Dynamic simulation of China's water-grain-meat system and evaluation of its support capability based on water footprint theory

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Abstract: The supply capacity of water resources, food and meat products is of great importance to the people's livelihood of a country. In recent years, although China has introduced many policies on water resources and grain production, the current situation of China's food self-sufficiency and imbalance between supply and demand of water resources has not been fundamentally changed. Food security and water security are facing a serious situation. This paper takes the water footprint as the connection point, and combines the water food meat system with mutual influence, mutual causation and dynamic feedback into a composite system. At the same time, the simulation model of the composite system is established by using system dynamics, and the dynamic simulation of water grain meat in China from 2000 to 2050 is carried out to explore the current situation and future development trend of China's water, grain and meat supply capacity. It was found that during the simulated period, the agricultural blue-green water footprint on the demand side would continue to dominate, followed by the gray water footprint. The blue water footprint on the supply side remained stable, whereas the green water footprint and the circulating water footprint showed an upward trend. According to the contemporary social and economic development and the model of water resources in China, there will be no meat shortage in the future, but issues have been found in the ability to guarantee water and food supply. The root of China's food support capability problem is excessive grain consumption due to meat production, whereas the cause of the water support capability problem is the slow development of the water conservation. Food support capability issues can be solved by regulating the meat output of livestock farming and fishery operations, reducing excess production capacity, and stabilizing the meat supply and demand. To solve the water support capability issue, China should focus on accelerating the pace of agricultural water-conservation development, improving the sewage treatment system, building rainwater-collection projects, and promoting the research and development of water recycling technology. This study provides support for optimizing the structures of the meat and grain industries and the policy formulation of the efficient use of water resources in China.

Keywords: system dynamics, water footprint, evaluation, water support capability, food support capability, meat support capability

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1 Introduction

China faces challenges in environmental pollution and conflicts between supply and demand for water resources. Under the influence of factors such as rapid social development, increasing population density, and climate change, the situation of water resources becomes increasingly problematic[1]. At present, China's grain import volume and external dependence are on the rise. Urbanization and economic growth aggravate the shortage of agricultural land, and the food support capability problem is prominent[2,3]. The production and consumption of meat products are closely related to the global meat eaters' standard of living but also closely related to national food support capability. With the improvement of living standards and the increased meat production in China, grain consumption for meat production is increasing, which has become the main driving factor for the growth of grain demand in China[4]. Water is an essential resource for grain production, and water and grain are indispensable materials for animal husbandry. At the same time, water quality and quantity determine the yield and quality of grain and meat. Therefore, water, grain, and meat are closely related and constrained by each other. So far, there have been a lot of studies on water support capacity[5-7], food support capacity[8,9] and meat support capacity[10,11] in China, but researchers have ignored the interaction, dynamic feedback and mutual causal relationship between water, food and meat. Most of these studies focus on a single support capability assessment. Some scholars conducted analysis and evaluation by coupling water

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food[12] and water food energy[13], without precedent of coupling water food meat, lacking integrity of research. In addition, the current research focuses on the qualitative analysis of the current situation, and there is still a lack of dynamic quantitative analysis.

The water footprint links water resource consumption and pollution with social production and consumption, which solves the problem of focusing only on the utilization of physical water resources while ignoring the virtual water consumption in the supply chain, as traditional studies have done. The water footprint reflects the real water resource utilization amount in the process of social production[14]. With the improvement and study of water footprint theory, the applications of the water footprint in the individual fields of water, grain, and meat are increasingly effective[15-17]. As an indicator of water consumption and pollution in the process of food and meat production, the water footprint can not only provide systematic coupling parameters and connection link for water-grain-meat support capability evaluation, but also describe the internal relationships of the three subsystems, i.e., water support capability, food support capability, and meat support capability, from a quantitative perspective.

In view of the above concerns, this article relies on water footprint theory, adapts system dynamics to establish the coupled model of the water-grain-meat system, and utilizes quantitative evaluation to assess the current situation and dynamic development trends of China's water, food, and meat support capability. This paper presents a theoretical basis for the optimization of the meat and grain industry structures in China and the formulation of policies for the efficient utilization of water resources.

2 Research methods

2.1 Establishing the system dynamics model

System Dynamics (SD) is a research method of system simulation based on system science and model. System dynamics was established by Professor Jay W. Forrest of MIT in 1956 to analysis the relationship between various elements in the system and their dynamic changes[18]. SD is suitable for dealing with complex, periodic, and nonlinear problems. Combining the SD modeling method and water footprint-related concepts, this paper conducts a dynamic evaluation of China's water, food, and meat support capability, using the water footprint supply-to-demand ratio, grain self-sufficiency rate, and meat self-sufficiency rate. In this paper, based on the analysis of the components, influencing factors, and interaction relationship of the water-grain-meat composite system in China, a cause-and-effect feedback relationship of China's water-grain-meat system was produced with Vensim DSS software (Figure 1), upon which a dynamic model of the water-grain-meat system in China was built. The spatial boundary of the model was the region of mainland China (excluding Hong Kong, Macao, and Taiwan), and the time boundary was 2000-2050. The step length was one year, among which 2000-2016 were the historical years, 2017 was the current year, and 2018-2050 were the planning years. According to the industrial classification and evaluation objectives, the water-grain-meat system in China was divided into three subsystems: water support capability subsystem, grain support capability subsystem, and meat support capability subsystem.

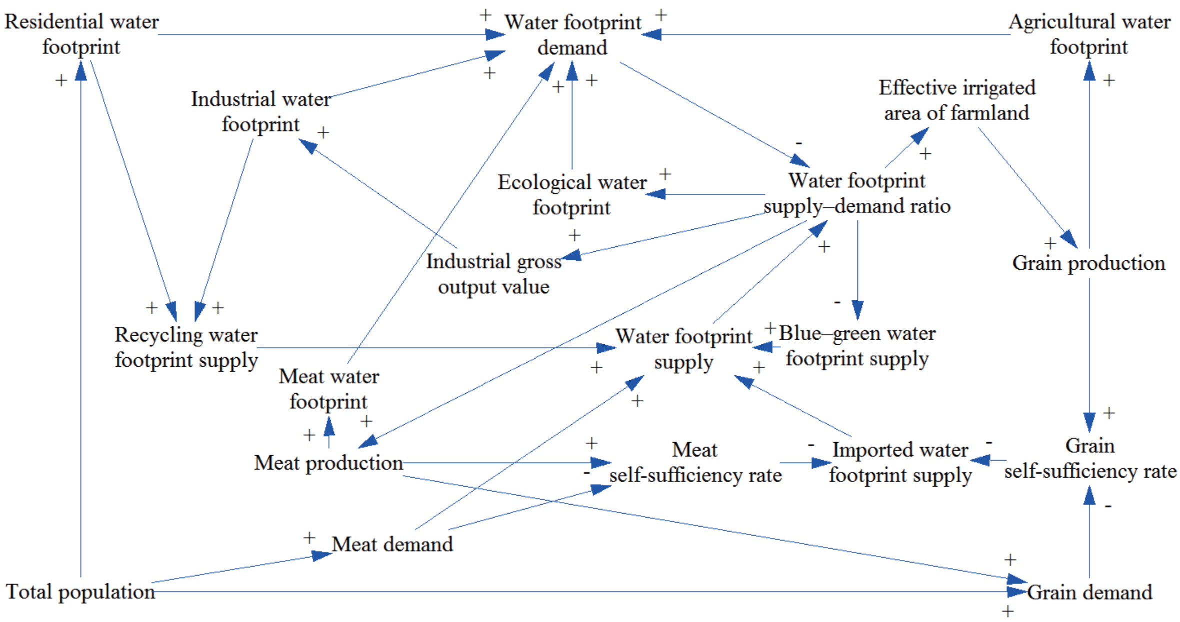
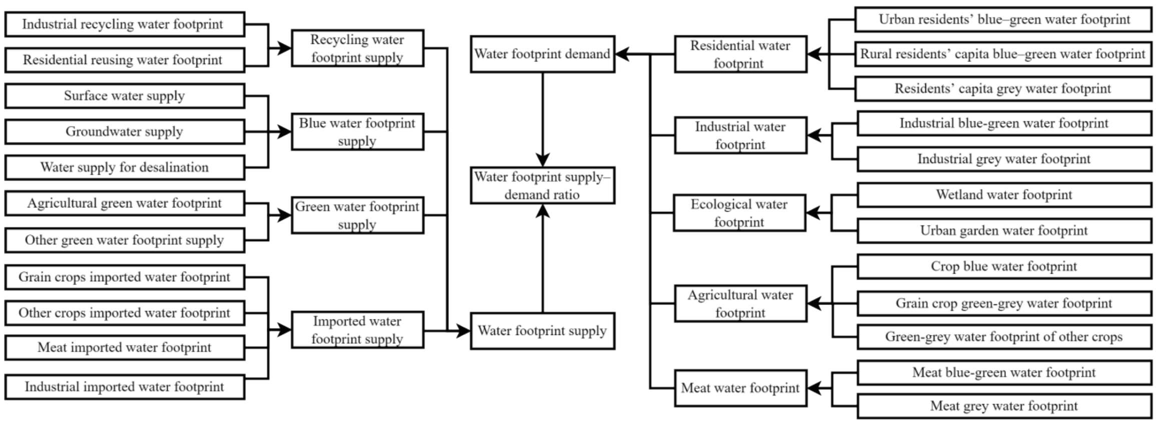


Figure 1 Causal feedback loop diagram of China's water-grain-meat system

2.1.1 Water support capability subsystem

Referring to the meaning of the traditional entity water resource supply and demand ratio[19], this paper adopts the water footprint supply-demand ratio as the evaluation index, which is used to measure the water support capability status of China. The water footprint supply-demand ratio is expressed by the ratio of the water footprint supply to the water footprint demand. This index can reflect the water resource supply/demand more truly and accurately by considering human society's utilization of physical and virtual water. The water footprint supply is determined by the type of water resources, whereas the water footprint demand depends on the real demand for water resources by different users (Figure 2).

In order to quantitatively measure the support capability level of water resources in China, this paper constructs an SD model of the water support capability subsystem (Figure 3) for the purpose of the calculation and simulation of the water footprint supply-demand ratio. The subsystem contained 80 variables, among which were the agricultural water footprint, meat water footprint, grain product water footprint, other imported crop water footprint, and imported meat water footprint data are introduced from the grain support capability and meat support capability subsystem. There are feedback and restriction relationships among various elements of the water support capability subsystem. Therefore, based on the analysis of the water footprint consumption and water footprint supply-demand relationship of users in various industries, this paper establishes the constraint relationship between the water footprint supply-demand ratio and the growth rate of industrial gross output value, the rate of change of green space areas and wetland areas, and the development and utilization degree of water resources. Through this work, the impact of the water footprint on industrial production, the ecological environment, and water resource utilization can be achieved. The years and schedule for planning a water support capability subsystem were set based on the results of previous research[20,21], and industrial production referred to China's economic development strategy planning[22]. Urban and rural residents' per capita blue-green water footprint and the blue-green water footprint of industrial ten-thousand-CNY output value were based on the "China Water Resources Bulletin"[23], and China National Bureau of Statistics data, and related resources in developed countries.



Note: This paper defines the recycling water footprint as the reusable part of the water footprint. It includes the industrial recycling water footprint and residential reusing water footprint. In addition, this article adds water supply for desalination to the blue water footprint supply. The supply of other green water footprints is mainly composed of rainwater storage of rainwater harvesting projects.

Figure 2 Water footprint supply-demand ratio elements

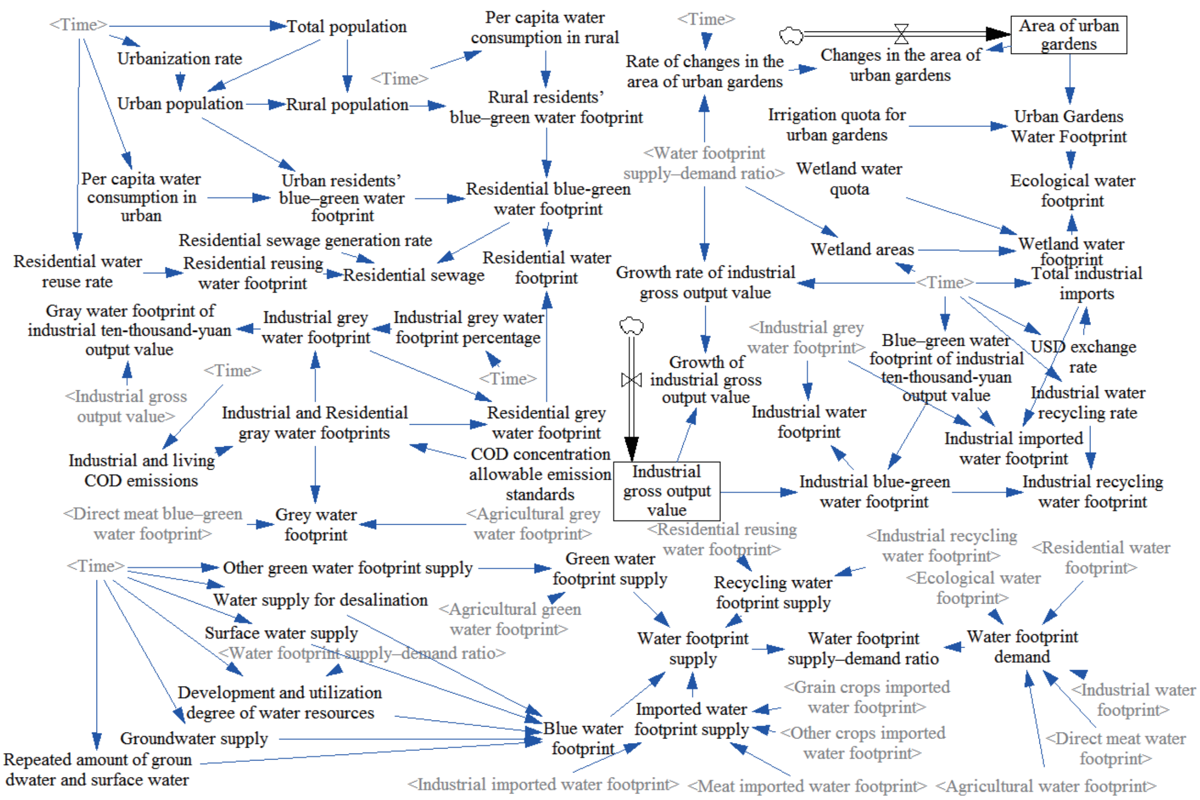


Figure 3 System dynamics model of the water support capability subsystem

2.1.2 Grain support capability and meat support capability subsystem

The self-sufficiency rate refers to the ratio between the total output and the demand for a certain product. This paper uses the self-sufficiency rate of grain and meat to measure the level of grain support capability and meat support capability in China. The grain self-sufficiency rate was calculated based on such factors as China's crop planting structure, basic demand for grain, grain reserve, consumption of grain by animal husbandry, and loss during grain processing and storage (Figure 4). This paper calculates China's meat self-sufficiency rate from the perspectives of the types of meat products in China, the demand for meat from different residents, and the loss of meat (Figure 4).

In order to quantitatively represent China's grain self-sufficiency rate and meat self-sufficiency rate, this paper constructs the grain support capability subsystem and meat support capability subsystem (Figures 5 and 6) based on the analysis of the interaction between each subsystem.

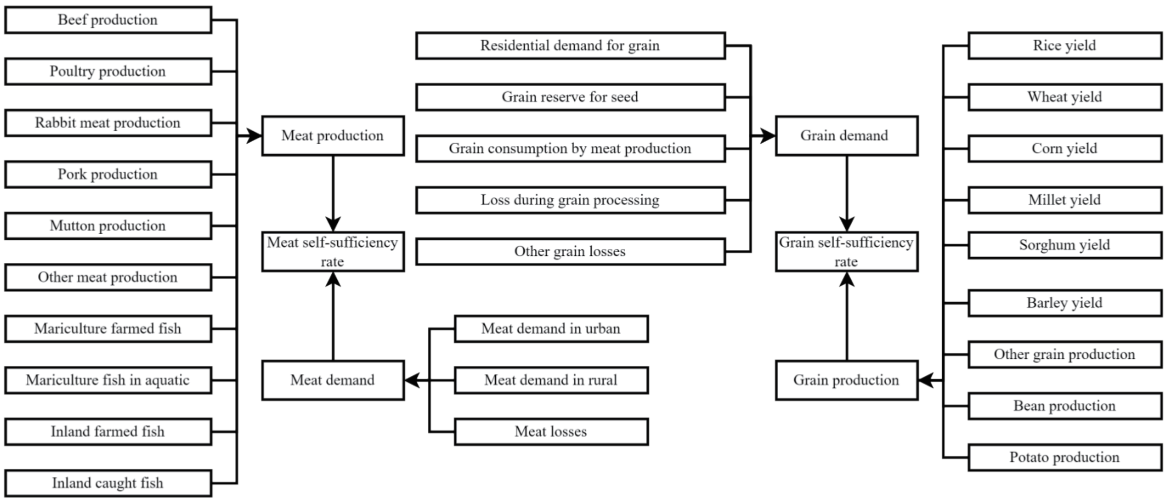


Figure 4 Components of grain self-sufficiency rate and meat self-sufficiency rate

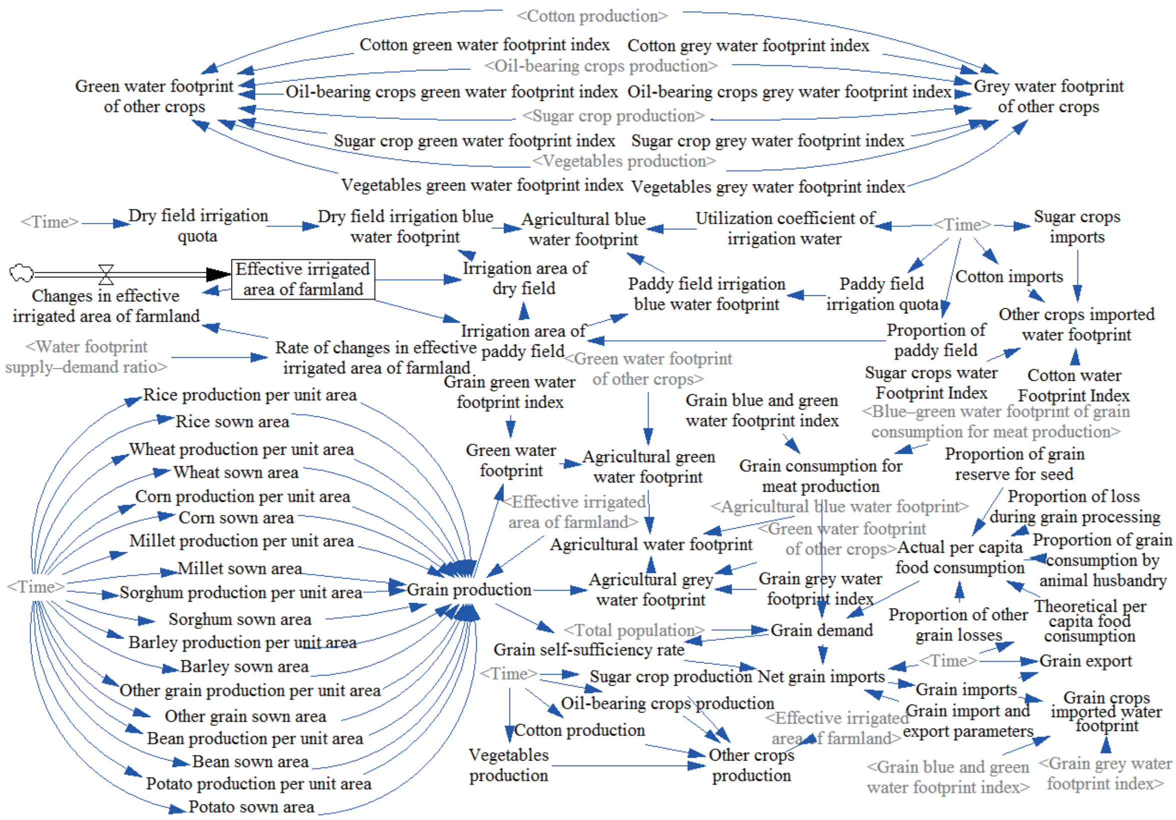
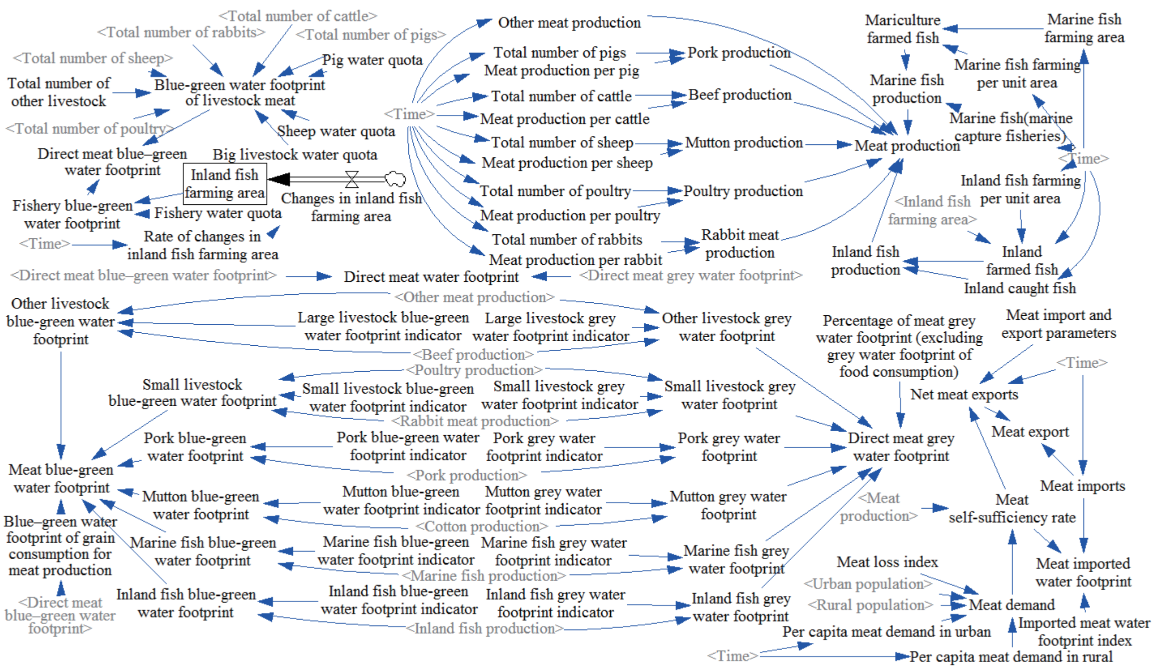


Figure 5 System dynamics model of the grain support capability subsystem

The grain support capability subsystem contained 91 variables, among which the total population, water footprint supply-demand ratio, and grain consumption for meat production blue-green water footprint were derived from the water support capability and meat support capability subsystem (Figure 5). The agricultural green water footprint, agricultural gray water footprint, and agricultural imported water footprint in the grain support capability subsystem were determined by the crop yield (import volume) and crop water footprint indexes. Water footprint indexes of different crops represent water footprint values of crops per unit mass, referring to relevant research results from domestic and abroad[24,25]. The agricultural blue water footprint was determined comprehensively according to the irrigated area, irrigation quota, and irrigation water utilization coefficient of the canal system of different crops. Grain consumption for meat production is the correlation index between the grain support capability subsystem and the meat support capability subsystem. It was determined by calculating the blue-green water footprint of grain consumed for meat production and the blue-green water footprint of grain per unit quality. The actual grain consumption per capita was from the research results of Tang[26]. There are mutual constraints among the elements of the system. Through the analysis of the relationship between agricultural production, water footprint, and food supply, the constraint relationship between the water footprint ratio and the effective irrigated area of farmland, and the constraint relationship between the food self-sufficiency rate and the net food import in the food support capability subsystem were established.

The meat support capability subsystem contained 102 variables, among which the water footprint supply-demand ratio, rural population, and urban population were derived from the water support capability subsystem (Figure 6). In the meat support capability subsystem, the meat demand in urban and rural areas was determined by the population and the meat demand per capita, and the meat consumption was from the research results of Si[27]. Since China has no official statistics on vegetarians, the total meat consumption and the total population were used to calculate the per capita meat consumption.

The meat blue-green water footprint is composed of the direct meat blue-green water footprint and the indirect blue-green water footprint from grain consumption in the process of meat production and breeding[25,28]. The blue-green water footprint of meat was comprehensively calculated based on the existing research results on the blue-green water footprint of meat per unit quality and meat yield[28,29]. The direct meat blue-green water footprint is the water used in the animal husbandry process, which can be calculated by the total quantity of livestock, livestock water quota, fishery breeding area, and fishery water quota. Therefore, the blue-green water footprint of grain consumption for meat production can be represented by the difference between the meat blue-green water footprint and the direct meat blue-green water footprint. This index is the connection point between the meat support capability subsystem and the grain support capability subsystem.



Note: Since the inland caught fish, marine fish (marine capture fisheries), and farmed marine fish do not need artificial water supplementation, only inland farmed fish were considered when calculating the aquaculture area.

Figure 6 System dynamics model of the meat support capability subsystem

2.2 Data sources

China's water-grain-meat system simulation model was built based on the social and economic development rules. The model considers the sustainable development goals of water resources demand of each water sector and the development situation of meat and grain production. It refers to the relevant parameter levels of developed countries, and corresponds to the interaction of China's population growth, economic development, scientific and technological level, water resources development and utilization, agronomic technology, and water-saving technology. The model adopts index analysis, mathematical fitting, and quota method to determine the initial value and future development rules of each parameter in the model. The data of water resources, meat-grain production, and social and economic development needed for the modeling in this paper were from China Statistical Yearbook[30], China Urban Construction Statistical Yearbook[31], and China Rural Statistical Yearbook[32].The meanings of key parameters and data sources of SD model are shown in Table 1.

Table 1 Meaning and data source of key parameters of the model

Name	Meaning	Data Sources
Agricultural green water footprint	Calculated from crops yield and green water footprint of crops per unit yield	
Grain crops imported water footprint	Calculated from the import volume of grain crops and the water footprint of grain crops per unit weight	
Other crops imported water footprint	Calculated from other crops import and other crops water footprints per unit weight	
Meat imported water footprint	Calculated from meat import volume and water footprint of meat per unit weight	[24,25,28,30,32]
Grain crop green-grey water footprint	Calculated from green grey water footprint from grain crop yield and unit weight	
Green-grey water footprint of other crops	Calculated from other crop yield and green gray water footprint of other crops per unit weight	
Meat blue-green water footprint	Calculated from meat output and blue green water footprint of meat per unit weight	
Meat grey water footprint	Calculated from meat output and gray water footprint of meat per unit weight	
Meat production	Including: beef production, poultry production, rabbit meatproduction, pork production, mutton production, marine fish production, inland fish production, other meat production	
Grain demand	Including: residential demand for grain, grain reserve for seed, grain consumption by meat production, loss during grain processing, other grain losses	[26,27,29,32]
Meat demand	Calculated from urban meat demand, rural meat demand and meat loss coefficient	
Grain production	Including: rice yield, wheat yield, corn yield, millet yield, sorghum yield, barley yield, bean production, potato, other grain production	
Industrial recycling water footprint	Industrial recycling water	
Residential reusing water footprint	Domestic water reuse	
Surface water supply	Surface water supply	
Groundwater supply	Groundwater resource supply	
Water supply for desalination	Desalinated water resources	
Wetland water footprint	Wetland water consumption	
Urban garden water footprint	Water consumption of urban garden	
Other green water footprint supply	It mainly includes the accumulated water volume of rainwater collection works	
Crop blue water footprint	Calculated from paddy field irrigation area, dry field irrigation area, paddy field irrigation quota and dry field irrigation quota	[23,30,31,32]
Industrial imported water footprint	Calculated from the industrial import volume and the water footprint of industrial output value in 10 000 CNY	
Urban residents' blue-green water footprint	Calculated from urban population and urban per capita water quota	
Rural residents' capita blue-green water footprint	Calculated from rural population and rural per capita water quota	
Residents' capita grey water footprint	Calculated from domestic COD emission and COD emission standard	
Industrial blue-green water footprint	Calculated from the total industrial output value and industrial water consumption per 10 000 CNY output value	
Industrial grey water footprint	Calculated from industrial COD emission and COD emission standard	

3 Results and discussion

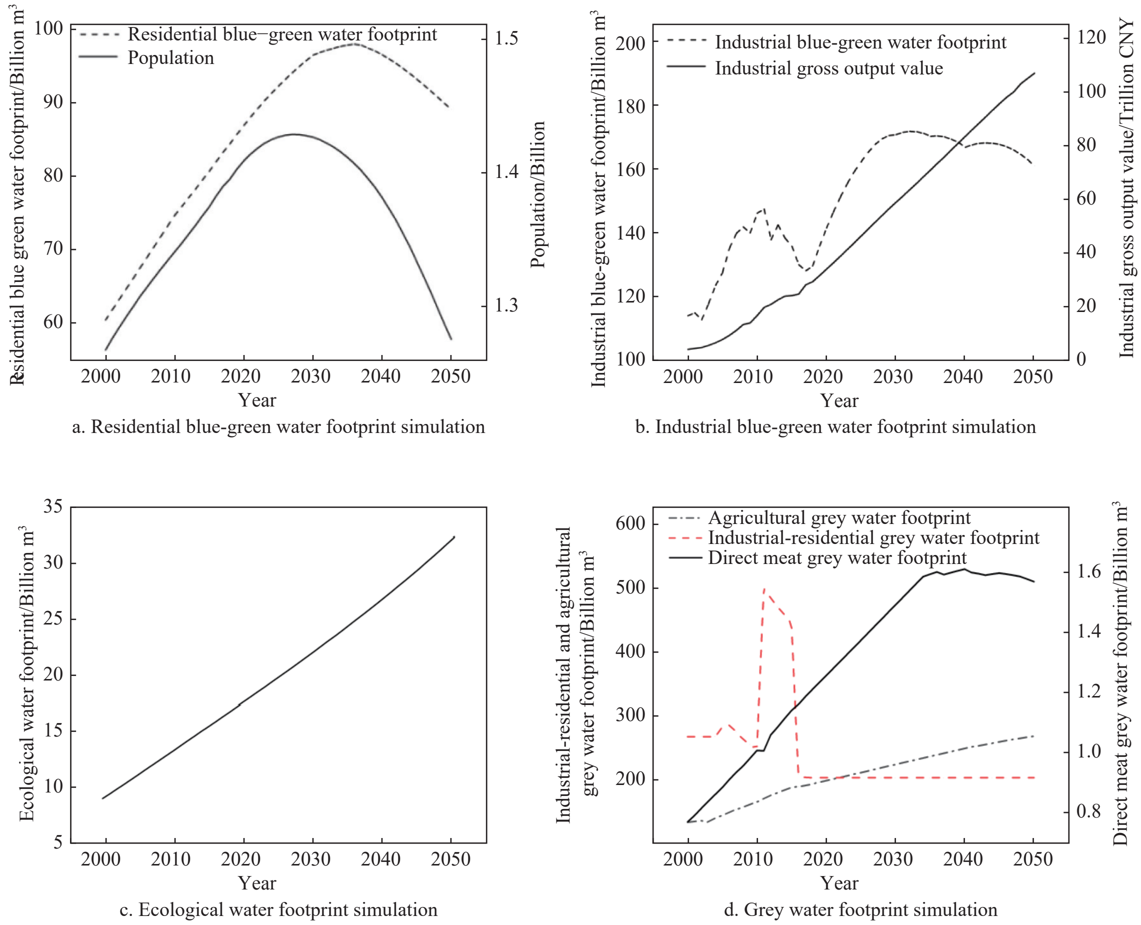
3.1 Dynamic simulation of water-grain-meat system in China

3.1.1 Dynamic simulation of the water support capability subsystem

The residential blue-green water footprint represents the amount of water resources necessary for people to maintain daily life and enjoy services, and its changing characteristics depend on per capita domestic water consumption and the population. With increased economic development and improvements to living standards, China's per capita water consumption will continue to increase. Although China's population has been growing recently, due to the slowdown of population growth caused by the decline in the natural growth rate, the number of people in China is expected to reach 1.43 billion in 2027, an increase of 12.73% compared with that in 2000. Subsequently, with the low fertility rate and an aging of the population, the Chine population first increased and then decreased[21]. In 2050, the Chinese population total is expected to fall back to the levels of 2001. Under the combined impact of per capita domestic water consumption and population, China's green and blue water footprints would also increase first and then decrease. The peak would lag behind the population curve, reaching 98.05 billion m^3 around 2036, increasing by 62.2% compared to 2000, and then steadily decreasing to 89.18 billion m^3 in 2050 (Figure 7a).

The industrial blue-green water footprint represents the consumption of groundwater, surface water, and precipitation in the industrial production process. The simulation results reflect the dynamic change process of industrial water consumption in China. During the research period, China's industrial blue-green water footprint showed two significant increases and then decreased (Figure 7b). From 2000 to 2017, China's industrial blue-green water footprint first increased and then decreased, reaching a peak of 147.3 billion m^3 in 2011. This shows that China's industrial water-conservation policy[33], introduced in 2010, effectively curbed the trend of the rapid growth of industrial water footprint after 2000. Before 2030, China's industrial footprint would continue to grow and then drop from 170.6 billion m^3 in 2030 to 160.8 billion m^3 in 2050. Calculated based on that data in Figure 7b, China's water footprint of industrial ten-thousand-CNY output value in 2000-2030 would fall to 29.01 m^3 from 282.91 m^3, reaching the requirements of the State Council[34] on the industrial water consumption of ten-thousand-CNY output value under 40 m³ in 2030. The above finding is consistent with the goal in The Strategic Issues of Medium and Long Term Development of China's Industry[35] that per unit of added value in China's industry of energy consumption, water consumption, and comprehensive utilization rate of resources will reach the world's advanced level by 2030. Industrial production cannot be separated from water resources, and economic growth drives industrial development and thus increases the demand for water resources. At present, China's industrial development is geographically uneven, and water resource management is weak[36]. With industrial modernization, the progress of social science and technology, the adjustment of industrial structure, formulation of policies, regulations, and standards, and implementation of departmental supervision mechanisms, China's industrial water-conservation system would be further improved, and the utilization efficiency of industrial water resources would be steadily improved. In 2050, China's water footprint of the industrial output value per ten thousand CNY would drop to 15.03 m³, which is a decrease of 48.19% compared to that predicted for 2030.

With the rapid development of society, China's efforts to protect the ecological environment are increasing, and the ecological water footprint is also increasing. From 2000 to 2050, China's ecological water footprint would keep steadily rising and reach 32.3 billion m³ in 2050 (Figure 7c). Water is the basis of ecology. An ecological water footprint, as an important index for measuring ecological environment protection, reflects the nation's attention to ecological environment protection. The Chinese saying "clear water and green mountains are gold and silver" indicates that ecological environmental protection and social industry are the future development direction of China[37].



a. Residential blue-green water footprint simulation

b. Industrial blue-green water footprint simulation

c. Ecological water footprint simulation

d. Grey water footprint simulation

Figure 7 Simulation of the water support capability subsystem of China

The gray water footprint is the amount of water resources needed to dilute and absorb pollutants to acceptable environmental water quality standards based on pollutant concentration and discharge standards[38]. Based on the composition of the water-grain-meat system in China and the water use characteristics of each department, the paper divides the gray water footprint into three footprints: the industrial and residential gray water footprint, the agricultural gray water footprint, and the meat gray water footprint. Then, dynamic simulation for each of them was conducted (Figure 7d). According to Figure 7b and Figure 7d, before 2016, especially 2011-2015, China was at a stage of rapid industrial development and low sewage treatment capacity. This is reflected in the rapid improvement of industrial output value and the substantial increase of domestic sewage, but the development of supporting facilities for pollution treatment lags behind, and relevant treatment measures are not in place, resulting in serious water pollution problems. The year 2010 is the inflection point of water use on a Kuznets curve between China's industrial water consumption and economic development[39]. It marks the arrival of the first peak of industrial water consumption and the peak of industrial grey water footprint. After the adjustment of the sewage prevention and control plan[40], China's industrial sewage discharge restriction has been strengthened, sewage treatment capacity has been gradually improved, and society is improving towards high-quality development. In 2016, the industrial and residential gray water footprints of in China decreased significantly, and the prevention and control of sewage showed initial results. In the future, the supporting facilities of sewage treatment and the laws and regulations of the departments would be improved, and the industrial and residential gray water footprints would remain at a low level and fluctuate steadily. In 2022, China's agricultural grey water footprint would be the same as the industrial and domestic grey water footprint, reaching 204.4 billion m^3, accounting for 49.84% of the total grey water footprint. The gray water footprint of meat would be 1.29 billion m^3, accounting for only 0.32%. From 2000 to 2040, the agricultural grey water footprint and meat grey water footprint would increase steadily with the increase of production. After 2020, the agricultural grey water footprint would replace the industrial one as the most important source of gray water footprint. After 2040, due to the decrease of population and the system adjustment, the gray water footprint of meat would show a stable trend, with stability of meat production. Due to the long-term existence of the food gap (see Figure 13), agricultural input intensity would not be reduced, grain output would increase steadily, and the agricultural grey water footprint growth trend would continue. By 2050, China's agricultural gray water footprint, industrial gray water footprint, and meat gray water footprint would be 56.69%, 42.99%, and 0.32%, respectively.

3.1.2 Dynamic simulation of the grain support capability subsystem

In this paper, key parameters such as the agricultural blue water footprint, agricultural green water footprint, and grain crop yield in the food support capability subsystem are simulated to analyze the interaction between grain production and the agricultural blue and green water footprints and to predict the dynamic change trend of the agricultural blue and green water footprints in the future.

Water is the lifeblood of agriculture, and agricultural development needs water resources to support it. Grain production is a decisive factor affecting the change of the blue and green water footprints. The increase in grain production will inevitably lead to an increase in agricultural water demand. From 2000 to 2050, the demand for the agricultural blue-green water footprint would increase by 0.44 trillion m^3, an increase of 49.9%. In 2050, China's agricultural green water footprint would be 0.93 trillion m^3, and grain output will be 901 million t, a growth of 87.5% and 94.2% compared to 2000. Meanwhile, China's agricultural blue water footprint would fluctuate between 0.376-0.396 trillion m^3, showing a relatively stable state. Water-saving irrigation technology[41] is an important part of China's agricultural development plan. The popularization of water-saving irrigation technology effectively reduces the agricultural water quota and maximizes the utilization efficiency of blue water footprint under the condition of limited physical water supply. With the popularization of water-saving irrigation technology, China's future agricultural green water footprint and grain output would show a synchronous growth, whereas the agricultural blue water footprint would fluctuate steadily due to the improvement of water resource utilization efficiency (Figure 8). This result shows that rainfall resources in China will play an increasingly important role in agricultural development in the future. The dependence of agriculture on groundwater and surface water resources is gradually decreasing, which is conducive to the improvement of problems such as overexploitation of groundwater and crowding out of ecological water. The simulation results are consistent with the goals of implementing strict water resource control and improving the efficiency of rainfall resource utilization in China's agricultural development plan[37].

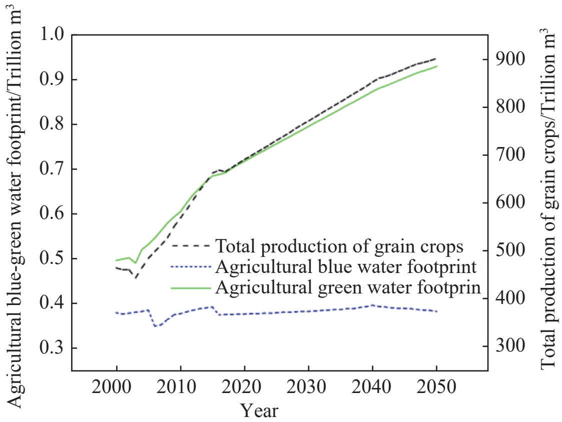


Figure 8 Simulation of the grain support capability subsystem of China

3.1.3 Dynamic simulation of the meat support capability subsystem

The key parameters of the meat support capability subsystem include the meat blue-green water footprint and the meat yield. Through the simulation of the above key parameters, this paper predicts the dynamic change trend of meat production and the meat blue-green water footprint in China in the future, providing data support for the analysis of meat production in China.

Data show that China's per capita meat consumption is increasing, and the gap with developed countries is gradually narrowing[42]. The simulation results are consistent with the data. As the most populous country, China has a huge potential for meat demand growth. Affected by the demand for meat, China's meat output would continue to grow in the future, reaching a peak of 192 million tons in 2036—an increase of 99.17% compared to data in 2000. In the future, the blue-green water footprint of meat in China would continue to rise with the increase in meat production, reaching a peak of 849 billion m^3 in 2040. The simulation results show that the blue and green water footprints of meat in China would increase synchronously with meat production before 2036, and then they would fluctuate and decrease (Figure 9). Due to the decrease of the total population and the feedback regulation of the system on meat production, the meat demand in China would not increase after 2036, and the meat production and the blue-green water footprint of meat would also tend to be stable with the stability of the meat demand.

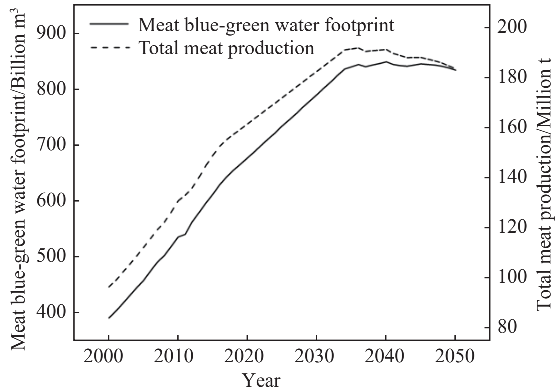


Figure 9 Simulation of the meat support capability subsystem of China

3.2 Support capability evaluation of the water-grain-meat system in China

The key parameters for the evaluation of the support capability of the water-grain-meat system include meat self-sufficiency rate, grain self-sufficiency rate, and water footprint supply-demand ratio, which respectively represent the self-sufficiency capacity of national meat and grain, and the equilibrium degree of water footprint supply and demand. Through the simulation analysis of key parameters, it is helpful to understand the drawbacks and possible problems in the future of grain and meat support capability and water resource allocation under the current development model of China. The policy simulation of China's water-grain-meat system is helpful to provide the decision makers with specific risk-averse development plans from the quantitative perspective, which is of great significance to the stable and healthy development of China's society.

3.2.1 Evaluation of water support capability issues

The change in water supply and demand has a direct impact on human survival and development[43]. The water footprint supply-demand ratio represents the ratio of water footprint supply to demand, discusses the dynamic change process and driving factors, provides the theoretical basis for solving the water support capability problem, and is of great significance for the rational development and utilization of water resources and economic development.

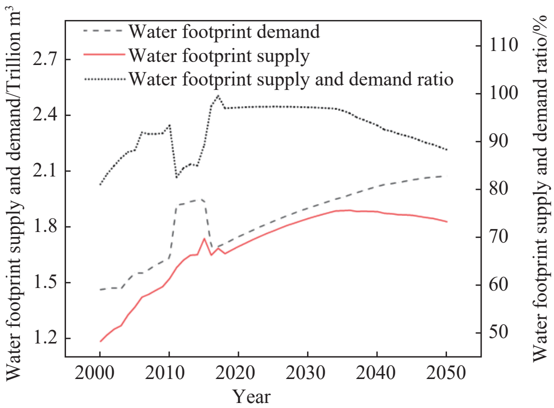


Figure 10 Changes in the water footprint of China

From 2000 to 2050, the ratio of water footprint supply and demand in China would vary from 83% to 96%, showing a trend of fluctuation, stabilization, and finally decline (Figure 10). The gap between water footprint supply and demand has existed for a long time. Before 2020, the water footprint ratio fluctuated significantly, reaching a trough (80.9%) and a peak (99.4%) in 2000 and 2017, respectively. From 2020-2032, the water footprint supply and demand would increase simultaneously, and the water footprint supply and demand ratio would remain stable between 96.9% and 97.2%. After 2032, the ratio between supply and demand of China's water footprint would steadily decline from 96.8% to 88.2%. The agricultural blue-green water footprint accounted for more than 50% of the water footprint demand (Figure 11). Since the grain gap has existed for a long time (Figure 13), the increase in agricultural production would not be reduced, so even if the population decreases, the growth trend of the agricultural blue-green water footprint would not be significantly affected. The residential blue-green water footprint and the meat blue-green water footprint would not increase with the change of population (Figure 7a), but as the proportion is relatively small, it would only slow down the growth trend of the water footprint. After 2032, the effect of population reduction on social development would gradually appear. The decrease in grain demand and the increase in grain output would lead to the gradual increase of grain self-sufficiency rate and the consequent decrease of grain import volume. Lower grain imports lead to lower water footprint supply, which in turn leads to lower water footprint supply. The gap between water footprint demand and supply would gradually increase, and the water footprint supply and demand ratio would decrease, which would aggravate the restriction of water resources to China's social and economic development in the future. Therefore, solutions should be proposed from the supply side and the demand side of the water footprint.

In this paper, China's water footprint demand users are divided into ecology, residential, industry, meat, and agriculture, and different water footprint proportions are simulated (Figure 11). The blue-green water footprint measures the user's usage of groundwater, surface water, and precipitation, whereas the gray water footprint measures the user's ability to discharge and treat wastewater. In this paper, the two footprints are analyzed separately, which is helpful to reflect the dynamic change process of water resources utilization and wastewater discharge of each user. During the simulation period, the proportion of the agricultural blue-green water footprint and the ecological water footprint showed an increasing trend, the proportion of the gray water footprint and the meat blue-green water footprint decreased significantly, and the proportion of the residential blue-green water footprint and industrial blue-green water footprint was relatively stable. The dominant position of the agricultural blue-green water footprint on the demand side would continue, showing an overall growth trend and increasing from 50.43% in 2000 to 56.83% in 2050. Compared with 2000 and 2010, the gray water footprint after 2020 would decrease, but would still maintain a proportion of slightly more than 22% (Figure 11). Agricultural blue-green water footprint and gray water footprint account for the majority of the water footprint demand. During the simulation period, the proportion of the sum of the two footprints changed little, ranging from 76.36% to 79.78%. Therefore, the agricultural blue-green water footprint and the gray water footprint are the main driving factors affecting the water footprint demand in China. The key to increasing the water footprint from the demand side is to reduce pollution and agricultural water use.

The water footprint supply includes the blue water footprint supply, green water footprint supply, recycling water footprint supply, and imported water footprint supply (Figure 12). During the research period, the proportion of recycling water footprint and green water footprint supply showed a rising trend with an increase of the reuse rate of reclaimed water, the utilization efficiency of industrial recycling water, and the utilization efficiency of precipitation. Most of the supply of the blue water footprint comes from the exploitation of surface water resources and groundwater resources by using water conservancy projects. From the perspective of ecology and resource sustainability, in order to avoid excessive exploitation, the development of water resources should be strictly based on sustainable development policies. At present, the comprehensive development and utilization of water resources in China have reached a very high level, among which, the utilization rate of water resources in the Huaihe River, Haihe River, and Yellow River has reached a very high level, i.e., 40% above the international standard[44]. If we continue to exploit water resources, it may exacerbate the problems of overexploitation of groundwater, ecological damage, and environmental degradation, so the supply of blue water footprint will not change much in the future. The imported water footprint is related to the grain and meat self-sufficiency rate, policy, economy, and other factors, and there is strong uncertainty. Considering the supply side of the water footprint, it is meaningless to improve the water footprint supply-demand ratio by increasing the imported water footprint and increasing the supply of the blue water footprint. According to the actual situation of water resources utilization in China, accelerating the popularization of recycling water utilization technology and improving the utilization efficiency of precipitation resources can effectively improve the supply of the recycling water footprint and the green water footprint, and alleviate the pressure of water.

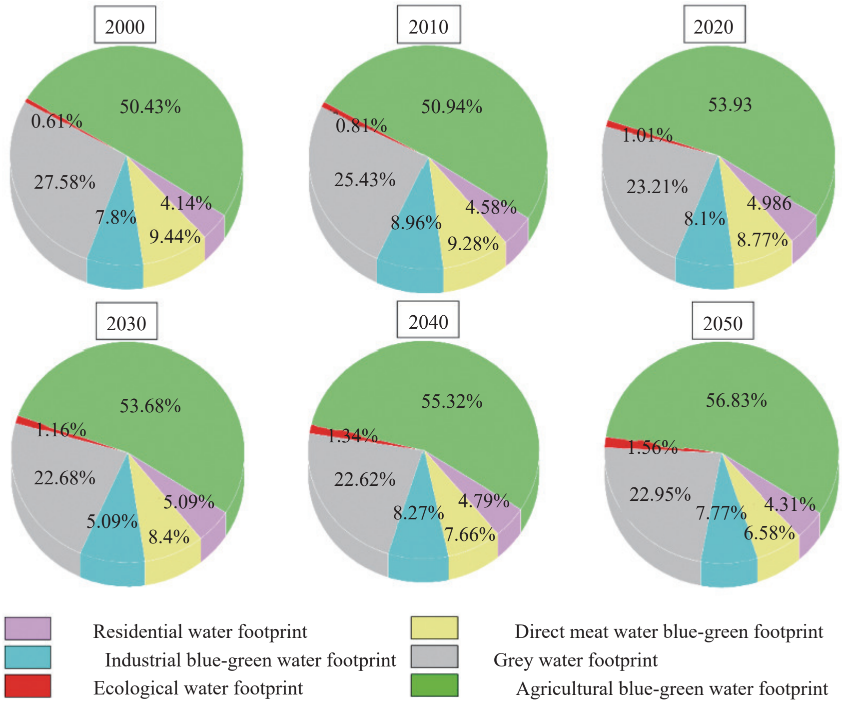


Figure 11 Composition of the water footprint demand of China

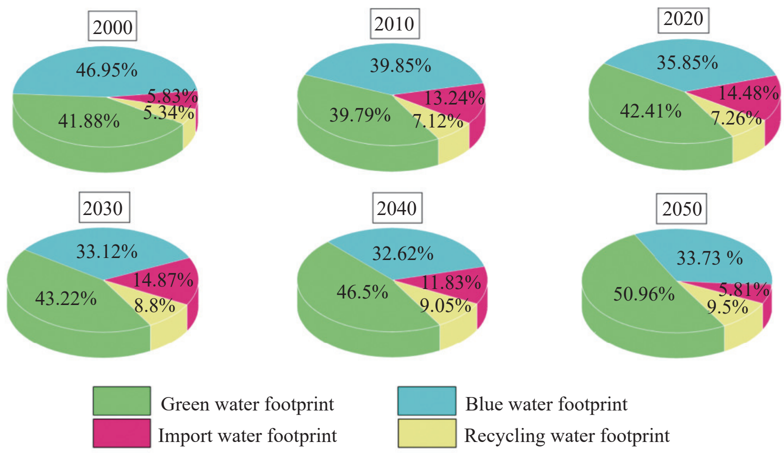


Figure 12 Composition structure of the water footprint of China

To summarize, based on the current development pattern, China's water footprint will be in a long-term unbalanced state of supply and demand in the future. From supply-side and demand-side analyses, to solve the water support capability problem, we need to start from three aspects: water conservation, pollution control, and increasing the water resource supply. Compared with the increasing demand for water, the investment in agricultural water conservation in China is still insufficient, so more investment should be made in agricultural water conservation. Specific measures such as developing and popularizing water-saving irrigation equipment, developing new materials to reduce water loss, strengthening the management of irrigated areas, and improving irrigation techniques can be taken. China has a huge potential in the field of pollution control. In the future, on the basis of accelerating the construction of sewage treatment projects and popularizing sewage treatment technologies, we should continue to strengthen and improve the utilization system of reclaimed water and industrial recycling water, so as to further improve the efficiency of sewage treatment, reduce pollution, and improve the recycling of water resources. In addition, China should continue to accelerate the construction of rainwater-collection projects, prevent the loss of rainwater and flood resources by building ditches and drainage and settling ponds to store rainwater to the maximum extent and make use of it.

3.2.2 Evaluation of grain and meat support capability issues

Before 2036, China's population growth and the improvement of living standards will lead to a continuous increase in grain demand, and grain output fluctuates with the demand. Under the combined impact of the two factors, China's grain self-sufficiency would fluctuate between 80% and 91%. After 2036, the decrease of China's population would reduce the demand for grain and alleviate the pressure of grain self-sufficiency, but the grain gap would not completely disappear, and the grain self-sufficiency gap would always exist. It can be seen that with the current development model, China's grain resources will be in an unbalanced state of production and demand for a long time in the future, and the food support capability problem will be further sustained. Compared with the grain self-sufficiency rate, the meat self-sufficiency rate would be relatively stable, staying at 1.4-1.5 for a long time (Figure 13). Although there is no problem regarding the supply of meat, the high self-sufficiency rate indicates that there is overcapacity in the meat industry. If no policy intervention is carried out, it is bound to lead to the waste of food resources and water resources in China, aggravating the food support capability problem.

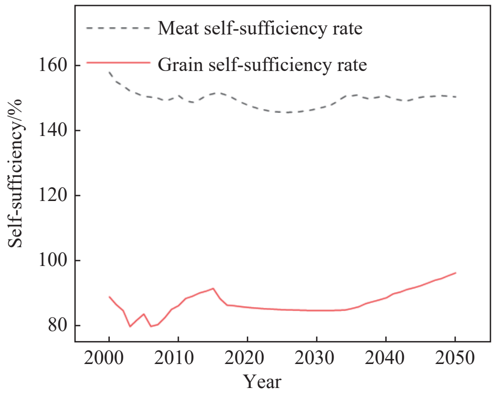


Figure 13 Simulation of grain and meat self-sufficiency rate of China

The process of animal husbandry requires direct consumption of grain feed, thus affecting the supply and demand of grain in China. In order to explore the internal relationship between grain supply and demand and meat farming, this paper analyzes the situation of meat consumption in China (Figure 14). During the research period, the proportion of grain demand for meat in China's grain demand would increase from 45.59% in 2000 to 63.1% in 2050 (Figure 14). It can be seen that consumption grain for meat production has gradually become a key factor affecting the rate of food self-sufficiency.

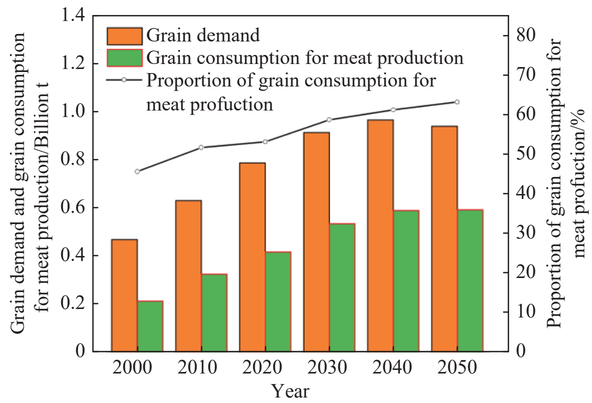
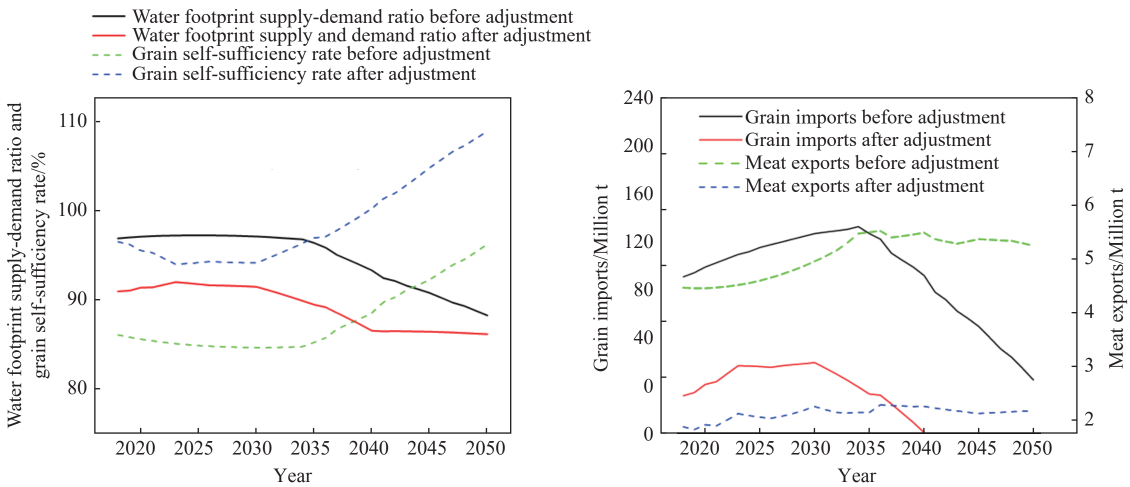


Figure 14 Simulation of grain consumption for meat production

Studies have shown that the consumption of meat production has become the main factor affecting the grain self-sufficiency rate[4]. In order to verify the quantitative influence of meat production on the grain self-sufficiency rate, this paper adjusts the meat production of all categories in the model to maintain the meat self-sufficiency rate of China at around 1.2 from 2017 to 2050 and carries out a water-grain-meat system simulation (Figure 15).



a. Simulation of water footprint supply-demand ratio and grain self-sufficiency ratio before and after adjustment

b. Simulation of grain import volume and meat export volume before and after adjustment

Figure 15 Simulation of the influence of the adjustment of meat self-sufficiency rate on the water-grain-meat system

When the meat self-sufficiency rate is controlled at 1.2, China's overall grain self-sufficiency rate would increase by about 10% in the future. After 2040, China would no longer rely on imports and reach full self-sufficiency (Figure 15a). Therefore, excess meat production capacity is a key factor in China's food support capability problems. Measures to control meat production not only reduce food dependency, but also reduce the water footprint of food imports, resulting in a decrease in the water footprint. At the same time, controlling meat production can also reduce the demand for the meat water footprint, which alleviates the pressure on water footprint supply and demand brought by the decrease of water footprint supply to some extent. According to the simulation results, before 2040, the water footprint supply-demand ratio would decrease by about 6% overall (Figure 15b) compared with that before the meat self-sufficiency ratio was adjusted. In 2040, China is expected to achieve the goal of self-sufficiency with respect to grain if grain output remains stable. The agricultural blue-green water footprint would not increase because the yield would be stable, which reduces the growth rate of water footprint demand. Therefore, the water footprint ratio after 2040 would be stable overall, and the gap between the water footprint supply and demand ratio before and after the adjustment would gradually narrow. It follows that while adjusting meat production will widen the gap between supply and demand in the water footprint, the impact will diminish over time.

In summary, food support capability can be solved by adjusting the industrial structure, reducing meat production, and then reducing grain consumption loss required by meat overcapacity. At the same time, regulation of meat production will put pressure on the water footprint supply and demand. Therefore, from the perspective of the water footprint supply and demand, measures to control meat production should be supplemented by measures to increase water footprint supply and demand so as to alleviate the pressure caused by the reduction of imported water footprint on water support capability.

4 Conclusions

The concept of the water footprint is introduced into the water-grain-meat system in China, and the key parameters of the water footprint in the system model are simulated. The results show that, according to the current development model, China will have no meat support capability problems in the future, but there are clear problems of water support capability and grain support capability. The problem of water support capability can be solved by increasing the water resource supply, reducing expenditure, and controlling pollution by adjusting the balance between the supply and demand of the water footprint. In the future, China should focus on improving agricultural water-saving efficiency, increasing investment in rainwater harvesting projects, strengthening sewage treatment, and increasing water resource recycling. The key to the grain support capability problem lies in the overcapacity of the meat industry. When the meat self-sufficiency rate is controlled at 1.2, China will achieve self-sufficiency in grain in 2040. Therefore, there is a need for China of controlling the development of the meat industry, reducing the overcapacity, and stabilizing the meat supply and demand so as to solve the current shortage of grain supply. The results of this article provide a basis for optimizing the structure of China's meat and grain industry and formulating policies for efficient utilization of water resources. At present, this paper only gives the solution of water footprint supply and demand from the qualitative point of view. In the future, parameter simulation and policy simulation can be further refined to provide the optimal solution to China's water support capability problems quantitatively.

Acknowledgements

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