Check for updates

Changes in China's food security driven by nutrition security and resource constraints

Ze Han[1] · Xinqi Zheng[3] · Lingling Hou[4] · Nan Xiao[5] · Xiangzheng Deng[1,2]

Abstract

Food security and the utilization of natural resources in a sustainable manner are vital to the expansion of China's agricultural system. The relationship between environmental pressure and dietary structure has influenced the quantity and spatial distribution of China's food supply and demand, but it has not been evaluated. Our research centered on the security of China's food nutrition–resources–food (NRF) system, considering the inherent relationship between food security, nutritional health, and resource security. The following are the study's findings: (1) The Chinese population is rapidly changing from a diet focused on grains to a more diverse diet. Between 1990 and 2019, the dietary quality and nutritional status of Chinese individuals have vastly improved. In terms of nutrient levels, discrepancies between urban and rural resident persist, with urban residents consuming a diet that is closer to the ideal structure. However, the structure of rural residents' food consumption is diversifying, and the gap between urban and rural residents is gradually narrowing. (2) From 2000 to 2019, the pressure, status, and response indices of China's NRF system all show an upward trend, and the security of the NRF system has steadily grown. The magnitude of change in the response index exceeded that of the state index, which exceeded that of the pressure index. This indicates that the increase in the pressure and state indices of the NRF system was primarily attributable to the effectiveness of policy efforts.

✉ Xiangzheng Deng
   dengxz@igsnrr.ac.cn

[1] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] School of Information Engineering, China University of Geosciences, Beijing 100083, China

[4] China Center for Agricultural Policy, School of Advanced Agricultural Sciences, Peking University, Beijing 100871, China

[5] School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China

1 Introduction

Rural revitalization is supported by the food business. In the context of international food market instability caused by, for example, the new COVID-19 pandemic and international trade conflicts, ensuring national food security and an adequate supply of essential agricultural products to "keep the Chinese people's rice bowls firmly in their own hands" are crucial tasks. Globally, the number of individuals experiencing acute food insecurity is rising due to climate change, population increase, and trade trends (FAO et al., 2020, Managi et al., 2009, Kumar et al., 2018; Xie et al., 2019; Seto & Ramankutty, 2016). The absence of a secure agricultural production system can lead to extreme hunger, malnutrition, and mortality. In this context, assessing the national nutrition and food security situation in China is urgently needed.

National nutrition and food security are related to dietary structure and human health and are affected by agricultural production activities, resource and environmental pressures, and food supply and demand patterns (Burchi & De Muro, 2016; Deng et al., 2015; He et al., 2018). In recent decades, the sustainable development of China's agriculture system has faced enormous challenges, including excessive water resource consumption in the north caused by the policy of "bringing bulk grain from North China to the South" widespread agricultural surface pollution due to excessive pesticide and fertilizer use, and the continuous reduction of arable land due to the promotion of urbanization (Liu & Deng, 2010). Because of these problems, research on national nutrition and food security is required to ensure that China's significant needs are met. Such research spearheads Future Earth, a major international earth science program initiated by the International Science Council and co-led by UNESCO (United Nations Educational, Scientific and Cultural Organization), UNEP (United Nations Environment Programme), UNU (United Nations University), and international global change funding agencies. The Future Earth research program aims to provide the necessary theoretical knowledge, research tools, and methodologies for sustainable global development by combining science and practice through international cooperation and innovation. It is designed to address challenges posed by global environmental change to regions, countries, and societies. Two integrated themes, global development, and sustainable transformation, include safeguarding human health and sustainable food system construction as major research tasks.

Sustainable food production and consumption that strike a balance between nutritional objectives and resource restrictions have become topics of concern for academics and policymakers (Jribi et al., 2020; Pieroni et al., 2021; Xie et al., 2021). There are complex feedback mechanisms linking food security, nutrition, and resource use (Burchi & De Muro, 2016; Young et al., 2021), and the scarcity of land and water resources is a major limitation on food security and nutrition provision (Bindraban et al., 2012; Holden, 2018). Major food production systems are at risk of deterioration, which threatens global food security, and land and water resource management practices must be improved in particular (FAO et al., 2020). Therefore, National and regional development agendas should prioritize integrating sustainable land and water resource management in terms of public investment, incentives for resource and environmental management, and management of externalities through internalization mechanisms (Song et al., 2017). The United Nations Convention to Combat Desertification (UNCCD) is the first international organization to build a policy framework and guarantee mechanism incorporating these measures, as well as to conduct a cost–benefit analysis of the food production-to-consumption process (Dudley et al., 2014; UNCCD, 2014). In response to

the impact of global land degradation on production, a general framework and pathway for "avoiding, mitigating, and restoring" have been proposed and are currently being implemented in several nations. Den Biggelaar et al. (2003) demonstrated that lowering production losses by minimizing soil erosion is effective for guaranteeing food security and that doing so necessitates changing traditional land management practices. However, this objective remains distant. According to research conducted by the Group on Earth Observations on land and water resource security for global food production, developing national plans for food security under resource and environmental restrictions necessitates institutional production, as well as environmental monitoring and evaluation programs utilizing surveys and participatory planning methods (Frei et al., 2013). These research findings indicate that sustainable food production and intensive resource and environmental management require more scientific and rational policy design and feasible institutional mechanisms.

The greatest challenge in contemporary Chinese society is the rising demand for a higher standard of living vs the unbalanced, insufficient rate of economic expansion (Deng et al., 2021a). Regional objectives for sustainable development include food security and nutritional health; enhancing the nutritional status of the population requires consideration of multiple aspects, including agricultural output, food consumption patterns, and government measures (Galli, 2020; He et al., 2018). This link has altered the quantity and spatial distribution of China's food supply and demand, but it has not been evaluated. Paying attention to these distinctions and assessing China's food security situation within the constraints of nutritional security objectives and resource availability, while considering the inherent relationship between food security, nutritional health, and resource security, can contribute to the improvement of the health of the Chinese population. This study evaluates the population's food intake and nutritional health based on urban and rural Chinese dietary consumption statistics from 1990 to 2019. Second, it studies the causal relationship between the components of the nutrition–resources–food (NRF) system and uses the pressure–state–response (PSR) analytical framework to build a regional NRF system security evaluation index system. Based on the entropy weight approach, a comprehensive evaluation of the NRF system security is undertaken to assess the NRF system security trend in China from 2000 to 2019 and to identify the most appropriate food security guarantee methods.

2 Methods and data

2.1 Methods

2.1.1 Food consumption and dietary nutrition evaluation

In this study, the food consumption of residents mainly covers seven plant-based foods (cereals, potatoes, legumes, edible vegetable oils, fresh fruits and vegetables, nuts, and fresh vegetables) and six animal-based foods (poultry, aquatic products, eggs, milk, and pork, beef, and mutton), comprising 13 food types in total. On this basis, six primary categories and ten secondary categories were divided according to the food sources (Tab. 1). The actual daily energy and macronutrient intake structure was estimated using the main foods' nutritional content and the population's dietary consumption data.

Table 1 The main foods' nutritional content[1]

Level 1	Level 2	Food	Source	Energy (kcal/100 g)	Protein (g)	Carbohydrate (g)	Fat (g)
Grain	Cereals	Cereals	Plant-based food	381.9	6	87	1.1
Grain	Cereals	Tubers	Plant-based food	87.3	1.6	20	0.1
Grain	Beans	Beans	Plant-based food	346.8	21	63	1.2
Oil	Animal oil	Fats	Animal-based food	900.4	0.1	0	100
Oil	Vegetable oil	Oil	Plant-based food	900	0	0	100
Vegetables and fruits	Vegetable	Vegetable and mushroom	Plant-based food	65.4	2.9	13	0.2
Meat and eggs	Meat	Pork	Animal-based food	234.4	27	0.1	14
Meat and eggs	Meat	Beef and button	Animal-based food	264	25.5	0	18
Meat and eggs	Meat	Beef	Animal-based food	239	26	0	15
Meat and eggs	Meat	Mutton	Animal-based food	289	25	0	21
Meat and eggs	Meat	Poultry	Animal-based food	183.1	18.8	1.1	11.5
Aquatic products	Aquatic products	Aquatic products	Animal-based food	100.5	17.3	1.3	2.9
Meat and eggs	Poultry eggs	Eggs	Animal-based food	155.4	13	1.1	11
Milk	Milk	Milk	Animal-based food	42.6	3.4	5	1
Vegetables and fruits	Melons and fruits	Melons and fruits	Plant-based food	46.6	0.7	10.5	0.2
Vegetables and fruits	Melons and fruits	Nuts	Plant-based food	650	20	21	54

[1]The macronutrient content refers to the content in a 100-g edible portion

2.1.2 Evaluation of the NRF system security

One regional sustainable development goal is to eradicate hunger and ensure access to sufficient and nutritious food (FAO et al., 2020). A complex relationship exists between population nutrition, food supply and demand, and land and water resources. People's demand for food and their dietary structure change along with rapid socioeconomic development, continuous population growth, and increases in income (FAO, 2019). Land and water resources are essential constraints on food security and nutrient supplies (Hou et al., 2019; Spiertz, 2010), and their access and utilization are related to the sustainability of regional ecosystems and economic development (Voet et al., 2009). As an ecosystem's critical natural capital, land and water resources are the basis for food security and nutrition, and unsustainable resource use practices weaken the ability of ecosystems to provide food and nutrition. The limited availability of land and water resources in the context of rapid urbanization has intensified competition among different sectors (agriculture, industry, and services) in land and water resource utilization (Haberl, 2015; Zeng et al., 2018). However, adequate land and water resource management can alleviate the pressure on food supply in resource-poor areas. This study argues that regional NRF system security refers to the achievement of food security and nutrition goals by improving agricultural production efficiency, land and water resource use efficiency, and to the level of coupling and coordination among subsystems under resource supply constraints that can support regional sustainable development.

In terms of evaluating the NRF system' security, both comprehensive fuzzy multi-objective evaluation models and the PSR framework have been widely used. The former is suitable for evaluating complex problems with multi-factor and multi-level influences (Mardani et al., 2015), but ignores the interaction between various indicators. The PSR framework divides the indicators into pressure, state, and response indicators and highlights the causal relationship between the pressure on food security and the restriction of water and land resources, which could affect the whole process of decision-making and formulation of countermeasures.

In the PSR framework, "stress" refers to human activities that consume resources and affect a region's sustainable development. The greater the pressure, the greater the urgency to improve the population's nutrition levels, ensure food security, and manage the efficient use of resources. To relieve the pressure, the usual response is to increase the production and supply of complementary foods and promote the efficient and sustainable use of land and water resources. The term "state" is used to reflect the background conditions of the regional food supply and land and water resources, which are the cause of the pressure and the result of policy measures. The better the state, the greater is the suitability of regional food production, and the higher is the feasibility of ensuring the nutritional health of the population and the efficient use of land and water resources. Moreover, to a certain extent, the possibility of alleviating the pressure on food security is higher as the state improves. "Response" refers to the policy recommendations and measures taken by policymakers and managers to promote sustainable resource use, the environment, and socioeconomic development. The stronger the response indicates a greater likelihood that behavior or policies will respond to the need to improve the health status of the population and resource security, and the greater is the possibility of the pressure being relieved. In the PSR, the relief of "pressure" is the goal of the policy response, the state is the background for the policy response, and the response measures are the means to achieve sustainable development of the NRF system (Fig. 1).
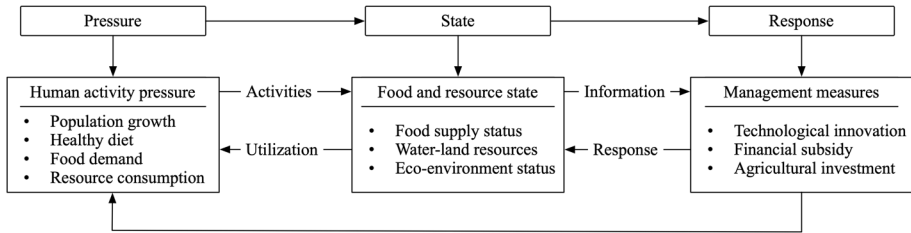
Fig. 1 The conceptual framework of the "Pressure–State–Response" model

The pressure layer of the framework involves three aspects—nutrition improvement, food supply, and resource utilization—as sub-criteria layers. The evaluation index for socioeconomic pressure involves the natural population growth rate and the urbanization rate, reflecting the pressure brought about by the regional population and economic development on the food system and agricultural production. The faster the natural population growth and urbanization rates, the stronger the urgency to ensure food supply and efficient resource utilization. The absolute gap between the actual intake of the three primary macronutrients (protein, carbohydrate, and fat) and their recommended levels, and the proportion of children with moderate-to-severe malnutrition are selected as evaluation indicators to reflect the pressure on the food system imposed by the need to improve regional residents' nutrition. The more that the per capita macronutrient structure deviates from the recommended levels, the more significant is the demand for nutritional improvement, and the smaller the proportion of children with severe malnutrition, the lower the pressure for nutritional improvement. The evaluation indicators selected for food supply pressure are the proportion of crops affected by disasters and the per capita yield fluctuation coefficient for primary foods (grains, vegetables, poultry, and fruits), which reflect the degree of stability of the regional food supply. The lower the proportion of crops affected by disasters and the lower the yield fluctuation coefficient of significant foods, the lower is the pressure on the food system and agricultural production. The evaluation indicators selected for resource use pressure are the amount of pesticide, fertilizer, and agricultural plastic film used per unit area and the agricultural water intensity. These indicators reflect the pressure on land and water resources in the regional agricultural production process. Agricultural chemical (pesticide, fertilizer, and agricultural plastic film) inputs are the primary source of agricultural surface source pollution. The more they are used, the more they are detrimental to the sustainable use of land and water resources, and the greater the pressure to prevent, control, and remediate pollution arising from agricultural production. The higher the intensity of agricultural water use, the greater the urgency to improve the efficiency of water resource use.

The status layer indicates the background status of regional food supply, water, and land resources. As sub-criteria layers, food security, food production, water, land resources, and ecological environment status are chosen. The Engel coefficient reflects the proportion of food expenditure to total expenditure. The lower the Engel coefficient is, the lower is the proportion of food in total expenditure, and the better is the food security status. The food price index reflects the essential supply and demand relationship for food. The higher the food price, the worse the food security status. From the perspective of resource supply, the per capita water resources, underground water resources, surface water resources, land reclamation rate, and per capita arable land area are selected as indicators for evaluating the status of water and land resources. The richer the regional water resources (per capita water resources, surface water

resources, and underground water resources), and the higher the land reclamation rate and per capita arable land area, the better the supply status of water and land resources. Forest cover reflects the service level of the regional ecosystem, with a higher value indicating a greater feasibility of sustainable regional development.

The response layer reflects the support for policies or measures affecting the food system and agricultural production. Agricultural production, farmers' income, and resource utilization are selected as sub-criteria layers. The evaluation indicators for agricultural production are the financial support for agriculture, the proportion of new fixed-asset investment in rural areas, the irrigation guarantee rate, and the mechanized power per unit area. Higher values indicate that the policy guidance is focused on improving decision-making about agricultural production conditions and is more conducive to alleviating food supply pressure. The farmers' income layer and the income effect on their production are evaluated by the farmers' per capita net income. When income is higher, farmers are more motivated to expand agricultural production, which is more conducive to ensuring food security. Finally, the evaluation indicators of the resource utilization response are the erosion control area and water-saving irrigation ratio, which reflect the social input of policy in improving the ecological environment and water resource use. In terms of a method for setting index weights, gray correlation, artificial neural network, analytic hierarchy process, and entropy weight methods have been widely used. However, some of these methods have certain limitations. For example, the gray correlation and artificial neural network methods need to consider the level of food security status. Because of constraints on food production conditions, such as resource endowments, the threshold level of food security varies between the regions, which would affect the accuracy of the results calculated. Thus, in this paper, the entropy weight method is used to determine the weights for the index system. This method determines the information entropy of the corresponding index and its entropy weight according to the degree of variation in each index's data, then corrects the weights of each index using the entropy weight to obtain more objective index weights (Tab. 2). The calculation process is as follows.

(1) Data standardization.

To eliminate the influence of the dimension of the index, the data standardization of each index was conducted based on its the positive and negative extreme value (Eq. 1):

$$\begin{cases} x_{ij} = (X_{ij} - \min x_j)/(\max x_j - \min x_j), & \text{positive indicators} \\ x_{ij} = (\max x_j - X_{ij})/(\max x_j - \min x_j), & \text{negative indicators} \end{cases}, \quad (1)$$

where X_{ij} and x_{ij} are the original and normalized values of indicator j in year i. $\max x_j$ and $\min x_j$ are the maximum and minimum values of indicator j, respectively.

(2) Information entropy.

After data normalization, the weight f_{ij} (Eq. 2) and information entropy H_{ij} (Eq. 3) are calculated for indicator j in year i. The magnitude of H_{ij} reflects the dispersion of its numerical distribution, and the larger is H_{ij}, the greater the dispersion of the indicator:

$$f_{ij} = \frac{x_{ij}}{\sum_{j=1}^{i} x_{ij}} \quad (2)$$

$$H_j = -\frac{1}{\ln n} \sum_{j}^{n} \left(f_{ij} \ln f_{ij} \right) \quad (3)$$

Table 2 Evaluation index system of the NRF system based on the PSR model

Criterion layer	Sub-criterion layer	Indicator (Unit)	Indicator meaning and sign	Weight
Pressure layer	Social-economic pressure	Natural population growth rate (‰)	Measuring system population growth pressure (-)	0.0112
		Urbanization rate (%)	Measuring the pressure of the system urbanization process (-)	0.0134
	Nutrition improvement pressure	Protein intake gap per capita (percentage points)	Measuring the pressure to improve the dietary structure of the regional population (-)	0.0151
		Carbohydrate intake gap per capita (percentage points)		0.0060
		Fat intake gap per capita (percentage points)		0.0052
		Proportion of children with moderate-to-severe malnutrition (%)	Measuring child nutritional status stress (-)	0.0032
	Food supply pressure	Proportion of crops affected (%)	Measuring the environmental impact pressure on agricultural production (-)	0.0040
		Coefficient of fluctuation of food production per capita (%)	Measuring stable regional food production capacity (-)	0.0005
		Fluctuation coefficient of vegetable production per capita (%)		0.0002
		Fluctuation factor of poultry meat production per capita (%)		0.0004
		Fluctuation coefficient of fruit production per capita (%)		0.0016
	Resource utilization pressure	Arable land reduction rate (%)	Measuring pressure on land resource supply (-)	0.0020
		Pesticide use per unit area (kg/ha)	Measuring the pressure of agricultural production on land and water resources (-)	0.0050
		Fertilizer use per unit area (kg/ha)		0.0002
		Amount of agricultural film used per unit area (kg/ha)		0.0029
		Agricultural water intensity (m^3/ha)	Measuring the pressure of agricultural production on water consumption (-)	0.0032
Status Layer	Food Security Status	Engel coefficient (%)	Measuring regional food security status (-)	0.0027

Table 2 (continued)

Criterion layer	Sub-criterion layer	Indicator (Unit)	Indicator meaning and sign	Weight
		Food Price Index	Measuring the state of regional food supply and demand (-)	0.0037
	Food production status	Food production per capita (kg)	Measuring regional production capacity for major foodstuffs (+)	0.0283
		Vegetable production per capita (kg)		0.0594
		Poultry meat production per capita (kg)		0.0911
		Per capita production of fruits and vegetables (kg)		0.0401
	Water Resources Status	Water resources per capita (cubic meters)	Measuring the state of regional water security (+)	0.2337
		Groundwater resources (billion cubic meters)		0.0441
		Surface water resources (billion cubic meters)		0.0675
	Land Resource Status	Land reclamation rate (%)	Measuring the state of regional land resource supply (+)	0.0241
		Arable land per capita (ha)		0.0703
	Ecosystem Status	Forest cover rate (%)	Measuring the ecological state of the region (+)	0.0270
Response layer	Agricultural production response	Financial support for agriculture (million yuan)	Measuring financial inputs to improve agricultural production (+)	0.0548
		The proportion of new fixed asset investment in rural areas (%)		0.0242
		Irrigation guarantee rate (%)	Measuring resource inputs to improve agricultural production (+)	0.0347
		Mechanized power per unit area	Measuring technological inputs to improve agricultural production (+)	0.0471
	Farmer Income response	Per capita net income of farmers (yuan)	Measuring the socio-economic benefits driven by improved agricultural production (+)	0.0453
	Resource Utilization response	Land erosion control area (thousand hectares)	Measuring social inputs to improve the ecological environment (+)	0.0278
		Proportion of water-saving irrigation (%)	Inputs to measure improvements in water use efficiency (+)	0.0112

(3) Determination of indicator weights.

Using the information entropy of indicator j in year i, the weight W_{ij} of each indicator is further calculated, as shown in Eq. 4:

$$W_{ij} = \frac{1 - H_{ij}}{\sum_{i=1}^{m} \left(1 - H_{ij}\right)} \tag{4}$$

where m is the study time span. In this study, $m = 20$. The more information that the indicator contains (H_{ij}), the greater the role it plays in the comprehensive evaluation, and the greater its weight (W_{ij}).

2.2 Data sources

In this study, we collected data on 35 indicators, including the natural population growth rate, the urbanization rate, the per capita protein intake gap, the per capita carbohydrate intake gap, the per capita fat intake gap, and the proportion of children with moderate-to-severe malnutrition (%) in China's 31 provinces (excluding Hong Kong, Macao, and Taiwan) from 1990 to 2019. Indicator data were obtained from the China Statistical Year-book (1991–2020). Indicators such as financial support to agriculture (RMB million), the proportion of new fixed-asset investment in rural areas (%), and the per capita net income of farmers (RMB) use the gross domestic product deflator to eliminate the effect of price fluctuations.

3 Results and analysis

3.1 Trends in the dietary intake and nutrition structure of residents

3.1.1 Trends in the dietary intake of urban and rural residents

Since 1990, with the rapid development of the Chinese economy and society, the quality of food consumption by Chinese residents has improved greatly, and the proportion of per capita food consumption expenditure to total expenditure has gradually declined, as reflected in the fall of the Engel coefficient from 45.51% to 28.54% over the period 1990–2019. There is a notable trend toward upgrading food consumption, manifested in the reduction in plant-based food consumption and the increase in animal-based food consumption (meat, poultry, eggs, and dairy products). However, the change in the dietary structure of Chinese residents is closely related to their stage of economic development. According to the rate of change in the food consumption structure, Chinese residents' food consumption can be divided into three periods (Fig. 2). In the first period, 1990–1999, food consumption remained largely grain-based. Per capita food consumption in this period was 372.02 kg; the consumption of grains (cereals and pulses) had begun to decline, but at a slower rate (-1.85% per year) compared with later periods. In the second period, 2000–2012, total food consumption declined, but grain-based consumption was rapidly upgraded to a more diversified, richer consumption pattern. As a result, grain consumption as a proportion of food consumption decreased from 45.21% in 2000 to 39% in 2012. During the same period, animal-based food consumption (meat, poultry, and dairy products) increased rapidly, from less than 9% in 2000 to 11.44% in 2012. In the third period,
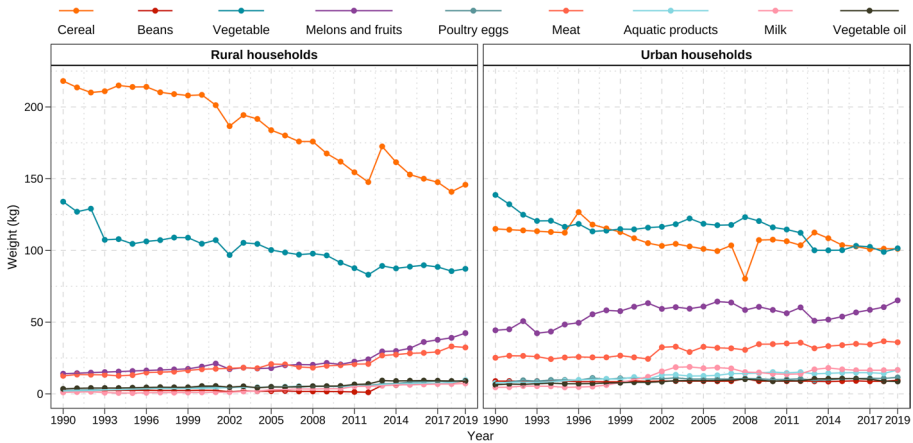
Fig. 2 Food consumption per capita by commodity group in China, 1990 to 2019

2013–2019, total food consumption continued to decline, but the structure of consumption changed from a diversified to a balanced intake. In this period, nutrition and health became the primary demand; food consumption gradually stabilized; the consumption of plant-based foods (vegetables, fruits, and vegetables) continued to decrease, and that of animal-based foods (meat and poultry) continued to increase.

It is notable that there were differences in the food consumption structure between urban and rural residents in China. Urban residents had a more stable food consumption structure and a relatively flat growth in their demand for animal-based food consumption. In contrast, for rural residents, changes in food consumption involved a continued growth in demand for animal-based food and a continued decline in demand for plant-based food. Regarding temporal trends, food consumption for urban residents underwent a phase of upgrading (1990–2000) and then structural change (2000–2019). Between 1990 and 2000, food and vegetable consumption decreased at an average annual rate of 0.52% and 1.73%, respectively. However, the consumption of fruits, eggs, milk, and aquatic products increased rapidly, with average annual increases of 3.99%, 7.77%, and 5.24%, respectively. While the consumption of poultry meat per capita only increased from 6.70 kg in 1990 to 8.77 kg in 2000, the increase was minor from 2000 to 2019, and the trend of urban residents' food consumption was the same as that from 1990 to 2000, but the magnitude of change tended to slow down. The food consumption structure of rural residents showed a trend of rapid upgrading and diversification, and the proportion of grain consumed decreased from 56.52% of food consumption in 1990 to 43.96% in 2019. However, vegetable oil consumption increased greatly, with an average annual increase of 5.24%. The proportion of animal-based food consumption has gradually increased, with eggs, milk, poultry, meat, and aquatic products continuing to grow at a high rate.

In terms of the nutrients provided by food consumption and the nutritional needs of residents, the dietary energy intake of residents in China showed a fluctuating downward trend over the period 1990–2019. Residents' caloric intake in 2019 was 2,158.94 kilocalories (kcal), a decrease of 20.17% compared with 1990. However, both exceeded the recommended intake of 1,738.5 kcal, and the energy supply was adequate. The total dietary energy intake of urban residents was lower than that of rural residents, but the gap between urban and rural areas narrowed from 736.49 kcal in 1990 to 330.42 kcal in 2000. In terms

of sources of energy intake, the energy supply ratio of food has dropped greatly as the food consumption structure has improved, with the energy supply ratio of poultry, eggs, milk, and oil showing a rapid increase. In contrast, the energy supply ratio of fruits and vegetables has remained stable (Fig. 3) over the period of analysis.

3.1.2 Structure of macronutrient intake and its spatial pattern among urban and rural residents

Carbohydrates, fats, and proteins release energy by oxidation, providing the basis for human life and activity. Among these three energy-producing nutrients, or "macronutrients," carbohydrates are the most critical source of energy for the human body; protein is a substance that constitutes human cells and tissues and provides the raw material for cell repair and renewal; and fat is the most critical substance for energy storage, regulating the endocrine system and protecting organs and tissues. According to the Dietary Guidelines for Chinese Residents (2016), a reasonable dietary structure should include 15%, 55%, and 30% of protein, carbohydrate, and fat, respectively, as the three macronutrients. The intake of macronutrients should be close to the recommended levels because excessive or insufficient intake increases the risk of health issues and disease.

Based on the intake structure of the three macronutrients, the quality of the Chinese people's dietary nutrition improved greatly between 1990 and 2019, with the proportions of protein and fat in the per capita intake increasing (Fig. 4). As a result, the protein energy supply ratio has increased from 9.75% in 1990 to 12.94% in 2019, and the fat energy supply ratio has increased from 10.77% to 21.57% over the same time. Comparatively, the proportion of carbohydrates in the macronutrient intake decreased. However, the food consumption pattern and the nutrient intake structure vary between urban and rural residents. Whereas the diet of urban residents is more closely aligned with the recommended dietary structure, the grain-based diet of rural residents means that carbohydrates account for a higher proportion of their macronutrient intake. Nevertheless, between 1990 and 2019, rural inhabitants' food consumption patterns varied, and the nutrition structural gap between urban and rural residents shrunk steadily.
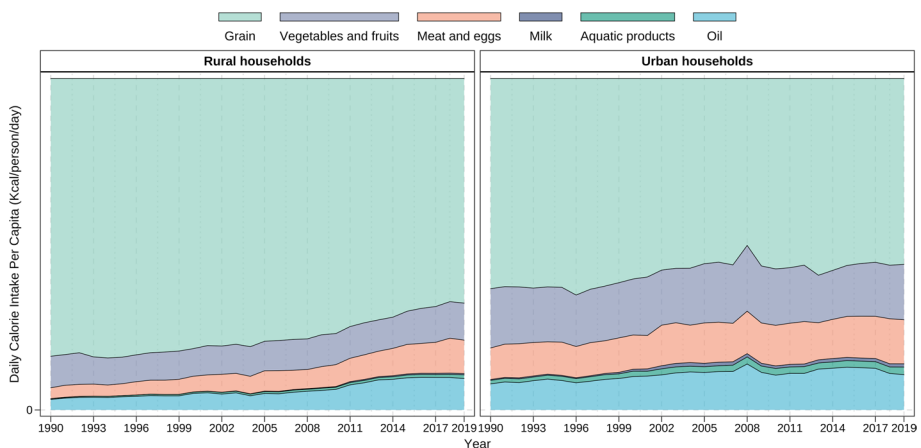

Fig. 3 Food sources of caloric intake of urban **A** and rural residents **B** in China, 1990–2019
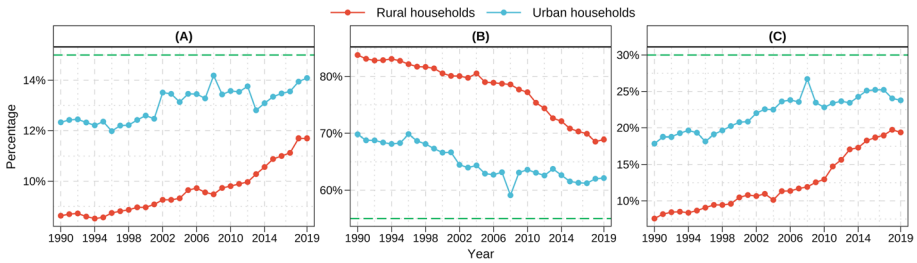
Fig. 4 Daily caloric supply derived from **A** protein, **B** carbohydrates, and **C** fat in China, 1990–2019

Residents of China are transitioning from a traditional plant-based diet to one that emphasizes both plant- and animal-based foods (Fig. 5). Currently, plant-based proteins make up the majority of the protein intake of Chinese residents, but the proportion of animal-based foods, such as poultry, meat, eggs, and milk, has increased significantly from 26.96% in 1990 to 49.20% in 2019. Nearly all carbohydrates (99.2%) are derived from plant-based sources. As a result, the average proportion of fat in the diets of Chinese residents is reasonable and remains below the upper limit of 30%. Nevertheless, in terms of dietary sources of fat intake, the proportion of animal fat intake has increased the most, from 28.55% in 1990 to 30.56% in 2019.

The total dietary energy per capita in China shows a spatial distribution pattern that is high in the north and west, and low in the south and east (Fig. 6). The total dietary energy intake per capita is relatively higher in Tibet, Sichuan, Chongqing, Xinjiang, and Inner Mongolia, with a per capita energy intake of 2,626.16 kcal per day, followed by Hunan, Jiangxi, and Heilongjiang Provinces in south central, east, and northeast China, with a per capita energy intake of 2,292.94 kcal per day. On the other hand, people in Beijing, Qinghai, Hainan, and Ningxia cities and provinces only get an average of 1,766.99 kcal per day from their food.

Regarding the spatial distribution of the macronutrient structure, the residents of the northern region favor a high carbohydrate, low protein, and low fat dietary structure. In contrast, those in the southern region consume more protein and fat (Fig. 6 and Table 3). The average whole-of-China energy intakes of protein, fat, and carbohydrate were 13.29%, 21.50%, and 65.17%, respectively. In north and northwest China, the carbohydrate intake ratio was much higher, averaging 68.81%, whereas the ratios of protein and fat were only 13.29% and 19.76%, respectively.
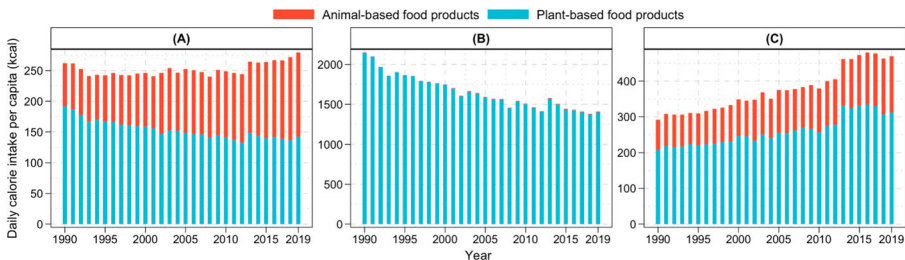

Fig. 5 Food sources of **A** protein, **B** carbohydrate, and **C** fat in the diets of Chinese residents, 1990–2019
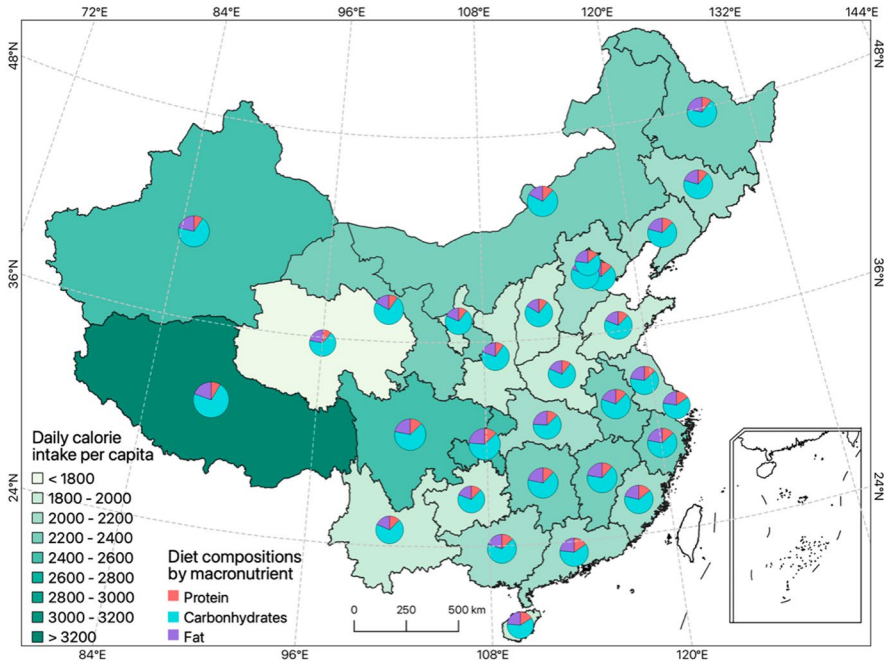
Fig. 6 Per capita daily caloric intake and the macronutrient supply structure of Chinese residents in 2019

Table 3 Structure of per capita dietary energy and nutrient intake of residents in six regions of China

Region	Energy intake (Kcal/ day)	Nutrient energy supply ratio (%)		
		Protein	Carbohydrates	Fat
Eastern region	2113.33	13.18	65.57	21.21
Northern region	2023.54	12.00	68.46	19.44
Southwest region	2419.46	11.88	67.50	20.57
Northwest region	2054.66	10.71	69.17	20.08
South central region	2053.48	13.39	64.77	21.79
Northeast region	2187.40	11.53	67.21	21.23

3.2 PSR-based security evaluation of the NRF systems

3.2.1 Security trends in the NRF system

Overall, despite fluctuations, there is an upward trend in the stress index of the NRF system in China (Fig. 7); this indicates that there has a reduction in system stress, but the relief has been slight. Temporally, we can distinguish three substages: first, during the period 2000–2003, system pressure was slightly relieved; second, during 2004–2007, the NRF system stress index decreased, and stress increased; third, during 2008–2019, the NRF system stress index increased, with the increasing trend being particularly evident from 2016. Overall, the NRF system stress index showed a trend of continuous improvement during
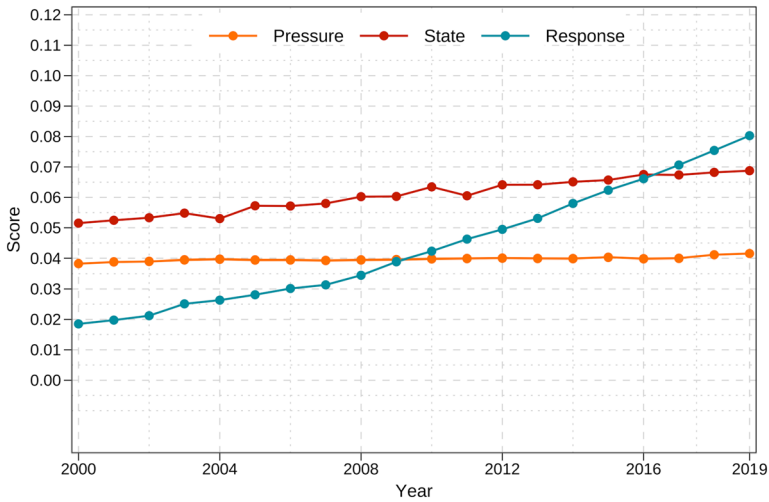
Fig. 7 Trends in the NRF system security in China, 2000–2019

the period 2008–2019. In terms of the state index, the overall trend for China was a steady increase. Two substages are evident: first, over the period 2000–2012, China's NRF system state showed a fluctuating upward trend; and second, from 2012 to 2019, there was a steady upward trend, indicating continuous improvement of the NRF system state. Turning to the response index in the NRF system, there was a steady increase from 0.019 in 2000 to 0.080 in 2019, which was an increase of 321.05%, with an average annual increase of 16.05%. This significant increase in the response index implies an increase in the number and efficacy of efforts to enhance nutrition, assure food security, and maximize resource utilization.

A comprehensive analysis of the stress, state, and response indices of the Chinese NRF system reveals a steady upward trend in the comprehensive system security index, indicating that the level of NRF system security is in a process of continuous improvement. Furthermore, in terms of the magnitude of change in the index, the response index exceeds the state index, which in turn exceeds the pressure index, indicating that the policy response is the most active and robust, and is the main driver of system state improvement and pressure relief.

3.2.2 Spatiotemporal patterns in the NRF system

There is an obvious spatial aggregation in the pressure index of the NRF system in four subperiods between 2000 and 2009, namely 2000–2004, 2005–2009, 2010–2014, and 2015–2019 (Fig. 8). Overall, the pressure index did not change much over the four subperiods, with only a small increase in some provinces. In terms of spatial distribution, the pressure index value was high in southwest, south, and north China during all four subperiods. Over time, the region with a high-pressure index value gradually expanded to the northeast, northwest, central, and east of China. Therefore, the pressure index of the NRF system in China was relatively stable as a whole from 2000 to 2019, and the disparity in the index between provinces exhibited a decreasing trend over the same time period. The state index value for the whole of China mainly showed an increasing trend. During the 2000–2004
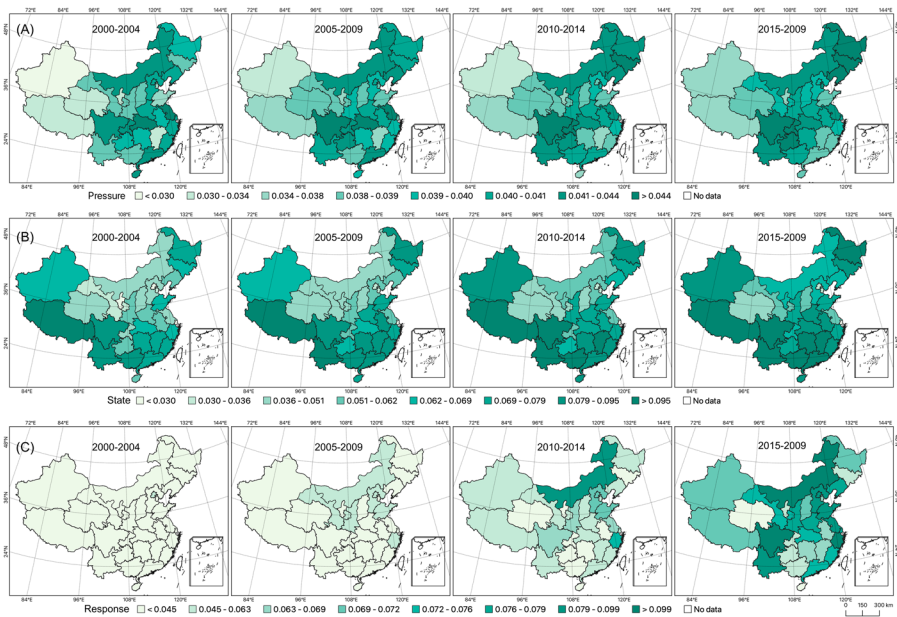
Fig. 8 The spatial distribution of the **a** pressure, **b** state, and **c** response indexes of the NRF system in China during four subperiods (2000–2004, 2005–2010, 2010–2014, and 2015–2019)

subperiod, the provinces with high state index values were mainly distributed in northeast, southwest, and south of China. From 2005 to 2019, the values for these areas remained high, and those of other regions showed an increasing trend. Over time, the regions with high state index values were mainly concentrated in northeast, southwest, east, and south of China, with some provinces in northwest and north China retaining low values.

The change in the response index is more obvious than those in the pressure and response indices in the four subperiods. During the 2000–2004 subperiod, the response index value was low in the whole of China. In the 2005–2010 subperiod, the values of provinces located in north and northwest China increased slightly compared with the previous period. During the subperiods of 2010–2014 and 2015–2019, the provinces with a great increase in the response index were clustered in the north, east, northwest, southwest, and central China. Ultimately, the regions with high values for the response index were mainly clustered in northern, southwest, and eastern China. Thus, between 2000 and 2019, there was a widening gap in the response index values across provinces.

4 Conclusions and policy implications

4.1 Conclusions

(1) Food consumption and nutrition intake of residents in China.

Since the 1990s, the lives of the Chinese people have continued to improve. This study assessed the food consumption and nutritional status of urban and rural residents in China from 1990 to 2019. Compared with 1990, the per capita consumption of eggs, milk, aquatic

products, and poultry increased by 1.77, 2.77, 2.56, and 4.77 percentage points, respectively. The proportion of animal protein and animal fat in the total intake has increased to a certain extent. However, there are great regional differences, with nutrition remaining imbalanced between urban and rural residents. With the diversification of the food consumption structure among rural residents, the gap in the nutrition structure has been gradually narrowing.

(2) The food security state in the context of nutrition improvement and resource constraints.

Human survival, social stability, and economic progress depend on nutrition, food, and resources. We utilized PSR to examine NRF security in China from 2000 to 2019. Overall, NRF safety is improving. The response index changed more than the pressure and state sub-indices of the NRF system, indicating the improved safety of NRF is mainly due to favorable policy responses. Spatially, the changes in pressure index rose in the "northeast-northwest-central-east" direction. China's northeast, southwest, east, and south had the highest state index values during 2015–2019. The response index and its interprovincial difference both rose from 2000 to 2019.

4.2 Policy implications

Currently, there is an urgent need for adjustments to China's national nutritional situation to avert severe nutritional shortages and imbalances. Optimization of dietary nutrition is necessary based on the nutritional state of the population. Residents must continue to maintain a sufficient calorie supply and a reasonable nutritional ratio. However, the food sources of nutrients can be modified to improve the quality of protein consumption, limit excessive fat intake, and boost the intake of high-quality carbohydrates. According to the Dietary Guidelines for Chinese Residents (2016), macronutrient consumption can be optimized to improve dietary nutrition. China has also proposed a series of agricultural regulation and control measures, such as a grain subsidy program, a minimum purchase price policy, a "red line" of 1.8 billion mu of arable land, and a "changing grain to feed" policy, in order to adapt to the changing dietary structure of its residents and resolve the contradiction between food supply and demand. However, the foundation of food security is relatively fragile, with the large population and, hence, the large demand for food in China. Judging from the development trends, demand for food will continue to increase in the future. The constraints on food production, such as the reduction of cultivated land, shortages of water resources, and climate change, have become increasingly prominent.

In the future, China should be able to rely on its own food supply, enhance input assistance, and protect cultivated land tightly (Han & Song, 2019, 2020). It is crucial to increase food production capacity through scientific and technological advancement. Improving the food circulation system and bolstering central government control over food production can contribute to the development of a food security system that is responsive to the difficulties of international trade, the reality of domestic resources, and environmental limits. From production to consumption, food security involves several chains, multiple sectors (agricultural, commerce, management, and others), and numerous stakeholders, including farmers, governments, and consumers. To attain food security in China, corresponding institutional innovation and strong governance mechanisms are necessary (Song et al., 2016). In the modern era, principles of green and sustainable consumption have been introduced. Sustainable production and consumption, which consider food security as well as resource and environmental conservation, have become a priority for decision-makers.

5 Data availability

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

Code availability Not applicable for this article.

Declarations

Conflict of interest No potential competing interest was reported by the authors.

References

Bindraban, P. S., van der Velde, M., Ye, L., van den Berg, M., Materechera, S., Kiba, D. I., Tamene, L., Ragnarsdóttir, K. V., Jongschaap, R., Hoogmoed, M., Hoogmoed, W., van Beek, C., & van Lynden, G. (2012). Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability, 4*, 478–488.

Burchi, F., & De Muro, P. (2016). From food availability to nutritional capabilities: Advancing food security analysis. *Food Policy, towards a Food Secure Future: Ensuring Food Security for Sustainable Human Development in Sub-Saharan Africa, 60*, 10–19.

den Biggelaar, C., Lal, R., Wiebe, K., & Breneman, V. (2003). The global impact of soil erosion on productivity. *Advances in Agronomy* (pp. 1–48). Elsevier.

Deng, X., Han, Z., Xie, W., Wang, G., & Fan, Z. (2021b). Risk evaluation of the grain supply chain in China. *International Journal of Logistics Research and Applications*. https://doi.org/10.1080/13675 567.2021.2009450

Deng, X., Jin, G., He, S., Wang, C., Li, Z., Wang, Z., Song, M., Yang, Q., Zhang, A., & Chen, J. (2021a). Research progress and prospect on development geography. *Journal of Geographical Sciences, 31*, 437–455.

Deng, X., Liu, J., Ma, E., Jiang, L., Yu, R., Jiang, Q., & Zhao, C. (2015). Impact assessments on water and heat fluxes of terrestrial ecosystem due to land use change. In J. Zhan (Ed.), *Impacts of land-use change on ecosystem services, springer geography* (pp. 149–209). Springer.

Dudley, N., MacKinnon, K., & Stolton, S. (2014). The role of protected areas in supplying ten critical ecosystem services in drylands: A review. *Biodiversity, 15*, 178–184.

FAO, IFAD, UNICEF, WFP, WHO, (2020). The state of food security and nutrition in the world 2020.

Food and Agriculture Organization of the United Nations, (2019). The state of food security and nutrition in the world: safeguarding against economic slowdowns and downturns.

Frei, T., Connolly, N., Bye B. L., Fritz, S., Massacand A. (2013). Assessment of the Achievements of the Group on Earth Observations (GEO): A European Perspective.

Galli, F. (2020). How do small farms contribute to food and nutrition security? Linking European small farms, strategies and outcomes in territorial food systems. *Global Food Security, 12*, 10027.

Haberl, H. (2015). Competition for land: A sociometabolic perspective. *Ecological Economics, 119*, 424–431.

Han, Z., & Song, W. (2019). Spatiotemporal variations in cropland abandonment in the Guizhou-Guangxi karst mountain area China. *Journal of Cleaner Production, 238*, 117888.

Han, Z., & Song, W. (2020). Abandoned cropland: Patterns and determinants within the Guangxi Karst Mountainous Area China. *Applied Geography, 122*, 102245.

He, P., Baiocchi, G., Hubacek, K., Feng, K., & Yu, Y. (2018). The environmental impacts of rapidly changing diets and their nutritional quality in China. *Nature Sustainability, 1*, 122–127.

Holden, S. T. (2018). Fertilizer and sustainable intensification in Sub-Saharan Africa. *Global Food Security, 18*, 20–26.

Hou, L., Keske, C., Hoag, D., Balezentis, T., & Wang, X. (2019). Abatement costs of emissions from burning maize straw in major maize regions of China: Balancing food security with the environment. *Journal of Cleaner Production, 208*, 178–187.

Jribi, S., Ben Ismail, H., Doggui, D., & Debbabi, H. (2020). COVID-19 virus outbreak lockdown: What impacts on household food wastage? *Environment, Development and Sustainability, 22*, 3939–3955.

Kumar, M., Singh, R. B., Pravesh, R., Kumar, P., Tripathi, D. K., & Sahu, N. (2018). Urban growth dynamics and modelling using remote sensing data and multivariate statistical techniques. *Current Science, 114*, 2080.

Liu, J., & Deng, X. (2010). Progress of the research methodologies on the temporal and spatial process of LUCC. *Chin. Science Bulletin, 55*, 1354–1362.

Managi, S., Hibiki, A., & Tsurumi, T. (2009). Does trade openness improve environmental quality? *Journal of Environmental Economics and Management, 58*, 346–363.

Mardani, A., Jusoh, A., Nor, K. M., Khalifah Z., Zakwan, N., & Valipour, A. (2015). Multiple criteria decision-making techniques and their applications – A review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istraživanja, 28*(1), 516–571.

Pieroni, A., Hovsepyan, R., Manduzai, A. K., & Sõukand, R. (2021). Wild food plants traditionally gathered in central Armenia: Archaic ingredients or future sustainable foods? *Environment, Development and Sustainability, 23*, 2358–2381.

Seto, K. C., & Ramankutty, N. (2016). Hidden linkages between urbanization and food systems. *Science, 352*, 943–945.

Song, M., Cen, L., Zheng, Z., Fisher, R., Liang, X., Wang, Y., & Huisingh, D. (2017). How would big data support societal development and environmental sustainability? Insights and practices. *Journal of Cleaner Production, 142*, 489–500.

Song, W., Han, Z., & Deng, X. Z. (2016). Changes in productivity, efficiency and technology of China's crop production under rural restructuring. *Journal of Rural Studies, 47*, 563–576.

Spiertz, J. H. J. (2010). Nitrogen, sustainable agriculture and food security. *A Review. Agronomy for Sustainable Development, 30*, 43–55.

UNCCD (United Nations Convention to Combat Desertification). (2014). *Desertification: The invisible frontline*. UNCCD.

van der Voet, E., Van Oers, L., De Bruyn, S., De Jong, F., & Tukker, A. (2009). Environmental impact of the use of natural resources and products. CML reports, (184).

Xie, H., Wen, Y., Choi, Y., & Zhang, X. (2021). global trends on food security research: A bibliometric analysis. *Land, 10*, 119.

Xie, W., Cui, Q., & Ali, T. (2019). Role of market agents in mitigating the climate change effects on food economy. *Natural Hazards, 99*, 1215–1231.

Young, S. L., Frongillo, E. A., Jamaluddine, Z., Melgar-Quiñonez, H., Pérez-Escamilla, R., Ringler, C., & Rosinger, A. Y. (2021). Perspective: The importance of water security for ensuring food security, good nutrition, and well-being. *Advances in Nutrition, 12*, 1058–1073.

Zeng, C., Song, Y., He, Q., & Liu, Y. (2018). Urban–rural income change: Influences of landscape pattern and administrative spatial spillover effect. *Applied Geography, 97*, 248–262.