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Assessing and optimizing the relationship between nutritional quality and environmental impacts of household food consumption: evidence from the longitudinal data in urban China

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Abstract

BACKGROUND: Food consumption is a critical nexus that links human health with environmental sustainability. However, existing research rarely considers the relationship between nutritional upgrading of dietary shifts and their environmental impacts simultaneously, especially in urban areas with significant income disparities. Therefore, it is necessary to assess the relationships between the two in the context of income stratification and promote sustainable transformation of the food system through dietary adjustments.

RESULTS: This study constructs an assessment indicator to quantify the relationship between nutritional quality and environmental burdens, including greenhouse gas emissions, freshwater use and land use. Then, we try to optimize current food consumption patterns to achieve a sustainable healthy diet. Our findings reveal that urban households' food consumption deviates significantly from the recommended intake, with low-income households displaying the poorest nutritional quality. The transition of dietary patterns significantly increases environmental burdens, with high-income households contributing the largest environmental footprints. As for the nexus between the two, the synergy relationship is achieved in high-income households, whereas middle-income households gain nutritional benefits at the expense of environmental health. Adopting optimized diets with less red meat can help urban households improve nutritional quality but lead to greater environmental unsustainability and economic unaffordability, especially for low-income households.

CONCLUSION: We argue that there is no single optimal dietary pattern that is universally applicable to all households or residents. The finding highlights the need to focus on vulnerable socioeconomic groups, especially low-income households, when shifting dietary patterns to reconcile nutrition, environment, cost and culture.

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Supporting information may be found in the online version of this article.

Keywords: nutritional quality; environmental sustainability; dietary optimization; income levels; dietary costs; urban China

INTRODUCTION

As a key stage in the food value chain, food consumption significantly shapes food system sustainability through its nutritional and environmental impacts. Currently, global food consumption is shifting toward a Westernized pattern, which includes excessive intake of red meat, refined sugar and processed foods, as well as insufficient intake of fruits, vegetables, nuts and whole grains.¹ Health and environmental burdens from dietary shifts must receive sufficient attention. On the one hand, approximately 2.1 billion people worldwide are overweight or obese,² leading to severe chronic non-communicable diseases such as type II diabetes, cardiovascular disease and cancer.^{3,4} Without changes in food

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consumption patterns, these diseases are expected to account for two-thirds of the global disease burden.⁵ On the other hand, the environmental burdens caused by food consumption cannot be ignored. In other words, feeding the global population with current diets and production modes results in climate change, water resource depletion, and land ecosystem degradation.^{6,7} Specifically, the food system contributes to more than 20% of global greenhouse gas (GHG) emissions, 37% of productive land appropriation and 70% of freshwater use.^{8,9} In many parts of the world, dietary shifts driven by food consumption will surpass population growth as the main driver of future food demands.¹⁰ Without targeted intervention, resource consumption and environmental impacts from food consumption will extend beyond planetary boundaries by 2050.¹¹ Therefore, quantitatively analyzing the relationships between food consumption, nutrition, and the environment is crucial for providing a growing population with healthy foods at the same time as minimizing environmental impacts.

Modifying food consumption patterns is considered the most promising approach to achieving a win-win situation for both nutrition and the environment. Typically, an omnivorous diet emits 1500 kg more carbon dioxide equivalent (CO₂-eq) than a vegetarian diet with the same energy intake. Among these, livestock meat is the primary contributor to the environmental burden as a result of the highest carbon emissions intensity.¹² Furthermore, excessive consumption of red and processed meat may increase disease risk, whereas higher consumption of vegetables and fruits is generally associated with reduced mortality and morbidity.^{13,14} Hence, reducing animal-based foods, especially red meat, and increasing the consumption of plant-based foods such as fruits and vegetables is a consensus for the transformation of food consumption in the future.¹⁵ However, dietary adjustments that only meet nutritional and environmental standards seem unfeasible because they do not consider economic affordability or cultural acceptability.¹⁶ In this context, the Food and Agriculture Organization (FAO)¹⁷ is the first to define sustainable diets as those diets with low environmental impacts that contribute to food and nutrition security and a healthy life for present and future generations. In other words, sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe, and healthy, at the same time as optimizing natural and human resources. Unfortunately, because of its complexity, there are still gaps in our knowledge of what a sustainable diet should comprise.¹⁸

With the development of urbanization, food consumption has experienced remarkable changes in transitional economies such as China, especially in urban areas. It is reported that more than 580 million people migrated to urban areas between 1985 and 2018, reshaping the urban food system, particularly food consumption patterns.^{19,20} More importantly, urbanization has driven the labor force to shift from the primary industry to the secondary and tertiary industries, which enhances residents' income, especially wage income.²¹ Increased food affordability has changed the traditional diets that are primarily based on grains and vegetables, and further led to nutrient-dense diets with higher intakes of animal-based foods.²² China's urbanization rate is expected to rise to 70% by 2030 and further increase to 80% by 2050.²³ We can expect that the demand for various foods will also change with income levels. For example, the consumption of dairy products, beef and lamb is expected to grow at a rate of over 2.0%, whereas vegetables, fruits, poultry, and soybeans will grow at a rate of 1.0% to 2.0%.²⁴ In addition, consumers begin to shift from eating enough to eating healthily when they have more income.

In other words, they place greater emphasis on food quality, nutritional attributes and health effects. However, food consumption patterns with more adequate nutrition do not necessarily result in lower environmental impacts.²⁵ Thus, understanding the relationship between nutritional quality and diet-related environmental impacts of food consumption in the context of increasing income helps achieve a sustainable food system.

Growing research indicates a close link between food consumption patterns in China and both public health and environmental burdens. On the one hand, dietary shifts become a key factor in the prevalence of overweight and obesity among Chinese residents.²⁶ More than 50% of adults and nearly 20% of children and adolescents are overweight or obese.²⁷ Excessive consumption of animal-based foods is a major cause of this phenomenon and contributes to the rising incidence of chronic non-communicable diseases, including type II diabetes and cancer.¹⁵ To address this, the Chinese Nutrition Society issues multiple versions of dietary guidelines to help residents make healthy food choices. On the other hand, over-consumption of animal-based foods also results in greater environmental impacts.²⁸ For example, Zhang *et al.*²⁹ point out that GHG emissions from food consumption in China increased by 64% from 1987 to 2017, which is mainly a result of the growing demand for meat.³⁰ It can be said that the improvement of food consumption patterns comes at the cost of increased environmental burdens. Specifically, the water footprint (WF), carbon footprint (CF) and ecological footprint (EF) increase from 4%, 5%, and 20% to 71%, 46% and 122%, respectively.³¹ However, previous studies generally focus on the nutrient intake or disease burdens of food consumption, or specific environmental indicators, such as GHG emissions. The food consumption of urban households and its multiple connections with environmental impacts and nutritional quality have not been clearly articulated.³² More importantly, the heterogeneity in food consumption caused by income disparities is not adequately discussed, which is particularly crucial for a rapidly urbanizing country like China. In addition, although some studies begin to adjust food consumption structures to achieve a win-win for both nutrition and the environment,^{33,34} neglecting economic costs and food culture may make it extremely difficult to implement optimized diets.

In the present study, we evaluate the nutritional quality of food consumption using Chinese urban household survey data (2002–2014) and quantify the environmental impacts (i.e. CF, WF and EF) through Life Cycle Assessment (LCA). Next, relationships between nutritional quality and environmental impacts are explored to reveal dietary performance and sustainability. Finally, we attempt to find sustainable diets that meet nutritional needs and minimize environmental burdens based on objective optimization. Compared to previous research, this study makes contributions in three aspects: methodological innovation, data strength and empirical findings. First, we develop a novel optimization model that minimizes environmental burdens while meeting nutritional needs, economic affordability and cultural acceptability. In other words, we advance existing research on dietary optimization by considering cost and cultural factors in addition to nutrition and environment. This study not only truly explores sustainable healthy diets according to its definition, but also provides a realistic pathway for sustainable dietary transition. Second, unlike previous statistical analyses, more than 130 000 urban households enable a comprehensive understanding of the relationships among food consumption, dietary quality and environmental impacts. High-resolution micro-survey data can not only capture macro-level trends in food consumption with precision, but also

better reveal the consumption heterogeneity across different income groups. More importantly, the data systematically reflects the socioeconomic gradient embedded in the nutrition–environment nexus, providing empirical support for developing group-specific sustainable dietary policy. Third, deteriorating dietary quality is often accompanied by higher environmental burdens among low-income households, whereas high-income households are more likely to achieve a win-win situation between nutrition and the environment. Furthermore, dietary transformation not only helps low-income households obtain the greatest nutritional benefits, but also creates greater environmental pressure and economic costs. By exploring the differences among subgroups in shifting toward optimized diets, this study considers households with low socio-economic status at the same time as improving the inclusiveness and feasibility of food system transformation.

MATERIALS AND METHODS

Data

Data are from the China Urban Household Survey (2002–2014), which covers demographic characteristics of urban households, food consumption, expenditure, etc. It provides a basis for the Chinese government to formulate policies on the production and supply of commodities and the improvement of residents' nutritional levels. The survey sample is representative, including 16 provinces from 2002 to 2009: Shanghai, Yunnan, Beijing, Sichuan, Anhui, Shandong, Shanxi, Guangdong, Jiangsu, Jiangxi, Henan, Hubei, Gansu, Liaoning, Chongqing and Heilongjiang, and four provinces from 2010 to 2014: Shanghai, Sichuan, Guangdong and Liaoning. The food items are calculated by 13 categories: cereals, tubers, soybeans, vegetables, fruits, cooking oil, pork, beef, lamb and mutton, poultry meat, aquatic products, eggs and dairy products. Considering the heterogeneity of household food consumption across income levels, income quintiles are obtained for each income level: low, lower-middle, middle, upper-middle and high. After excluding invalid samples, we obtained data from 130 000 urban households between 2002 and 2014.

Methods

Environmental impact assessment

Life cycle assessment (LCA) is a comprehensive tool to evaluate the various environmental impacts associated with a product, process or activity by quantifying resource consumption and waste emissions.³⁵ The LCA framework is an iterative process that includes: defining the objectives and scope of the study, life cycle inventory analysis, life cycle impact assessment and interpreting the results.³⁶ It should be noted that the system boundary in this study includes the entire supply chain from land use to retail, and we define the environmental footprint per kilogram of food as the functional unit. Thus, LCA is used to calculate the environmental burdens of diets, namely GHG emissions, freshwater use and land use. Specifically, we use CF to measure the amount of GHG emissions produced directly and indirectly during the life cycle of food (see Supporting information, Fig. S1). WF is used to measure freshwater use caused by food consumption. EF is a measure of the demands placed on the biosphere by human activities under current levels of technology and management.³⁷ A detailed introduction to the LCA, calculation methods and environmental footprint factors (see Supporting information, Table S1) are listed in the Supporting information (Doc. S1A.1.1).

Evaluation of nutritional quality

The deviations from the recommended diet are used to evaluate nutritional quality and can reflect the nutritional adequacy and health of residents' diets.²² In general, smaller deviations indicate higher nutritional quality and better health, and vice versa. However, individuals from different age-gender groups have their own estimated energy requirement. We therefore divide the population into five groups according to official documents, namely preschoolers, school-age children, adults, older people and the oldest old (see Supporting information, Table S2). Based on diet composition under energy requirement levels (see Supporting information, Table S3), we then obtain the recommended food intake for different age-gender groups (see Supporting information, Table S4). Finally, the dietary deviation at the household level for individual food and overall food consumption patterns can be calculated (see Supporting information, Doc. S1A.1.2).

Relation between dietary quality and environmental sustainability

Referring to the research of Zhang and Chai,³⁸ elasticity is used to measure the diet–environment nexus (see Supporting information, Doc. S1A.1.3). In other words, elasticity can reveal the percentage change in environmental sustainability resulting from the percentage change in diet quality. If nutritional quality and environmental sustainability change in the same direction, we call it synergy. Similarly, trade-off implies that dietary quality and environmental sustainability move in opposite directions. Based on the elasticity value, there are 5 types, including synergy, mild trade-off, moderate trade-off, high trade-off, recessive trade-off and recessive synergy (see Supporting information, Table S5).

Objective optimization

Another purpose of this study is to optimize dietary structure to reduce pressure on resources and the environment. We use objective programming to determine optimal food consumption patterns that satisfy constraints and minimize impacts on resources and the environment.³⁹ Optimization objectives are set to ensure that diets are environmentally friendly, namely, minimizing CF, WF, EF and comprehensive environmental impacts. According to FAO and World Health Organization (WHO),⁴⁰ sustainable healthy diets are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable. We all know that residents will not pay for the optimized diets when they cannot afford them. Furthermore, residents are usually not willing to accept major dietary changes because of dietary habits and cultural reasons.⁴¹ In other words, it is so difficult to implement optimized diets based solely on objective environmental and nutritional requirements.^{42,43} Thus, we consider nutrition, cost and culture when optimizing diets. The optimization process was subject to some constraints. Firstly, the optimized diet has to meet the daily intake of 20 nutrients, including carbohydrates, protein, fat, minerals, vitamins, and dietary fiber (see Supporting information, Tables S6 and S7). Second, changes in dietary structure should be in line with the dietary culture of Chinese residents, that is, cultural acceptability. Third, optimized dietary patterns should be affordable for residents (see Supporting information, Doc. S1A.1.4).

RESULTS

Food consumption transition and nutritional quality assessment

The changes in food consumption among urban households can be divided into two stages (Fig. 1). Specifically, the quantity of foods shows an upward trend from 2002 to 2009 and then decreases with a certain degree of volatility. Plant-based foods decrease significantly, and the proportion of animal-based foods increases slightly, but this does not change the traditional food consumption patterns. In terms of income groups, households in the middle and upper-middle income consume more food and prefer red and white meat. By contrast, low and lower-middle-income households consume more plant-based foods such as grains, vegetables, and fruits. It is worth noting that the food intake of low-income families decreased from 318.113 kg person⁻¹ year⁻¹ in 2009 to 155.667 kg person⁻¹ year⁻¹ in 2010, with the main reason being the decrease in plant-based foods.

Although the food consumption structure of urban households changes significantly, the nutritional quality is not significantly improved (Fig. 2). Compared to balanced dietary patterns, deviations in food consumption patterns are greater than 55% throughout the study period. Although dietary deviations reached a minimum in 2007, food consumption patterns are still unreasonable, and the deviations become larger and larger thereafter. Especially for low-income families, dietary deviations are significantly higher than those in other income groups. When it comes to food items, intakes of cooking oil and livestock and poultry meat exceed nutritional needs. The good news is that

the consumption of these two foods deviates less and less from the recommended values. Meanwhile, intakes of cereals, vegetables, fruits, aquatic products and dairy products are seriously insufficient. In addition, eggs change from overconsumption to underconsumption.

As shown in Fig. 2, low-income households have the worst nutritional quality. Whether it is the overall diet or a single food item, the dietary deviations of low-income families are much higher than those of the other four income groups. Specifically, the consumption of all foods in low-income households is significantly below recommended values, and dietary deviations are increasing. For example, the dietary deviations of dairy products exceeded 90% and were even close to 100% between 2010 and 2014. Similarly, the deviations in aquatic products are also over 60%. Other foods also show varying degrees of deviations, but the phenomenon of irrational consumption is becoming more serious.

Environmental impacts of food consumption

Food consumption structure is the major driver of environmental burdens. Similar to the changing trend of dietary structure, CF caused by food consumption can also be divided into two stages. The CF of urban households first increased from 1179.553 kg CO₂-eq person⁻¹ year⁻¹ in 2002 to 1386.412 kg CO₂-eq person⁻¹ year⁻¹ in 2009 and then dropped to 1134.640 kg CO₂-eq person⁻¹ year⁻¹ in 2014. Compared with the other income groups, the CF of low-income households decreased the most after 2010. Although total food quantity and plant-based food

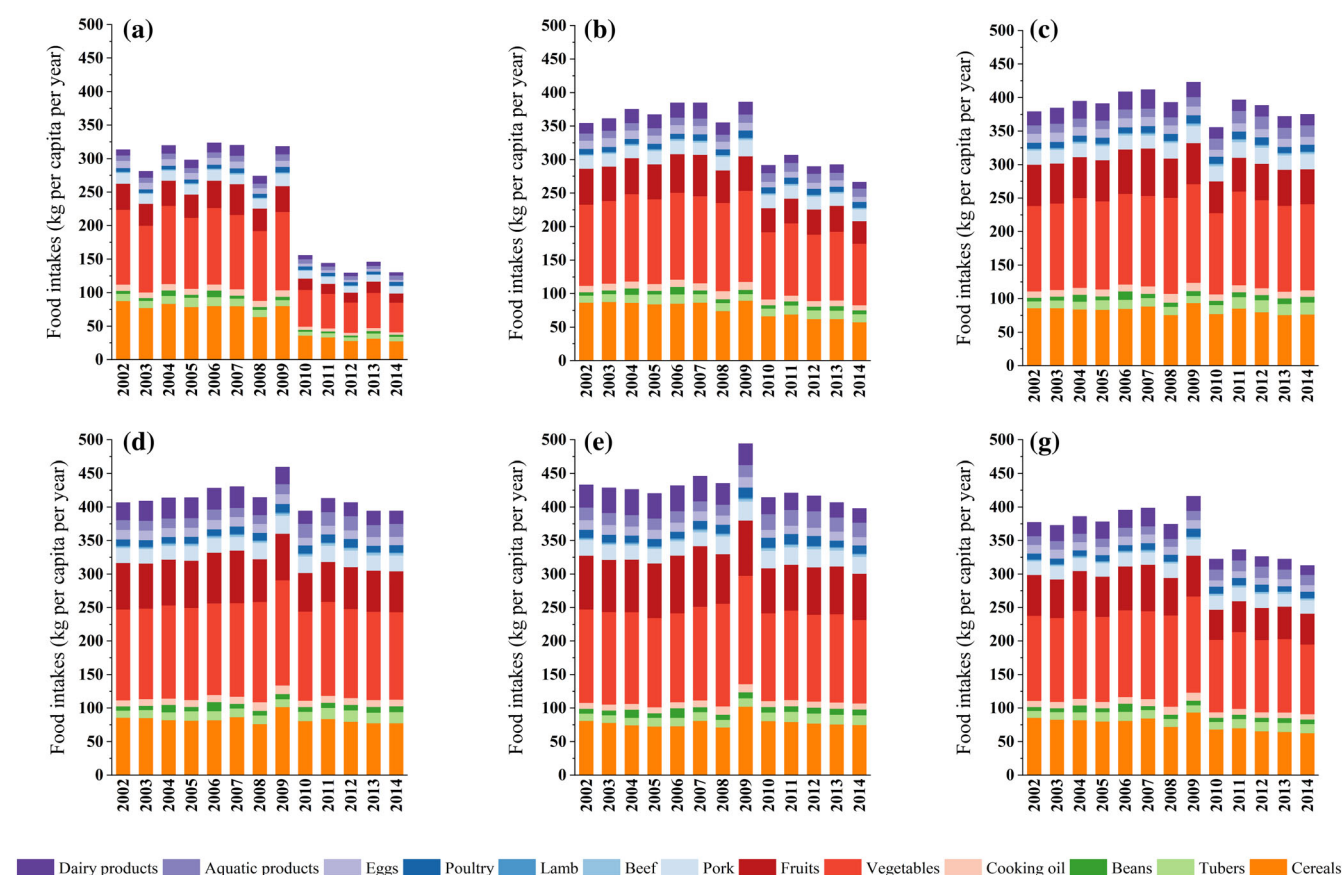


Figure 1. Food consumption structure of urban residents. (a) Low income; (b) lower-middle income; (c) middle income; (d) upper-middle income; (e) high income; and (g) all residents.

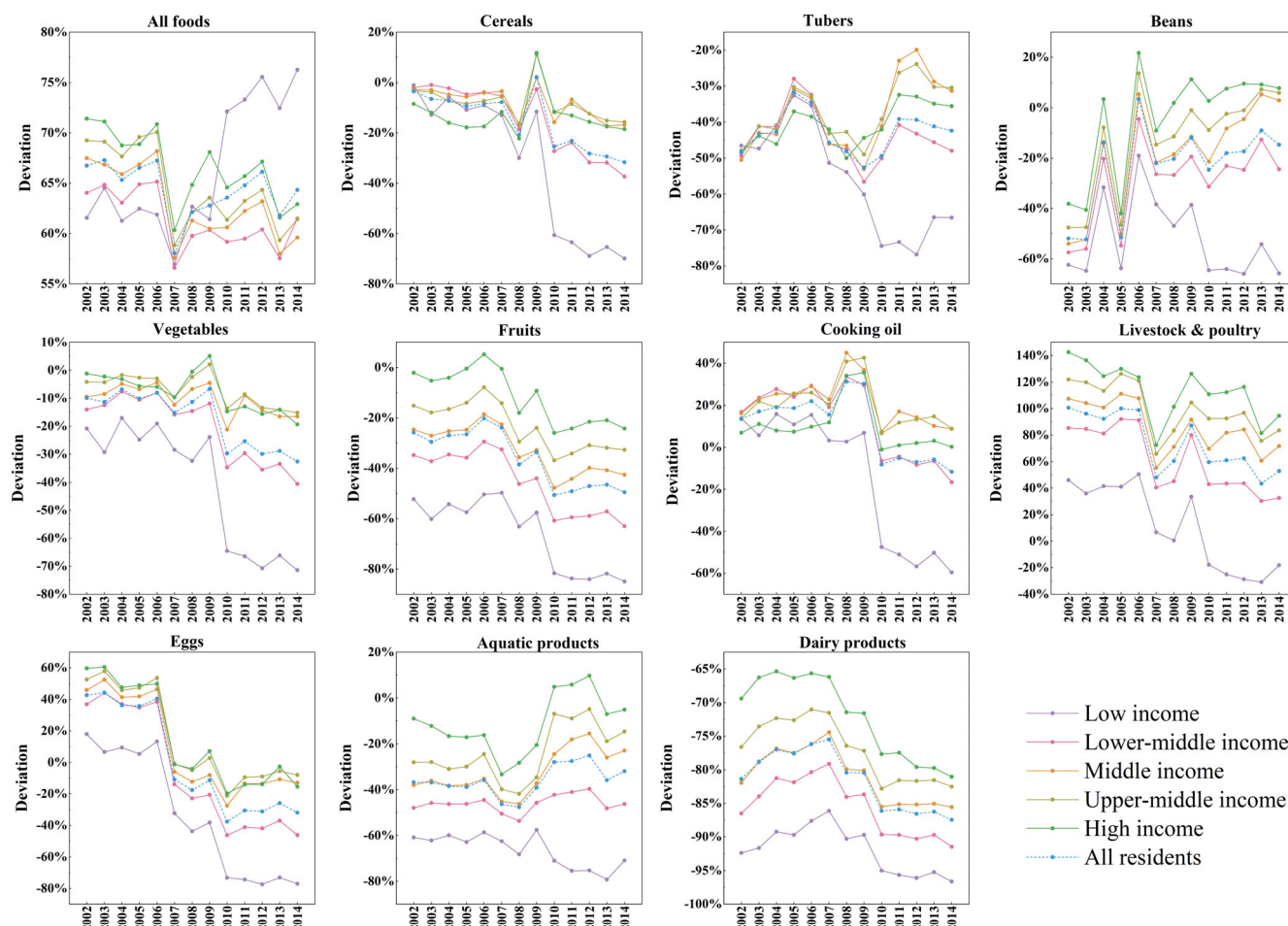


Figure 2. Dietary deviation from the balanced dietary patterns. The line-connected points show food deviations at different income levels. Connected by a dotted line, the points represent food deviations for the population as a whole.

consumption decreased, animal-based foods remained the largest contributor to GHG emissions, especially pork, beef and aquatic products (Fig. 3(a)). In addition, upper-middle and high-income households are more responsible for GHG emissions because they consume more red and white meat. Similarly, the WF of foods increased from 234.770 m³ person⁻¹ year⁻¹ in 2002 to 262.324 m³ person⁻¹ year⁻¹ in 2009 and then decreased to 210.219 m³ person⁻¹ year⁻¹. Furthermore, low-income households consume the least water resources, whereas high-income households generate the highest WF (Fig. 3(b)). An interesting finding is that plant-based foods account for an increased share of WF compared to the other two environmental footprints, but animal-based foods, such as pork and aquatic products, are still the largest contributors.

As for land use, the EF from food consumption increased by 486.654 m² person⁻¹ year⁻¹ from 2002 to 2009 and decreased to 2036.242 m² person⁻¹ year⁻¹ in 2014. Although the EF has declined since 2010, the land pressure caused by food consumption has not been substantially alleviated. We can see that animal-based foods contribute the most to the EF (Fig. 3(c)). Pork, beef and mutton have a higher EF than all plant-based foods, including cereals, tubers, vegetables and fruits, which is verified at all income groups. In addition, the EF resulting from food consumption among upper-middle and high-income households is significantly higher, which means that they should

bear more responsibility for alleviating land supply and demand pressures.

Evaluating the nutrition-environment nexus

Changes in environmental impacts are associated with decreases and increases in nutritional quality due to the changing food consumption patterns. According to the previous analysis, livestock and poultry meat consumption is excessive. Therefore, increasing meat consumption not only further increases dietary deviations, but also increases environmental burdens. On the other hand, increasing the intake of eggs, milk, and other foods reduces dietary deviations, but the increase in quantity will also lead to environmental unsustainability. We calculate the nutrition-environment nexus and divide it into six types. For example, if nutritional quality improves when environmental sustainability is enhanced, there is a synergy relationship. Vice versa, forming a recessive synergy relationship. If nutritional quality improves while environmental burdens increase, then there are three trade-off relationships based on elasticity values: mild trade-off (−0.8, 0), moderate trade-off [−1.2, −0.8] and high trade-off (−∞, −1.2). In addition, if the decrease in nutritional quality is associated with increasing environmental sustainability, the nexus is defined as a recessive trade-off.

Figure 4 depicts the relationship between environmental sustainability and nutritional quality for households of different

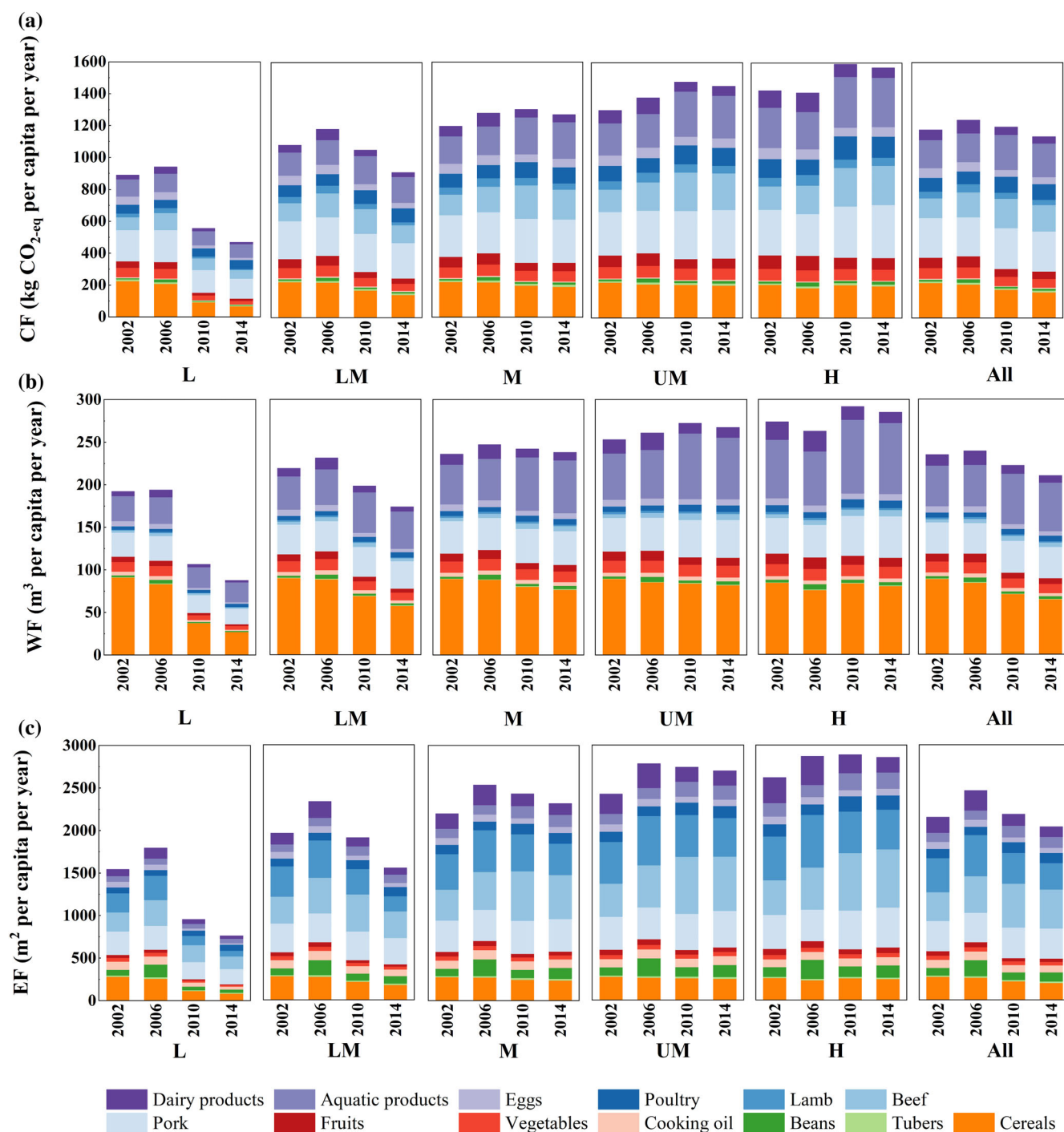


Figure 3. Environmental footprint of dietary patterns. (a) Carbon footprint; (b), water footprint; (c), ecological footprint. L, low income; LM, lower-middle income; M, middle income; UM, upper-middle income; H, high income; All, all residents.

income groups from 2002 to 2014. First, urban households mainly show recessive synergy before 2010. In other words, as dietary deviations increase, they also bring greater burdens to the environment. Subsequently, environmental sustainability has improved significantly, although dietary deviations continue to expand. There is a recessive trade-off nexus; the elasticity changes from -0.241 in 2010 to -21.648 in 2014. Additionally, no moderate trade-off relationships are demonstrated throughout the study period. Second, the synergy

relationships are mainly concentrated in high-income households, which means that a win-win situation between nutritional improvement and environmental sustainability can be achieved. Low-income households show a more recessive trade-off nexus, which means that although dietary deviations are expanding, environmental health is improving. The trade-off is evident among middle-income households, indicating that the improvements in nutritional quality come at the expense of environmental health.

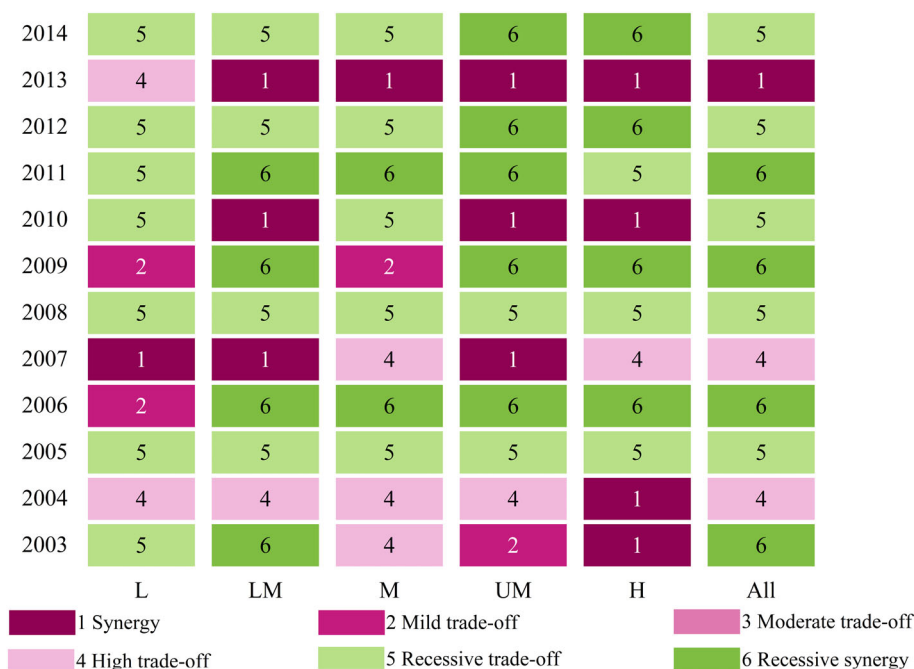


Figure 4. Synergy and trade-off of environmental sustainability and nutritional quality. Elasticities of environmental sustainability score change in response to dietary deviation score change are used to depict the relationships of synergy and trade-off. L, low income; LM, lower-middle income; M, middle income; UM, upper-middle income; H, high income; All, all residents.

Optimizing food consumption structure

Four optimized diets are designed by using the linear programming method, namely S_{cf} with the minimizing of CF, S_{wfr} with the minimizing of WF, S_{ef} with the minimizing of EF and S_{ee} with the minimizing of comprehensive environmental effects (see Supporting information, Table S8). The differences between the current and optimized food consumption patterns (OFCPs) are shown in Table 1. In terms of quantity, the shift in food consumption patterns increases cereals, tubers, vegetables, dairy products, eggs and aquatic products. For example, the amount of dairy products consumed in the OFCPs is more than 300 g higher than the current amount, and aquatic products also significantly increase. By contrast, over-consumed foods such as livestock, poultry meat and cooking oil need to be reduced. However, the reduction in meat does not harm the nutritional status of urban households. Specifically, the protein in the different OFCPs (i.e. S_{cf} , S_{wfr} , S_{ef} and S_{ee}) is 68.731 g, 68.181 g, 75.858 g and 68.232 g higher than the current diet, respectively). Unfortunately, shifting to OFCPs increases environmental burdens and dietary costs. Although S_{cf} aims to minimize GHG emissions, it still has a CF 4.362 kg higher than the current food consumption. Similar situations can also be found in other OFCPs. In addition, the dietary costs are 10.408 CNY, 10.991 CNY, 11.68 CNY and 10.411 CNY higher than those in the current food consumption. Another way to adjust the current diets is to adopt the global sustainable diet proposed by the EAT-Lancet Commission.⁴⁴ Compared with optimized diets, the EAT-Lancet diet requires residents to increase the intake of all plant-based foods except vegetables, while reducing the consumption of all animal-based foods except dairy products. However, the EAT-Lancet diet does not yield significant environmental benefits, reducing CF and EF by only 0.281 kg and 0.048 m², respectively. More importantly, the nutritional improvement achieved by the EAT-Lancet diet is far less pronounced than that of optimized diets. For example,

although the EAT-Lancet diet increases energy intake by 500.146 kcal based on the current diet, it still cannot meet the minimum daily energy requirement of 2250 kcal. In addition, the improvements in the three macronutrients (i.e. protein, fat and carbohydrate) are also significantly lower than the optimized diets. In terms of the economic aspect, the EAT-Lancet diet has a lower cost, despite increasing the cost by 1.229 CNY compared to the current diet. It is important to note that the EAT-Lancet diet, designed for a global population, may not fully align with Chinese dietary culture. More efforts in the future will be required to adapt and promote it within the context of China.

Interestingly, some unexpected things happen when we focus on a certain goal (Table 1). First, there is a trade-off nexus among environmental footprints. S_{cf} and S_{wfr} have the smallest CF and WF, but both result in the highest EF. Likewise, S_{ef} produces the highest CF and WF at the same time as minimizing EF. Therefore, environmental impacts should be comprehensively considered when optimizing food consumption patterns. Second, some differences can be seen in nutrient intakes among different OFCPs. As shown in Table 1, energy, fat and carbohydrate intakes of S_{ef} are significantly lower than those of other OFCPs, but the protein intake (+75.858) is the highest. S_{ee} can achieve an overall improvement in nutritional status. Third, the economic costs of OFCPs are similar, but the cost of S_{ef} is 1.262 CNY and 0.689 CNY higher than S_{cf} and S_{wfr} , respectively.

Furthermore, we compare the nutrient intakes, environmental footprints, and dietary costs in four OFCPs across different income groups (Fig. 5). The results indicate that nutrition improvement is more pronounced in the low-income group than in other income groups. S_{ef} can increase protein intake by more than 200%, and S_{ee} maximizes the energy, fat and carbohydrate intake of low-income households. The nutritional improvement effect of OFCPs gradually weakens as the income groups increase. In addition, OFCPs also bring greater burdens to the environment, with

Table 1. Changes from the current diet to the optimized diet

Items	Current diet	Changes from the current diet to				
		S_{cf}	S_{wf}	S_{ef}	S_{ee}	EAT-Lancet
Food groups (g day ⁻¹)						
Cereal	210	+44	+30	+63	+63	+22
Tuber	34	+10	+10	+8	+10	+16
Soybean	19	+6	+6	-5	-5	+6
Vegetable	336	+101	+101	+101	+101	-36
Fruit	152	-45	+46	-45	-45	+48
Cooking oil	26	-8	-8	-8	-8	+14
Pork	56	-17	-17	-17	-17	-30
Beef	7	-2	-2	-2	-2	-4
Lamb	3	-1	-1	-1	-1	-1
Poultry	26	-8	-8	-8	-8	-14
Dairy product	56	+302	+301	-17	+305	+194
Egg	32	+45	+47	+161	+45	-19
Aquatic product	38	+257	+257	+413	+255	-10
Environmental footprint						
CF (kg)	3.307	+4.362	+4.428	+6.053	+4.374	-0.281
WF (m ³)	0.628	+1.173	+1.173	+1.630	+1.182	+0.039
EF (m ²)	6.231	+4.205	+4.245	+3.276	+4.104	-0.048
ES	3.213	+3.177	+3.211	+3.654	+3.154	-0.098
Nutrients intake						
Energy (kcal)	1699.920	+989.981	+989.464	+687.612	+1027.853	+500.146
Protein (g)	59.161	+68.731	+68.181	+75.858	+68.232	+8.641
Fat (g)	64.161	+27.471	+27.541	+15.242	+27.461	+19.090
Carbohydrate (g)	232.268	+119.035	+119.572	+64.062	+129.432	+74.393
Dietary cost (CNY)	9.275	+10.408	+10.991	+11.68	+10.411	+1.229
Note: '+' indicates an increase and '-' indicates a decrease.						

Note: '+' indicates an increase and '-' indicates a decrease.

low-income groups being the hardest hit. It is worth noting that the trade-off relationship among the three environmental footprints is verified again among households at different income levels. For example, S_{ef} , which aims to reduce the EF, has the highest WF. Similarly, S_{cf} results in the highest EF at the same time as reducing the CF. Finally, we find that OFCPs lead to greater dietary costs, especially a more than two-fold increase in costs for low-income households. Therefore, affordability is an important aspect that cannot be ignored in optimizing food consumption.

DISCUSSION

We should use a systems perspective to examine the nexus between nutritional improvement and environmental sustainability. Previous studies have only analyzed specific environmental impacts and do not consider multiple environmental outcomes simultaneously.^{45,46} We all know that adjustments in food consumption structure may result in different impacts on multiple environmental dimensions, including GHG emissions, land use and freshwater use. Therefore, studying one single type of environmental impact can lead to misleading or even completely wrong conclusions. Furthermore, policies formulated based on these findings fail to solve practical problems. This is because they neither alleviate ecological pressures nor reduce resource consumption, but do lead to overestimation or underestimation of dietary costs.^{47,48} As shown in our results, the food consumption patterns with the smallest CF result in a higher EF, whereas the OFCPs with the smallest EF result in higher WF and CF. We have to integrate multiple environmental outcomes when we optimize

food consumption because of the trade-offs among different environmental impacts. In this way, we can not only achieve sustainable diets, but also avoid inconsistencies and conflicts among different environmental policies.

This study provides new evidence for the debate about whether improving nutritional quality can bring environmental benefits. So far, many studies focusing on developed countries believe that adjusting food consumption patterns is a feasible way to achieve environmental sustainability and human health.^{49,50} The reality is that, although developed countries consume more animal foods, especially meat, their overall dietary structure follows a healthy dietary pattern. Thus, reducing meat consumption and increasing vegetable intake can bring more environmental benefits, which is different in developing countries such as China. We have to say that Chinese urban households do consume excessive amounts of meat and cooking oil, but overconsumption is less severe compared to developed countries. By contrast, underconsumption of foods such as dairy products and aquatic products seems to be a more serious problem. As we all know, dairy products and aquatic products are rich sources of calcium and omega-3 fatty acids, respectively.⁵¹ From this perspective, the nutritional status of Chinese households still needs to be improved. Thus, shifting to recommended or optimized diets means increasing these under-consumed foods. Although dietary optimization encourages residents to reduce the consumption of foods with high environmental footprints (e.g. pork, beef and lamb), the substantial increase in eggs, dairy products and aquatic products offsets

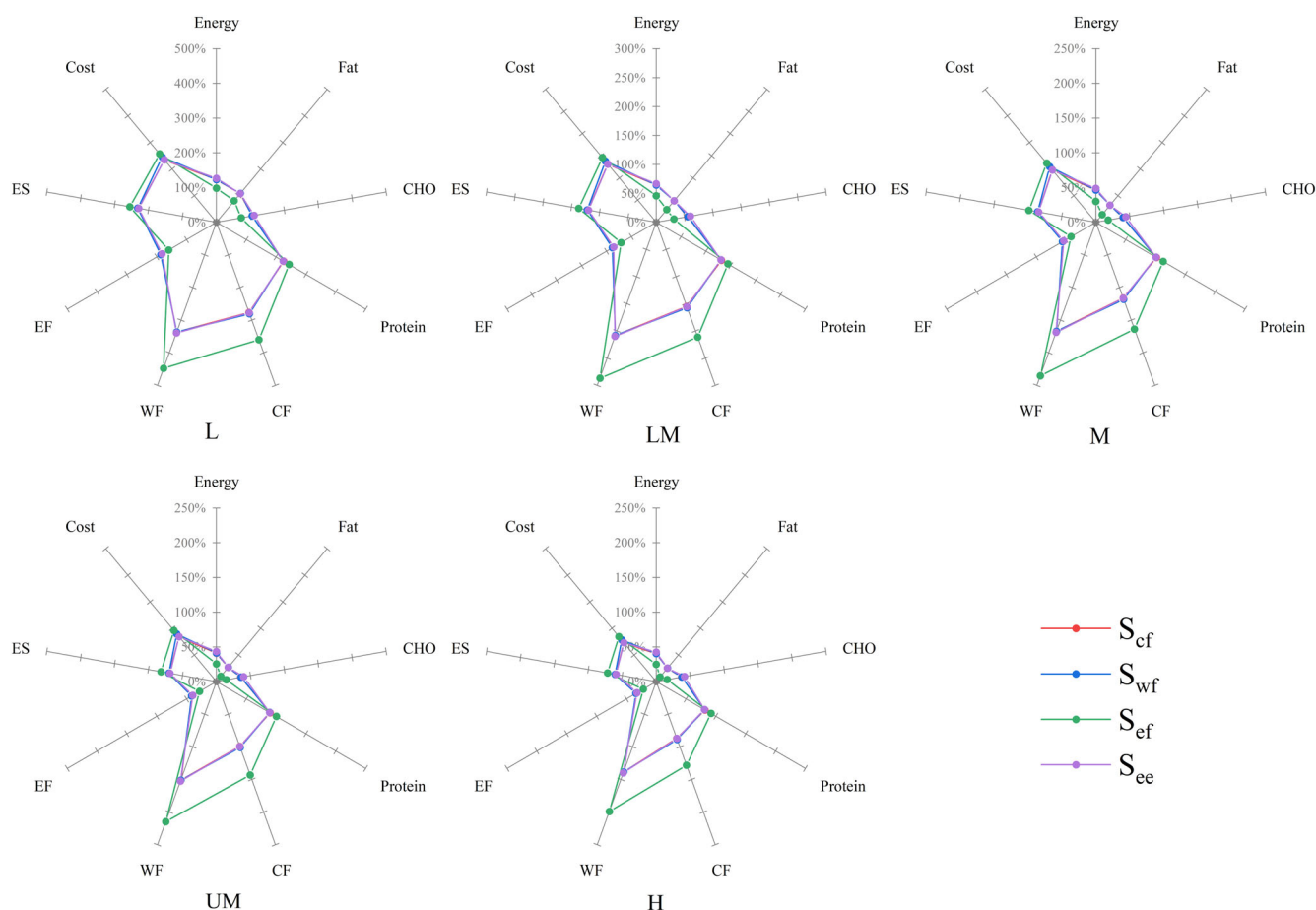


Figure 5. An assessment of the shift towards optimized diets across income levels. The value of each indicator is expressed as the percentage change from the current diet to the optimized diet. L, low income; LM, lower-middle income; M, middle income; UM, upper-middle income; H, high income. ES indicates the total environmental outcomes.

the environmental benefits from the modest reduction in meat. In addition, the increased food quantity requires more storage, transportation and distribution, which in turn leads to greater environmental burdens. Finally, adopting optimized dietary guidelines leads to greater environmental impacts. Moreover, differences in data and study periods may also lead to different conclusions because households' food consumption patterns continue to evolve. Considering that conditions vary across countries, more research is needed to explore the environmental outcomes caused by food consumption changes in developing countries.

Household income deserves more attention while achieving a win-win situation between nutrition and the environment. Existing studies point out the differences in nutrition and the environment among groups with different socioeconomic characteristics.⁵² Therefore, it is necessary to conduct such exploration in China, which is undergoing drastic urbanization. In this study, we find that OFCPs increase economic costs, with the largest impact on low-income households. Given the lower purchasing power of low-income households and their higher sensitivity to price changes, pricing policies and sustainable diets promotion should prioritize this group.⁵³ Otherwise, it will lead to the uneven hierarchical distribution of the environment and nutrition. For example, the government can guide low-income groups to consume more nutritious and environmentally

friendly foods by providing food subsidies, such as vouchers or cash transfers. Meanwhile, agricultural production subsidies can support agricultural producers in supplying more sustainable healthy foods. We all know that expanding supply helps lower market prices, thereby alleviating the financial burden on low-income groups. In addition, greater propaganda should be made to raise the awareness of sustainable healthy diets among low-income groups and enhance their willingness to change current diets. However, high-income groups do not face affordability constraints. For them, taxation could be used to reduce the consumption of animal-based foods, especially red meat. Retail interventions such as footprint label and nutrition label also help dietary adjustments to reduce environmental impacts and address issues of overnutrition. On the other hand, cultural acceptability is an important factor influencing food choices. If OFCPs are based solely on nutritional needs and environmental limitations without considering cultural acceptability, then it is only formal and therefore cannot be implemented.⁵⁴ In addition, introducing limits on cultural acceptability may increase economic costs.⁵⁵ Thus, defining sustainable diets is particularly important because it not only leads to different conclusions, but also provides a reference for designing dietary guidelines and formulating food policies. Unfortunately, to date, there is still no consistent answer to what a sustainable diet is and what constitutes it.

CONCLUSIONS

The present study aims to assess and optimize the relationship between nutritional quality and environmental impacts of household food consumption across different income groups to achieve a sustainable and healthy food system. First, we measure the dietary deviation of Chinese urban households and quantify the environmental impacts resulting from food consumption, namely, CF, WF and EF. Based on this, we further evaluate the synergy and trade-off relationships between nutrition and the environment. Finally, the current food consumption patterns are optimized taking into account nutritional requirements, dietary cost, and cultural acceptability. The results indicate that the current food consumption deviates greatly from the recommended diet, and the consumption of dairy products and aquatic products is insufficient. Changing food consumption patterns leads to serious environmental burdens, with animal-based foods making the largest contribution. The relationships between nutritional quality and environmental sustainability are mainly recessive trade-offs and recessive synergy. The synergy relationship is achieved in high-income households, whereas middle-income households gain nutritional benefits at the expense of environmental health. According to OFCPs, adjusting food consumption patterns can not only improve nutritional status, but also increase environmental burdens and dietary costs. In addition, low-income households should receive more attention to dietary adjustment.

Although this study focuses on the Chinese context, it offers a case reference for other developing countries undergoing rapid urbanization, such as India and Nigeria. In particular, a long-term perspective should be adopted to design feasible methodological frameworks that balance nutrition, environment, culture, and cost when adjusting dietary structures. Moreover, although China differs from other high-income regions such as Europe, this study can still offer valuable insights for dietary transitions in those contexts. For example, given the vulnerability of low-income households, recommended diets must be inclusive to ensure that disadvantaged groups are not marginalized during the transition process. However, this study does have a few limitations. First, as a result of data availability, optimizing current food consumption patterns only targets adults aged 18–50 years and does not consider the elderly population and school-age children. We all know that China is experiencing severe population aging, and the elderly population will continue to grow in the future.⁵⁶ Therefore, providing sustainable dietary guidelines for the elderly is a key direction for future research. Second, eutrophication, biodiversity loss and nitrogen and phosphorus cycling are not included to fully analyze the environmental impacts of food consumption. In the future, the latest assessment instruments and targeted measures may be adopted to analyze the relationship between dietary changes and planetary boundaries. Third, salt is not included in this study because of its minimal consumption and lower environmental burden. Salt intake is often closely linked to high blood pressure, which is a major health risk faced by Chinese residents.⁵⁷ We will consider salt as a food item in future studies to explore the health benefits of reducing salt consumption.

AUTHOR CONTRIBUTIONS

SL and QL were responsible for conceptualization. SL and QL were responsible for methodology. SL and QL were responsible for writing the original draft. XC was responsible for software and data curation. YR was responsible for supervision. YR and TG were responsible for reviewing and editing. YR was responsible for

visualization. YR was responsible for funding acquisition. TG was responsible for validation. All authors have approved the final version of the manuscript submitted for publication.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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