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Optimization of land use to accommodate nutritional transformation of food systems: a case study from the Beijing–Tianjin–Hebei region

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The transformation and reconstruction of China's food system not only faces many risks, such as the unceasing growth of food consumption on the demand side and the structural imbalance of dietary nutrition, but also must address serious challenges, such as constraints of resources, environment, and production capacity on the supply side. The optimal allocation of land use structure is an important method to realizing a transformation of sustainable food systems, achieving the goal of nutrition security, and guiding coordinated spatial development. This study takes the Beijing–Tianjin–Hebei region as an example, analyzing the development trends of the region's dietary nutrition structure clarifies the objectives for improving dietary nutrition. This study uses comprehensive optimization model and dynamic land system model, exploring land use optimization schemes under different nutritional goals and development scenarios. The result show that the dietary structure in the Beijing–Tianjin–Hebei region is transitioning from "food based" to "intake balance" and gradually evolved to "intake diversity," with the main objectives being to maintain stable calorie intake while moderately increasing protein intake and reducing fat intake. Achieving this goal will gradually increase demand for cultivated land and intensify spatial competition for land use. However, by optimizing land use allocation, it is possible to free up more spatial resources to balance economic development and ecological protection and reduce land use fragmentation, thereby significantly enhancing regional economic benefits and the value of ecosystem services based on improvements in dietary nutrition.

KEYWORDS

nutrition targets, comprehensive optimization model, land use dynamic simulation, food security, Beijing–Tianjin–Hebei region

1 Introduction

Agriculture is the foundation of country. Food and nutrition security is related to the national movement and people's livelihood. It is an important cornerstone for maintaining national security and promoting social development. The Chinese government has always regarded solving the problem of peoples' food as the top priority in governing the country.

After more than 70 years of efforts, the food security concept of "Grain is basically self-sufficient and cereals are absolutely safe" has been basically realized, the nutritional level of residents has been significantly improved, and a high-level, high-quality, efficient and sustainable food security system is being preliminarily established (Fan and Brzeska, 2014). With the accelerating process of urbanization, Chinese residents' dietary structure and consumption concepts have also undergone historic changes (Tian and Yu, 2015). According to the National Bureau of Statistics in 2019, the consumption of livestock and poultry meat, egg products, aquatic products, vegetables and fruits increased by 28.66, 47.99, 123.86, and 18.06%, respectively, compared with 2000, and grain consumption decreased by 31.14%. The decrease in rations and the rapid increase in the consumption of non-grain crops such as meats, vegetables, and fruits reflects the strong demands of Chinese residents for food diversity, nutrition, and health.

With the change in the global food supply and demand and society's attention to individual rights, the concept of nutritional safety has attracted extensive attention. The food security concept emphasizing national or regional food production and supply capacity is changing to focus on the level of access to food and nutrients by families or individuals (Xie et al., 2021). China has conducted six national surveys on residents' nutrition and health to understand changes in residents' dietary structure and nutritional health. The latest monitoring results show that, although the dietary nutrition and health status of residents have been greatly improved, the intake of beans, eggs, dairy, aquatic products, vegetables and fruits is low, but the intake of meat, oil, and salt is too high. Energy acquisition decreased gradually, the fat energy supply ratio remained high, and trace elements such as calcium and selenium were deficient and decreased year by year. Obesity and overweight rates reached 5.2 and 30.1%, respectively, and the incidence of hypertension and diabetes related to diet among adults over 18 increased to 25.2 and 9.7%, respectively. The unreasonable dietary structure and nutrient intake are further aggravated, and the health risk of residents' food consumption is continuously expanding (Zhao et al., 2023).

The transformation and reconstruction of China's food system not only faces many risks, such as the rigid growth of food consumption on the demand side and the structural imbalance of dietary nutrition, but also needs to address a series of challenges, such as the constraints of resources, environment, and production space on the supply side (Shi et al., 2013; Song et al., 2019). The realization of the goal of nutrition security increasingly depends on the optimal allocation of land resources, water resources, labor resources, technical resources, climate resources and other elements in the food system (Song et al., 2016; Imoro et al., 2021; Kang et al., 2023). Among them, land resources are the most important and basic resource guarantee related to the construction of a sustainable food system and the realization of national nutrition goals. However, the environmental cost of high investment in agricultural production has begun to appear, which has become a limiting factor restricting the further improvement of crop yield. It will be more difficult to achieve sufficient and diversified nutrition supply by relying only on growth in crop yield (Xu et al., 2017). Meanwhile, in the future, residents' nutrition-oriented food consumption will rely more on biogenetics and modern precision agricultural technology, and the technological progress of land promotion will also effectively improve the supply of nutritional elements *per capita* (Smith, 2013). This emergence and progress of innovative technologies will require optimal allocation of land resources.

The optimal allocation of land resources is to achieve various objectives and improve spatial benefits under different constraints through the adjustment of land use structure and spatial layout. The early optimal allocation of land use was mainly based on quantitative calculation, in which the goal was to achieve a high grain self-sufficiency rate. Land resources with the same structure will produce different benefits under different spatial layouts, and the adjustment of quantity is due to the lack of explicit characteristics of space, which has no strong practical significance for the realization of optimization objectives (Deng et al., 2008). The emergence of the land use dynamic simulation method provides a new theory and method for research on the spatial layout of land use optimization structures (Li et al., 2013).

At present, research on the optimal allocation of land use mostly takes the regional ecological and economic balance as the main goal (Yang et al., 2020; Ma and Wen, 2021) takes cultivated land protection as a subgoal under the multi-situation weight balance or simply takes the grain yield as the constraint condition (Wang et al., 2021). It lacks reflection on the new situation of food security and generally an insufficient description of the changes in agricultural supply structure and land demand affected by the improvement needs of residents' dietary nutrition in the future. At the same time, the optimization of land resources mostly focuses on the distribution among departments, and the consideration of interregional overall planning and coordination is relatively less. Food and nutrition supply is the most direct ecosystem service function of land. The necessary development space and good environmental experience are the benefits that today's society is more eager to obtain from land. Balancing the relationship between nutrition improvement, economic development and ecological protection and coordinating land use allocation based on this relationship can make the research more reasonable.

The Beijing, Tianjin and Hebei region (BTH) is one of the world-class urban agglomerations that China focuses on building. Its positioning is to build a "leading area for regional overall coordinated development and reform, a new engine of national innovation driven economic growth, and a demonstration area for ecological restoration and environmental improvement." However, at present, there is a large internal development gap in BTH, and there are obvious differences in industrial structure and population structure (Tian et al., 2019). In addition, income levels and market development levels will make the dietary structure and nutritional level of residents in the region at different development stages (Rischke et al., 2015). Food availability and nutritional security also face different challenges (Li et al., 2023). Taking BTH as an example, based on the analysis of residents' dietary structure and main nutrient intake since the 21st century, this paper establishes the regional nutrition improvement goal, constructs a comprehensive decision-making model, and discusses the optimal allocation scheme of land use under the balance of nutrition targets, economic targets, and ecological targets in the study area in 2030 (Figure 1). The research results have theoretical and practical significance for expanding the research on the coupling relationship between man and land under the change of food system and promoting the improvement of dietary nutrition level of regional residents, the improvement of labor quality and the coordinated and sustainable development of society, economy and ecology.

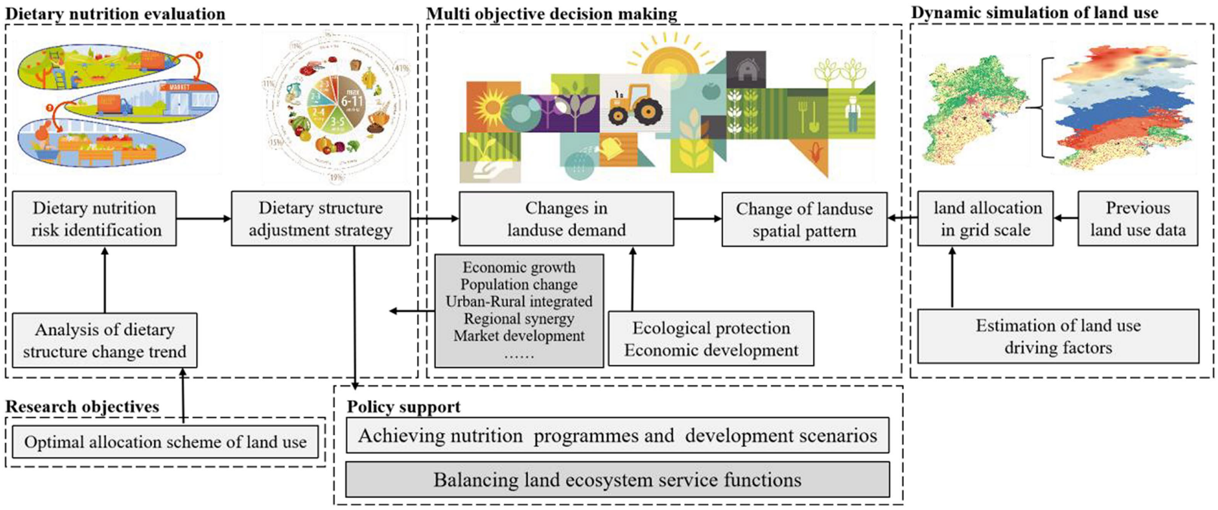

FIGURE 1
Optimal allocation of land use in BTH for serving dietary nutrition improvement.

2 Materials and methods

2.1 Study area

The Beijing-Tianjin-Hebei region (113°27′E ~ 119°53′E、36°03′N ~ 42°37′N) is located in the heart of the Bohai Sea Rim and has a temperate continental climate, including two municipalities directly under the central government of Beijing and Tianjin and 11 prefecture-level cities in Hebei Province, and is one of the three major urban agglomerations in China. It has a total population of about 110 million and covers a land area of about 215,000 km^2, accounting for 8.28 and 2.26% of the country's population and land area, respectively. The region has the most completed topography in China, with the Bashang Plateau in the north, the North China Plain in the south, and the Taihang Mountains in the west. The region has a variety of ecosystem types and functions and it's also a major source of food production and consumption. The net contribution rate of regional agricultural products to the national food production in 2018 reached 4.23, 5.70, 7.38 and 10.35% for cereals, vegetables, eggs, and dairy products, respectively (Figure 2).

2.2 Data sources

The spatial data used in this paper include the 30 m resolution grid data of land use in BTH in 2018, 2015 and 2010 from the resource and environment data center of the Chinese Academy of Sciences.[1] The land use types are reclassified to cultivated land, woodland, grassland, water body, construction land and unused land and then resampled to a 1 km grid. The data of land use driving factors include the kilometer grid dataset of GDP and population spatial distribution of the resource and environment data center of the Chinese Academy of Sciences and the 30 m dataset of China's altitude spatial distribution. Spatial distribution data of soil organic carbon content of Nanjing Institute of soil research, Chinese Academy of Sciences,[2] and spatial distribution data of precipitation of national meteorological science data center.[3] The socioeconomic data are derived from the *China Food Composition* and the statistical yearbooks of Beijing, Tianjin and Hebei Province from 2000 to 2018. Due to the lack of food consumption data of urban residents in Beijing from 2000 to 2015, the CPI index method is used for iterative calculation and mutual correction based on the food consumption and expenditure in 2000 and 2016, respectively. The specific equation is Eq. (1):

$$Q_{i,n+1} = \frac{Q_{i,n} \times C_{i,n+1}}{C_{i,n} \times CPI_{n+1}} \tag{1}$$

where $Q_{i,n}$ is the consumption of Class i food in year n and $C_{i,n}$ is the consumption expenditure of Class i food in year n.

2.3 Dynamics of land systems

Previous research has developed frameworks for studying land use patterns, integrating theoretical and empirical analyses of land use structures with models of land use change and interactions with environmental factors (Kauffman and Hayes, 2013). Studies often focus on the attributes of land units, examining their relationships with nearby or external environmental influences, using tools like Cellular Automata (CA), the Conversion of Land Use and its Effects (CLUE), and its variant for smaller areas (CLUE-S) to model spatial changes (Lambin et al., 2003; Veldkamp and Verburg, 2004). While

1 https://www.resdc.cn/

2 http://soil.geodata.cn

3 http://data.cma.cn/

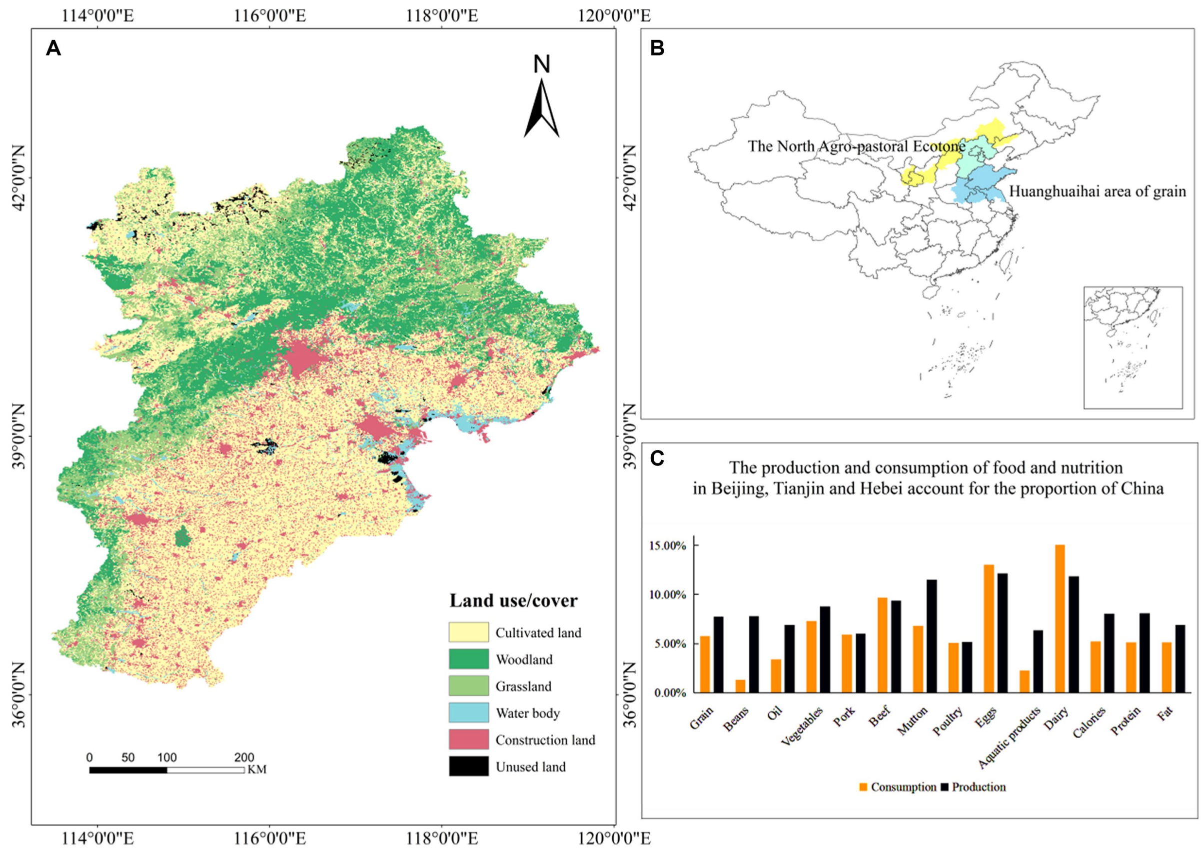

FIGURE 2
Basic information of the study area. **(A)** The type of regional ecosystem, **(B)** the spatial location of the area, **(C)** the contribution of regional food production to national food consumption and nutrition supply.

these models offer operational and scale advantages, they also need to be improved, such as the CA model's subjectivity in land use predictions and the CLUE models' inadequate consideration of land self-organization processes.

The Dynamic Land System (DLS) model is specifically developed to simulate dynamic land use/cover pattern changes. It represents a collection of applications for simulating changes in terrestrial ecosystem structures and succession models (Deng, 2011). Based on spatial analysis, the DLS model classifies and quantifies the impacts of driving factors to predict the probability of occurrence of different land use types. It simulates the macro patterns of land system succession and integrates the distribution probability of different land use types at the pixel level to achieve a spatial distribution of land area changes. The DLS model employs nonlinear models to simulate land use succession patterns. It assumes that the probability of grid i belonging to the kth land use type is $p_i^k = P\left(y_i^k = 1 \mid X_i, \hat{y}_i^k\right)$. Eq. (2) expresses this conditional probability in the form of a logistic function (Jin et al., 2019).

$$
\begin{aligned}
p_i^k &= \frac{1}{1+\exp\left[-\left(\alpha_0^k + \alpha_1^k x_{i1} + \alpha_2^k x_{i2} + \cdots + \alpha_l^k x_{il} + \cdots + \alpha_L^k x_{iL} + r\hat{y}_i^k\right)\right]} \\
&= \frac{1}{1+\exp\left[-\left(\alpha_0^k + \alpha^k X_i + r\hat{y}_i^k\right)\right]}
\end{aligned}
\quad (2)
$$

where, p_i^k represents the likelihood of encountering the *k-th* land-use type in grid *i*, where x_{iL} encapsulates both natural and socioeconomic influences. The term α_i^k denotes the impact coefficient of these drivers, with $\alpha^k = \left(\alpha_1{}^k, \alpha_2{}^k, \cdots, \alpha_i{}^k, \cdots, \alpha_L{}^k\right)$ forming a coefficient vector. The spatial autocorrelation factor is signified by $\hat{y}_i^k$ and r stands for a specific coefficient. By applying a logarithmic transformation, we calculate the logit function, *logit(t)*, representing the grid i's logarithmic likelihood ratio for the *k*-th land use, leading to a nonlinear model for predicting land-use distribution as depicted in Eq. (3).

$$
\begin{aligned}
\text{logit}(t) &= \ln\left(p_i^k / \left(1 - p_i^k\right)\right) \\
&= \ln\left(\exp\left(\alpha_0^k + \alpha_1^k x_{i1} + \alpha_2^k x_{i2} + \cdots + \alpha_l^k x_{il} + \cdots + \alpha_L^k x_{iL} + r\hat{y}_i^k\right)\right) \\
&= \alpha_0^k + \alpha^k X_i + r\hat{y}_i^k
\end{aligned}
\quad (3)
$$

The concept of grid-scale land supply and demand balance highlights a state where the supply and demand for various land types are equalized at the grid level. A self-organizing simulation incorporating the neighborhood effect was employed to enhance model precision during the land-use competition and trade-offs simulation. This approach involves two key factors. One is the neighborhood enrichment factor, which quantifies the relative abundance of a specific land-use type within adjacent grids. This factor is determined by Eq. (4):

$$F_{i,k,d} = \frac{n_{i,k,d} / n_{i,d}}{N_k / N} = \frac{P_{i,k,d}}{P_k} \quad (4)$$

where, i represents the grid count; k denotes the land use type; d is the model's neighborhood radius. The neighborhood enrichment factor, $F_{i,k,d}$, calculates the relative concentration of a land use type k within a neighbourhood based on the ratio $P_{i,k,d}$ of the count of grids of type k to the total number of grids in the neighborhood centered on grid I . P_k indicates the ratio of the count of grids of type k to the total number of grids in the study area. An equation results greater (or lesser) than 1 suggests that the concentration of land use type k within a radius of i is higher (or lower) than its concentration across the entire study area.

The neighborhood interaction factor quantitatively measures the impact of different land use types across various neighborhoods, calculated using Eq. (5):

$$G_{l,k,d} = \frac{1}{N} \sum_{i \in l} F_{i,k,d} \quad (5)$$

where G_{idk} is the factor of neighborhood interaction for land-use types l and k; N_l denotes the total number of grids of the i-th land-use type in he study area; $i \in l$ denotes the grid of the l-th land-use type; and $£_{i \in l} F_i, d$ denotes the sum of the neighborhood enrichment of the k-th landise type within the neighborhood of the l-th land-use type. When the equation's solution is greater than (less than) 1, there may be a spatial, nutually promoting (suppressing) effect between land-use types, l and c, in the range of radius d that is statistically significant. Thus, the landuse factors relating to neighborhood interactions in different neighborhoods can be calculated within a quantitative analysis of the interactions of different land-use types in different neighborhoods by adjusting the neighborhood radius d.

2.4 Comprehensive optimization model

Through the comprehensive optimization model, solving the land use structure under different scenarios and objectives as input parameters for the DLS model. Firstly, the cultivated land area required by consumers to achieve the improvement goal by minimizing the existing dietary change is calculated. Then, under different nutrition improvement objectives, the economic and ecological benefits of land use were weighed, and the land use needs were obtained under different development scenarios. The comprehensive programming function is as follows, where Eq. (6) is the maximum target value, Eq. (7) is the minimum change in dietary structure when the goal is achieved, Eqs. (8) and (9) are the dietary nutrition goal constraints, Eq. (10) is the value constraint, and Eqs. (11), (12), and (13) are the land use area constraints.

$$V^* = \max \sum_{i}^{n} v_i S_i^* \quad (6)$$

$$\min\left[x_i^*\right] = \sum_{i=1}^{n} \alpha_i \left(\frac{x_i^* - x_i}{x_i} \right)^2, \ \alpha_i = \frac{e_i x_i}{\sum_{i=1}^{n} e_i x_i} \quad (7)$$

$$\text{s.t:} \quad \beta_p^1 \sum_{i=1}^{n} C_i^p x_i \le \sum_{i=1}^{n} C_i^p x^* \le \beta_p^2 \sum_{i=1}^{n} C_i^p x_i \quad (8)$$

$$x_{i,\min} \le x_i^* \le x_{i,\max} \quad (9)$$

$$S_1^* = \sum_{i=1}^{n} \frac{x_i^* p_i g_i}{f_i n_i} \times 365 \quad (10)$$

$$\sum_{i=1}^{6} q_i S_i^* \ge Q \quad (11)$$

$$S_i^{\min} \le S_i^* \le S_i^{\max} \quad (12)$$

$$\sum_{i=1}^{6} S_i^* = S \quad (13)$$

where V^* is the total target value, v_i is the target value per unit area of Class i land use type (Appendix Table A1), and S_i^* is the area of Class i land use type in 2030. x_i^* is the consumption of Class i food after achieving the nutrition improvement goal, and x_i it is the current consumption of Class i food. α_i is the proportion of energy intake of Class i food in total food intake. Refer to the China Food Composition and calculate the main nutritional components of food according to the nutritional content of food and the food structure of residents, as shown in Appendix Table A2. β_p^1 and β_p^2 represent the upper and lower limit coefficients of nutrition improvement objectives. C_i^p represents the content of P nutrients in Class i food. $x_{i,\min}$ and $x_{i,\max}$ represent the minimum and maximum recommended intake of Class i food. S_i^* is the cultivated land area required to meet the nutrition improvement goal, p_i is the population available for food production calculated by calories in 2030, and the land carrying capacity from 2000 to 2018 is converted by using food production data and nutrition data and extrapolated into GM (1,1). f_i represents yield of Class i food in 2030, and the yield of plant food is extrapolated by the GM (1,1) model using the yield data from 2000 to 2018. Animal food is converted by introducing the feed to meat ratio g_i. The feed to meat ratios of pork, beef and mutton, poultry, aquatic products, poultry eggs and milk are 3.3, 2.6, 2.1, 1.9, 2.5 and 0.3, respectively. n_i is the multiple cropping index of various foods in BTH. Referring to the results of remote sensing data monitoring and farmer interviews, the multiple cropping indices of grain crops in Beijing, Tianjin and Hebei were 1.05, 1.1 and 1.35, respectively, and those of vegetables were 2.8. q_i is the constrained value per unit area of Class i land use type, and Q is the present value of the constrained value. $S_i^{\min}, S_i^{\max}$ is the

TABLE 1 Connotation of development scenario.

Development scenario	Goal orientation	Value constraint	Land type constraints
Business as usual	Refer to the current development scenario	According to the current economic growth rate	The area of woodland, grassland, water body and unused land shall not be less than the current area.
Priority of economic development	Principle of maximizing economic benefits	Value of ecosystem services increased by 5%	The area of woodland, grassland, water body and unused land shall not be less than the current area.
Priority of ecological protection	Principle of maximizing ecological benefits	The economic value of land use increased by 5%	The area of construction land and unused land shall not be less than the present value, and the total area of woodland, grassland, water body shall not be less than 40% of the regional area.

minimum and maximum area limit of Class *i* land use type, and S is the total area of regional land.

2.5 Scenario design

This paper sets up three development scenarios of "Business as usual," "Priority of economic development" and "Priority of ecological protection" under different nutrition improvement objectives. The goal orientations of the three development scenarios are different, and the meanings of the constraint value and target value are also different (Table 1). The "Business as usual" emphasizes the future land use scenario under the mutual game between economic value and ecological value according to the current land use decision and land type transformation preference. The "Priority of economic development" relaxes the demand restrictions on construction land, takes the pursuit of maximizing the benefits of economic development as the value target, considers the protection of ecological land to a certain extent, and takes the low-speed growth of ecosystem service value as the value constraint. The "Priority of ecological protection" emphasizes the preference of ecological land such as woodland and grassland, limits the use conversion of ecological land, takes the maximization of ecosystem service value as the value target, and takes the low economic growth rate as the value constraint. It should be noted that, due to the concern that COVID-19 may cause disturbance to the normal food structure and dietary level, the goals and scenarios we designed are based on 2018 before the start of the COVID-19 pandemic.

3 Results

3.1 Dietary nutrition evaluation of residents in BTH from 2000 to 2018

The food consumption of residents in BTH from 2000 to 2018 can be divided into two periods prior to and after 2009. In the first period, the food consumption structure upgraded rapidly, from "grain based" to "intake balance." "grain base" refers to the large proportion of grains in the structure of food consumption and the single nutrient structure, with the main source of nutrients being grains for energy. "intake balance" refers to the increase in animal food consumption, the consumption of animal and plant food tends to be reasonable, and the dietary structure can reflect the nutrition mix. The rate of grain consumption decreased, and the proportion of grain in the dietary structure decreased from 47.74% in 2000 to 31.14% in 2009. During this period, the consumption of animal food increased rapidly. Driven by meat and milk, the consumption proportion of animal food increased from less than 9 to 13.89%, of which the consumption of dairy products reached 13.14 kg, 2.7 times that of 2000. The second period is from 2009 to 2018, from "intake balance" to "intake diversity," "Intake diversity" refers to a richer variety of food consumption, with the proportion of meat, eggs, milk, fruits, and vegetables increasing further in the dietary structure. Which is specifically reflected in the dynamic stability of the consumption of plant food represented by grain. The consumption of grain and vegetables fluctuated approximately 120 kg and 105 kg, and the consumption of fruits maintained a slight increase. The consumption of animal food increased faster than that in the previous period, and its proportion in the dietary structure further expanded (Figure 3).

Geographically, the dietary structure in BTH is similar, but they are in different adjustment periods. Beijing residents' dietary consumption is more balanced in structure, the change in dietary structure is relatively stable, the consumption level of grain is low, and the proportion of animal food is relatively high. Its evolution law is objectively in line with the dietary structure of residents in economically developed areas in pursuit of reasonable nutrition intake (Figure 4B). The main trend of dietary structure change of residents in Tianjin is diversification, the proportion of animal and plant foods is basically stable, the internal changes of animal and plant foods are more obvious, the consumption of aquatic products has an obvious geographical environment impact, and the consumption is higher than that of Beijing and Hebei (Figure 4C). The succession of residents' dietary structure in Hebei Province (Figure 4D) reflects the general law of BTH (Figure 4A) to a certain extent. The trend of consumption upgrading is obvious, which is specifically reflected in the reduction of plant food consumption dominated by grain and the expansion of animal food consumption represented by meat and milk, and the trend of consumption upgrading will continue.

The changes in the main nutrient intake of residents in BTH from 2000 to 2018 are shown in Table 2. The calorie intake of residents in the three places showed a downward trend from 2000 to 2009, which is related to the rapid reduction in food consumption, such as grain, during this period. After 2009, with the slight increase in grain consumption of urban residents and the stabilization of grain consumption of rural residents, the caloric intake of residents also gradually increased, and all exceeded the recommended minimum intake of 1648.95 kcal/day. Protein intake is generally low, and due to

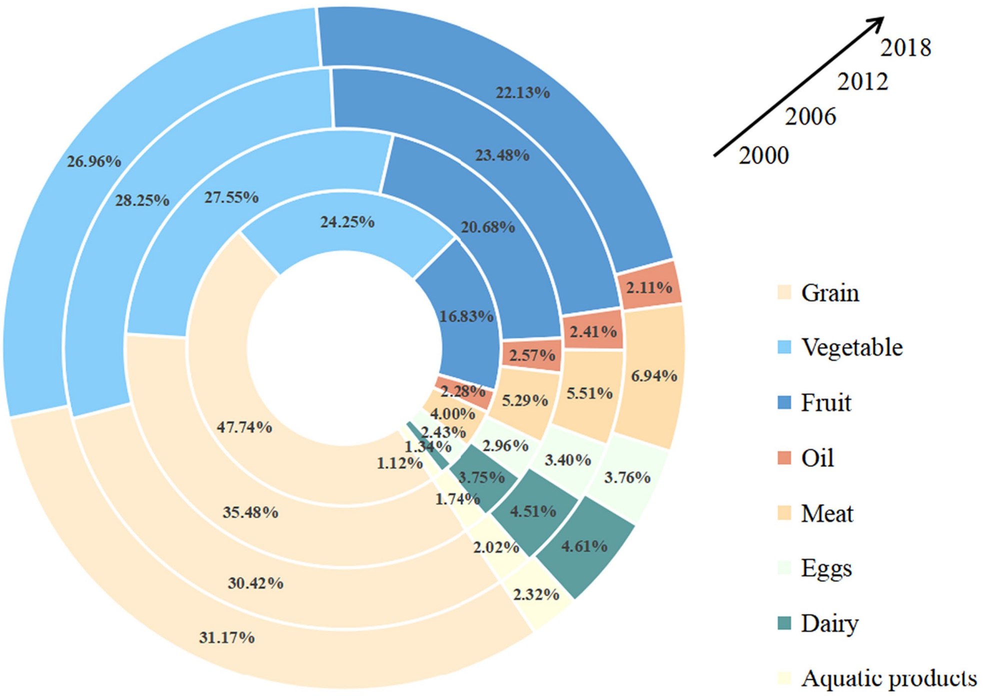

FIGURE 3
Changes in the dietary structure of residents in BTH,2000, 2006, 2012 and 2018.

the change in residents' dietary structure, the substitution of animal food for grain is insufficient; the protein intake in Hebei and Tianjin decreased year by year before 2012. Among the food sources of protein, the proportion of high-quality protein (the proportion of protein provided by animal food and beans in the total protein intake) of residents in Beijing, Tianjin and Hebei region increased to 50.86, 44.25 and 37.93%, respectively. There are regional differences in fat intake, and the fat intake of residents in the Tianjin and Hebei regions is generally at a low level.

3.2 Land use change in BTH from 2000 to 2018

The land utilization landscape in BTH changed significantly from 2000 to 2018, with the area of construction land and forest land increasing by 9,947 km^2 and 949 km^2, respectively, while the area of cultivated land, grassland, water, and non-utilized land decreased to a certain extent. It is mainly due to the increase in demand for construction land from major cities in the region such as Beijing, Tianjin, Shijiazhuang, and Tangshan caused by rapid economic development and the implementation of the policy of "returning farmland to the forest." The proportion of cultivated land decreased from 50.80% in 2000 to 46.13% in 2018, the proportion of construction land increased from 8.21% in 2000 to 12.81% in 2018, and the proportion of other land types decreased slightly but was relatively stable in the land utilization structure. In terms of land-use dynamics, the rate of change of various land utilization types in different periods showed inconsistency, and the rate of land utilization change gradually accelerated. The rate of decrease of cultivated land is −1.35, −0.55%, and −7.45% in 2000–2010, 2010–2015, and 2015–2018, respectively, and the rate of increase of construction land is 11.85, 3.65, and 34.54%, respectively, and the decrease of cultivated land and increase of construction land is significantly accelerated since 2015. The characteristics of land utilization structure and land utilization change rate reflected that the competition intensity of land utilization in the region gradually increased, the land utilization demand for economic development and ecological protection formed a greater threat to the land utilization for food production, and the function of food production and nutrition supply undertaken by the region was under greater pressure.

3.3 Nutrition objectives and dietary structure

According to the recommendations of the Chinese Dietary Guidelines, the daily energy requirement provided by the diets of Chinese residents should be maintained at 1600 ~ 2,400 kcal, and 120 ~ 200 g of meats intake should be maintained to ensure sufficient protein sources. At the same time, the fat intake is controlled at 80 g or less. When setting the nutrition improvement target, based on the multi-period Chinese residents' nutrition and health monitoring data, the energy intake of Chinese residents declined from excessive intake to insufficient. This is evidenced by the residents of Beijing, Tianjin, and Hebei, especially urban residents, whose caloric intake in recent years has been in the lower range of recommended values. Meanwhile, the protein intake of residents in the Beijing-Tianjin-Hebei region is on the low side, and there is still much room for improvement. As requested by the Chinese Dietary Guidelines for Residents and the reality of fat intake of residents in Beijing, Tianjin, and Hebei, fat

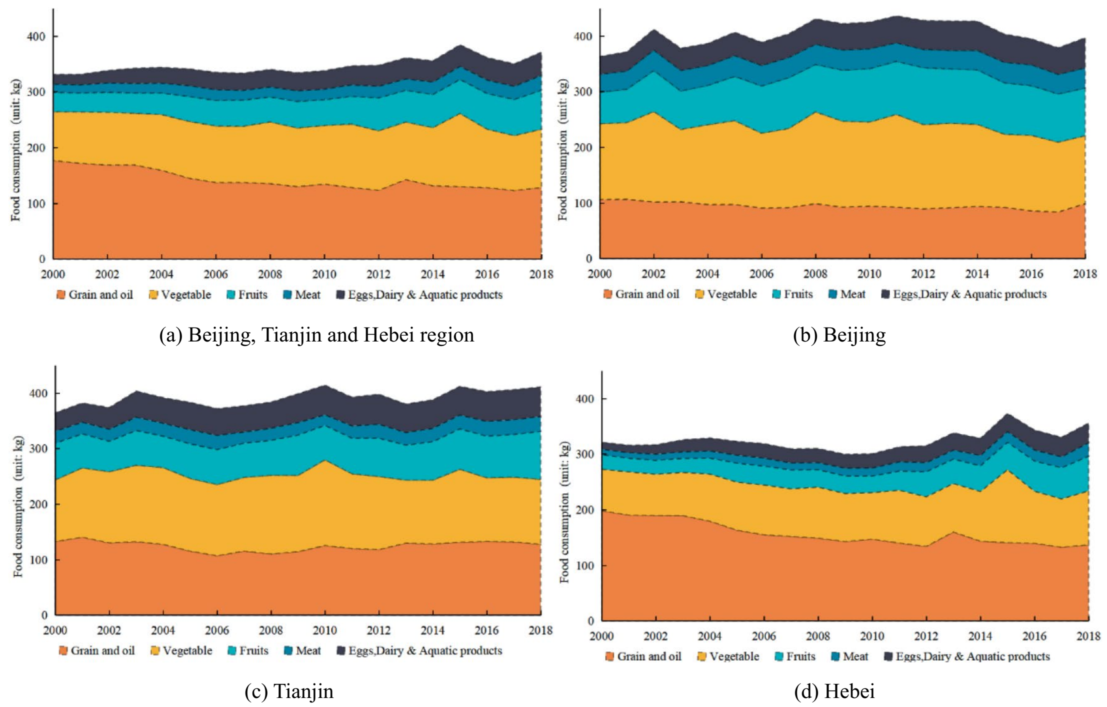

FIGURE 4
Comparison of dietary structure changes among residents in BTH from 2000 to 2018. **(A)** Beijing, Tianjin, and Hebei region, **(B)** Beijing, **(C)** Tianjin, **(D)** Hebei.

TABLE 2 Nutrient intake of residents in Beijing, Tianjin and Hebei from 2000 to 2018.

		2000	2003	2006	2009	2012	2015	2018
Calorie(KJ)	Beijing	1694.99	1796.00	1645.45	1747.36	1708.25	1763.49	1799.77
	Tianjin	2047.03	2069.28	1938.56	1859.62	1786.19	1996.73	1875.92
	Hebei	2282.02	2257.60	2000.99	1880.42	1850.92	1981.86	2011.46
	Recommended value	1648.95 ~ 2454.35						
Protein(g)	Beijing	50.36	52.49	51.02	54.57	53.33	54.54	58.38
	Tianjin	63.10	61.43	58.89	57.63	54.16	59.72	57.24
	Hebei	60.50	60.93	55.47	52.32	51.34	54.91	59.87
	Recommended value	56.69 ~ 82.97						
Fat(g)	Beijing	70.31	78.29	77.28	72.79	70.86	77.13	72.06
	Tianjin	74.72	78.70	75.62	69.54	70.91	69.11	62.22
	Hebei	47.07	52.45	55.79	55.65	58.60	67.48	65.29
	Recommended value	68.49 ~ 99.71						

intake should be reduced. However, the improvement of protein and calorie intake through the adjustment of dietary structure will inevitably lead to an increase in fat intake. Therefore, fat intake is set as a constraint indicator to keep the increase as low as possible. Therefore, taking the dietary structure of Beijing, Tianjin and Hebei residents in 2018 as the benchmark scheme and referring to the index requirements of the *Healthy China Initiative (2019–2030)*, the proposed three nutrition improvement targets and the dietary structure of Beijing, Tianjin and Hebei residents in 2030 that can achieve the three targets according to the principle of minimum change are shown in Table 3.

3.4 Land use demand under different nutrition targets and development scenarios

The calculated land use demand of the three nutrition objectives under the three development scenarios is shown in Figure 5. The cultivated land areas required for the three objectives are 83,777 km^2, 86,838 km^2 and 93,301 km^2, respectively, which are less than the current cultivated land area of 99,808 km^2. However, with the improvement of nutritional objectives, the demand for protein intake increases, the proportion of animal food in the dietary structure increases, the required cultivated land area will gradually expand, and the spatial competition of land use will become fierce. For different development scenarios, the reduced and vacated land space of cultivated land will be further balanced and distributed in production space and ecological space. Specifically, it mainly occurs in the land competition between construction land and woodland. Under the low nutrition target, the demand for construction land in the "Priority of economic development" is the largest, reaching 42,674 km^2, and the area for woodland is the smallest (45,770 km^2). The demand for woodland in "Priority of ecological protection" is the largest, reaching 59,090 km^2, and the area for construction land is the smallest (29,165 km^2). The land demand of grassland under different nutrition objectives and development scenarios changes little, which reflects that grassland plays a more balanced role in ecological protection, economic development and nutrition improvement. The demand for water in "Priority of ecological protection" is greater than that in "Priority of economic development," and profound changes have taken place in "Business as usual," indicating that water plays a key balance effect in the competition for ecological protection and economic development.

3.5 Comparison of land spatial patterns and land use benefits under different nutrition targets and development scenarios

Compared with "Business as usual" (Figure 6C), in "Priority of economic development" (Figure 6A), the spatial expansion effect of construction land is obvious, and most of them expand radially outward with the existing construction land as the center. Geographically, the conversion of cultivated land to construction land is more prominent in the northwest and southwest of Beijing, the north of Shijiazhuang, the south of Tangshan and the coastal areas of Tianjin. The scattered cultivated land in the woodlands of Chengde and Zhangjiakou in northern Hebei Province will be converted to construction land, and the forest areas in eastern Shijiazhuang will form new construction land. The dominant growth of ecological land in space occurred in the Bashang Plateau, with the transformation from cultivated land to forestland as the main type.

In "Priority of ecological protection" (Figure 6B), the distribution of forestland is more concentrated. The transfer effect of cultivated land to forestland is obvious in southwestern Beijing, the Middle East of Zhangjiakou, Chengde, Tangshan and northern Qinhuangdao. Along the Taihang Yanshan Mountains, an ecological corridor with forest and grassland as the main land type can be formed in Handan, Shijiazhuang, Baoding, west of Beijing, Zhangjiakou and Qinhuangdao, and the regional ecological space is more reasonable. The growth of construction land is mainly around the regional twin cities, and the outer ring of Beijing and the coastal area of Tianjin are the main growth points of construction land.

Under the same nutrition goal, the realization of spatial ecological benefits after land use optimization is more difficult than that of economic benefits. Under the low nutrition target, the spatial economic and ecological benefits of "Priority of economic development" and "Priority of ecological protection" are the largest, reaching 10309.08 billion yuan and 49.634 billion yuan, respectively, higher than 8771.48 billion yuan and 488.53 billion yuan in "Business as usual." In "Priority of economic development," the economic benefits of land use to achieve the three nutritional goals increased by 34.35, 27.80 and 13.98%, respectively. In "Priority of ecological protection," the ecological benefits of land use to achieve the three nutrition goals are increased by 16.08, 14.12 and 9.99%, respectively, compared with the current situation. Although higher levels of nutrition improvement solutions would trend toward more cultivated land utilization demands, they are all lower than the existing cultivated land area. The land utilization structure of service dietary nutrition improvement can release more spatial resources, the reduction of cultivated land area required for food generation can ease the current land constraint, and the cultivated land can be converted into construction

TABLE 3 Nutrition targets and corresponding dietary structure of residents in BTH in 2030 (kg/year).

	Region	Grain	Beans	Vegetable	Pork	Beef	Mutton	Poultry	Eggs	Dairy	Aquatic products	Oil
Current	Beijing	91.96	7.64	121.88	20.38	4.50	3.10	8.26	14.57	26.04	13.58	7.05
	Tianjin	117.96	7.15	116.85	16.79	2.95	1.58	5.78	17.71	18.65	16.73	9.86
	Hebei	129.78	8.27	97.13	16.06	1.58	1.55	5.03	13.94	15.39	6.11	7.33
Increase calorie intake by 10%, protein intake by 15% and fat intake no more than 5%												
Low nutrition target	Beijing	103.08	9.01	142.82	20.81	5.41	3.27	10.91	16.72	28.82	17.49	6.99
	Tianjin	131.71	8.48	136.85	17.20	3.58	1.68	7.71	20.44	20.69	21.72	9.79
	Hebei	144.13	10.11	115.49	16.35	2.00	1.66	7.18	16.59	17.25	8.43	7.16
Increase calorie intake by 15%, protein intake by 25% and fat intake no more than 10%												
Medium nutrition target	Beijing	105.63	10.14	154.16	21.55	6.31	3.49	13.43	18.84	30.92	21.12	7.06
	Tianjin	123.69	9.54	147.99	17.90	4.17	1.80	9.44	23.05	22.25	26.14	9.95
	Hebei	135.43	11.63	126.79	16.96	2.39	1.78	9.12	19.10	18.76	10.50	7.19
Increase calorie intake by 20%, protein intake by 35% and fat intake no more than 15%												
High nutrition target	Beijing	108.19	11.27	165.50	22.30	7.21	3.70	15.94	20.97	33.03	24.75	7.13
	Tianjin	126.97	10.63	159.30	18.57	4.77	1.91	11.24	25.72	23.84	30.72	10.08
	Hebei	139.14	13.21	138.40	17.55	2.80	1.91	11.15	21.70	20.29	12.66	7.19

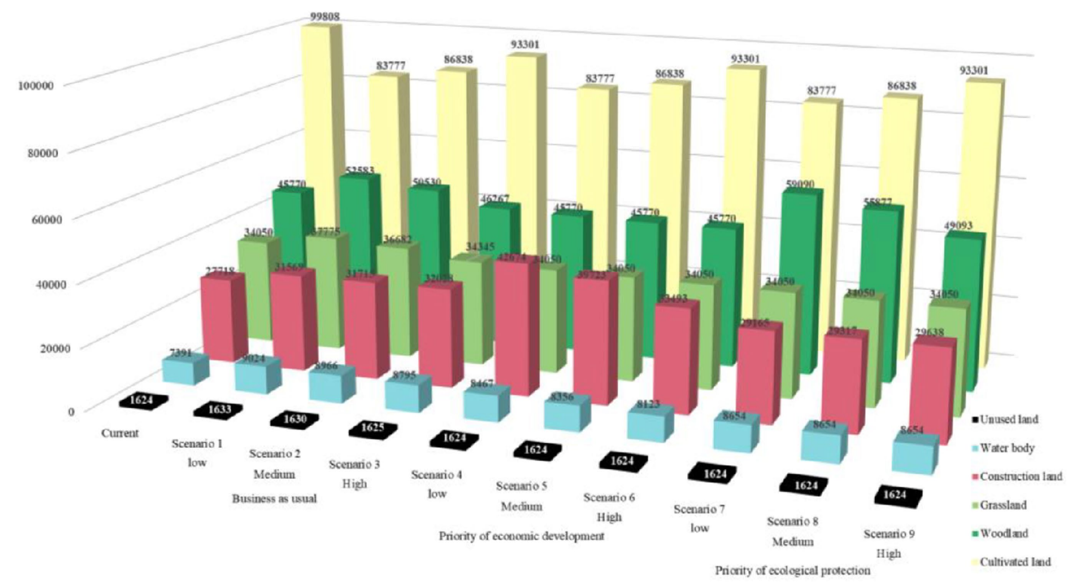

FIGURE 5
Land use demand under different nutrition targets and development scenarios.

land or ecological land. Thus, the economic benefits and ecological value of the region can be improved. Under the condition that the value of ecosystem services and economic benefits per unit area remains unchanged, the optimized spatial economic benefits and ecological benefits will increase by 4.99% ~ 10.01 and 2.22% ~ 7.09%, respectively.

4 Discussion

Adequate food guarantees and adequate nutrition access are the key material basis for global sustainable development. Establishing a sustainable food production system and eliminating all forms of nutrition problems on a global scale plays an irreplaceable supporting role in the realization of other sustainable goals. As the fundamental source of nutrients and energy required by human beings, land is the basic channel for the food system to realize material exchange and value exchange (Lambin and Meyfroidt, 2011). Therefore, integrating the food system with the regional system of human-land relationships and discussing the transformation and reconstruction of the food system (and the construction of a sustainable model from the perspective of the interactive relationship and driving factors between humans and the environment) can provide a scientific research paradigm for the goal of sustainable development (Zhuang et al., 2022). Starting from the changes in residents' food consumption structure and the diversified, hierarchical and differentiated characteristics of dietary nutrition needs, this study focuses on the optimal allocation scheme of resource elements under the balance of social value, economic value and ecological value in the socioeconomic-ecological composite system formed by the food life cycle. It has certain value for the theoretical expansion and practical innovation of the research on the coupling relationship between man and land under the change of food system.

As the country with the widest range, fastest speed and largest scale of urbanization in the world, China's land use structure has undergone great changes in the past 20 years. Different development needs shape the form of land use and promote the change of land use types. On the one hand, the rapid expansion of construction land has led to the occupation of a large number of high-quality ecological land, and the continuous reduction of grassland, forest land, water area and farmland (Wu et al., 2013) On the other hand, with China's emphasis on ecological and environmental protection, the construction of ecological projects has also affected the land use pattern. Some cultivated land has been returned to forests, grasslands and lakes (Zheng et al., 2018; Kong et al., 2022). Drastic land use change has put great pressure on the achievement of sustainable development goals at the regional and national levels. It is more urgent to balance the functions of land use, such as food production, economic development and ecological protection, and realize the optimal allocation of land use to meet the needs of different social development. From the perspective of future food consumption demand, we examined the land use optimization scheme under the priority of economic development and ecological protection according to the nutrition objectives determined by the healthy China strategy and the dietary guidelines for Chinese residents.

The results show that on the one hand, the adjustment of dietary structure can realize the reasonable nutritional intake of residents, on the other hand, it can also reduce the demand for cultivated land and release more space to meet the needs of other development. In the current context of rapid population growth, rapid changes in food consumption patterns, and surging demand for bioenergy production, competition for agricultural land has been tense for a long time. More and more suggestions point out that the intensive use of animal husbandry, the optimization of diet structure, the reduction of animal product consumption, and the substitution of food types can form the diet optimization path with the least impact on the environment to achieve the consumption of water and soil resources and the reduction of global greenhouse gas emissions (Shaikh et al., 2020; Mazac et al., 2022). Our research on the basis of further provide evidence and, in respect of dietary structure on the basis of existing in accordance with

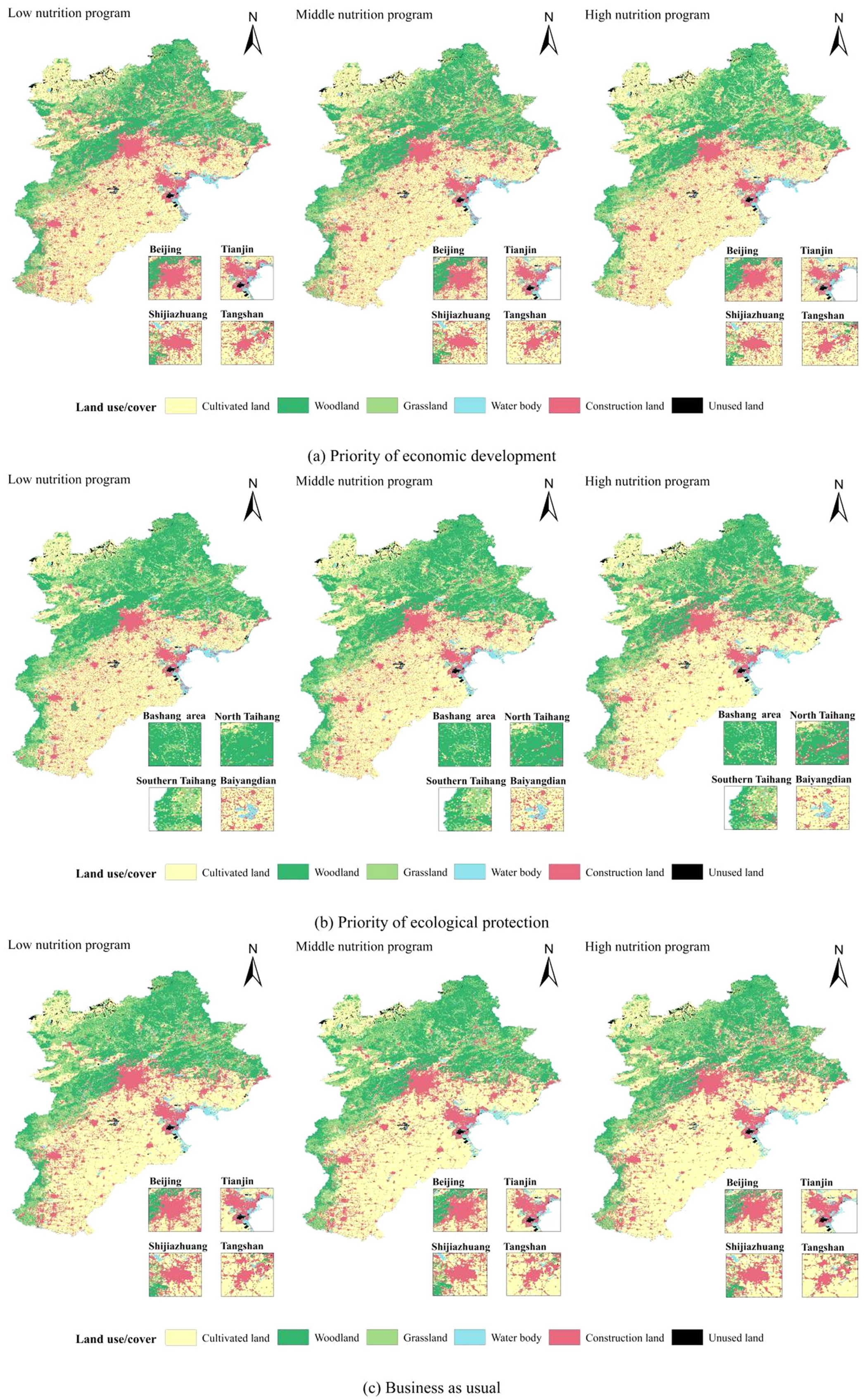

FIGURE 6
Land spatial pattern under different nutrition objectives and development scenarios. **(A)** Priority of economic development. **(B)** Priority of ecological protection. **(C)** Business as usual.

the principle of minimal changes to the pursuit of reasonable nutrition improvement targets, in the future under the condition of regional land capacity to maintain reasonable growth, changes in diet can alleviate the pressure of the current global land, and at the regional level to control the food consumption within the planet boundary.

In previous studies, there are few tools to solve the uncertainty between land use and natural and social system benefits. Even if the land use structure under the target benefit is determined, it is often unable to allocate the land demand to the most appropriate position. This study uses comprehensive optimization model and the DLS model to better solve this problem. At the same time, previous studies on optimizing the allocation of land resources have paid less attention to micro objectives. Some studies have incorporated residents' happiness, environmental satisfaction, and other factors into the objective functions of regional resource optimization, but these indicators are difficult to quantify. We also compared the results of this study with other studies on land use optimization in the Beijing-Tianjin-Hebei region (Bao et al., 2021; Meng et al., 2023), where the land use change trends showed spatial consistency under the same context, and the scale of the transformation of land classes into each other was roughly the same, but due to the differences in benefit coefficients selection, the economic value of the optimized and the ecosystem service values may be measured differently due to differences in the selection of benefit coefficients. However, compared with the traditional multi-objective optimization, this study based on nutritional goals and taking into account other development scenarios, achieving a combination of micro and macro levels. At the same time, the original intention of nutritional improvement is to enhance human capital, which is also an important way to achieve weak sustainability, land use optimization solutions from this perspective are more conducive to the achievement of regional sustainable development goals.

Indeed, there is still room for improvement in this study. For example, the BTH we studied is not a closed food system, and the nutritional goals include all residents involved in the production and consumption of BTH foods. The scenario selected and set based on statistical data and empirical parameters may make the accuracy of optimization results different from the real value. In the design of the nutrition improvement scheme, representative macronutrients are mainly selected, and less consideration is given to nutritional problems such as the lack of trace element intake common to residents in China's developed urban agglomerations. These problems can be solved by refining parameters and using more complex models in the future.

5 Conclusion

China's socio-economic development and people's growing demands for a better life pose new challenges and requirements for the transformation of land and food systems. Systematic research on the coupling relationship of the land system and the food system, and proposing the optimization scheme of land use are crucial for guaranteeing the nutritional supply demand and sustainable transformation of the food system. Based on the dietary structure and main nutrient intake of residents in the Beijing, Tianjin, and Hebei regions since the 21st century, this paper constructs a comprehensive land use structure optimization model based on serving dietary nutrition improvement and weighing socioeconomic development and regional ecological protection and uses the DLS model to simulate the allocation scheme of land use space optimization in Beijing, Tianjin, and Hebei in 2030. The main conclusions are as follows:

From 2000 to 2018, the dietary structure in BTH experienced a transformation from "focusing on grain" to "balanced intake" and then to "diversified intake," and the proportion of animal food consumption in the dietary structure further expanded. Maintaining a stable calorie intake, appropriately increasing protein intake and decreasing fat intake are the main objectives of future dietary restructuring in this region. The improved land use structure for nutritional transformation can release more space resources, better realize the balance between economic development and ecological protection and reduce the fragmentation of land use. On the basis of realizing the dietary nutrition improvement scheme, the regional economic benefits and ecosystem service value are greatly improved compared with the planned scenario.

Comparing the land use optimization scheme for serving dietary nutrition improvement with the planning scenario, the layout of the same land type in the spatial layout is more concentrated, which is more conducive to the exertion of land use function. In the scenario of "Priority of economic development," the construction land in the optimized scenario tends to be distributed in the regional dual core and the existing construction land concentration area. In the scenario of "Priority of ecological protection," more cultivated land in the north of the region is transferred to forestland, the policy space for returning farmland to forest is strengthened, the ecological corridor with forestland as the main land use type formed along the Taihang-Yanshan Mountains is further strengthened, and the role of the BTH ecological environment support area is more significant.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WW: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. ZG: Conceptualization, Data curation, Writing – review & editing. ZH: Project administration, Writing – review & editing. ZL: Investigation, Software, Writing – review & editing.

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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.

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Appendix

TABLE A1 Economic and ecological benefit coefficient per unit area of various land types.

	Cultivated land	Woodland	Grassland	Water body	Construction Land	Unused land
Economic value per unit area	10.915	19.148	17.122	40.264	184.994	0
Ecosystem service value per unit area	0.706	3.269	2.130	19.584	0	0.164

TABLE A2 Nutrients of main foods (Edible part of per kilogram food).

	Grain	Beans	Pork	Beef	Mutton	Poultry
Calorie (KJ)	3,553	3,900	5,278	1,496	2,670	627
Protein (g)	93	350	86.5	174.9	96.5	113.8
Fat (g)	25.7	160	544.2	88.7	250.6	176

	Oil	Vegetable	Fruits	Aquatic products	Eggs	Dairy
Calorie (KJ)	9,000	180	436	782	1,468	690
Protein (g)	0	11.4	6.2	125	123.8	33.6
Fat (g)	1,000	1.6	2.4	24.2	101.4	40.2