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RECEIVED 11 February 2025

ACCEPTED 24 July 2025

PUBLISHED 05 August 2025

CITATION

Liu C, Chen Y and Yu H (2025) The impact mechanism and governance of dietary structure upgrading on grain security in China.

Front. Sustain. Food Syst. 9:1575066.
doi: 10.3389/fsufs.2025.1575066

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The impact mechanism and governance of dietary structure upgrading on grain security in China

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Based on the panel data of 31 provinces in China, this paper empirically examines the impact mechanism and governance pathways of dietary structure upgrading on grain security by employing a two-way fixed effects model. The study finds that: (1) Dietary structure upgrading has a significant negative impact on grain security in China, and this finding still holds after multiple robustness tests; (2) Water resources are the mediating path that causes this negative impact, while international trade exhibits a significant positive moderating role in the impact process; (3) Simulation analysis further indicates that China's current dietary structure still exhibits irrationality when compared to various global dietary health standards, transitioning toward a nutritious and healthy dietary structure could mitigate the pressure on China's grain security. In terms of overall savings, when simulation scenarios adhere to the primary global dietary guidelines, the total grain savings range from 40 to 120 million tons, equivalent to 7 to 18% of the current total grain production. Consequently, in the context of the continuous upgrading of residents' dietary structure, emphasizing water resource conservation, efficient utilization of international trade, and advancing rational dietary improvements can offer fresh perspectives and guidelines for formulating policies aimed at reducing the burdens on grain security in China.

KEYWORDS

dietary structure, grain security, water resource, international trade, global dietary health structure

1 Introduction

Grain security remains fundamental to China's national economic development and state governance. At present, China has basically been able to feed 21% of the global population using only 7% of the world's arable land, maintaining overall grain security stability (NBSC, 2023). However, in the long term, China's grain security still encounters the following three primary challenges (Huang and Yang, 2017). Firstly, on the domestic demand side, continuous dietary restructuring among urban and rural residents drives rapid growth in grain demand, particularly for feed grains, intensifying structural imbalances across grain varieties and exacerbating supply-demand tensions. Secondly, on the domestic supply side, resource endowment constraints and environmental pressures severely constrain sustainable grain production capacity, leaving limited potential for output expansion and creating immense pressure to maintain and increase yields. Thirdly, on the international trade side, protectionism and regional conflicts increasingly disrupt global grain market stability, amplifying uncertainties and undermining import reliability. Consequently, against a backdrop of relatively stable domestic production and volatile global trade, changes in China's grain

consumption caused by dietary restructuring on the demand side have generated a persistent tight grain supply–demand balance, emerging as a critical long-term determinant of China's grain security.

Following China's entry into the new millennium, sustained economic growth and rising household incomes have propelled China into a development stage characterized by 'eating well', which is manifested specifically as continuous dietary restructuring, with consumption patterns transitioning from grain-dominated diets toward greater reliance on animal-sourced foods such as meat, eggs, and dairy products (Shimokawa, 2015). Calculations based on National Bureau of Statistics data reveal that China's per capita grain consumption declined by 30.39% between 2001 and 2022, whereas per capita meat and egg consumption increased by 116.67 and 64.90%, respectively. Research generally indicates that the upgrading of China's dietary structure will exacerbate its grain security situation, especially intensifying the pressure on safeguarding feed grain security. Therefore, it is necessary to redefining grain security to prioritize enhancing essential agricultural and sideline product supply capacity while maintaining absolute staple grain self-sufficiency (Huang, 2021). From the perspective of production input factors, Liu (2014) argues that dietary restructuring escalates water consumption, which in turn exacerbates resource constraints, thus affecting grain production. Conversely, Zhan (2022) argues that expanded import trade can alleviate agricultural production resource constraints in China, simultaneously safeguarding the smooth development of the livestock industry driven by dietary structure changes and ensuring national grain security. Additionally, scholars like Fan and Brzeska (2014) focus on analyzing the rationality of the current Chinese residents' dietary consumption patterns, in response to the characteristic fact that dietary structure upgrading continuously aggravates the pressure on China's grain security, advocating for the construction of nutritionally balanced dietary structures. And based on this, Fan et al. (2023) further propose developing a distinctive Chinese strategic grain security system. Collectively, existing literature offers valuable insights into dietary structure and grain security issues, but no consensus so far has been emerged on the overall effect of dietary structure upgrading on grain security and the corresponding mechanistic pathways are inadequately elucidated. Furthermore, there is still room for further improvement in terms of empirical methodology and research perspectives. Therefore, this study empirically analyses the impact of dietary structure upgrading on grain security based on China's provincial panel data from 2001 to 2022, investigates water resources as a mediating mechanism, examines the moderating effect of international trade in this process, as well as further simulates the effects of different dietary structure scenarios on grain security.

The marginal contributions of this paper are as follows: First, this study provides empirical evidence at the macro level regarding the impact of dietary restructuring on grain security in China by constructing a four-dimensional grain security evaluation index system encompassing availability, accessibility, stability, and sustainability. Second, the study examines the mediating roles of water resource consumption and international trade in the process through which dietary structure upgrading affects grain security, thereby enriching the elaboration of relevant theoretical mechanisms. Third, by comparing domestic dietary structure with global dietary nutritional standards, this study introduces nutritional health considerations to discuss strategies for promoting rational dietary

restructuring, yielding novel policy insights for alleviating grain security pressures.

2 Literature review and theoretical analysis

2.1 Literature review

Currently, the perspectives for international research on grain issues are constantly being enriched. Many scholars have analyzed how to ensure grain security in China from various angles, including food supply chains (Yan et al., 2023), trade and arable land resource availability (Ge et al., 2018), as well as population structure (Lee et al., 2024). However, few scholars have explored the impact of dietary structure upgrading on grain security. Although some scholars have examined the potential grain security issues arising from the upgrading of dietary structures among Chinese residents from the perspective of food demand (He G, et al., 2019), domestic research and forecasting on residents' food demand have primarily relied on government-released statistical data, with a narrow focus limited either to the national level or exclusively between urban and rural areas. Additionally, some researchers have converted major food items consumed by residents into grain equivalents based on certain standards, allowing for the calculation of national grain-especially feed grain-demand (Wang, 2019). The resulting per capita grain consumption and national consumption volumes are substantial, and exhibit a trend of rigid growth. Furthermore, based on the theories of virtual water and water footprint, numerous scholars have confirmed that, amidst the already critical domestic water resource situation, the increase in the consumption of animal-based foods such as meat, eggs, and dairy driven by dietary structure upgrading will lead to greater water resource consumption, thereby exacerbating the pressures on domestic water resource constraints (Wang et al., 2017). Consequently, against the backdrop of increasing grain demand, coupled with the dual rigid constraints of resources and environment, the difficulty in increasing domestic grain production is mounting, with water resource constraints exerting an increasingly significant impact.

Furthermore, based on the characteristic phenomenon that the ongoing upgrading of dietary structure is increasingly influencing grain security, some scholars have examined the rationality of this dietary shift. Chang et al. (2018) reviewed the transformations in the dietary structure of Chinese residents over the past 30 years from the perspectives of nutrition and health, highlighting significant nutritional issues and proposing policies for nutritional intervention. Other researchers, focusing on nutrition, have found that establishing a balanced dietary structure not only benefits consumers' health but also reduces excessive food waste. In particular, reducing meat consumption can lead to significant savings in feed grain and water resources (He P, et al., 2019). In this context, some scholars have suggested the development of nutrition-oriented agriculture based on market-driven approaches, aiming to create a new agro-food system that integrates nutrition, safety, and sustainability (Wang, 2022). Thus, from the perspectives of pursuing nutrition, health and protecting the ecological environment, dietary structure upgrading should shift from a sole focus on 'quantity' to a more comprehensive approach that includes 'quantity and quality', gradually moving toward establishing a balanced and rational dietary structure.

It is evident that there is a limited amount of existing research on the impact of dietary structure upgrades on grain security, with the few studies available presenting inconsistent conclusions regarding their effects and lacking an exploration of the underlying mechanisms. Additionally, discussions on the rationality of dietary structures often rely on phenomena and lack comparative analyses against comprehensive nutritional health standards within a broader food system framework.

2.2 Theoretical analysis

In the new century, with the rapid development of China's economy and the continuous increase in national income, the consumption levels of urban and rural residents have been steadily rising. This growth has led to significant changes in dietary consumption patterns, primarily characterized by a continuous decline in per capita grain consumption from 233.71 kilogram in 1981 to 130.56 kilogram in 2023, with the share decreasing from 62 to 40%; whereas the per capita annual consumption of animal-based foods such as meat, eggs, and dairy has continued to grow rapidly to 78.09 kilogram with approximately 20% in consumption share (see Figure 1). Given that staple grains possess the characteristics of essential consumption goods, their demand curve exhibits low elasticity, resulting in relatively stable consumption levels. Once per capita grain consumption decreases to a certain threshold, it becomes particularly difficult for it to decline further. In contrast, the consumption of animal foods is subject to greater fluctuations. Thus, this study focuses on the perspective of changes in animal foods such as meat, eggs and dairy and seeks to construct an analytical framework for understanding how dietary structure upgrading impacts grain

security in China, drawing on the concepts of virtual water and international trade (see Figure 2).

2.2.1 Analysis of the impact of dietary structure upgrading on grain security

At present, it is undeniable that the demand for animal foods, such as meat, eggs and dairy, has been increasing steadily among urban and rural residents in China. In 2020, the OECD-FAO Agricultural Outlook report predicted that China's meat consumption would reach 95.05 million tons by 2028, representing a nearly 76% increase from 2020. According to the research conducted by Wang (2022), per capita meat consumption in China has been rapidly rising over the past few decades, reaching 49 kilograms. The large-scale development of domestic livestock farming, as the primary source of meat supply, significantly impacts grain security in two key areas. Firstly, on the production side: studies have shown that producing an equivalent unit of animal protein foods requires several to even over 10 times the land area and water usage compared to plant protein foods (Reijnders and Soret, 2003). Given China's existing constraints on land and water resources, this discrepancy poses serious challenges for sustainable food production, particularly in terms of resource conservation and environmental protection. Secondly, on the consumption side: the large scale of expansion of the livestock sector necessitates increased consumption of feed grains. How to balance feed grain security and meat security remains a crucial yet unresolved issue, significantly influencing China's overarching grain security objectives (Yang and Cui, 2023). In summary, the upgrading of dietary structure not only affects the sustainability of grain production capabilities but also perpetuates rising grain demand, thereby exacerbating the pressure on the balance between grain supply and demand from both production and consumption sides.

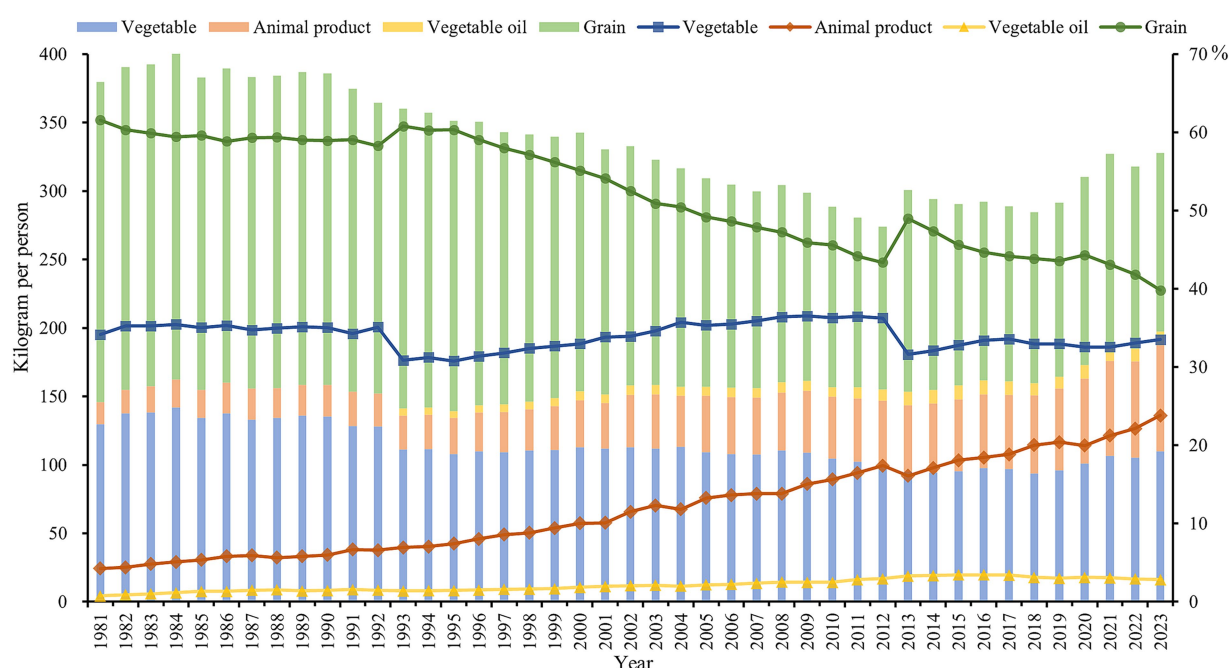


FIGURE 1
Changes in per capita consumption and percentage share of various food types in China from 1981 to 2022.

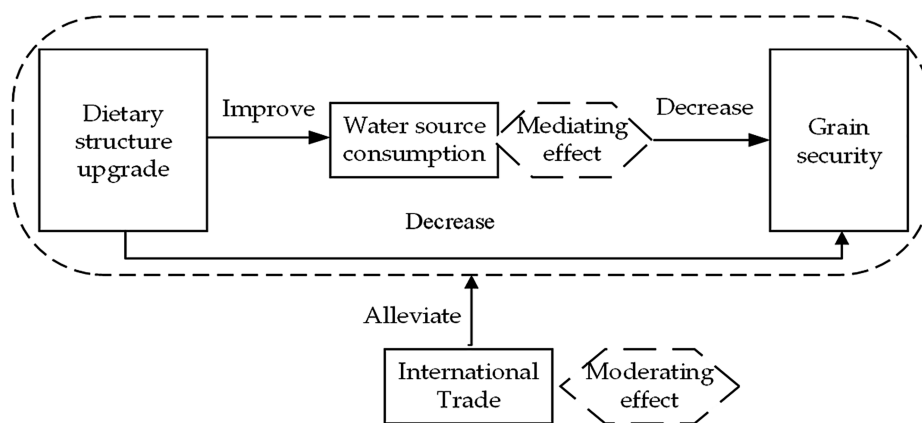


FIGURE 2

The analytical framework for the impact of dietary structure upgrading on grain security.

Accordingly, Hypothesis 1 (H_1) is proposed: Dietary structure upgrading negatively affects grain security.

2.2.2 Analysis of the impact of dietary structure upgrading on grain security in the virtual water perspective

From the perspective of virtual water, the large-scale development of the livestock industry in China, which serves as the main source of food supply such as meat, eggs and dairy products, impacts grain security in the following two aspects.

On the one hand, the upgrading of dietary structure will lead to more water consumption. According to the theory of virtual water and water footprint (Allan, 1993; Hoekstra and Hung, 2005), which expresses the consumption of specific water resources in terms of virtual water content, it is found that the same unit of animal food products, such as meat, eggs and dairy, requires more water resources than plant food such as grain in the production process. Scholars have also measured the virtual water content per unit mass of major food products, revealing that the virtual water content per unit mass of food products such as meat, eggs and dairy is approximately 1 to 20 times that of grains, with beef and mutton exhibiting the highest virtual water content (Zhang et al., 2020). Chinese scholars have also confirmed that the water footprint of per capita food consumption of both urban and rural residents in China has indeed continued to rise during the period 1985–2018, from 448.14 billion cubic meters in 1985 to 689.83 billion cubic meters in 2018, due to a decrease in the consumption of plant foods that consume less water and an increase in the consumption of animal foods that consume more water (Jiang et al., 2021).

On the other hand, the encroachment on water resources will adversely affect grain security. Since the virtual water consumption of the same unit of meat, eggs and dairy products is significantly higher than that of grains, the upgrading of the dietary structure will result in increased water consumption and compete for water resources that are otherwise used for grain production, provided that water resources are finite. As water is an important input factor for grain production, ensuring water security is extremely important for grain security. As a matter of fact, water scarcity in China has seriously constrained the pace of agricultural development. Many scholars have found that

water resources exert a significant damping effect on grain production in China by measuring the water resource damping effect, necessitating urgent attention to ensuring water resource security (Zhao et al., 2018). In summary, the increasing consumption of meat, eggs and dairy products displaces more water usage, and since water resources are a crucial input factor for grain production, water scarcity will constrain the enhancement of grain production capacity.

Accordingly, Hypothesis 2 (H_2) is proposed: dietary upgrading will negatively affect grain security by inducing more water consumption.

2.2.3 Analysis of the impact of dietary structure upgrading on grain security in the international trade perspective

At present, the stability of international grain market supply and circulation has emerged as a significant factor affecting China's grain security amidst rigid growth in domestic food consumption demand, constraints on resource and environmental carrying capacity and rising production costs. In response to the upgrading of the Chinese dietary structure, rational utilization of international trade in agricultural products has the potential to mitigate the adverse impact of such upgrading on grain security in two ways.

One is the direct impact, which entails ensuring grain supply through increased imports. Currently, China maintains a relatively high level of grain self-sufficiency, allowing for a moderate increase in import scale to alleviate domestic production pressures (Zhan, 2022). However, while enhancing the scale of grain imports can help ensure grain security, it may also disrupt domestic grain production, leading to a decline in self-sufficiency and a loss of autonomy in grain supply. Therefore, for a populous country like China, it is not advisable to fully liberalize grain trade. In this regard, research by Duan et al. (2021) indicates that China can exercise dominance in grain trade through precise policy combinations under the existing rules of WTO, while adhering to the red line for grain self-sufficiency. Hence, judiciously leveraging the international market and moderately increasing grain imports can further ensure China's grain security.

The other, conversely, is the indirect impact, which entails achieving a balance in grain supply and demand by increasing the import scale of animal products such as meat, eggs, and dairy, thereby reducing the

consumption of feed grains and water resources. Previous theoretical analysis indicates that the production of meat, eggs, dairy and other animal products requires more feed grains and water resources compared to grains, thus increasing the import scale of animal products is equivalent to importing additional foreign feed grains and water resources, which can alleviate the domestic production pressure and help ensure the absolute security of staple grain supplies (Ali et al., 2017). Furthermore, other scholars have confirmed that since the beginning of the 21st century, China's imports of virtual water resources associated with grain and animal products have increased annually, effectively conserving domestic water resources and improving the ecological environment (Jiang et al., 2021).

In summary, to ensure grain security in China, it is essential to make prudent use of the international market without developing an excessive dependency. Therefore, while adhering to a certain threshold for grain self-sufficiency, increasing the imports of food, particularly those of meat, eggs, and dairy products which consume high levels of grains and water, will help further reduce domestic consumption of feed grains and water resources, mitigating the adverse impact of dietary structure upgrading on grain security.

Based on this, Hypothesis 3 (H_3) is proposed as follows: International trade exerts a positive moderating effect in the process where dietary structure upgrading adversely impacts grain security, meaning that international trade alleviates the adverse effects of dietary structure upgrading on China's grain security.

3 Research design and data description

3.1 Model construction

Firstly, this paper establishes a bidirectional fixed effects model to assess the impact of dietary structure upgrading on grain security, as detailed below:

$$Y_{it} = \alpha_0 + \alpha_1 \ln DIE_{it} + \lambda X_{it} + \eta_i + \gamma_t + \varepsilon_{it} \quad (1)$$

In Equation (1), the variable subscripts i and t denote the province and the year, respectively. Y_{it} represents grain security, while DIE_{it} indicates dietary structure. X_{it} includes a series of control variables. η_i denotes the regional fixed effects. γ_t represents the temporal fixed effects, and ε_{it} is the random error term. Parameters α_0 , α_1 , λ are the coefficients to be estimated.

Furthermore, the aforementioned theoretical analysis suggests that dietary structure upgrading is likely to adversely impact grain security by inducing increased water resource consumption. Drawing on the methodology of Jiang (2022), we directly examine the influence of dietary structure upgrading on the mediating mechanism of water resource consumption, constructing the following model:

$$\ln M_{it} = \alpha_0 + \alpha_1 \ln DIE_{it} + \lambda X_{it} + \eta_i + \gamma_t + \varepsilon_{it} \quad (2)$$

In Equation (2), M_{it} represents the mediating variable, specifically denoting the water resource consumption induced by the consumption of meat, eggs, and dairy products. The other variables and coefficients are set in accordance with those in Equation (1). Given that both the

theoretical analysis presented earlier and existing literature have confirmed that induced water resource consumption indeed negatively impacts grain security levels, it suffices to validate how dietary structure influences water resource consumption to determine whether this mediating variable constitutes a significant pathway through which dietary structure upgrading affects grain security.

Finally, in order to identify the moderating effect of international trade, this paper constructs the following model for testing the moderating effect:

$$Y_{it} = \beta_0 + \beta_1 \ln DIE_{it} + \beta_2 N + \beta_3 DIE_{it} \times N + \lambda X_{it} + \eta_i + \gamma_t + \varepsilon_{it} \quad (3)$$

In Equation (3), N represents the moderating variable: international trade in agricultural products, while β_0 , β_1 , β_2 , β_3 are the parameters to be estimated. The other variables and coefficients are defined in the same manner as in Equation (1).

3.2 Variable selection

3.2.1 Dependent variable

Grain Security (GS). To comprehensively assess the level of grain security, this study adopts the four-dimensional taxonomy (availability, accessibility, utilization, stability) proposed by Agriculture Organization of the United States (2013), which is consistent with existing empirical studies on food security in China: Nie et al. (2020) applied it provincially, validating its relevance for regional policy analysis; Wang et al. (2024) demonstrated its efficacy in evaluating national policies using multidimensional indicators. Considering provincial data availability, an evaluation indicator system including four dimensions of availability, accessibility, stability and sustainability is finally constructed (see Table 1) while considering the specific conditions of China. The integration of sustainability (replacing utilization) maintains conceptual coherence with FAO principles while addressing China's agricultural transition needs.

The methodology for calculating this index is outlined as follows:

In the first step, due to the presence of both positive and negative variables in the indicator system, a range standardization method is first employed to standardize the data, which presents as Equations (4, 5).

Positive indicator:

$$X'_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}} \quad (4)$$

Negative indicator:

$$X'_{ij} = \frac{\max X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}} \quad (5)$$

Wherein X_{ij} represents the original value of the j -th indicator for province i .

In the second step, the weight of each indicator, presenting as Equation (7) is calculated using the coefficient of variation weighting method of Equation (6) (Pélabon et al., 2020).

TABLE 1 Grain security evaluation index system construction.

Dimension	Indicator variable	Calculation method	+/-
Availability	Per capita grain output (kg/person)	Total grain output/permanent population	+
	Per capita cultivated land area (mu/person)	Cultivated land area/resident population	+
	Water and soil coordination degree (cubic meters/mu)	Total water resources/crop planting area	+
Accessibility	Railway density (km/km ²)	Regional railway operating mileage/regional administrative area	+
	Regional development level (yuan/person)	GDP per capita	+
	Engel coefficient (%)	Food consumption expenditure/total consumption expenditure	–
Stability	Grain price volatility (%)	(Current grain price index - previous grain price index) / Current grain price index	–
	Fluctuation rate of total grain production (%)	(Current grain output - average grain output in the last five periods) / Current grain output	–
	Planting structure of grain crops (%)	Sowing area of grain crops/Sowing area of agricultural crops	+
	Crop damage rate (%)	Area of crops affected by disasters/area of crops sown	–
Sustainability	Fertilizer application amount (kg/mu)	Fertilizer application/crop planting area	–
	Pesticide application amount (kg/mu)	Pesticide application/crop planting area	–

$$CV_j = \frac{S_j}{X_j} \quad (6)$$

$$w_j = \frac{CV_j}{\sum CV_j} \quad (7)$$

Specifically, w_j denotes the weight of indicator j , S_j represents the standard deviation, X_j is the mean value and CV_j is the coefficient of variation.

In the third step, the comprehensive grain security index (GS) is calculated through Equation (8).

$$GS = \sum_{i=1}^m \sum_{j=1}^n X_{ij}' w_j \quad (8)$$

3.2.2 Independent variable

Dietary Structure (DIE). Based on the primary manifestations of dietary structure upgrading discussed earlier, this paper focuses on examining the structural changes in the consumption of animal foods, such as meat, eggs, and dairy, in comparison to plant foods, such as grains. With reference to the existing literature (Jiang et al., 2021) and considering data availability, the specific formula for calculating the dietary structure is as follows:

$$DIE_{it} = \frac{PMC_{it}}{PGC_{it} + PMC_{it}} \quad (9)$$

Herein DIE_{it} represents the dietary structure of residents in province i during period t ; PMC_{it} represents per capita consumption of meat and egg (primarily pork, beef, lamb, poultry, and eggs), and PGC_{it} represents per capita grain consumption. Both are calculated by aggregating the per capita consumption and the resident population in urban and rural areas separately. Specifically, following the standards by Luo et al. (2020), the dining-out rate for urban residents was assumed to be 12% before

2005 and 20% thereafter, while for rural residents, it was uniformly set at 4%. Due to the fact that grain consumption statistics for urban residents were reported as processed grain, these figures were converted to raw grain equivalents by dividing by 0.85 for inclusion in the calculations. It should be noted that the aforementioned indicators have not been included in this study due to the inability to differentiate between natural production and aquaculture of aquatic products in different regions, as well as a significant lack of data on per capita dairy consumption during the sample period. According to data released by the National Bureau of Statistics, in 2022, the per capita grain consumption of Chinese residents accounted for nearly 50% of the total consumption of plant foods, including grains, vegetables, edible mushroom, dried and fresh fruits, while per capita meat and egg consumption comprised approximately 70% of total animal foods consumption. Therefore, due to the high representativeness of grains and meat and egg products within plant and animal foods categories, respectively, there exists a sound rationale for selecting per capita grain and meat and egg consumption as indicators to measure dietary structure escalation.

3.2.3 Mediating variable

Water Resource Consumption (WAT). Water resource consumption is represented by the virtual water resources consumed during the production of meat, eggs, and dairy products. However, considering that water consumption occurs during the food production process, this study builds on previous research by adopting the concept of virtual water theory to estimate virtual water consumption based on the production of meat, eggs and dairy products (Jiang et al., 2021). The specific calculation formula is as follows:

$$WAT_{it} = \sum_{m=1}^7 p_{m,it} v_{m,t} \quad (10)$$

In Equation (10), the corresponding variables are defined as follows: WAT_{it} represents the virtual water consumption caused by the

production of meat, eggs, and dairy products in region i during period t ; $p_{m,n}$ denotes the production quantities of various meat, eggs, and dairy products; the subscript m indicates specific types of products, primarily pork, beef, mutton, poultry, aquatic products, eggs, and dairy; $v_{m,t}$ represents the virtual water content of these products. Based on previous research, the virtual water content (in cubic meters per kilogram) for various meat, eggs and dairy products is summarized as follows: for the year 2010 and before, the virtual water content was 3.56 for pork, 9.72 for beef, 4.63 for mutton, 3.97 for poultry, 5.00 for aquatic products, 3.09 for eggs, and 2.20 for dairy products (Hoekstra and Hung, 2005); while after 2010, the virtual water content changed to 2.52 for pork, 12.60 for beef, 5.95 for mutton, 3.97 for poultry, 5.00 for aquatic products, 6.17 for eggs, and 5.98 for dairy products (Zhang et al., 2020).

3.2.4 Moderating variable

International Trade of Agricultural Product (TRA). Theoretically, there is no uniformity about the measurement of international trade indicators, which mainly include tariffs, trade dependence and so on. Specifically for this study, following the methods of Li and Huang (2021), international trade is represented by the dependence on agricultural product trade, calculated as the ratio of the total import and export value of agricultural products to the value added of the primary industry, with the logarithm taken.

3.2.5 Control variables

Taking into account the research subjects and existing literature (Jiang and Luo, 2022; Wang et al., 2024), this study selects the following control variables. The input factors: 1. Rural aging (OLD), represented by the proportion of the population aged 65 and above in rural areas; 2. Human capital level (EDU), measured by the average years of education of the rural labor force, calculated by assigning weighted education years to six levels: illiterate (0 years), elementary (6 years), junior high (9 years), senior high (12 years), vocational secondary (12 years), and college or above (15 years); 3. Mechanization level (MAC), represented by the ratio of total power of agricultural machinery to cultivated land area; 4. Effective irrigation level (IRR), measured by the ratio of effectively irrigated area to cultivated land area; 5. Agricultural electricity input (ELE), represented by the ratio of rural electricity consumption to cultivated land area. The development characteristics: 6. Industrial structure level (IND), represented by the ratio of the added value of the primary industry to the regional GDP; 7. Urbanization level (URB), measured by the ratio of the permanent urban population to the total resident permanent in the region. The policy support: 8. Financial support for agricultural (FIN), measured by the ratio of fiscal expenditure on agriculture, forestry, and water conservancy to cultivated land area, adjusted to remove the effects of price changes by using the agricultural product price index; 9. Grain subsidy policy (POL), a dummy variable with 0 for years prior to 2004 (when the national grain subsidy policy was comprehensively promoted) and 1 for 2004 and subsequent years.

3.3 Data sources

Considering data availability, this study utilizes panel data from 31 Chinese provinces (including municipalities and autonomous regions) spanning 2001–2022 to examine the impact of dietary

structure upgrading on grain security. This sample period selection is justified by two considerations: first, prior to 2001, there was a significant lack of relevant dietary consumption data across regions, coupled with significant variations in statistical standards; second, provincial-level data for multiple indicators discussed in the study remain unpublished beyond 2022. Therefore, this time-frame (2001–2022) represents the most comprehensive sample range currently available.

Herein, core variables, mechanism variables, and relevant control variables were sourced from authoritative repositories including the *China Statistical Yearbook*, *China Rural Statistical Yearbook*, *China Agricultural Yearbook*, *China Financial Yearbook*, and *China Population and Employment Statistical Yearbook*, as well as from information provided by the *Ministry of Commerce and statistical Yearbooks* from various provinces, municipalities, and autonomous regions. All of these are collated based on the publicly available statistical data from Chinese government departments. To mitigate the adverse effects of outliers, all data were winsorized at the 1 and 99% percentiles. Descriptive statistics of the variables are detailed in Table 2.

4 Empirical analysis

4.1 Baseline regression results

Based on Equations (8, 9), Figure 3 illustrates the changing trends in dietary structure (DIE) and grain security (GS) from 2001 to 2022. Before 2004, the dietary structure upgrading progressed while the level of grain security index exhibited a declining trend. After 2004, although both continued to rise, the rate of the dietary structure upgrading accelerated more rapidly. Statistical tests reveal a significant negative Pearson correlation coefficient (−0.17) between dietary restructuring (DIE) and grain security (GS). Therefore, this descriptive analysis provides preliminary evidence suggesting that the dietary structure upgrading exerts a negative influence on food security in China.

Based on Equation (1) and employing a stepwise regression method, control variables related to input factors, development characteristics, and policy support were introduced sequentially. Table 3 reports the regression results of the impact of dietary structure upgrading on grain security. Initially, a Hausman test was conducted, and the results, with a p -value far below 0.05, confirmed that a two-way fixed effects panel model is more suitable. The baseline regression results indicate that a consistent dietary structure upgrading has a negative impact on grain security levels, passing the significance test at the 1% level, thereby validating Hypothesis 1 (H_1). Taking the results from column (4) as an example, it shows that, under the premise of other conditions remaining unchanged, for every one-unit upgrade in dietary structure, grain security levels will decline by 1.9 percentage points. This finding is consistent with the research findings of Zhan (2022), which suggests that over the past 40 years, the upgrading of residents' dietary structure has transformed China from a net grain-importing country in 2000 to the world's largest grain importer, highlighting an increasingly severe grain security situation.

In terms of control variables, the results in column (4) indicate that: firstly, both rural aging and grain subsidy policies have a significant positive effect, suggesting that both contribute to improving

TABLE 2 Sample distribution.

Type	Variable name	Obs	Mean	Std. Dev	Min	Max
Dependent Variable	Grain security <i>GS</i> (–)	682	0.21	0.07	0.13	0.56
Independent Variable	Dietary structure <i>DIE</i> (%)	682	2.98	0.35	2.09	3.58
Mediating Variable	Water resource consumption <i>WAT</i> (cubic meter)	682	7.42	0.99	5.14	9.29
Moderating Variable	International trade of agricultural product <i>TRA</i> (%)	682	1.71	1.52	–0.79	6.01
Control Variable	Rural aging <i>OLD</i> (%)	682	2.34	0.37	1.58	3.20
	Human capital level <i>EDU</i> (year)	682	1.99	0.14	1.41	2.24
	Mechanization level <i>MAC</i> (kW/mu)	682	6.07	0.56	4.72	7.06
	Effective irrigation level <i>IRR</i> (%)	682	3.88	0.47	2.86	4.69
	Agricultural electricity input <i>ELE</i> (kWh/mu)	682	5.34	1.54	2.41	10.35
	Industrial structure level <i>IND</i> (%)	682	2.35	0.67	0.26	3.39
	Urbanization level <i>URB</i> (%)	682	3.89	0.36	2.81	4.49
	Financial support for agriculture <i>FIN</i> (Yuan/mu)	682	6.14	1.45	3.27	9.89
	Grain subsidy policy <i>POL</i> (–)	682	0.82	0.39	0	1

grain security levels. Among them, the positive effect of grain subsidy policies aligns well with theoretical expectations, while the positive impact of rural aging on grain security may be attributed to the fact that older individuals have become a primary source of labor in rural grain production. Although, theoretically, an aging labor force may hinder grain supply increase, the development of agricultural production services can incentivize more aging farmers to engage in grain production. Furthermore, studies have revealed that aging contributes to a direct reduction in staple grain consumption on the one hand, and on the other hand, indirectly decreases feed grain consumption through lower animal foods consumption, such as meat (Gossard and York, 2003). Thus, the significant positive role of rural aging in the comprehensive evaluation of grain security, in this study is reasonable. Secondly, the coefficients for mechanization level, urbanization level, and financial support for agriculture are significantly negative, indicating that these factors exert a negative influence on grain security levels. Among them, the negative effect of urbanization is consistent with theoretical expectations and aligns with existing research conclusions, which suggests that urbanization can both crowd out grain production resources on the supply side and increase total grain consumption on the demand side (Gandhi and Zhou, 2014). The potential reasons for negative impact of mechanization level and financial support for agriculture on grain security may stem from two aspects. On the one hand, while enhancements in both areas generally favor grain production, the comprehensive grain security index system constructed in this study also encompasses dimensions such as grain circulation, volatility, and sustainability. On the other hand, research has suggested that improvements in China's mechanization are currently constrained by factors like farmers' financial limitations, low land scale, and terrain slope variation (Li et al., 2018), furthermore, the promotional effect of financial support for agriculture on grain output also exhibits strong regional characteristics and is susceptible to the constraints of marketization levels (Hu and Xiang, 2021). Therefore, the significant negative impact of the mechanization level and financial support for agriculture on the comprehensive grain security evaluation in this study, is reasonably justified. Finally, the coefficients for human capital level, effective irrigation level, agricultural electricity input, and

industrial structure level suggest that these variables do not necessarily exert an influence on grain security.

4.2 Robustness test

4.2.1 Substitution variable test

To further assess the impact of dietary structure upgrading on China's grain security and to address the rationality of variable selection in this study, a robustness test with alternative variables is conducted. Specifically, this study selects five indicators per capita grain output, per capita arable land area, regional development level, Engel's coefficient, and grain total output volatility from Table 1 to calculate a narrow grain security index as a replacement for the dependent variable. Additionally, given that per capita meat consumption constitutes a substantial proportion of total per capita meat, egg, and dairy consumption (with data from the National Bureau of Statistics indicating that in 2022, per capita meat consumption accounted for nearly 60% of this total), per capita meat consumption is used to replace total per capita consumption of meat, egg, and dairy products to re-evaluate dietary structure upgrading (narrow dietary structure index) for robustness testing. The results in columns (1) and (2) of Table 4 indicate that after substituting the variables, the regression coefficients of the independent variables remain significantly negative and have passed the significance level tests, confirming that dietary structure upgrades continue to negatively impact grain security, thereby aligning with the previous findings.

4.2.2 Non-parametric estimation

Theoretically, parameter estimation results hinge on the correct specification of parameter forms; however, in practice, the specification of parameter models often encounters biases. Specifically, if there exists a nonlinear relationship between dietary structure upgrading and grain security, the results from the previously specified linear equation may contain substantial errors. To address this, this study employs a nonparametric estimation method to test the baseline regression results. The results in column (3) of Table 4 indicate that

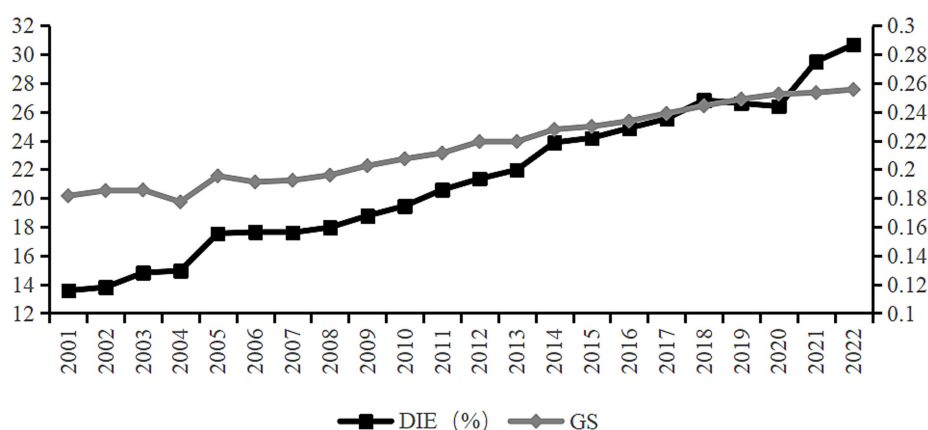


FIGURE 3

The changing trends of dietary structure upgrading and grain security from 2001 to 2022.

under the nonparametric estimation approach, the model fitting coefficient remains significantly negative, suggesting that the finding of a negative impact of dietary structure upgrades on grain security is robust and not a contingent outcome of a specific estimation method.

4.2.3 Endogenous test

Given the potential bidirectional causal relationship between dietary structure and grain security, which may result in endogeneity issues, this study utilizes the first-order lag of the independent variable as an instrumental variable to conduct robustness tests by using the systematic Generalized Method of Moments (GMM) model. The results in column (4) of Table 4 indicate that the impact coefficient of the first-order lag of dietary structure remains negative and is statistically significant at the 1% level. This suggests that the first-order lagged term of dietary structure still significantly and negatively impacts grain security, thereby further confirming the validity of H_1 .

4.3 Mechanism tests

4.3.1 Mediating mechanism test

Based on the analysis of the mediating effect model in Equation (2), column (1) of Table 5 shows that the coefficient for dietary structure upgrading on virtual water consumption is significantly positive and has passed the 1% significance level test. This indicates that, with other variables held constant, the upgrading of dietary structure significantly leads to an increase in virtual water consumption. Meanwhile, the theoretical analysis section presented earlier has basically concluded that water resource scarcity negatively impacts grain security. Thus, the proposed mediation pathway involving water resource consumption is validated, confirming that dietary structure upgrading, by inducing water resource consumption, does indeed negatively affect grain security, thereby supporting H_2 .

4.3.2 Moderating mechanism test

According to the moderating effect model analysis in Equation (3), the results in column (2) of Table 5 indicate that after incorporating the moderating effect of international agricultural trade, the impact of dietary structure upgrading on grain security remains significantly

negative over the sample period. However, the interaction term between dietary structure and trade dependence has a significantly positive coefficient, which is significant at the 1% level. This suggests that as trade dependence increases, the negative effect of dietary structure upgrading on grain security gradually diminishes, indicating that international agricultural trade alleviates the impact of dietary structure upgrading on grain security. A possible explanation is that international agricultural trade, particularly import trade, not only increases grain supply but also reduces the consumption of grain resources for animal foods production, thereby lessening the constraints on Chinese food production posed by water resources and alleviating the negative effects of dietary structure upgrading on grain security from the production side. Therefore, the previous hypothesis 3 (H_3) is validated.

5 Simulation to analyze the impact of different dietary structure scenarios on grain security in China

From the perspectives of pursuing nutritional health and protecting the ecological environment, the upgrade of dietary structures should shift from a simple focus on “quantity” to a model that encompasses “quantity + quality,” gradually moving toward the establishment of a balanced and reasonable dietary structure. In this context, Chinese government emphasized the need to “establish greater food approach and build a diversified food supply system.” Therefore, in the new era, it is essential to incorporate a food nutrition perspective in analyzing grain security issues and optimize dietary consumption structures in order to construct a strategic safeguard system for grain security with distinctive Chinese characteristics.

5.1 Nutritional dietary guidelines

The dietary guidelines formulated and issued by the Chinese Nutrition Society, based on food production and supply, as well as the actual needs of residents and existing evidence related to dietary nutrition and health, serve as advisory documents designed to

promote balanced diets, aiming to assist consumers in achieving a balanced diet through reasonable food pairings, maintaining and promoting health, and preventing and reducing nutrition-related

TABLE 3 Baseline regression results.

Variable	GS			
	(1)	(2)	(3)	(4)
<i>DIE</i>	−0.029*** (0.005)	−0.026*** (0.004)	−0.019*** (0.005)	−0.019*** (0.005)
<i>OLD</i>		0.027*** (0.007)	0.025*** (0.007)	0.023*** (0.007)
<i>EDU</i>		−0.036 (0.022)	−0.038* (0.023)	−0.037 (0.023)
<i>MAC</i>		−0.013*** (0.003)	−0.013*** (0.003)	−0.012*** (0.003)
<i>IRR</i>		0.001 (0.005)	−0.002 (0.005)	0.001 (0.005)
<i>ELE</i>		−0.003 (0.002)	−0.002 (0.002)	−0.002 (0.002)
<i>IND</i>			0.008 (0.005)	0.005 (0.005)
<i>URB</i>			−0.014*** (0.005)	−0.015*** (0.005)
<i>FIN</i>				−0.009** (0.004)
<i>POL</i>				0.125*** (0.017)
<i>Cons_</i>	0.269*** (0.015)	0.356*** (0.052)	0.397*** (0.055)	0.441*** (0.058)
Region control	YES	YES	YES	YES
Time control	YES	YES	YES	YES
R ²	0.973	0.978	0.978	0.976
Obs	682	682	682	682

***, **, * represent significance levels of 1, 5 and 10% respectively; the numbers in parentheses represent standard errors.

diseases. To guide the upgrading of residents' dietary structure toward nutrition, health food standards are regularly developed for reference both in China and around the world. Among these, significant guidelines include the Chinese Dietary Guidelines, the Planetary Health Diet, the Mediterranean Diet, and the Flexitarian Diet, all of which collectively provide consumers with recommended healthy intake levels for various types of food.

5.1.1 Chinese dietary guidelines

The Chinese Dietary Guidelines are primarily designed based on the food supply in China and the physical constitution of its residents, serving as a balanced dietary guideline for individuals to make reasonable food choices and promote health. Since 1989, China has published and revised five editions in total.

The first edition, titled "Dietary Guidelines for China (1989)," was released during the early stages of China's reform and opening up. While living standards were gradually improving, addressing basic food and clothing needs remained a top priority. The dietary guidelines outlined in this edition emphasized the following recommendations: first, maintaining dietary diversity; second, achieving an appropriate balance between hunger and fullness; third, consuming fats and oils in moderation; fourth, incorporating both coarse and refined grains into the diet; fifth, restricting salt intake; sixth, minimizing the consumption of sweet foods; seventh, moderating alcohol consumption; and eighth, ensuring that meals are consumed in a balanced and regular manner throughout the day. The second edition, titled "Dietary Guidelines for Chinese Residents (1997)," came as residents had largely achieved basic food and clothing security due to deeper reforms and rapid economic development. This version refined dietary recommendations for different population groups, emphasizing the importance of regular consumption of dairy and soy products to compensate for inadequate calcium intake, and quantified various dietary recommendations for the first time. The third edition, titled "Dietary Guidelines for Chinese Residents (2007)," was published in the 21st century, addressing the issue of regional disparities in development by advocating reasonable food choices and adequate physical activity to tackle the contradictory issues of high incidence of obesity and hypertension in some areas and ongoing nutritional deficiencies in others. The fourth edition, titled "Dietary Guidelines for Chinese Residents (2016)," acknowledged significant improvements in living standards for both urban and rural residents due to rising national income, with previous

TABLE 4 Robustness test results.

Variable	(1)	(2)	(3)	(4)
	Replace dependent variable	Replace independent variable	Nonparametric Estimation	GMM
<i>DIE</i>	−0.004* (0.002)		−0.046*** (0.015)	
<i>die</i>		−0.012*** (0.004)		
<i>I. DIE</i>				−0.018*** (0.005)
Control variable	YES	YES	YES	YES
Region control	YES	YES	YES	YES
Time control	YES	YES	YES	YES
R ²	0.951	0.978	0.130	0.980
Obs	682	682	682	651

***, **, * represent significance levels of 1, 5 and 10% respectively; the numbers in parentheses represent standard errors.

issues of malnutrition and nutrient deficiencies largely resolved but new chronic diseases like the “three highs” (high blood pressure, high blood sugar, and high blood lipids) and nutritional imbalances emerging as a result of unreasonable dietary structures. In this context, the 2016 guidelines promoted a healthy diet culture, reduced salt intake, and for the first time emphasized the importance of minimizing food waste, thereby enhancing practicality. The fifth edition, titled “Dietary Guidelines for Chinese Residents (2022),” aims to ensure the scientific and effectiveness of residents’ balanced diets by regularly updating the guidelines based on the latest evidence related to dietary nutrition. This version underscores the importance of rational food combination, regular meal times, adequate water intake, and the use of separate chopsticks for communal dining. Overall, in recent editions of the Chinese Dietary Guidelines, while there has been a trend toward reduced grain recommendations and increased recommendations for meat, eggs, and dairy, the decline in grain recommendations stabilizes at a certain threshold and the increase in meat, eggs, and dairy recommendations does not continue infinitely but rather seeks to establish a nutritious dietary structure, with the purpose of promoting balanced dietary consumption among residents. The specific recommended consumption levels for various foods in China from the latest guideline are detailed in [Table 6](#).

5.1.2 Planetary health diet

The Planetary Health Diet is a novel dietary model jointly published by the non-profit organization EAT and *The Lancet*. In 2019, *The Lancet* published a significant article highlighting that by

2050, the global population was expected to reach 10 billion, necessitating a major transformation of the world’s food systems to ensure that all people can have access to healthy and sustainable food by that time. Therefore, to protect the ecological environment of the planet and promote human health, *The Lancet* collaborated with 37 nutritionists and economists from 16 countries to comprehensively revise current dietary structures. This effort culminated in the proposal of “the Planetary Health Diet” based on an integrated analysis of extensive research findings. The aim of formulating *the Planetary Health Diet* is to reduce premature mortality, lower greenhouse gas emissions, conserve water and land resources, preserve biodiversity, and create a health barrier that supports sustainable development of both humans and other organisms. Overall, the Planetary Health Diet advocates for plant protein as the primary source of protein, with a particular emphasis on reducing red meat intake ([Willett et al., 2019](#)). The specific recommended consumption levels for various foods are detailed in [Table 6](#).

5.1.3 Mediterranean diet

The Mediterranean Diet refers to the culinary styles of Southern European countries along the Mediterranean coast, including Greece, Spain, France, and Southern Italy. It primarily promotes the consumption of a variety of vegetables and fruits, along with a significant intake of aquatic products, and recommends substituting animal fats with plant oils. Due to its potential to reduce the risk of heart attacks, protect the brain from vascular damage, and decrease the likelihood of strokes and memory decline, the Mediterranean Diet is recognized as beneficial for health, offering a simple, light, and nutrient-rich dietary structure. Overall, compared to dietary habits in other parts of the world, the Mediterranean Diet is characterized by eating fish twice a week, limiting egg consumption to no more than seven per week, and controlling red meat intake to once a month on its foundation of a wide variety of plant foods. The specific recommended consumption levels for various foods are detailed in [Table 6](#).

5.1.4 Flexitarian diet

The Flexitarian Diet, also known as ‘flexible vegetarianism’, as the name implies, does not strictly require the consumption of vegetarian foods. It allows for the consumption of meat based on personal habits and environmental circumstances, while advocating for a diet with reduced meat intake. This diet can be understood as primarily focusing on the consumption of plant foods, with moderate inclusion of animal products. What sets the Flexitarian Diet apart from dietary habits in other parts of the world is its emphasis on listening to one’s inner voice, cultivating a vegetarian eating habit, and nurturing a lifestyle that includes fresh vegetables once a week and adheres to “meatless” days. The specific recommended consumption levels for various foods are detailed in [Table 6](#).

TABLE 5 Mechanism test results.

Variable	(1)	(2)
	WAT	GS
DIE	0.370*** (0.120)	−0.015*** (0.004)
TRA		−0.017*** (0.005)
DIE×TRA		0.010*** (0.005)
Control variable	YES	YES
Region control	YES	YES
Time control	YES	YES
R ²	0.966	0.954
Obs	682	682

***, **, * represent significance levels of 1, 5 and 10% respectively; the numbers in parentheses represent standard errors.

TABLE 6 Recommended per capita consumption of major foods in various major dietary guidelines (g/day).

Various dietary guidelines	Chinese dietary guidelines	Planetary health diet	Mediterranean diet	Flexitarian diet
Grain	325	282	260	325
Meat	125	71	99	74
Eggs	45	13	28	45
Dairy	400	250	250	300

The relevant data has been compiled by the author with reference to [Sheng et al. \(2021\)](#), with the data from the Chinese Dietary Guidelines represented as the average values for the 2022 edition. According to industry standards, one egg is assumed to weigh approximately 45 grams.

The results in Table 6 indicate that the recommended per capita consumption of grain, eggs, and dairy, according to “the Chinese Dietary Guidelines,” does not differ significantly from that of other dietary guidelines. However, the recommended consumption of meat is slightly higher than that of other dietary guidelines. Herein there may exist some controversy regarding meat consumption in China, which requires special clarification. When comparing nutritional dietary guidelines, the Chinese Dietary Guidelines recommend a slightly higher meat consumption than other global dietary guidelines, but this difference is confined solely to the variations in guideline standards. In terms of actual consumption, data released jointly by the Organization for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization (FAO) of the United Nations indicate that, in 2018, the per capita meat consumption in China was only 98 grams per day, which is below the global average of 118 grams per day and significantly lower than the 252 grams per day typical in OECD countries. Thus, using 2018 as a baseline, Chinese residents’ meat consumption according to the Chinese Dietary Guidelines (2022), needs to be moderately increased, aligning closely with the standards of the Mediterranean Diet, while compared to other dietary guidelines, it should be moderately reduced. Conversely, per capita meat consumption in the world, particularly in OECD countries, should be significantly decreased according to all four dietary guidelines mentioned. In summary, although the recommended meat consumption levels in the Chinese Dietary Guidelines are slightly higher than those of other global guidelines, the actual consumption remains far below global average levels. Therefore, rather than blindly reducing meat consumption, adjustments to the recommended levels should be made appropriately based on national conditions.

5.2 Model construction

Based on the theoretical analysis and empirical results presented earlier, the upgrading of dietary structures leads to increased production of meat, eggs, and dairy, which in turn consumes more feed grains, negatively impacting grain security in China. Therefore, constructing a nutritionally balanced dietary consumption structure may have significant implications for enhancing the level of grain security, as variations in the consumption of staple grains and animal foods significantly influence grain consumption. Hence, in this section, we formulate the following equations to simulate and calculate the grain-saving effects of a nutritious dietary structure.

$$csave_{m,t} = c_{m,t} - c_{guide_n} \quad (11)$$

$$gsave_{m,t} = csave_{m,t} \times r_m \quad (12)$$

In Equation (11), $csave_{m,t}$ represents the projected savings in major dietary consumption, while $c_{m,t}$ denotes the actual consumption of major dietary items, and c_{guide_n} indicates the recommended intake as per various dietary guidelines. The variable m refers to grain, meat, eggs, and dairy, while n represents the Chinese Dietary Guidelines, the Planetary Health Diet, the Mediterranean Diet, and the Flexible Vegetarian Diet. In Equation (12), $gsave_{m,t}$ denotes the simulated savings in grain consumption, and r_m represents the feed

grain-to-food conversion rates for various animal foods. According to the standards set by Xin et al. (2015), the feed conversion rates for pork, beef, mutton, poultry, aquatic products, eggs, and dairy are 2.9, 2.6, 3.1, 2.4, 1.0, 1.7, and 0.4, respectively.

5.3 Simulation analysis results

In order to be able to compare the differences more comprehensively and avoid the problem of consumption anomalies in specific years, this paper selects the 2018–2022 samples to simulate and measure the grain-saving effect by evaluating the per capita consumption of major dietary items of Chinese residents in the last 5 years against four types of dietary standards, namely, the Chinese Dietary Guidelines, the Planet Healthy Dietary Guidelines, the Mediterranean Diet, and the Flexible Vegetarian Diet, as detailed in Table 7.

On the one hand, when the simulation complies with the consumption standards outlined in the Chinese Dietary Guidelines: meeting the recommended intake results in the most significant savings in feed grain consumption due to reduced meat consumption, followed by savings in staple grain consumption. Conversely, inadequate consumption of eggs and dairy leads to increased demand for feed grains, particularly in the case of dairy products. Overall, achieving the recommended intake levels specified in the Chinese Dietary Guidelines does not yield grain savings; instead, it increases overall grain demand. Two noteworthy findings emerge from the above analysis: First, constructing a rational dietary structure has a substantial impact on grain security, potentially generating savings in both staple and feed grain consumption, thereby alleviating pressures on grain security. Second, while a reasonable dietary structure reduces feed grain demand by lowering meat consumption, a significant increase in dairy consumption could counteract these savings by further intensifying the imbalance between grain supply and demand.

On the other hand, when the simulation meets the consumption standards set by global dietary guidelines: apart from an increase in dairy consumption leading to a certain scale of additional demand for feed grain, changes in the consumption of staple grain, meat, and eggs tend to generate significant savings in either staple or feed grain consumption. Notably, the feed grain savings resulting from reduced meat consumption are significantly greater than those outlined in the Chinese Dietary Guidelines and exceed the feed grain demand associated with higher dairy consumption. This indicates that a balanced consumption of meat, eggs, and dairy produces a positive feed grain-saving effect. In terms of overall savings, when simulation scenarios adhere to the primary global dietary guidelines, the total grain savings range from 40 to 120 million tons, equivalent to 7 to 18% of the current total grain production. Thus, it is evident that if the per capita consumption of major dietary items among Chinese residents over the past 5 years aligned with the primary global dietary guidelines, substantial savings in both staple and feed grain would have been achieved, thereby alleviating pressures on grain security.

6 Conclusion and policy recommendations

Based on provincial panel data from 2001 to 2022, this paper empirically examines the effects of dietary structure upgrading on

TABLE 7 Recommended per capita consumption of major foods in various major dietary guidelines (g/day).

Variable	Chinese dietary guidelines	Planetary health diet	Mediterranean diet	Flexitarian diet
Grain	1085.30	3298.91	4431.45	1085.30
Meat	3319.51	10741.79	6893.20	10329.44
Eggs	−1191.15	1938.80	471.64	−1191.15
Milk	−7508.93	−4420.17	−4420.17	−5449.75
Staple grain savings	1085.30	3298.91	4431.45	1085.30
Feed grain savings	−5380.57	8260.42	2944.67	3688.54
Total grain savings	−4295.27	11559.33	7376.12	4773.84
Proportion of grain production (%)	−6.39	17.20	10.97	7.10

The relevant data has been compiled and calculated by the author with reference to the China Statistical Yearbook, with meat consumption including pork, beef, mutton, poultry, and aquatic products.

grain security, verifies the mediating role of water resources, and reveals the moderating effect of international trade. Additionally, it simulates and analyses the effects of different dietary structure scenarios on grain security in China. The conclusions of the study mainly include the following three points: Firstly, under the condition that other variables remain unchanged, the continuous upgrading of dietary structure poses a significant challenge to grain security in China. This conclusion holds even after conducting multiple tests, including the substitution of core variables, non-parametric estimation, and considerations of endogeneity. Secondly, water resources serve as the primary pathway through which dietary structure upgrading adversely affects grain security. Specifically, animal foods such as meat, eggs, and dairy require more water resources compared to plant foods like grain, and thus the upgrading of dietary structure exacerbates domestic grain production pressure by increasing water consumption, subsequently exerting a negative impact on grain security. However, international trade plays a significant positive moderating role in this process, mitigating the adverse effects of dietary structure upgrading on grain security. Finally, there exists a certain degree of irrationality in the current dietary consumption structure of Chinese residents, necessitating an emphasis on a balanced diet across various food to establish a nutritional and reasonable dietary structure under greater food approach. Simulation analyses indicate that while increased dairy consumption leads to higher feed grain consumption, reductions in staple grain and meat consumption can save even more feed grain, thereby alleviating pressures on grain security.

Based on the above theoretical analyses and empirical results, this paper provides the following policy implications for simultaneously safeguarding dietary structure upgrading and grain security:

Firstly, addressing the mediating pathway that induce water resource consumption requires targeted measures to secure water supply safety, particularly regarding agricultural water use. Specifically, attention should be given to the research and application of water-saving technologies in livestock farming. By enhancing economies of scale in livestock farming and developing resource efficient and environmentally sustainable farming models, we can increase the utilization rate of agricultural water resources, thereby reducing the water consumption per unit of animal foods production and conserving the overall water resources involved in producing animal foods. Additionally, it is essential to encourage and support equipment upgrading in the livestock farming, such as the promotion of

automatic drinking systems and waste management facilities, to minimize unnecessary water wastage during manual operations, thereby reducing water usage in livestock farming. Lastly, improving the wastewater treatment rate in livestock farming is crucial, which can be achieved by promoting green farming practices and technologies for water resource recycling, thereby maximizing water resource efficiency, reducing pollution, and enhancing the overall utilization of domestic water resources.

Secondly, it is essential to judiciously leverage the positive regulatory effects of international markets to enhance the utilization efficiency of international resources and ensure the stability of import trade. Adhering to the principle of maintaining national control over grain sovereignty, it is crucial to leverage international markets and resources while simultaneously avoiding excessive dependence on them. Adhering to the China's grain security strategy of "prioritizing domestic production and relying primarily on ourselves," it is crucial to focus particularly on optimizing the structure of agricultural product imports. For instance, increasing the scale of importing animal food, particularly those that require significant feed grain, can alleviate domestic pressures on feed grain supply and demand. Additionally, expanding imports of water intensive agricultural products while reducing exports of water saving agricultural products can further mitigate constraints on feed grain security and water resources within the country. By leveraging the positive role of limited international trade in safeguarding national grain security, this strategy can achieve a more efficient balance between supply and demand.

Thirdly, under the greater food approach, Chinese residents should be guided and cultivated to develop a rational dietary consumption structure. This will help maintain a balance between dietary improvements and grain security and alleviate the increasingly serious imbalance between grain supply and demand in China. Specifically, on the one hand, guided by issues stemming from unreasonable dietary structure, such as undernutrition, micronutrient deficiencies, and the rising prevalence of overweight and obesity, Chinese Dietary Guidelines should be regularly revised based on the nutrition and health research to better tailor the physical constitution of Chinese residents. On the other hand, these revisions should also interact positively with grain security policies, with mutual guidance and forward-looking planning. Particular attention should be given to the potential surge in demand for feed grain and water resources,

which could be triggered by increased dairy consumption, so as to proactively address any future shifts in supply and demand structures.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

CL: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft. YC: Data curation, Project administration, Validation, Visualization, Writing – review & editing. HY: Data curation, Investigation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was supported by Post-Funded Project of Social Science Foundation of Jiangsu Province, grant number 23HQB014; and Start-up Fund for New Talented Researchers of Nanjing University of Industry Technology, grant number 2024SKYJ02.

Acknowledgments

We would like to thank all members of the Doctoral Program in Collaborative Innovation Center of Modern Grain

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Conflict of interest

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

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1575066/full#supplementary-material>

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