determined by the Jonckheere–Terpstra test. 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.
[3] Smoking (based on the self-reported history and current smoking status, smoking status was categorized into nonsmokers, ex-smokers, and current smokers).

The HRs and 95% CI of all-cause mortality, the risk of CVD, and T2D based on the quartiles of ELDI score are presented in Table 6.2. Participants in the highest quartile showed a 50.9% (HR Q4 vs. Q1: 0.49, 95% CI: 0.37–0.66) lower risk of CVD, and a 64.9% (HR Q4 vs. Q1: 0.35, 95% CI: 0.28–0.44) lower risk of T2D, compared with those in the lowest quartile of ELDI score after adjustment for multiple potential confounding variates. When the ELDI score was assessed continuously, each 1 SD increase in the index had a statistically significant 8% decreased risk of mortality (95% CI: 2.2%-14.1%), 16.1% decreased risk of CVD (95% CI: 9.2%-20.3%), and 25.3% decreased risk of T2D (95% CI: 19.5%–28.4%) (Table 6.2). However, the trend analyses of the quartiles shows that the association between score and risk of mortality was non-linear. To further test the presence of non-linear association between ELDI score and mortality, a three-knot restricted cubic spline was adopted. As is shown in Figure 6.1, the curve presents an overall declining trend, indicating that there is a negative association between ELDI score and mortality.

Table 6.2. HRs (95% CIs) for the associations between ELDI score and incidence of T2D, CVD, and all-cause mortality, CHNS 1997–2015 (n = 59,849)*.

	Quartiles of ELDI score with the mean scores (cutoffs values in parentheses)				**P for linear trend**	**Per SD of ELDI score increment (per SD= 12.45)**
	Q1 (9.42, 50.03)	**Q2 (47.5, 59.33)**	**Q3 (54.21, 68.26)**	**Q4 (62.54, 110.89)**		
All-cause mortality						
Cases of all-cause mortality	279	249	218	162		908
Model 1[†]	1.00 [ref]	0.97 (0.82, 1.16)	0.95 (0.79, 1.13)	0.76** (0.63, 0.92)	0.006***	0.88*** (0.84, 0.94)
Model2[‡]	1.00 [ref]	1.05 (0.86, 1.28)	1.09 (0.89, 1.34)	0.85 (0.67, 1.07)	0.336	0.92* (0.86, 0.98)
Cardiovascular disease						
Cases of CVD	188	156	129	90		563
Model 1[†]	1.00 [ref]	0.95 (0.77, 1.17)	0.82 (0.65, 1.02)	0.61*** (0.47, 0.77)	<0.001***	0.91** (0.86, 0.97)
Model2[‡]	1.00 [ref]	0.991 (0.78, 1.26)	0.71** (0.55, 0.92)	0.49*** (0.37, 0.66)	<0.001***	0.84*** (0.80, 0.91)
Type 2 diabetes						
Cases of T2D	283	216	173	131		803
Model 1[†]	1.00 [ref]	0.82* (0.69, 0.98)	0.65*** (0.54, 0.79)	0.49*** (0.41, 0.61)	<0.001***	0.85*** (0.81, 0.92)
Model2[‡]	1.00 [ref]	0.81* (0.66, 0.98)	0.57*** (0.46, 0.69)	0.35*** (0.28, 0.44)	<0.001***	0.75*** (0.72, 0.81)

[*] *The details of models can be found in the Supplementary Table 6.3.*
[†] *Adjusted for age, gender and dietary energy.*
[‡] *Adjusted for age, gender, dietary energy, educational level, physical activity, household income, smoking status, and alcohol consumption.*

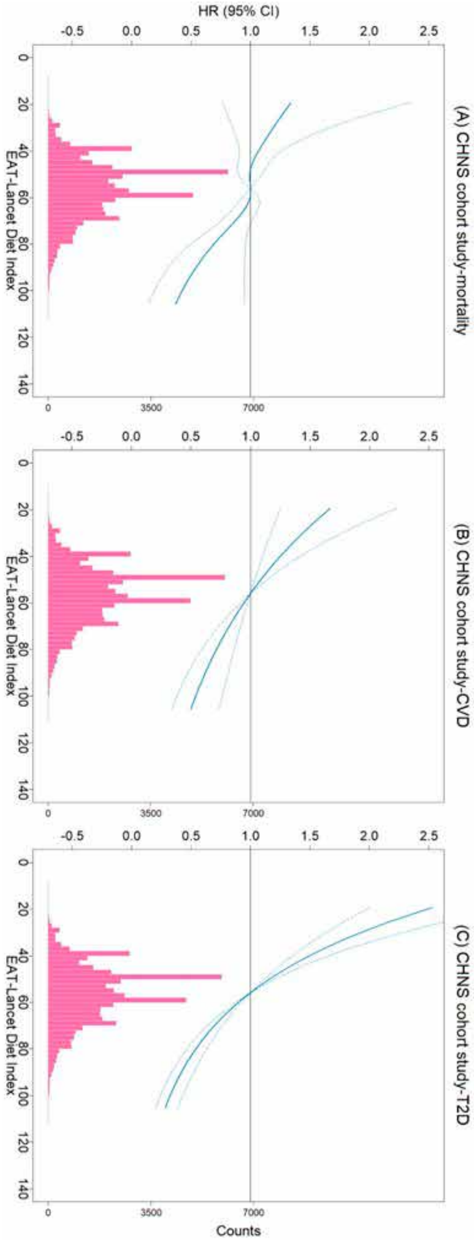

Figure 6.1. Restricted cubic splines for the non-linear association between the HRs (95% CIs) of mortality (A) and the ELDI score in CHNS 1997-2015. Linear association between the HRs (95% CIs) of incidence of CVD (B), T2D (C) and ELDI score in CHNS 1997-2015*.

**Models were all adjusted for the covariates included age, gender, BMI, dietary energy, physical activity, household income, educational level, residence location, dietary knowledge, smoking habits and alcohol consumption.*

Regarding the sensitivity analyses carried out on distinct subgroups (Supplementary Figure 6.1), the association between the ELDI score and mortality risk remained consistently significant within certain demographic segments. Notably, these segments included males, individuals with a BMI ≥ 24, those within the highest tertile of household income, individuals with a secondary education level or higher, those with alcohol consumption exceeding 0 g/day, and current smokers. The inverse association between the ELDI score and the risk of CVD persisted across subgroups categorized by gender, BMI, lower household income, lower education level, lower physical activity level, nonsmoking status, alcohol consumption, and residential location. Negative associations between the ELDI score and risk of T2D were consistent across subgroup analyses.

Figure 6.2 shows the association between ELDI score and dietary-related GHGE, TWU, LU, and cost of diet (logarithmic transformation) in the linear mixed-effect models. The association between ELDI score and dietary-related GHGE, TWU, LU, and cost of diet was not significantly in the Model 1, respectively (Supplementary Table 6.4). In Model 2 (Regression coefficients are all back-transformed from analysis on the log scale), an increase of 10 points in ELDI was associated with a 2.1% reduction in GHGE (95% CI, -2.4% to -1.9%, $p < 0.001$) and a 2.2% decrease in LU (95% CI, -2.6% to -1.8%, $p < 0.001$) (Figure 6.2). Notably, for every 10-point increase in ELDI score, cost of diet increased by 2.7% (95% CI, 2.3% to 3.1%), while the association between ELDI score and dietary-related TWU was not found to be statistically significant. For similar ELDI scores, the diets with a higher proportion of animal-based food, the higher the dietary environmental impacts (Figure 6.2). In addition, Model 2 of GHGE, TWU, LU, and cost of diet had the lowest AIC and BIC, underscoring its better goodness of fit.

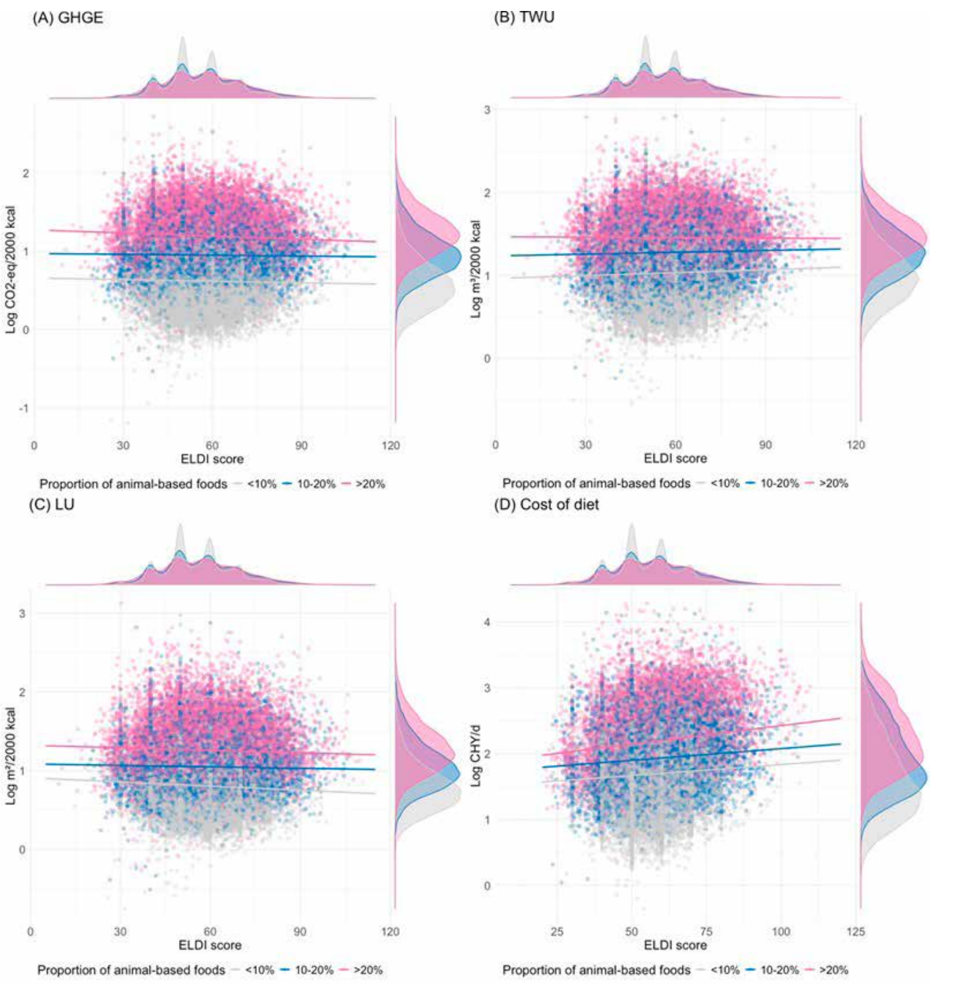

Figure 6.2. Associations between the ELDI score and environmental impacts and cost of diets of Model 2 in the China Health Nutrition Survey 1997–2015*.

** Individual data points are displayed as dots. The lines represent mixed effect regression model relating mean (A) GHGE, (B) TWU, (C) LU, and (D) cost of diet (logarithmic transformation), and ELDI score (across the proportion of animal-based foods). The distribution of the ELDI score is plotted above the scatterplots, and the distribution of dietary environmental impacts and cost of diet is plotted to the right of the scatterplots (on the log scale), respectively. Model 2 was adjusted for the covariates age, gender, BMI, dietary energy, physical activity, household income, educational level, residence location, dietary knowledge, smoking habits and alcohol consumption.*

As the consumption of "beef, pork, and lamb" decreased (94.7g in Q1 to 67.3g in Q4) along with "whole grains" (454.5g in Q1 to 419.1g in Q4), a weak negative correlation exists between ELDI scores and the environmental impacts of the diet. Conversely, it is mainly due to an increase in the consumption of "fruits" (14.5g in Q1to 103.5g in Q4), "whole milk or derivative equivalents" (7.4g in Q1 to 50.9 g in Q4), and "soy foods" (23.2g in Q1 to 66.1g in Q4) (see Figure 6.3 & Supplementary Table 6.2). Additionally, the increase in ELDI score is associated with a rise in the dietary cost, driven mainly by elevated consumption of "whole milk or derivative equivalents" and "fruits".

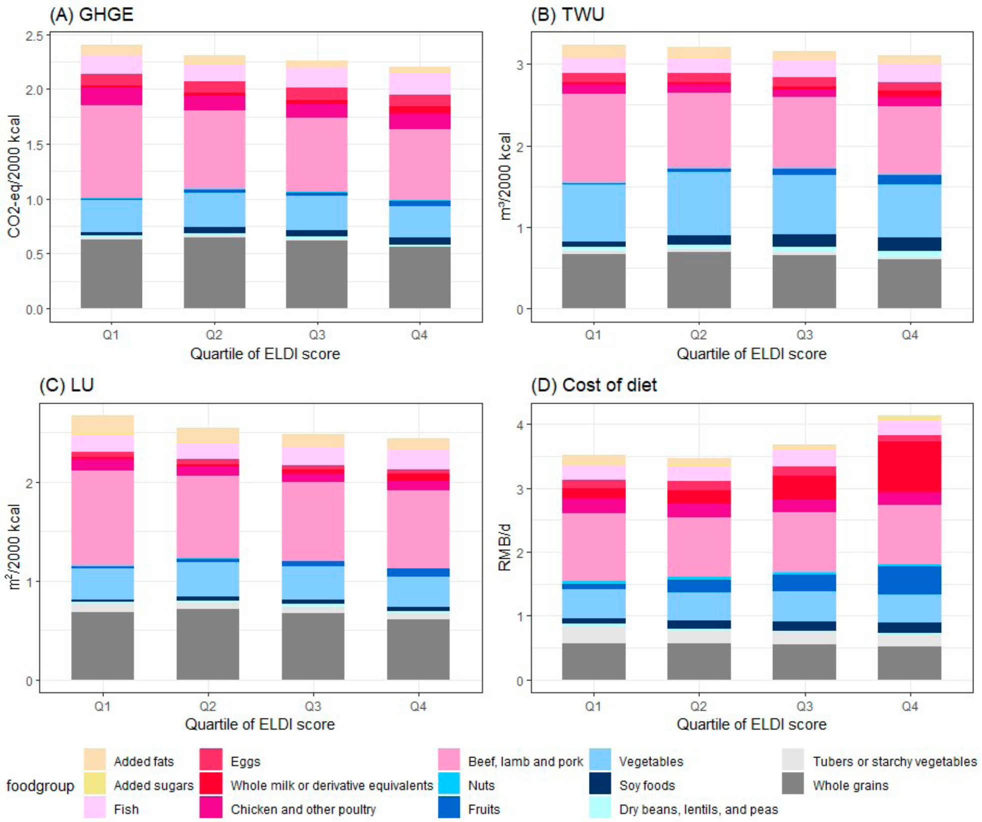

Figure 6.3. GHGE (kg CO_2-eq/2000 kcal), TWU (m^3/2000 kcal), and LU (m^2/2000 kcal) across quartiles of the ELDI by different food groups CHNS 1997-2015*.
**Values are adjusted means (95% CI) estimated from general linear models with GHGE, TWU, and LU as dependent variables, respectively, and quartiles of ELDI score, total energy intake, and sociodemographic variables as independent variables.*

Discussion

In this analysis of 16,029 participants from the CHNS study from 1997-2015, we observed inverse associations for the ELDI score and risk of all-cause mortality, CVD, and T2D. Participants with the highest scores (Q4) for adherence to the EAT-Lancet diet had a 16.1% decreased risk of CVD (95% CI: 9.2%-20.3%), and a 25.3% decreased risk of T2D (95% CI: 19.5%-28.4%), and a 8% decreased risk of mortality (95% CI: 2.2%-14.1%) compared to participants in the lowest quartile (Q1). We observed weak mitigating effects for the environmental impacts GHGE, TWU and LU, but with each 10-point rise in the ELDI score, the costs of the diet increased by 2.7%. The primary driver behind the reduced environmental impacts was related to lowered consumption of red and processed meat, whereas the increase in diet costs was primarily related to a larger share of dairy products. The research investigated the impacts of the EAT-Lancet reference diet on health, the environment, and dietary costs, with a focus on the trade-off and synergy between these indicators. Our study aligns with previous research and supports the potential of the EAT-Lancet reference diet to synergistically improve human health and dietary environmental impact. However, this paper further points out that the EAT-Lancet reference diet is also more expensive, requiring a trade-off between health and dietary environmental impacts against dietary costs.

The scientific literature on the impact of adherence to the EAT-Lancet reference diet on health outcomes is not consistent. Stemming from varied interpretations of the EAT-Lancet Committee's recommendations and using different cut-off values, binary and gradual scoring criteria have been developed to assess adherence, yielding inconsistent results(42). Colizzi et al.(26) and Cacau et al.(20) developed continuous scoring systems, and showed an association between higher EAT-Lancet diet scores and lower risk of cardiovascular events. However, studies by Berthy et al.(43) and Rebeca et al.(44) using binary scoring systems found no significant association between cardiovascular disease risk and adherence to the EAT-Lancet diet. Moreover, these discrepancies can be attributed, in part, to differences in specific food components within each food group of the EAT-Lancet diet and variations in dietary patterns among populations in different regions and countries. Knuppel et al., based on an EPIC-Oxford cohort study, revealed no association between higher EAT-Lancet diet scores and stroke risk(22). In contrast, Ibsen et al., conducting a study on Danish adults using the EAT-Lancet diet index developed by Knuppel et al., indicated that higher EAT-Lancet diet scores were associated with a lower risk of stroke(19). In this study, we have specifically used one (continuous scoring) of these dietary indices. Therefore, future studies could explore the possibility of combining multiple dietary indices and incorporating cohort data from diverse regions.

The impacts of the transition to the EAT-Lancet diet on health and the environment depend on the current proportion of animal-based foods in the dietary pattern. In low- and middle-income countries (LMIC), current dietary patterns are characterized by low intake of vegetables, fruits, nuts, legumes, and animal-based foods such as fish, eggs, dairy, poultry, and meat. In LMIC, transitioning to the EAT-Lancet diet improves health but not always environmental impacts. For example, in sub-Saharan Africa and South Asia, adopting the EAT-Lancet diet may result in a significant increase in per capita water use, ranging from 25% to 75%(35). In countries like Yemen, Indonesia, Ethiopia, etc., adopting the EAT-Lancet diet would lead to an increase in per capita GHGE by 12-283%(36). In this study in China, the EAT-Lancet Diet Index showed a weak reduction of both GHGE and LU. This may be attributed to the limited consumption of dairy products and fruits in the current stage of dietary transition in China. Consequently, the reduction in environmental impacts by lower consumption of meat and cereals, is offset by the increased environmental impacts resulting from the higher consumption of fruits and dairy. Conversely, high-income countries transitioning to the EAT-Lancet diet experience improved health and a reduction of per capita dietary environmental impacts by 40%-50%(37). This synergistic association is because a significant portion of the typical diets in HIC are dominated by resource-intensive meat and dairy products. Moreover, within the same range of ELDI scores, the higher the proportion of animal-based food consumption, the higher the diet-related environmental impacts. Due to the lack of differentiation in food sub-groups (such as beef and pork) within ELDI scoring, diets with similar ELDI scores may have significantly different environmental impacts. For instance, differences in the choice of meat consumption, such as pork (lower environmental impact) versus beef (higher environmental impact), can result in variations in environmental impacts despite similar ELDI scores. Discrepancies in food consumption quantities can also lead to differences in dietary environmental impacts. For example, consuming 500 grams of vegetables per day may result in a score of 10 in the vegetable section of the ELDI, while consuming 600 grams per day may also result in a score of 10, but with much higher environmental impacts. Future EAT-Lancet Diet scoring systems should be further refined based on food sub-groupings.

Affordability of transitioning to a healthy diet varies across different income groups and regions(38). In a modeling study encompassing 150 countries worldwide, the cost of the EAT-Lancet diet was found to decrease by an average of 22-34% in upper-middle-income countries, but it would be at least 18-29% more expensive in LMIC(39). Similarly, Hirvonen et al. found that the EAT-Lancet diet presents affordability challenges for an estimated 3 billion people with low to moderate incomes globally(8). In LMICs, however, staple crops are among the most cost-effective foods and dominate diets, which makes a shift towards healthy and sustainable diets challenging for these countries (41). This is because fruits, vegetables, fish and animal-based foods tend to be the most expensive(40). The findings from this study indicate that an increase of 10 points of ELDI score was associated with an increase in diet costs of 2.7% (95% CI: 2.3% to 3.1%). This may be attributed to the current low consumption of fruits, vegetables, and milk among the Chinese population, while the consumption of red meat is mainly from pork and does not materially exceed the EAT-Lancet diet recommendation. Therefore, the cost reduction resulting from the decrease in red meat consumption cannot offset the increase in the cost of fruits and vegetables.

To our knowledge, this is the first prospective cohort in China that evaluates the association between adherence to the EAT-Lancet Diet as related to health, dietary environmental impacts and cost of diet among adults. Strengths include the sample size, long term follow-up for diet-related CVD, T2D and mortality as well as assessment of food consumption, environmental impacts and dietary costs. The robustness of the study results was evaluated by a comprehensive array of confounding variables, assessment of heterogeneity and use of restrict cubic spline to evaluate the shape of the associations between the ELDI and health outcomes. Nevertheless, despite the thorough adjustments for covariates, residual confounding from unmeasured or unrecorded risk factors such as sleep, stress, and genetic predispositions (e.g., family history of cardiovascular disease) cannot be entirely ruled out. Secondly, regarding the diagnosis of T2D, we consistently followed the guidelines throughout the study period, However, HbA1c levels were only assessed in the 2009 round and fasting blood glucose only during follow-up sessions, which limited our ability to provide precise assessments of T2D. Additionally, our study was conducted in 12 provinces in China, which may limit the generalizability of our results to other regions and populations within the country. Although this will not have affected the associations we observed, further research will be necessary to assess the impact on sustainability of the diets in China as a whole.

Given the unbalanced economic development, substantial income disparities between urban and rural residents, and diverse dietary cultures across regions, it is crucial to implement tailored strategies for a sustainable dietary transition(45). Research findings from HIC suggest that encouraging the dietary shift towards healthy and sustainable diets through interventions can help fulfill national climate change commitments and reduce public health expenditures(46). Therefore, for areas with high levels of urbanization and higher income, implementing a carbon tax by incorporating the cost of GHGE into food prices can help reduce the consumption of unhealthy foods such as meat products. This, in turn, contributes to improving health conditions and mitigating environmental impacts(47). Research findings in LMIC indicate that the current shift towards a healthy diet would increase dietary costs and environmental impacts(48). Therefore, for economically disadvantaged regions in China, the promotion of affordably priced and nutritionally rich plant-based protein sources, such as legumes and tofu, can help people from various economic backgrounds have access to proteins(49). Additionally, increasing agricultural subsidies for fruits, vegetables, nuts, and whole grains can lower their market prices, stimulating consumption among low-income populations(50). Furthermore, future Chinese Dietary Guidelines should consider sustainable indicators such as dietary quality, environmental sustainability, and economic affordability(51).

This study provides evidence of an inverse association between adherence to the EAT-Lancet Diet and mortality, CVD, and T2D in a Chinese cohort setting. Furthermore, it reveals that greater adherence to the EAT-Lancet Diet is linked to a decrease in diet-related GHGE and LU, albeit at the cost of increased dietary expenses. These findings underscore the trade-offs and synergies among health, environmental sustainability, and economic factors in dietary choices. Considering the unbalance development in various regions of China, a tailored sustainable dietary strategy should consider economic development, income disparities, and regional dietary cultures.

Reference

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Supplementary Material

Supplementary Table 6.1a. Cut-off for each component of the EAT-Lancet Diet Index for men based on 2,500 kcal/day.

Food group	Component type*	EAT-Lancet diet recommendation (g/day)	Minimum score (0 points)	Proportional score	Maximum points (10 points)	Proportional score
Whole Grains†						
Rice, wheat, corn, and other	A	464 (or 60% of total energy)	0 g/d	0-464 g/d	≥464 g/d	
Vegetables						
All vegetables‡	A	300	0 g/d	0-300 g/d	≥300 g/d	
Fruits						
All fruit§	A	200	0 g/d	0-200 g/d	≥200 g/d	
Tubers or starchy vegetables						
Potatoes and cassava	O	50	0 g/d	0-50 g/d	50-100 g/d	100-150 g/d
Dairy foods						
Whole milk or derivative equivalents (e.g., cheese)	O	250	0 g/d	0-250 g/d	250 – 500 g/d	500-750 g/d
Protein Sources						
Dry beans, lentils, and peas	A	50	0 g/d	0-50 g/d	≥50 g/d	
Soy foods	A	25	0 g/d	0-25 g/d	≥25 g/d	
Beef, lamb and pork	M	14	≥14 g/d	14 -0 g/d	0 g/d	
Chicken and other poultry	O	29	0 g/d	0-29 g/d	29-58 g/d	58-88 g/d
Eggs	O	13	0 g/d	0-13 g/d	13-25 g/d	25-38 g/d
Fish	O	28	0 g/d	0-28 g/d	28-100 g/d	100-128 g/d
Nuts	O	50	0 g/d	0-50 g/d	50-100 g/d	100-150 g/d
Added sugars						
All sweeteners	M	31	≥31 g/d	31-0 g/d	0 g/d	
Added fats	R					

Food group	**Com-ponent type***	**EAT-Lancet diet recom-mendation (g/day)**	**Minimum score (0 points)**	**Propor-tional score**	**Maximum points (10 points)**	**Propor-tional score**
Palm oil		6.8	No consumption of unsaturated fats OR ratio of unsaturated to saturated fats of ≤0.6 ||		No consumption of saturated fats OR ratio of unsaturated to saturated fats of ≥13 ||	
unsaturated oils		40				
dairy fats included in milk		0				
lard and tallow		5				

**A = adequacy component; O = optimum component; M = moderation component; R = ratio component.*
†Reference diet refers to dry, raw weight. Recommendations for whole grains were converted, as described by Dooren et al.39
‡ Including dark green vegetables, red and orange vegetables, other vegetables. § Excluding fruit juice.
|| Cut-offs and threshold values were derived from the 15th percentile and 85th percentile of the intake distribution of the Dutch reference population, as described in Looman et al. 15

Supplementary Table 6.1b. Cut-off for each component of the EAT-Lancet Diet Index for women based on 2,000 kcal/day.

Food group	Component type*	EAT-Lancet diet recommendation (g/day)	Minimum score (0 points)	Proportional score	Maximum points (10 points)	Proportional score
Whole Grains†						
Rice, wheat, corn, and other	A	372 (or 60% of total energy)	0 g/d	0-372 g/d	≥372 g/d	
Vegetables						
All vegetables‡	A	240	0 g/d	0-240 g/d	≥240 g/d	
Fruits						
All fruit§	A	160	0 g/d	0-160 g/d	≥160 g/d	
Tubers or starchy vegetables						
Potatoes and cassava	O	40	0 g/d	0-40 g/d	40-80 g/d	80-120 g/d
Dairy foods						
Whole milk or derivative equivalents (e.g., cheese)	O	200	0 g/d	0-200 g/d	200 – 400 g/d	400-600 g/d
Protein Sources						
Dry beans, lentils, and peas	A	40	0 g/d	0-40 g/d	≥40 g/d	
Soy foods	A	20	0 g/d	0-20 g/d	≥20 g/d	
Beef, lamb and pork	M	12	≥12 g/d	12-0 g/d	0 g/d	
Chicken and other poultry	O	23	0 g/d	0-23 g/d	23-46 g/d	46-69 g/d
Eggs	O	10	0 g/d	0-10 g/d	10-20 g/d	20-30 g/d
Fish	O	22	0 g/d	0-22 g/d	22-80 g/d	80-102 g/d
Nuts	O	40	0 g/d	0-40 g/d	40-80 g/d	80-120 g/d
Added sugars						
All sweeteners	M	25	≥25 g/d	25-0 g/d	0 g/d	
Added fats	R					

Food group	Component type*	EAT-Lancet diet recommendation (g/day)	Minimum score (0 points)	Proportional score	Maximum points (10 points)	Proportional score
Palm oil		5	No consumption of unsaturated fats OR ratio of unsaturated to saturated fats of ≤0.5 ‖		No consumption of saturated fats OR ratio of unsaturated to saturated fats of ≥11 ‖	
unsaturated oils		32				
dairy fats included in milk		0				
lard and tallow		4				

**A = adequacy component; O = optimum component; M = moderation component; R = ratio component.*
†Reference diet refers to dry, raw weight. Recommendations for whole grains were converted, as described by Dooren et al.39
‡ Including dark green vegetables, red and orange vegetables, other vegetables. § Excluding fruit juice.
‖ Cut-offs and threshold values were derived from the 15th percentile and 85th percentile of the intake distribution of the Dutch reference population, as described in Looman et al. 15

Supplementary Table 6.2. Baseline average intake of food components across EAT-Lancet Diet Index quartiles*.

Food group (g/day)	All	Quartile of ELDI score Q1 (n=3,782)	Q2 (n=3,727)	Q3 (n=4,061)	Q4 (n=4,459)	P value
Whole Grains						
Rice, wheat, corn, and other	438.28 (171.46)	447.39 (188.95)	464.01 (175.17)	441.55 (166.87)	406.05 (150.78)	<0.001***
Vegetables						
All vegetables	325.9 (191.92)	317.08 (214.21)	339.75 (198.64)	335.22 (187.35)	313.31 (167.65)	0.089
Fruits						
All fruit§	54.25 (136.85)	14.46 (68.92)	31.93 (105.43)	57.68 (165.81)	103.52 (157.4)	<0.001***
Tubers or starchy vegetables						
Potatoes and cassava	35.94 (71.32)	39.71 (92.4)	33.71 (78.71)	33.46 (63.55)	36.87 (46.58)	0.143
Dairy foods						
Whole milk or derivative equivalents (e.g., cheese)	24.27 (82.29)	7.42 (51.84)	12 (58.69)	21.95 (80.27)	50.94 (110.62)	<0.001***
Protein Sources						
Dry beans, lentils, and peas	23.79 (45.13)	12.74 (37.84)	18.46 (41.9)	27.86 (48.22)	33.92 (47.74)	<0.001***
Soy foods	47.67 (71.29)	23.2 (50.3)	42.48 (70.41)	54.98 (73.21)	66.12 (78.63)	<0.001***
Beef, lamb and pork	75.44 (75.66)	90.46 (80.73)	74.03 (74.66)	71.08 (75.75)	67.85 (70.02)	<0.001***
Chicken and other poultry	23.47 (56.52)	26.66 (72.49)	21.26 (53.83)	20.07 (48.48)	25.7 (49.37)	0.558
Eggs	30.09 (41.77)	29.36 (46.73)	28 (42.38)	31.18 (41.5)	31.45 (36.67)	0.002***
Fish	33.63 (61.86)	31.01 (75.39)	27.89 (58.02)	33.81 (60.13)	40.5 (52.46)	<0.001***
Nuts	5.68 (19.52)	2.19 (15.43)	3.72 (17.54)	5.23 (18.05)	10.68 (23.99)	<0.001***
Added sugars						
All sweeteners	1.99 (9.32)	4.01 (13.94)	2.07 (9.37)	1.26 (7.14)	0.85 (4.74)	<0.001***
Added fats						
Saturated fats	4.88 (13.71)	11.03 (20.15)	4.95 (13.13)	3.02 (10.19)	1.28 (6.63)	<0.001***
Unsaturated fats	21.03 (19.79)	19.63 (22.03)	21.59 (20.34)	21.82 (19.26)	21.03 (17.61)	0.004***

*Differences across the ELDI score quartile were tested using generalized linear models.

Supplementary Table 6.3. HRs (95% CIs) for the associations between ELDI score and incidence of T2D, CVD, and all-cause mortality in Model 2, CHNS 1997–2015 (n = 59,849).

	All-cause mortality				Cardiovascular disease				Type 2 diabetes			
	Model 1†	**Model2‡**	**Model3***	**Model4+**	**Model 1†**	**Model2‡**	**Mode3***	**Model4**	**Model 1†**	**Model2‡**	**Mode3***	**Model4+**
Quartiles of ELDI score (ref: Q1)												
Q2	0.97 (0.82,1.16)	1.05 (0.86,1.28)			0.95 (0.77,1.17)	0.991 (0.78, 1.26)			0.82* (0.69, 0.98)	0.81* (0.66, 0.98)		
Q3	0.95 (0.79,1.13)	1.09 (0.89,1.34)			0.82 (0.65,1.02)	0.71** (0.55, 0.92)			0.65*** (0.54, 0.79)	0.57*** (0.46, 0.69)		
Q4	0.76** (0.63,0.92)	0.85 (0.67,1.07)			0.61*** (0.47,0.77)	0.491*** (0.37, 0.66)			0.49*** (0.41, 0.61)	0.35*** (0.28, 0.44)		
ELDI (continue variable, per SD of ELDI score increment)			0.88*** (0.84, 0.94)	0.93* (0.87, 0.99)			0.91** (0.86, 0.97)	0.84*** (0.80, 0.91)			0.85*** (0.81, 0.92)	0.75*** (0.72, 0.81)
Age (per years)	1.09*** (1.08,1.10)	1.08*** (1.07, 1.09)	1.09*** (1.08, 1.10)	1.08*** (1.07, 1.09)	1.08*** (1.07, 1.09)	1.07*** (1.06, 1.08)	1.08*** (1.07, 1.09)	1.07*** (1.06, 1.08)	1.05*** (1.04, 1.05)	1.05*** (1.04, 1.05)	1.04*** (1.04, 1.05)	1.04*** (1.03, 1.05)
Gender (ref: male)	0.62*** (0.54,0.71)	0.65*** (0.53, 0.79)	0.62*** (0.54,0.71)	0.65*** (0.53, 0.79)	0.64*** (0.54, 0.77)	0.58*** (0.46, 0.74)	0.64*** (0.54, 0.77)	0.58*** (0.46, 0.74)	0.94 (0.82, 1.09)	0.94 (0.82, 1.09)	0.94 (0.81, 1.08)	0.83 (0.68, 1.00)
Dietary energy	0.99* (0.99,1.00)	0.99 (0.99,1.00)	0.99* (0.99,1.00)	0.99 (0.99,1.00)	0.99 (0.99,1.00)	0.98 (0.73, 1.32)	0.99 (0.99,1.00)	0.99 (0.99,1.00)	0.99 (0.99,0.99)	0.99 (0.99,1.00)	0.99 (0.99,1.00)	0.99 (0.99,1.00)
BMI		0.93 (0.91, 0.96)		0.93*** (0.91, 0.96)		1.10*** (1.07, 1.12)		1.10*** (1.07, 1.12)		1.11*** (1.09, 1.13)		1.11*** (1.09, 1.13)

	All-cause mortality				Cardiovascular disease				Type 2 diabetes			
	Model 1†	**Model2‡**	**Model3***	**Model4+**	**Model 1†**	**Model2‡**	**Mode3***	**Model4**	**Model 1†**	**Model2‡**	**Mode3***	**Model4+**
Resident place (ref: urban)		1.27** (1.06, 1.51)		1.26** (1.05, 1.50)		0.80* (0.65, 0.98)		0.82 (0.67, 1.01)		0.49*** (0.42, 0.59)		0.51*** (0.43, 0.59)
Income		0.99 (0.97, 1.02)		0.99 (0.97, 1.02)		0.99 (0.97, 1.02)		0.99 (0.97, 1.02)		0.99 (0.97, 1.02)		0.99 (0.97, 1.02)
Education (ref: Primary school or below)												
Secondary school		0.90 (0.69, 1.17)		0.91 (0.69, 1.18)		0.93 (0.71, 1.24)		0.92 (0.69, 1.22)		1.11 (0.91, 1.35)		1.09 (0.89, 1.34)
High school and above		0.49* (0.27, 0.91)		0.50* (0.27, 0.92)		0.91 (0.59, 1.39)		0.89 (0.58, 1.36)		0.91 (0.65, 1.25)		0.89 (0.64, 1.24)
Activity level (ref: low)												
Medium		0.63** (0.47, 0.86)		0.63** (0.47, 0.85)		0.38*** (0.24, 0.62)		0.39*** (0.24, 0.62)		0.65** (0.49, 0.86)		0.66** (0.54, 0.87)
High		0.72*** (0.60, 0.87)		0.73*** (0.60, 0.88)		0.56*** (0.43, 0.74)		0.57*** (0.43, 0.75)		0.47*** (0.37, 0.61)		0.47*** (0.37, 0.61)
Dietary knowledge (ref: No)		0.63** (0.45, 0.88)		0.64** (0.46, 0.89)		0.98 (0.73, 1.32)		0.99 (0.73, 1.32)		1.26 (0.87, 1.56)		1.31 (0.89, 1.58)
Alcohol		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)		1.00 (0.99, 1.00)
Smoking (ref: Non-smokers)												
Ex-smokers		1.08 (0.89, 1.32)		1.08 (0.89, 1.31)		1.08 (0.89, 1.31)		1.07 (0.88, 1.30)		1.08 (0.89, 1.31)		1.08 (0.89, 1.31)
current smokers		1.16 (0.85, 1.59)		1.17 (0.86, 1.60)		1.76*** (1.27, 2.43)		1.76*** (1.27, 2.43)		1.12 (0.79, 1.57)		1.13 (0.81, 1.59)

†Adjusted for age, gender and dietary energy, and the key variable is the quartile of the ELDI score.
‡Adjusted for age, gender, dietary energy, educational level, physical activity, household income, smoking status, and alcohol consumption, and the key variable is the quartile of the ELDI score.
** Adjusted for age, gender and dietary energy, and the key variable is the ELDI score (continuous).*
+ Adjusted for age, gender, dietary energy, educational level, physical activity, household income, smoking status, and alcohol consumption, and the key variable is the ELDI score (continuous).

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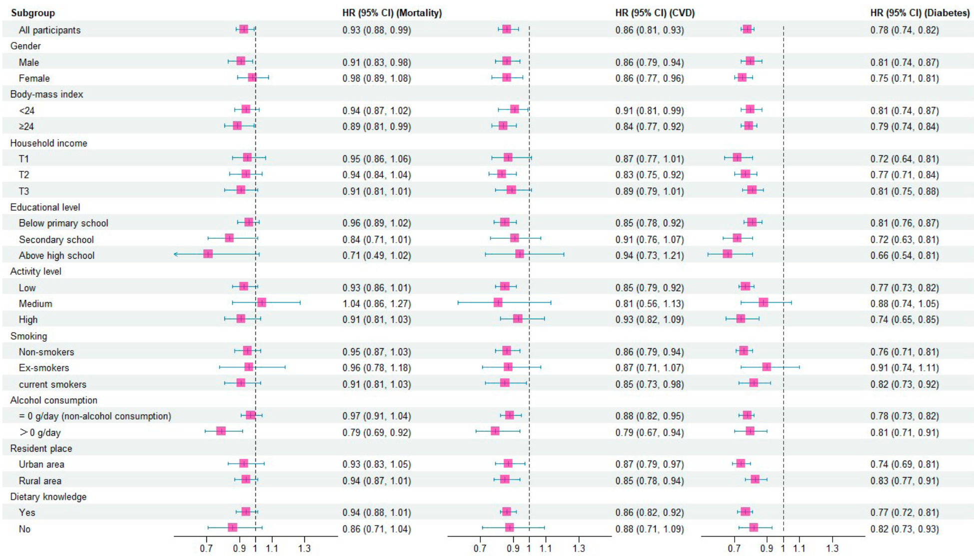
Supplementary Table 6.4. Diet-related environmental impacts and cost of diet as related to the ELDI-score (China Health Nutrition Survey 1997–2015) †

Quartile of ELDI score	**GHGE (kg CO_2-eq/2000 kcal)**		**TWU (M^3/2000 kcal)**		**LU (M^2/2000 kcal)**		**Cost of diets (RMB/day)**	
Fix effects								
	Model 1	Model2	Model 1	Model2	Model 1	Model2	Model 1	Model2
(Intercept)	3.79 (3.64, 3.95)	5.48 (5.34, 5.61)	4.99 (4.87, 5.11)	6.82 (6.71, 6.94)	4.31 (4.17, 4.44)	5.93 (5.81, 6.05)	11.61 (9.65, 13.55)	16.07 (14.27, 17.87)
Q1	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]
Q2	-0.17 (-0.21, -0.14)	-0.16 (-0.18, -0.14)	-0.11 (-0.15, -0.07)	-0.11 (-0.13, -0.08)	-0.17 (-0.21, -0.13)	-0.17 (-0.19, -0.14)	0.11 (0.02, 0.19)	0.12 (0.03, 0.21)
Q3	-0.136 (-0.17, -0.09)	-0.19 (-0.21, -0.17)	-0.04 (-0.09, 0.01)	-0.11 (-0.14, -0.08)	-0.16 (-0.19, -0.11)	-0.22 (-0.24, -0.19)	0.21 (0.12, 0.29)	0.26 (0.17, 0.36)
Q4	-0.02 (-0.07, 0.04)	-0.18 (-0.21, -0.16)	0.13 (0.05, 0.21)	-0.06 (-0.11, -0.02)	-0.04 (-0.11, 0.03)	-0.21 (-0.24, -0.17)	0.56 (0.47, 0.65)	0.65 (0.56, 0.75)
P for trend	0.985	<0.001***	0.643	0.338	0.757	0.003**	<0.001***	<0.001***
Random effects*								
SD of intercept	0.36	0.31	0.29	0.22	0.33	0.24	3.89	3.55
SD of slope (Q1)	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]	1.00 [ref]
SD of slope (Q2)	0.07	0.03	0.08	005	0.07	0.05	0.36	0.27
SD of slope (Q3)	0.08	0.03	0.12	0.06	0.09	0.04	0.39	0.32
SD of slope (Q4)	0.12	0.05	0.20	0.09	0.16	0.08	0.89	0.81
AIC	141807.3	114150.9	167328.3	138128.1	158367.2	130030.3	197057.9	162640.8
BIC	141956.9	114376.0	167477.9	138353.2	158516.8	130255.4	197200.8	162855.4
10-point increment in diet score	0.001 (-0.02, 0.01)	-0.05*** (-0.06, -0.05)	0.04 (0.01, 0.07)	-0.02 (-0.03, -0.01)	-0.01 (-0.03, 0.01)	-0.06** (-0.07, -0.05)	0.18*** (0.15, 0.21)	0.22*** (0.19, 0.25)

†Regression coefficients are all back-transformed from analysis on the log scale.
**Random effect of the model included intercept and slope for time, and other covariates were fitted as fixed effects.*
AIC: Akaike Information Criterion, BIC: Bayesian Information Criterion, SE: Standard Error, SD: Standard deviation. $p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.



Supplementary Figure 6.1. Stratified analysis of HRs (95% CIs) for the associations between ELDI score (continuous) and incidence of T2D, CVD, and all-cause mortality, stratified by selected sociodemographic characteristics.

CHAPTER 7

General discussion

To address the interconnected challenges of health, environmental impact, and dietary costs, the current Chinese diet should change. Simultaneously, when reforming towards sustainable food systems, it is necessary to adopt tailored approaches to meet the diverse needs of populations in different regions. This chapter not only examines the research findings of this thesis to inform policies but also identifies research gaps for future studies, aiming to provide valuable insights for policy debates and facilitate the development of effective strategies for sustainable dietary choices. Additionally, it critically reflects on the applied research methods and strengths and limitations of the chosen approach.

1 Main findings and interpretations

1.1 Synergies and trade-offs and between dietary sustainability indicators

This thesis examined the synergies and trade-offs between dietary sustainability indicators in China, with a focus on dietary quality, environmental impacts, and dietary costs. For instance, enhancing dietary quality by encouraging the consumption of nutrient-dense foods such as milk and fruits, as recommended in the Chinese Dietary Guidelines. However, this goal may introduce trade-offs, where the emphasis on certain foods may contribute to increased environmental burdens (**Chapter 2, 3, & 4**) or increased diet costs (**Chapter 2, 3, & 6**). To develop future sustainable dietary guidelines, it is essential to prioritize not only nutritional health but also account for the environmental and economic implications. This thesis provides insights that can inform the development of guidelines capable of navigating the balance between dietary improvements and the potential adverse impacts on other sustainability dimensions.

This thesis found synergies ('win-win') for decreased dietary environmental impact and dietary cost in the Chinese dietary context. As Chinese diets undergo changes, incorporating diverse and often animal-based food choices, the dietary Greenhouse Gas Emissions (GHGE) and Land Use (LU) increased by 23.8% and 29.1% from 1997-2011, respectively (**Chapter 2, 3, 4; Figure 7.1**). Meanwhile, the costs of diets also continued to rise, with inflation-adjusted dietary costs increasing by 80% during the period from 1997 to 2011 (**Chapter 2; Figure 7.1**). When diet quality was assessed by adherence to the Eat-Lancet Diet Index (ELDI), we found synergies between dietary quality and reduced chronic disease risk (**Chapter 6**). Higher adherence to this diet was associated with decreased mortality (8% per standard deviation increase, 95% CI: 2.2%-14.1%), cardiovascular disease (16.1% decrease, 95% CI: 9.2%-20.3%), and type 2 diabetes (25.3% decrease, 95% CI: 19.5%-28.4%). In addition, adherence to the ELDI score moderately reduced the dietary environmental impacts. It led to a small reduction in GHGE (-2.1% per 10-point increase, 95% CI:-1.9%; -2.4%) and LU (-2.2%, 95% CI: -1.8%; -2.6%).

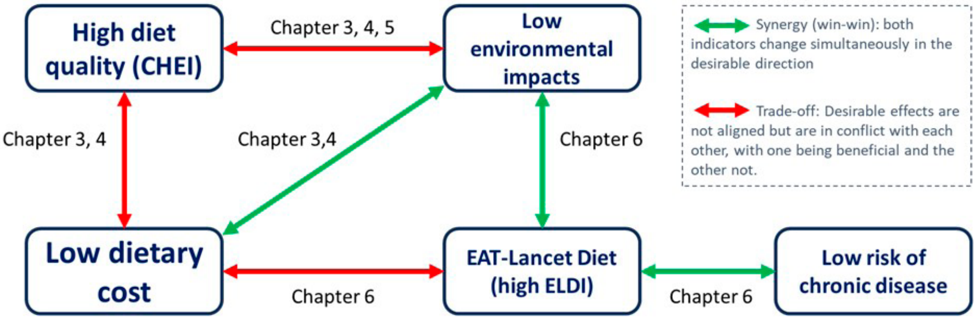


Figure 7.1. Summary of synergies and trade-offs for sustainability indicators resulting from dietary changes in China as reported in the chapters of this thesis[1].

[1]*Diets of high nutritional quality (assessed by CHEI) do not synergize with low costs or low environmental impacts, whereas the EAT Lancet sustainable diet (ELDI score) synergizes with low environmental impact and low chronic disease risk, but not with low diet costs. In addition, low environmental impacts synergized with low diet costs.*

Further, we found a trade-off between dietary quality and dietary environmental impacts when using the Chinese Healthy Eating Index (CHEI 2016) (**Chapter 2, 3, 4; Figure 7.1**). 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 (**Chapter 4**). Moreover, we observed a trade-off between dietary quality and dietary costs, whether using CHEI 2016 or the ELDI to evaluate dietary quality. The CHEI2016 score increased from 39.4 in 2004 to 41.9 in 2011 (+ 6.3%), while the inflation-corrected dietary cost increased from CNY 4.50/day/2,000 kcal in 2004 to CNY 8.1/d/2,000 kcal in 2011 (+80%)(**Chapter 2**). Similarly, for one standard deviation increase in the ELDI, dietary costs increased by 2.7% (95% CI: 2.3% to 3.1%).

1.2 Exploring the factors influencing synergies and trade-offs in China

Transitioning from the findings on synergies and trade-offs between dietary sustainability indicators, the following sections delve into the underlying factors influencing these dynamics. One of the reasons for the synergy between dietary environmental impacts and dietary costs lies in the rapid economic and urbanization growth of China (**Chapter 3).** With increasing incomes, people can spend a larger share on animal-based foods such as meat, which lead to increased GHGE and LU(1). Additionally, red meat and dairy products are relatively expensive due to their high demands for feed, water, and land(2).

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Adhering to the EAT-Lancet diet is associated with synergistic improvements in both health outcomes and environmental impacts (**Chapter 6**). The EAT-Lancet Diet centers around a more plant-based and sustainable dietary pattern, seeking to enhance individual health while lessening the environmental burden of food production(3). The reasons behind this dynamic can be categorized into two factors. Firstly, the health benefits arise from the

EAT-Lancet Diet's emphasis on higher consumption of fruits, vegetables, whole grains, and plant-based foods, coupled with a limitation of red and processed meat consumption(4). This dietary focus is associated with improvements in cardiovascular health, better blood sugar control, and an overall reduction in the risk of cardiovascular diseases, diabetes, and mortality(5). Secondly, the modest environmental improvements of the EAT-Lancet Diet result from its recommendation to prioritize plant-based foods, thus reducing the consumption of animal products. However, **Chapter 6** pointed out that Chinese residents shifted towards the EAT-Lancet Diet, but the decrease in dietary environmental impact was not significant. This may be due to the limited consumption of dairy and fruit during the current dietary transition period in China, which falls short of The EAT-Lancet Diet recommendations(6). Consequently, the reduction in environmental impacts by lower consumption of meat and cereals are partially offset by the increased environmental impacts resulting from the higher consumption of fruits and dairy. In contrast, the reduction in Total Water Use (TWU) is not significant. This may be due to water-intensive plant-based foods in the EAT-Lancet Diet, such as nuts, seeds, or vegetables(7), which offsets the water-saving gained from reducing animal product consumption.

The trade-off between CHEI scores and environmental impact was mainly attributed to increased consumption of currently under-consumed foods like cereals, vegetables, fruits, dairy, and fish, along with reduced consumption of red meat and sodium (**Chapter 3, 4, 5**). The per capita meat consumption in China is higher than the recommended amount in the Chinese Dietary Guidelines (the average meat consumption per 2,000 kcal in our study was 30% higher than recommended), while dairy, eggs, and fruit, were 90%, 30%, and 40% lower than the recommended consumption amounts, respectively. Similarly, the consumption of aquatic products, tubers, vegetables, and fruit among the Chinese population still fall short of the recommended levels (**Chapter 5**). The environmental benefits of reducing meat consumption were thus offset by the necessity to increase the consumption of fruits, 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) compared to High-Income Countries (HICs), where they on average range from 55.7% to 68.7%(8)). In Spain(9) and the UK(10), animal-based foods were the primary contributors to dietary GHGE, e.g. meat contributed 33% and 32%; fish: 22% and 8%, and dairy products: 17% and 14%, respectively). Furthermore, **Chapter 4** suggests that, at similar diet quality scores, the environmental impacts were positively associated with the proportion of animal-based foods in the diet. A trade-off exists between the diet quality and diet-related environmental impacts of the Chinese population, suggesting that a shift to a healthier diet may not necessarily be beneficial for environmental sustainability.

Using the Chinese Dietary Guidelines and the EAT-Lancet Diet to assess dietary quality, it was found that the association between the two index scores and environmental impact was inconsistent. The Chinese Dietary Guideline aims to enhance dietary quality by advocating for a varied and balanced diet, encompassing a diverse range of foods like fruits, vegetables, dairy, and cereals, and only small reductions in meat consumption (**Chapter 4**). The emphasis on dietary diversity contributes significantly to an overall enhancement in dietary quality by ensuring a broader intake of essential nutrients (**Chapter 5**). In contrast to the Chinese Dietary Guidelines, the EAT-Lancet Diet is designed to achieve both health and environmental sustainability(11). By emphasizing plant-based foods and limiting the consumption of red and processed meats(12), it reduces the risk of chronic diseases(13) while also contributing to a decrease in GHGE and LU associated with animal agriculture(14). However, the reduction in GHGE and LU is relatively small. This may be because the recommended consumption of red meat, and poultry (84 g/day in the EAT-Lancet Diet vs 160 g/day in the Chinese Dietary Guideline), dairy products (250 g/d vs 300 g/d), and fruits (200 g/d vs 275 g/d) is lower in the EAT-Lancet Diet compared to the Chinese Dietary Guidelines.

Using the Chinese Guidelines or the EAT-Lancet Diet Guidelines to assess dietary quality, both dietary indices exhibited a trade-off with dietary costs (**Chapter 4, 6**). Dietary guidelines typically recommend consuming nutrient-rich foods such as fresh fruits, vegetables, and milk. However, these foods may be more expensive than processed foods or foods high in sugar and fat(15). Moreover, the affordability of healthy foods is linked to socio-economic factors(16). In regions undergoing rapid economic development, such as China, rising dietary costs may reflect increased purchasing power and the ability of some segments of the population to afford more diverse and nutritious diets (**Chapter 4, 5**). However, this trend may not be universal across all socio-economic strata or geographic regions. Economically disadvantaged communities may face heightened challenges in accessing and affording healthy food options(17).

1.3 Shift to healthy dietary guidelines in LMICs and HICs

The transition to healthy reference diets (e.g. FBDGs, EAT-Lancet Diet) in countries at different economic levels starts from varied dietary patterns (**Figure 7.2**).This transition leads to different synergies and trade-offs for health and environmental impacts, mainly depending on the current proportion of animal-based foods in their dietary patterns (**Chapter 5 & 6; Table 7.1**). As illustrated below, the trade-off between health and environmental impact in LMICs like China, often changes into a synergy in HICs.

In LMICs, there is a trade-off between health and environmental impacts when transitioning to the EAT-Lancet diet. This is mainly attributed to the current dietary patterns characterized by low consumption of vegetables, fruits, nuts, legumes, and animal-based foods (fish, eggs, dairy, poultry, and meat) (**Figure 7.2**). In LMICs, such as those in sub-Saharan Africa and South Asia, adopting the EAT-Lancet diet may result in a significant increase in per capita water use, ranging from 25% to 75%(18). Moreover, if countries like Yemen, Indonesia, Ethiopia adopt the EAT-Lancet diet, this would lead to an increase in per capita GHGE by 12-283%(19) (**Table 7.1**). Consequently, the reduction in environmental impacts due to decreased consumption of meat and cereal is offset by the increased environmental impacts resulting from the higher consumption of fruits and dairy products. Conversely, in high-income countries, the transition to the dietary guidelines was accompanied by a 40%-50% reduction in per capita dietary GHGE(20,21). This synergistic association is mainly observed because a significant portion of the typical diets in HIC is dominated by animal-based foods, and especially ruminant meat (**Figure 7.1**)(22). However, in the Netherlands, improved diet quality is associated with increased blue water use(23).

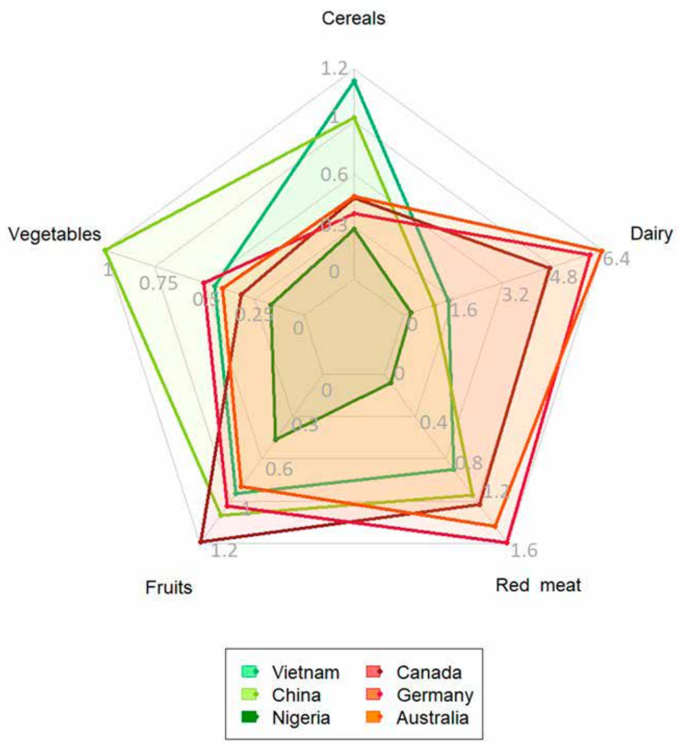

Figure 7.2. Illustration of typical dietary patterns in LMICs (China as reference, Vietnam, Nigeria as example) and HICs (Canada, Germany, Australia as examples)

Note: The numbers in the figure represent proportions, with food group consumption in China as the reference (proportion set to 1). Data source: UN Food and Agriculture Organization (FAO), https://www.fao.org/faostat/en/#home

Table 7.1. Impact of dietary guidelines (e.g. FBDG, EAT-Lancet Diet) on health outcomes, the environment, and affordability in LMICs and HICs

Outcome	**Impact of the shift to healthy dietary guideline by different countries**	
	Impacts in LMICs	**Impacts in HICs**
Health	Healthy dietary guidelines contribute to the prevention of malnutrition in all its forms(24), reduce risk of NCDs, and lead to increased quality-adjusted life years and save costs for health care(25).	
Environmental impacts	Consumption of vegetables, fruits, and dairy products remains currently below recommended levels in LMICs(26). Transitioning to recommended diets requires an increase in dairy, fruit, and poultry consumption while reducing bread, rice, and meat. The environmental impact of increasing dairy, fruit, and poultry consumption outweighs the reduction from reducing bread, rice, and meat(27), leading to a net increase in GHGE (12-283%)(19) and WU (25%-75%)(18).	Following dietary guidelines led to decreased GHGE (26-54%) and LU (20-37%) due to substantial reductions in meat and dairy consumption, major contributors to per capita dietary-related environmental impacts(28). The amount of blue water use associated with the diets slightly increased as more fruits, vegetables, nuts, and non-alcoholic beverages are needed to meet dietary recommendations(29).
Dietary cost	Grains are low cost compared to other food groups. For LMIC heavily reliant on grains, transitioning to healthier dietary guidelines involves substituting grains with expensive foods such as fruits, vegetables, and milk(30). The cost of dietary guidelines are 41%-83% higher than average household food expenditures(31).	In 16 out of 24 EU countries, over 10% of the population face financial barriers to healthy eating, with higher prevalence in Eastern and Southern Europe(32).

1.4 Associations between socio-demographic characteristics and sustainable diets in China

As illustrated in the previous section, synergies and trade-offs in the diet transition can differ by the level of socioeconomic development. As this likely also holds for large geographical regions in China, this thesis highlighted the role of socio-demographic factors in influencing dietary quality, dietary environmental impact, and dietary costs. As summarized in **Table 7.2, Chapter 3, 4, and 5** illustrated that various demographic characteristics, including gender, age, education level, physical activity, income level, and urbanization level, exert a considerable influence on the sustainability indicators. Based on these results, the following sections address the three most significant variables: education level, income, and degree of urbanization.

Table 7.2. Demographic characteristics, CHEI2016 score, diet-related GHGE, TWU, LU, and dietary cost of participants in the China Health Nutrition Survey 2011, aged 18–64 years.*

Demographic characteristics	**GHGE** (kg CO_2-eq/ 2000 kcal)	**TWU** (m^3/ 2000 kcal)	**LU** (m^2/ 2000 kcal)	CHEI2016	Dietary cost (CNY/2000 kcal)
Age (in years)					
18-30	3.05 (1.12)	3.95 (1.38)	3.49 (1.38)	53.2 (10.1)	12.7 (5.0)
50-65	2.76 (1.06)	3.59 (1.29)	3.13 (1.21)	51.1 (10.8)	11.5 (5.0)
Gender					
Female	2.84 (1.06)	3.73 (1.32)	3.26 (1.26)	51.6 (10.1)	11.7 (4.5)
Male	2.91 (1.12)	3.76 (1.37)	3.32 (1.38)	52.2 (10.8)	12.1 (5.4)
Educational level					
Primary school and below	2.55 (1.01)	3.36 (1.24)	2.93 (1.13)	48.8 (9.9)	10.4 (4.6)
High school and above	3.33 (1.11)	4.31 (1.37)	3.84 (1.46)	55.6 (10.4)	14.1 (5.1)
Activity level					
Low	3.11 (1.09)	4.01 (1.34)	3.55 (1.36)	53.4 (10.5)	12.8 (5.1)
High	2.28 (0.84)	3.08 (1.09)	2.71 (1.02)	48.6 (9.9)	9.7 (4.3)
Annual income (CNY)					
< 6,000	2.44 (0.98)	3.23 (1.22)	2.87 (1.21)	48.1 (9.8)	10.1 (4.4)
> 80,000	3.31 (1.07)	4.27 (1.34)	3.74 (1.35)	55.5 (10.5)	13.9 (5.1)
Degree of urbanization					
Urban	3.32 (1.09)	4.22 (1.37)	3.79 (1.41)	54.3 (10.8)	13.7 (5.1)
Rural	2.55 (0.97)	3.41 (1.22)	2.94 (1.13)	50.2 (9.9)	10.6 (4.5)

* Table summarizes model results (adjusted for the other variables) of descriptive Chapter 3, 4, and 5. The numbers in the table represent the mean and standard deviation (SD).

Firstly, education level is an important factor among socio-demographic characteristics and is closely associated with dietary quality (**Chapter 3**). Individuals with higher education levels often have a better understanding and awareness regarding nutrition, making them more likely to adopt healthier and balanced dietary habits(33). They are likely to have a better understanding of various nutritional requirements and are more inclined to choose foods rich in fruits, vegetables, whole grains, and protein sources(34). As their diets tend to align more closely with the Chinese Dietary Guidelines, their dietary environmental impact and costs are relatively higher as well (**Chapter 4 & 5**). Research from high-income countries suggests that education level has little impact(35) and is only weakly correlated with knowledge and behavior(36) regarding sustainable diets. This may be due to a skewed distribution of education levels in samples from high-income areas, with a high proportion of participants having a college degree or higher (over 50%)(37). Conversely, in China, we observed a strong correlation between the level of education and the dietary environmental impacts and dietary costs. This indicates that in China, when formulating food policies and promoting sustainable food consumption, education level remains a key factor to consider.

Secondly, income level is also a significant factor influencing dietary quality (**Chapter 3, 4, 5, 6**). Individuals with higher income levels may be better positioned to afford higher food costs(38) and can purchase a variety of high-quality foods, including fresh fruits, vegetables, and organic products(39). They may also choose to consume larger amounts of meat and high-energy-dense foods, which often require more resources and energy for production, thereby exerting a greater environmental impact(40). This aligns with Bennett's Law, which states that when household income increases, the budget share allocated to staple foods such as grains and rice tends to decrease, while the budget share for meat products often rises(41). In contrast, low-income groups may face economic constraints, leading them to prefer cheaper and plant-based staple foods (such as grains), which may lower dietary quality but also result in lower dietary environmental impact (**Chapter 3 & 5**).

Firstly, level of urbanization can influence an individual's dietary quality (**Chapter 3, 5, 6**). In urban areas, people may have easier access to fresh fruits and vegetables, as well as a diverse range of food choices(42). In remote or impoverished areas, individuals may face restrictions on dietary quality due to inadequate supply(43). Secondly, the environmental impact and dietary cost of rural diets are lower than those in urban areas. **Chapter 4** indicated that in low-urbanized areas, the environmental impact and the growth rate of dietary costs are faster than in highly urbanized areas (e.g. diet-related GHGE in the lowest vs. highest quartile of urbanization increased by 86.9% compared to 17.8%; and cost of diet increased by 124.4% compared to 64.7% during the period 1997 to 2011).

Notably, metropolitan areas stand out with the highest dietary environmental impacts compared to the other regions studied (**Chapter 5**). The heightened environmental impacts in metropolitan areas can be attributed to a combination of factors. Firstly, a higher proportion of highly-educated residents is observed in these areas, influencing dietary choices and potentially contributing to increased environmental impacts. Additionally, the high proportion of animal-based foods in dietary patterns within metropolitan regions further increases the environmental impact, emphasizing the need to consider the composition of diets in different demographic contexts. It is noteworthy that the study does not imply a straightforward causation between lower physical activity or higher educational levels and increased environmental impacts (**Chapter 5**). Indeed, the study underscores the interaction between lifestyle and dietary patterns in metropolitan areas, which collectively contribute to heightened diet-related environmental impacts. Metropolitan living, characterized by factors such as increased reliance on convenience foods, higher demand for animal-based foods, and food waste, collectively contributes to the observed environmental impact(44).

The divergent correlations between socio-demographic characteristics and dietary patterns can be attributed to the interplay of cultural, economic, and lifestyle factors that shape individual food choices (**Chapter 3, 5, 6**). **Chapter 3** identified specific patterns associated with different demographic groups, shedding light on the association between socio-demographic indicators and dietary preferences. The urban residents, those in low-intensity labor, and with higher income toward the "High animal-based food" pattern suggests a complex interplay of factors. Urban lifestyles, potentially also influenced by factors such as convenience, availability of processed foods, and cultural preferences, might contribute to a higher reliance on animal-based foods(45). This pattern may be associated with higher environmental impacts, given the emphasis on animal-based products. Rural residents, those in labor-intensive work, and with lower income tend to follow the "High wheat, low pork" pattern. This association may reflect cultural and regional preferences, where rural areas with labor-intensive activities may have traditional dietary patterns emphasizing wheat and lower meat consumption(46). Therefore, in promoting sustainable dietary policies, it is necessary to consider socio-demographic characteristics comprehensively, rather than just focusing on a single factor(47).

2 Reflection on current and future methods for assessing Chinese sustainable diets

The assessment and analysis of sustainable diets represent a multifaceted endeavor, demanding an understanding of methodologies that encompass not only nutritional considerations but also environmental impact and economic viability. This section describes the methodological considerations most relevant to the overall thesis.

2.1 The Chinese Food Life Cycle Assessment (LCA) Database

This thesis incorporated various environmental impact indicators, including GHGE, TWU, and LU. While GHGE is commonly used as a proxy for the total environmental impact due to its high correlation with other environmental impacts(48), it is important to recognize that it primarily addresses global challenges. In contrast, issues such as nitrogen pollution may be confined to a limited geographical area, spanning only a few hundred kilometers, and eutrophication might be localized to specific bodies of water, such as lakes. Despite the use of multiple indicators, this thesis did not include metrics like terrestrial acidification, freshwater eutrophication, marine water eutrophication, and biodiversity loss due to data limitations. Therefore, the selection of indicators should be contextual, considering both local and global perspectives.

Data availability poses a challenge, even for the currently employed environmental indicators. Food items were linked to LCA data through direct matching or extrapolation based on similarities in food type or production methods. The LCA datasets encompassed primary data for 242 foods and beverages, with items lacking primary data (1,200 foods and beverages) relying on extrapolations. Despite increased uncertainty from extrapolations, our studies had complete LCA data for all foods in the CHNS. To fortify the foundation of sustainable dietary assessments, ensuring accuracy and comprehensiveness in the food life cycle assessment database is crucial.

Continuous improvement requires strengthening data accuracy and integrating up-to-date information on agricultural practices, transportation, and processing methods(49). Governments play a vital role in facilitating data collection efforts by setting standards, regulations, and mandates. For instance, in the European Union, legislation mandates the reporting of scope emissions by large businesses(50). Producers could provide information regarding their production processes, resource usage, and emissions. This not only increases transparency but also ensures that relevant data is available for informed decision-making and policy development (51). Reflecting China's agricultural diversity, continuous improvement also involves integrating regional specifics into the database. This includes expanding the database to encompass a broader range of agricultural practices, considering the diverse ecosystems and climates characterizing different regions in China. Given the dynamic nature of food supply chains, continuous improvement extends to monitoring and adapting to changes(52). Establishing mechanisms for regular updates to the database ensures it reflects evolving supply chain dynamics, technological advancements, and shifts in consumer behavior(53).

2.2 Food price and affordability

This thesis adopted food market prices to assess individual dietary costs, sourced from community surveys in the China Health and Nutrition Survey, where residents living in the same community have uniform food prices(54). However, this approach has its limitations. Some foods may have different prices due to variations in variety, quality, or the supply chain, and these differences may not have been fully considered in the survey. Even within the same community, there may be differences in dietary habits and purchasing power among different groups of people. Therefore, applying the overall food prices of the community to assess individual dietary costs may not accurately reflect the circumstances of each individual.

Addressing the shortcomings of using food market prices, future research directions can be explored: Firstly, there's a need to consider differences in individual consumption habits and purchasing power by surveying individuals' economic status and lifestyle to personalize food prices for a more accurate reflection of individual dietary costs(55). This could involve innovative methods such as shopping basket surveys, barcode scanning, or other advanced technologies to capture real-time data on food purchasing behavior(56).

Secondly, exploring alternative methods for measuring residents' dietary costs, such as estimating food expenditure proportions based on household spending data or conducting basket surveys(57), could provide valuable insights.

2.3 Cultural acceptability and social equity

This thesis primarily evaluated sustainable diets based on dietary quality, environmental impact, and dietary cost. However, sustainable indicators such as cultural acceptability, social equity, and inclusivity have not been adequately explored. Although in **Chapter 4**, attempts were made to identify sustainable dietary patterns in China based on the Reduced Rank Regression model, none of the four dietary patterns achieved the ideal combination of high CHEI2016 scores, reduced environmental impact, and lower dietary costs. To address this gap, future research could delve deeper into the sustainability of diets through multi-dimensional assessments. For example, the "Sustainable, Healthy, Acceptable, Realistic and Preferable (SHARP) model(58), which involves learning from peers without extreme changes in diets as a first step, could provide valuable insights into the practical implementation of sustainable dietary practices. This approach assumes a certain level of acceptability and aims to gradually transition towards healthier and more sustainable diets. Additionally, it is essential to understand how people perceive new foods like meat replacers and artificial meat, as well as their attitudes towards dietary changes(59). Addressing the cultural side of traditions and expectations is crucial in promoting the adoption of sustainable diets. By conducting social surveys and focus group discussions(60), qualitative and quantitative data on the cultural acceptability and inclusivity of sustainable diets can be gathered.

2.4 The China Health and Nutrition Survey

To assess regional differences, cultural customs, and dietary preferences at the individual level, **Chapters 3-6** utilize data from the Chinese Health and Nutrition Survey. However, due to the unavailability of more recent data from public sources, the most recent individual-level data is from 2011. Although the per capita food group consumption data from the Chinese National Bureau of Statitics has been updated to 2023, individual-level data, including personal dietary habits and demographic characteristics are required to comprehensively understand the sustainable dietary consumption characteristics of different population groups.

Furthermore, research indicates a 20% increase in Chinese residents' consumption of pre-made and highly processed foods with the improvement of online food delivery platforms(61,62). Yet, these changes in food processing levels and consumption habits are not reflected in the per capita food balance sheet data. Furthermore, China's dietary survey data still lacks nationwide representativeness, covering only 47% of the population. Regions such as the Northwest remain unexplored, potentially impacting the comprehensive understanding of the regional dietary pattern.

To address the challenges in assessing China's dietary patterns, efforts could focus on making updated survey data openly available to reflect recent dietary transition, conducting in-depth research on the impact of online food delivery platforms, and exploring regional disparities and cultural influences on dietary patterns. Additionally, efforts should be made to increase survey coverage in areas currently not included to ensure a comprehensive understanding of the Chinese dietary pattern.

3 Policy options for sustainable diets in China

China, as a vast country with a large population, faces unique challenges and opportunities in pursuing sustainable diets. Currently, the dietary GHGE for Chinese residents is 2.7 kg CO_2-eq/2000 kcal (this study), compared to 4.4 kg CO_2-eq/2000 kcal for the United States(63), 5.7 kg CO_2-eq/2000 kcal for the UK(64), 4.8 kg CO_2-eq/2000 kcal for Netherlands(65) and 6.5 kg CO_2-eq/2000 kcal for Ireland(66). However, despite China's lower per capita dietary emissions, its national diet-related emissions are the highest globally (**Figure 7.3**). Meanwhile, there is still significant room for improvement in the dietary quality of Chinese residents (CHEI: 51.9, out of 100; ELDI: 55.3, out of 120) (**Chapter 5, 6**). However, if Chinese resident adhere to the current FBDGs, inevitably there will be an additional burden on the environment. Therefore, effective implementation and achievement of sustainable diets in China requires comprehensive strategies. This necessitates multi-party cooperation, where the government, society, and individuals each play distinctive roles(67). It is crucial to recognize that we cannot expect companies and consumers to take the lead, as they may lack the interest (companies) or power (consumers)(68). Instead, governments should lead the way, highlighting the urgency to create new policies(69). Further details on specific policy recommendations will be elaborated in the following sections. (**Table 7.4**).

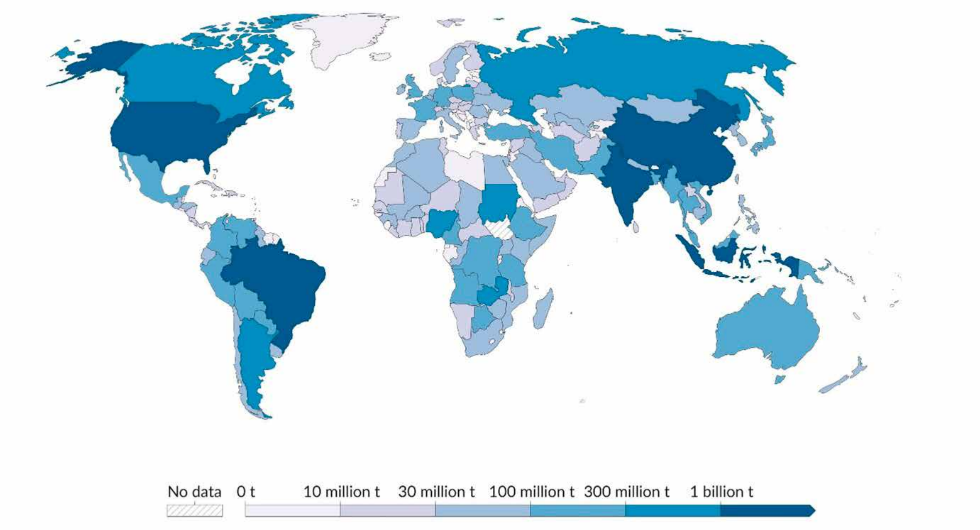

Figure 7.3. Greenhouse gas emissions from food systems across countries, 2015.
Note: Emissions are measured in tonnes of carbon dioxide-equivalents. Data source: Crippa, et.al, 2021(70).

3.1 Reforming dietary guidelines for sustainability

The association between sustainability indicators in the current Chinese diet, as evident from **Chapters 3 and 4**, highlights synergies and trade-offs. Therefore, in the development of future Chinese Dietary Guidelines, an emphasis should be placed on the integration of dietary quality, environmental sustainability, and economic affordability(71). Dietary guidelines in more and more countries (e.g., Sweden, Germany, the Netherlands, Brazil, Qatar, etc.) take environmental considerations into account(72). For example, Qatar focuses on food waste reduction and local production of food(73). Brazil emphasizes socially and environmentally sustainable food systems(74), and Italy specifically discusses food waste reduction(75). Furthermore, adopting a healthy and environmentally sustainable diets can be financially burdensome for low-income groups (**Chapter 3, 4, 6**). In LMICs in Africa, the Americas, and the Middle East, this affordability concern is explicitly addressed in their FBDG, for instance, by promoting activities like "growing your own vegetables"(76,77). When revising China's dietary guidelines, multiple departments, such as the Chinese Nutrition Society(78), the Ministry of Agriculture, the Ministry of Finance, and the Ministry of Natural Resources should collaborate. Together, they should formulate comprehensive policies, considering the trade-offs between health and environmental impact indicators(79).

Food choices within the same food group can significantly affect environmental impacts. For example, opting for pork over beef within the red meat food group can lower the environmental impact of the diet despite similar CHEI2016 scores (**Chapter 3 & 5**). However, the current Chinese Dietary Guidelines classify meat into a single category. Future food groups in dietary guidelines should be further subdivided, distinguishing between pork, beef, lamb, poultry, etc., and appropriately reducing recommended values for beef, lamb, and other meats with high environmental impact.

3.2 Towards sustainable diets for specific subpopulations

In essence, a regionally differentiated approach ensures that sustainable diets are not only effective but also culturally sensitive, economically feasible, and tailored to the unique characteristics of each region and subpopulation in China (80). Sustainable dietary recommendations were developed for different subgroups based on various socio-demographic characteristics, ensuring greater specificity and personalization (**Table 7.3**).

The need for a regionally differentiated strategy in achieving dietary guidelines in China is paramount due to the country's vast and diverse landscape, encompassing various cultures, and dietary preferences(81). A one-size-fits-all approach to dietary guidelines may not effectively address the unique challenges present in different regions(82). Therefore, tailoring sustainable diet recommendations to different demographic characteristics ensures inclusivity and relevance. This approach ensures that dietary guidelines are not only effective but also culturally sensitive, economically feasible, and tailored to the unique characteristics of each region and subpopulation in China. In summary, future Chinese dietary guidelines should consider the association between dietary choices, environmental sustainability, and economic factors, providing inclusive dietary guidance for the population(83).

The environmental impact of the diet increases with younger age (GHGE, 18-30 years: 3.05 CO_2-eq/2000 kcal vs 53-65 years: 2.76 CO_2-eq/2000 kcal) (**Chapter 3, 4, 5; Table 7.2**). The government can employ various measures to address the issue of high dietary environmental impact of younger people. Firstly, strengthening regulations on advertising to ensure the accuracy and transparency of food information, reducing misleading advertising of unhealthy foods(84). Secondly, restricting the opening of fast-food chains near schools, and encouraging the availability of nutritious meal options in school cafeterias(85), thereby improving the school food environment(86). Additionally, the government can strengthen health and nutrition education among young people, conveying correct dietary concepts and behaviors to guide them in choosing more environmentally friendly and healthy foods(87).

This thesis found that individuals with higher levels of education (bachelor's degree or above) tend to have higher environmental impacts and costs associated with their diets (per 2,000 kcal)(**Chapter 3, 4, 5; Table 7.2**). Therefore, the government can start by implementing a series of targeted sustainable food policy measures in university cafeterias. Firstly, school cafeterias should offer education and awareness programs customized for sustainable diets, including workshops and promotional events to enhance students' understanding of sustainable food choices(88). Secondly, providing information on sustainable food labeling can convey the importance of sustainable diets to students(89). Additionally, measures could be taken to reduce food packaging and waste, promote vegetarian and low-meat diets, and thereby mitigate environmental impacts(90).

The higher the income level of a population, the greater the environmental impact and cost of their diets (**Chapter 3, 4, 5; Table 7.2**). By imposing higher taxes on high environmental impact and high-energy-dense foods (such as red meat)(91), it can effectively encourage the choice of healthier and more sustainable diets. Additionally, government collaboration with the food service industry can promote more delicious vegetarian options (e.g., Meatless Monday) and offer discounts, as well as attracting high-income individuals to choose vegetarian options(92). The government can provide subsidies or offer discounts specifically for low-income groups to purchase healthy foods (e.g. fruits, vegetables, whole grains)(93).

In addressing the issues of dietary environment impact and cost for urban residents (**Chapter 3, 4, 5; Table 7.2**), the government could take a series of measures. These include: the government could provide funding and support to assist healthy food retailers in establishing stores in urban areas, offering a greater variety of healthy food options(94). Establishing urban farms and community gardens enables residents to more easily access local, organic vegetables and fruits, thus reducing the cost of purchasing healthy ingredients(95). Additionally, the government can provide funding and support to facilitate online purchasing and delivery services for healthy food, thereby offering urban residents convenient, high-quality, and low-cost food options(96,97).

Besides targeted recommendations for various demographic groups regarding sustainable diets, the government can implement several measures for the general population. The research in Chapter 4 and Chapter 5 demonstrates significant differences in the environmental impacts of diets, even with similar dietary scores. This is attributed to the consumption of foods with high environmental impacts or proportion of animal-based foods in the diet. Therefore, the government can introduce food labelling indicating environmental impacts to provide information about the environmental footprint of food(98). This might be especially helpful for comparing foods within food groups and facilitate citizens to choose the more sustainable option.

Table 7.4. Summary of suggested sustainable dietary recommendations and policies stratified for different socio-demographic subpopulations

Policy recommendations	Age	Educational level	Income level	Degree of urbanization
Restricting/ **promoting access**	Limiting advertising aimed at teenagers**(84)**. Increasing the availability of nutritious meal options in school cafeterias(85) Limiting fast food chains near schools(86).			Establishing urban farms and community gardens**(95)**
Fiscal measures			Tax on fat, sugar, meat**(91)**. Subsidies on sustainable foods/ vouchers for people on income support**(93)**.	Government funds aid healthy food retailers in urban areas**(94)**. Establishing urban farms and community gardens**(95)** Facilitating online purchasing and delivery services for healthy food**(96,97)**
Persuasion/ campaigns		Offer education and awareness programs customized for sustainable diets, including courses, workshops, lectures, and promotional events**(88,90)**.	"Meatless Mondays" (Aim for a more 'plant-rich' diet)**(92)**	
Information	National Dietary Guidelines Food labels, certification programs**(98)**			
Research and development	Funding for research on how to shift diets in different contexts and geographies**(100)** Technology support for plant-based meat substitutes**(99)**			

7

4 General conclusion

This thesis emphasizes the need for a shift towards sustainable diets that improve nutritional health and reduce diet-related environmental impacts in China simultaneously. It suggests that socio-demographic developments contribute to the diversity of regional dietary habits and this needs to be accounted for in targeted strategies towards sustainable diets.

The main findings point at both synergies and trade-offs among sustainability indicators for dietary quality, environmental impact, and dietary costs. Interestingly, these are different for China as compared to HICs. Current diet patterns do not comply with the Chinese dietary guidelines and would require increased consumption of animal-based foods such as dairy and fruits during the dietary transition, which leads to a trade-off between dietary quality and diet-related environmental impacts. However, increased adherence to the EAT-Lancet Diet simultaneously reduced disease risks and environmental impacts. A common trade-off was that increased adherence to the Chinese Dietary Guidelines or the EAT-Lancet diet also increased the diet costs.

In areas with higher levels of urbanization, education and income levels are higher. In more urbanized areas, between 1997 and 2011, dietary quality improved, but there was also an increase in environmental impact and dietary costs. However, in less urbanized areas the rate of increase in dietary environmental impact and costs exceeded that of more urbanized areas.

Achieving sustainable diets in China requires targeted strategies tailored to different population subgroups and regions. Reforming dietary guidelines requires multi-sectoral collaboration, that consider dietary quality, environmental sustainability, and economic feasibility simultaneously.

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Summary

The Chinese food system is facing challenges such as poor dietary quality, adverse health outcomes, and climate change, necessitating a shift towards sustainable diets. During the rapid economic growth and urbanization, dietary patterns in China have shifted towards increased consumption of refined grains, salt, oils, and red meat, and inadequate consumption of dairy products and fruits. This thesis analyzed the changes in dietary quality, environmental impact, and costs during the transition of Chinese dietary patterns, evaluating the trade-offs and synergies between sustainability indicators over the last two decades. Additionally, it identified sustainable dietary patterns and assessed the implications of transitioning towards recommended diets. This thesis thereby aims to provide scientific evidence for developing future sustainable dietary transition policies in China.

Part I -- Assessment of sustainability of Chinese diets

The first part of this thesis examined how to assess the dietary quality, environmental impact, and dietary cost of Chinese diets, and discussed the synergies and trade-offs between sustainability indicators.

Chapter 2 developed a Chinese Food Life Cycle Analysis Database (CFLCAD) in which 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 through a literature review. To estimate the environmental footprints of food from production to consumption, the study applied conversion factors for the edible portion of food, food loss ratio and processing, storage, packaging, transportation, and food preparation stages. In addition, when no LCA data of a certain food was available, data from food groups with similar nutritional composition or cultivation conditions were used as proxies. The database covered 17 food groups and each food item was referenced to the Chinese Food Composition Table with a unique food code. The CFLCAD can be used to link individual-level food consumption data with the national nutrition survey in China, to allow estimation of the environmental footprints of Chinese diets.

Chapter 3 aimed to identify sustainable diets, which are nutritious, culturally acceptable, affordable, and have low environmental impacts, based on self-reported diets in China. Dietary data was collected with a 3-day 24-h dietary recall among 10,324 subjects aged 18–64 year, who participated in the China Health Nutrition Survey (CHNS) 2011. Reduced rank regression derived dietary patterns with 34 food groups as predictor variables, and used the Chinese Healthy Eating Index 2016 (CHEI2016) score, dietary GHGE, TWU, LU, and dietary cost as response variables. Four distinct dietary patterns emerged from the analysis. Participants in the top adherence decile (decile 10) of the "High animal-based

food" pattern experienced a significant increase in CHEI2016 by 11%, dietary GHGE by 57%, TWU by 51%, LU by 54%, and dietary costs by 64% compared to the average population's diets. Equally, those following the "High fruit, low ruminant meat" pattern had a 21% higher CHEI2016 score but also higher dietary GHGE (+17%), TWU (+22%), LU (+19%), and costs (+46%) than average diets. Participants adhering to the "High fish, low beverages" pattern showed similar CHEI2016 scores but faced higher environmental impacts (GHGE +39%, TWU +32%, LU +28%) and costs (+19%). Lastly, the "High wheat, low pork" pattern demonstrated reduced environmental impacts (GHGE -17%, TWU -12%, LU -2%) and lower diet costs (-2%) but also a slightly lower CHEI2016 score (-1%) compared to the average population. This study revealed the trade-offs between diet quality, environmental sustainability, and dietary costs of current dietary patterns. None of the four patterns achieved the desirable combination of high CHEI2016 scores, reduced environmental impact, and reduced dietary costs.

Chapter 4 used multilevel mixed-effects models to estimate associations between the time trends of dietary sustainability indicators and degree of urbanization. Food consumption of 8,330 participants (18–64y) of the China Health and Nutrition Survey cohort (1997, 2000, 2004, 2006, 2009, and 2011) was examined. 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 other sociodemographic and lifestyle factors. 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. Moreover, in less urbanized areas, the rate of increase in dietary environmental impact and costs exceeded that of more urbanized areas.

Part II -- Sustainability of shifting to recommended diets

The second part of this thesis discusses the impacts on health outcomes, dietary environmental impact, and dietary costs if Chinese residents would shift to better adherence to the Chinese Dietary Guidelines and the EAT-Lancet Diet.

Chapter 5 aimed to evaluate the association between CHEI2016 score and environmental impacts across demographic subgroups and regions. Dietary data from 10,324 participants aged 18–64 in the CHNS 2011 was collected using a combined 3-day 24-hour dietary recall and weighed food record method. Multilevel regression models were used to quantify the association of the CHEI2016 score and the diet-related environmental impacts across regions. 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. Unlike the synergistic association found in high-income countries, this study reveals a trade-off between dietary quality and environmental impacts. This is because increasing the consumption of currently under-consumed foods (dairy products and fruit), partially offsets the environmental benefits of a slightly reduced meat consumption. Demographic subgroups characterized by either a higher education or a higher income consumed 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.

Chapter 6 examined health outcomes, environmental impacts, and costs of following the EAT-Lancet diet in China. It involved 16,029 participants from the China Health and Nutrition Survey (1997–2015). Hazard Ratios for the EAT-Lancet Diet Index (ELDI) score were obtained by Cox models with time-varying covariates, adjusted for potential confounders. Multilevel mixed-effects linear regression was used to assess the association of environmental impacts and dietary costs to the ELDI score. Adherence to the diet was associated with decreased mortality (increase per standard deviation of the score 8%, 95% CI: 2.2%-14.1%), cardiovascular disease (16.1% decrease, 95% CI: 9.2%-20.3%), and type 2 diabetes (25.3% decrease, 95% CI: 19.5%-28.4%). In addition, it led to reduced GHGE (-2.1% per 10-point increase, 95% CI:1.9% - 2.4%) and LU (-2.2%, 95% CI: 1.8% -2.6%), but increased diet costs by 2.7% (95% CI: 2.3% to 3.1%).

General discussion

This thesis explores the synergies and trade-offs of dietary sustainability indicators in China, focusing on quality, environmental impact, and costs. Adhering to the Chinese Dietary Guidelines involves a trade-off between dietary quality and environmental impact, unlike in high-income countries where mainly synergies are observed. Despite the environmental benefits of cutting down meat consumption, the need to increase consumption of fruits, vegetables, nuts, fish, and dairy partially offsets these gains. Adherence to the EAT-Lancet diet correlates with reduced environmental impacts. The dietary quality, environmental impact, and cost of diets in China are influenced by socio-demographic factors. For instance, higher education was associated with better dietary quality but also higher environmental impact and costs. Conversely, lower-income groups tend towards cheaper, low diet quality, plant-based diets, resulting in lower environmental impact. Urban areas generally exhibited higher dietary quality, environmental impact and costs of diets. In less urbanized areas, the growth rate in dietary environmental impact and costs over time surpassed that of more urbanized regions. Factors such as reliance on convenience foods and animal-based foods contributed to the highest environmental impacts in metropolitan areas.

Although China has lower per capita dietary environmental impacts compared to high-income countries, its overall diet-related impacts remain the highest globally. Therefore, implementation of sustainable diets in China requires comprehensive strategies, with the government taking the lead. Future revisions of Chinese Dietary Guidelines should prioritize the integration of dietary quality, environmental sustainability, and affordability. Furthermore, they can be refined by e.g. distinguishing between types of meat and their consumption levels. Collaboration among various government departments, including the Chinese Nutrition Society and ministries of Agriculture, Finance, and Natural Resources, is essential for crafting comprehensive policies that balance health and environmental considerations. Finally, because of the heterogeneity in dietary habits, addressing sustainable diets need to ensure effectiveness, cultural sensitivity, economic feasibility, by aligning policies with the unique characteristics of each region and demographic group.

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List of publication

Cai, H., Biesbroek, S., Wen, X., Fan, S., Van't Veer, P., & Talsma, E. F. (2022). Environmental footprints of Chinese foods and beverages: Literature-based construction of a LCA database. Data in Brief, 42, 108244.

Chang, Z.*, **Cai, H.***, Talsma, E. F., Fan, S., Ni, Y., Wen, X., ... & Biesbroek, S. (2023). Assessing the diet quality, environmental impact, and monetary costs of the dietary transition in China (1997–2011): Impact of urbanization. Frontiers in Sustainable Food Systems, 7, 1111361. (* first co-author)

Cai, H., Talsma, E. F., Chang Z., Wen, X., Fan, S., Van't Veer, P., & Biesbroek, S. (2024). Aligning health, environment, and cost aspects of diets: Identifying sustainable dietary patterns in China. Environmental Impact Assessment Review, 106, 107531.

Cai, H., Biesbroek, S., Chang, Z., Wen, X., Fan, S., van't Veer, P., & Talsma, E. F. (2024). How do regional and demographic differences in diets affect the health and environmental impact in China?. Food Policy, 124, 102607.

Submitted manuscripts

Cai, H., Talsma, E. F., Chang Z., Wen, X., Fan, S., Van't Veer, P., & Biesbroek, S. (2024). Health outcomes, Environmental Impacts, and Diet Costs of Adherence to the EAT-Lancet Diet in the China Health and Nutrition Survey 1997–2015. (*submitted*)

Overview of completed training activities

Category A: Discipline specific activities		
Name of the course/meeting	**Organizing institute**	**Year**
Agricultural green development	China Agriculture University	2020
System analysis theory and method	China Agriculture University	2020
Exposure assessment in nutrition research	VLAG	2021
Modelling of habitual dietary intake	VLAG	2021
Healthy and sustainable diets	VLAG	2021
Introduction to R	VLAG	2022
LCA food 2022	Department of Engineering Research Group: Peruvian Life Cycle Assessment and Industrial Ecology Network (PELCAN)	2022
the 7th Agriculture Green Development Symposium	China Agriculture University	2023
2023 Agriculture, Nutrition and Health Academy Week	ANH Academy	2023
14th European Nutrition Conference (FENS)	Federation of European Nutrition Societies	2023

Category B: General courses		
Name of the course	**Organizing institute**	**Year**
Scientific Writing and Presenting	China Agriculture University	2020
Scientific Writing	WGS	2022
Efficient Writing Strategies	WGS	2022
Intensive Writing Week	WGS	2023
Career Orientation	WGS	2023
Last Stretch of the PhD Programme	WGS	2023
Ethics in Plant and Environmental Sciences	WGS	2023
PhD Workshop Carousel	WGS	2023
Writing propositions for your PhD	WGS	2024

Category D: Other activities		
Name of the course	**Organizing institute**	**Year**
Preparation of research proposal	Global Nutrition, Human Nutrition & Health	2021
PhD study tour	Global Nutrition, Human Nutrition & Health	2023
Paper café (every two weeks)	Global Nutrition, Human Nutrition & Health	2022-2024
Radish meeting (every six weeks)	Global Nutrition, Human Nutrition & Health	2022-2024
Discussion group diet optimization	Global Nutrition, Human Nutrition & Health	2022-2024

About the author

Hongyi Cai started the Bachelor education in Agricultural economics at South China Agricultural University in 2011. During his studies, Hongyi focused on issues related to Chinese agricultural production systems, agricultural product trade, urbanization, and farmers' employment. In 2014, he was selected by his university to exchange at the Institute of Agriculture Resources and Environment at the University of Western Australia, where he studied the characteristics and differences in agricultural planting and agricultural product trade structures between China and Australia.

In 2015, he started his Master education in Agricultural economics at Chinese Academy of Agricultural Sciences. He participated in several national projects, including those funded by the National Natural Science Foundation and the Ministry of Agriculture's Science projects. As a team leader, he conducted multiple field investigations in rural areas. Hongyi has received the second prize for the Ministry of Agriculture's Science Excellent Report in 2016 and the second prize for the Excellent Paper at the Annual Meeting of the Chinese Society of Agricultural Economics. He has published over ten papers in journals indexed by CSSCI and Peking University's Core Chinese Journals.

Due to his interest in the transformation of China's agricultural food system, Hongyi was selected in 2020 for the "China Agricultural Green Development Project." He spent the first year of his Ph.D. program at China Agricultural University, and the following three years conducting research on sustainable diets and food systems in China at Global Nutrition, Wageningen University & Research. In 2021, Hongyi served as a human nutrition and health expert and national advisor for the FAO/World Bank Cooperative Program, participating in the "China Rural Food Systems Transformation Project." He analyzed China's agricultural and food policies, focusing on improving the sustainability and nutritional quality of rural food systems. Since August 2024, he has been working as a postdoctoral researcher in the Zero Hidden Hunger EU project at the University College Cork.

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