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A system dynamics model to simulate the water-energy-food nexus of resource-based regions: A case study in Daqing City, China



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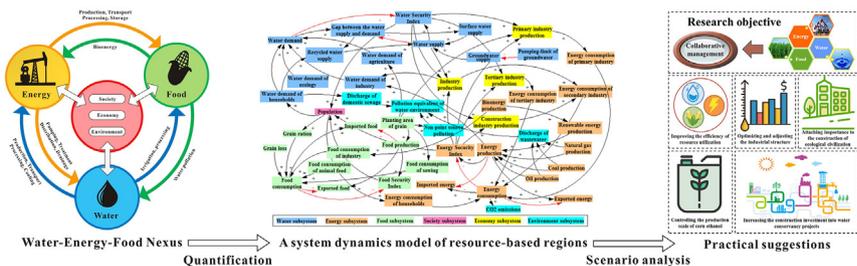
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HIGHLIGHTS

- A system dynamics model for the water-energy-food nexus of resource-based regions is developed.
- This nexus is simulated with classification of water, energy and food resources.
- The water-energy-food nexus is studied from both the supply and demand sides.
- The impacts of real policies on the water-energy-food nexus system are assessed.
- Adjusting production and saving water, energy and food have prominent co-benefits.

GRAPHICAL ABSTRACT



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ABSTRACT

Resource-based regions (RBRs) have made significant contributions to the social and economic development of nations. The long-term and high-intensity development of resources puts tremendous pressure on water, energy and food resources and the ecological environment. Exploring the water-energy-food nexus (WEF nexus, WEFN) of RBRs is key to making informed decisions about regional sustainable development. In this study, a feedback model for the WEFN of RBRs was developed using a system dynamics approach. The WEFN model not only describes the WEFN system from both the supply and demand sides, but also classifies WEF resources. Using Daqing, China, as a case study, five future scenarios were designed to explore the impacts of real policies designed by different government departments on the WEFN system. Comparing the predicted results of a scheme for business as usual, a scheme for developing bioenergy, a scheme for adjustment of the production structure, a scheme for strengthening the development of water and food resources and a scheme for saving WEF resources revealed that the schemes for adjustment of the production structure and for saving WEF resources will not only improve the security of WEF resources, but also reduce pollution of the water environment by human activities, which is conducive to improving the overall benefits of the WEFN system. Finally, some practical suggestions are put forward to promote the coordinated development of the WEFN system. The WEFN model is a multi-centric tool for integrated resources management, and can be expanded to other RBRs and provides scientific support for decision-makers.

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1. Introduction

As indispensable resources for human survival and development, water, energy and food are important topics for sustainable development studies of human society. With rapid population increase, urbanization and climate change, global demands for water, energy and food in 2050 will increase by 55%, 80% and 60%, respectively, compared with 2015 (IRENA, 2015). Shortages of resources in the world are becoming increasingly severe (Zhang et al., 2019a, 2019b). Water, energy and food are closely related resources (Alsaïdi and Elagib, 2017). The inter-relations between the water-energy-food nexus (WEF nexus, WEFN) components are represented in Fig. 1. With management policy directed to any single one among water, energy and food resources, it is difficult to meet the needs of collaborative management of multiple resources, which will lead to some unexpected, serious consequences (Karabulut et al., 2016). For example, the technology of seawater desalination and recycled water treatment can improve the development and utilization of water resources, but consumes large amounts of

energy (Mo et al., 2011; Gu et al., 2016). Trade-offs among water, energy and food resources are important measures to coordinate development of the WEFN system are important measures to achieve the global Sustainable Development Goals. Resource-based regions (RBRs) refer to regions where the exploitation and processing of local natural resources are the leading industries (Li et al., 2013). As the supply bases of energy, food and raw materials, RBRs have made significant contributions to the social and economic development of nations (Jing and Wang, 2020). The long-term and high-intensity development of resources puts tremendous pressure on water, energy and food resources and the ecological environment. Extensive production has led to increasingly serious environmental pollution (Li et al., 2020), which threatens the survival and development of RBRs. Therefore, exploring the WEFN of RBRs is key to making informed decisions about regional sustainable development.

The 2011 International Conference on the WEFN, held in Bonn, Germany, brought this topic to the international stage (Hoff, 2011). Since then, the research content and scope of the WEFN have gradually

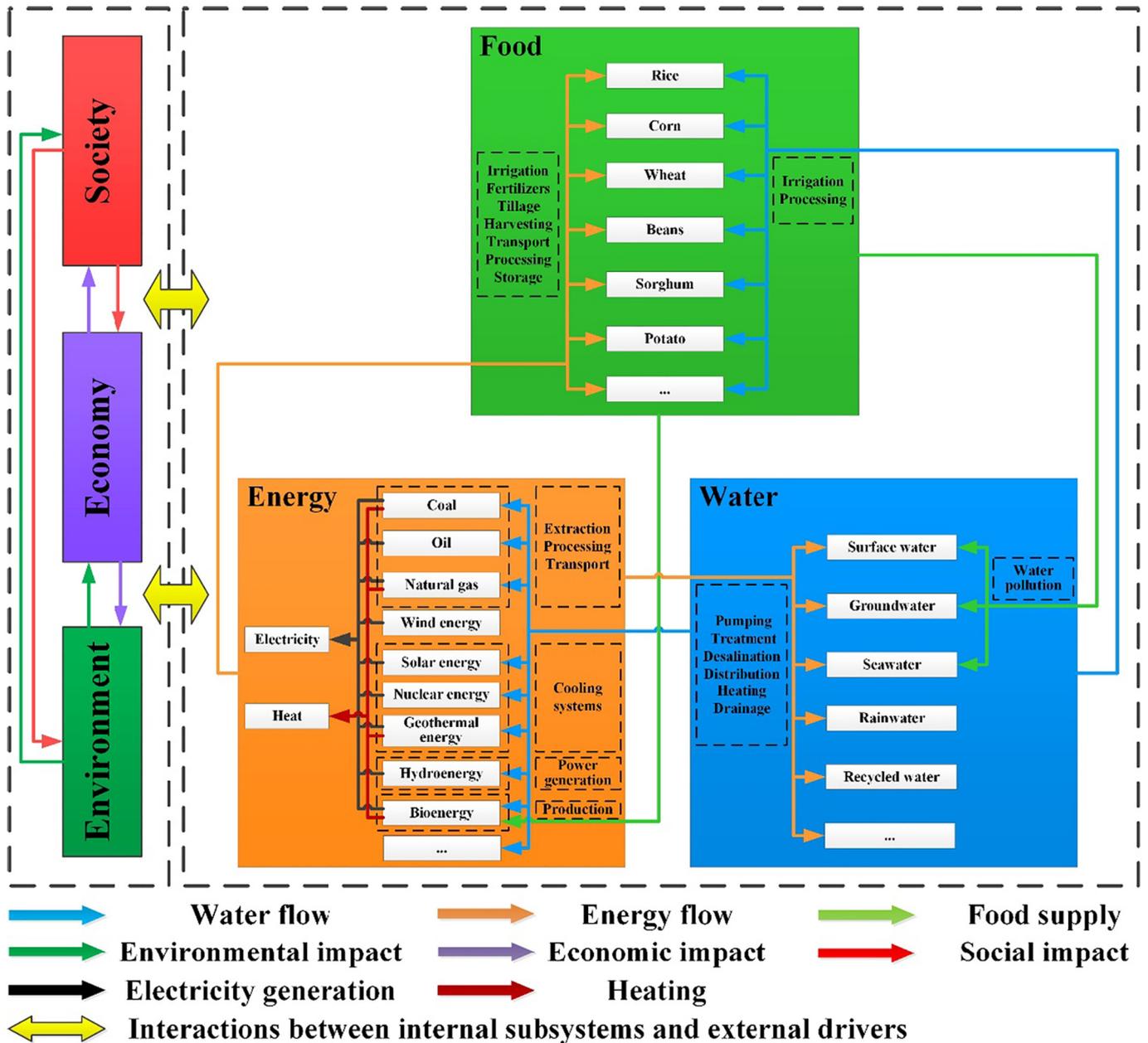


Fig. 1. Summary of the water-energy-food nexus.

diversified (Albrecht et al., 2018), across the global (Dodorico et al., 2018; Susnik, 2018), national (Lee et al., 2018; Wicaksono and Kang, 2019), regional (Cansinoloeza and Ponceortega, 2019; Si et al., 2019; Yang et al., 2018), urban (Romerolankao et al., 2017; Schlor et al., 2018) and household scales (Hussien et al., 2017; Spiegelberg et al., 2017). However, previous studies have mainly focused on the WEFN issues of metropolitan regions. Metropolitan regions are highly dependent on resources delivered from outside their physical boundaries (Heard et al., 2017). In contrast, the resources production of RBRs is often larger than their consumption. The WEFN of RBRs is less well-understood and has only recently started gaining attention from researchers. The most commonly used simulation models for the WEFN include the agent-based model (Bazzana et al., 2021; Ding et al., 2021; Falconer et al., 2020), life cycle assessment (Caputo et al., 2021; Leivas et al., 2020; Storch et al., 2020; Subramanian et al., 2021), and the input-output model (Lee et al., 2021; Tabatabaie and Murthy, 2021; White et al., 2018; Zhang et al., 2019a, 2019b). For instance, Abdel-Aal et al. (2020) developed an agent-based model to simulate the relations between the main players within the WEFN and took Great Britain as an example to quantify the impacts of future possible anaerobic digestion technology diffusion choices on the environment, society and economy. Their results showed that decentralisation resulted in the largest carbon reduction, but could incur more costs. Using a life cycle assessment method, Lin et al. (2019b) developed a GIS-based Regional Environmental Assessment Tool for WEFN, and indicated that non-nuclear homeland policy caused the lowest environmental impacts due to better energy structures and maintenance of agricultural lands. Feng et al. (2019) constructed a food-energy-water physical input-output model to quantify food, energy and water flows and applied it to the Detroit Metropolitan Area to demonstrate its usefulness. Their results suggested that intermediate processes used relatively large amounts of food, energy and water, and should be more concerned. However, the existing models are limited by the original design purpose and specific structure, and may lead to a partial description of the interactions and feedback mechanism of the WEFN (Miralleswilhelm, 2016). It is necessary to build a special model to provide a systematic and dynamic perspective of the WEFN. The system dynamics (SD) model is suitable for the study of complex systems that exhibit nonlinear, multi-feedback and time-varying properties (Yang et al., 2019). The SD model provides a feasible way to simulate the behaviors of the WEFN system and predict future scenarios. Many existing studies have failed to explore the potential impacts of real policy across all nexus sectors or to offer effective guidance because they lack real-world applicability and are limited to hypothetical scenarios (Sunik et al., 2021). Additionally, most studies involve simple linkages between the water, energy and food sectors, whereas far fewer SD models comprehensively analyze the WEFN system from both the supply and demand sides. For example, the energy sector often only refers to hydropower generation (Gallagher et al., 2020), without considering other electricity generation (e.g., thermal power, wind power, photovoltaic power and biomass power), raw resources production (e.g., crude oil, natural gas and coal), energy import and export (e.g., crude oil, natural gas, coal and electricity), and energy consumption (e.g., agriculture, industry, construction, tertiary industry and households). In addition, several scholars have tried to classify WEF resources in the process of SD model design. Resources classification can help the SD model to better simulate sector interactions and evaluate the trade-offs and benefits of different management policies.

This study addresses the above-mentioned gaps by developing a SD model to quantify the WEFN of RBRs. The WEFN model not only describes the WEFN system from both the supply and demand sides, but also classifies WEF resources. Taking Daqing, a typical energy and grain production base in China, as an example, scenario analysis was applied to examine the impacts of different development policies on the WEFN system, including business as usual, developing bioenergy, adjustment of the production structure, strengthening the development of water and food resources, and saving WEF resources. The predicted

outcomes were used to explore any side effects of those policies and provide scientific support for decision-makers. The objectives of our study are to (1) establish a SD model for the WEFN of RBRs, (2) predict the impacts of real policies designed by different government departments in the WEFN system, and (3) provide decision-makers with practical suggestions to promote the coordinated development of the WEFN system. The proposed model is a multi-centric tool for integrated resources management, and can provide a scientific basis for other RBRs to formulate collaborative management strategies from the perspective of the WEFN.

2. Methods

2.1. Conceptual model of the WEFN

The WEFN system is a complex system composed of water, energy, food, society, the economy, and the environment (Zhang et al., 2018a). Because there are many causal relationships among the subsystems and variables in the WEFN system, it is difficult to simulate the WEFN system with general mathematical methods. SD is a method based on feedback control theory (Bahri, 2020). The SD model can be used to study the interactions of the WEFN system qualitatively and quantitatively (Bakhshianlamouki et al., 2020) to realize system simulation and prediction.

The WEFN of RBRs can be conceptualized using a causal loop diagram as shown in Fig. 2. The parts in green, blue, orange, pink, yellow and cyan relate to the food, water, energy, society, economy and environment subsystems, respectively. The interactions among variables in the WEFN system are indicated by black arrows for positive correlation and red arrows for negative correlation. The simulation model was constructed using VENSIM software.

2.2. WEFN model formulation

In the following sections, the subsystems of the WEFN system are briefly described. The key variables of the WEFN system are the Water Security Index (the ratio of water supply to demand), the Energy Security Index (the ratio of energy production to consumption) and the Food Security Index (the ratio of food production to consumption). Food import would not be able to enhance the Food Security Index because the self-sufficiency of the study area depends on the production of the region (Ravar et al., 2020). The Energy Security Index is similar to the Food Security Index. The governing equations in each subsystem were developed based on the law of conservation of mass and a flowchart of each subsystem.

2.2.1. Water subsystem

In the water subsystem, the supply side is composed of surface water, groundwater and recycled water, and the demand side is divided into four sectors: agriculture, industry, households and ecology. The energy subsystem is related to the water subsystem through the water demand for energy production, processing and thermal power generation. The food subsystem is related to the water subsystem through the water demand for grain production and processing. The society subsystem is related to the water subsystem through the water demand for urban and rural households.

2.2.2. Energy subsystem

In the energy subsystem, the supply side is composed of coal, oil, natural gas and renewable energy, and the demand side is divided into four sectors: primary industry, secondary industry, tertiary industry and households. The water subsystem is related to the energy subsystem through the energy demand for water extraction, treatment, distribution, drainage and wastewater reuse. The food subsystem is related to the energy subsystem through the energy demand for grain production. The society subsystem is related to the energy subsystem

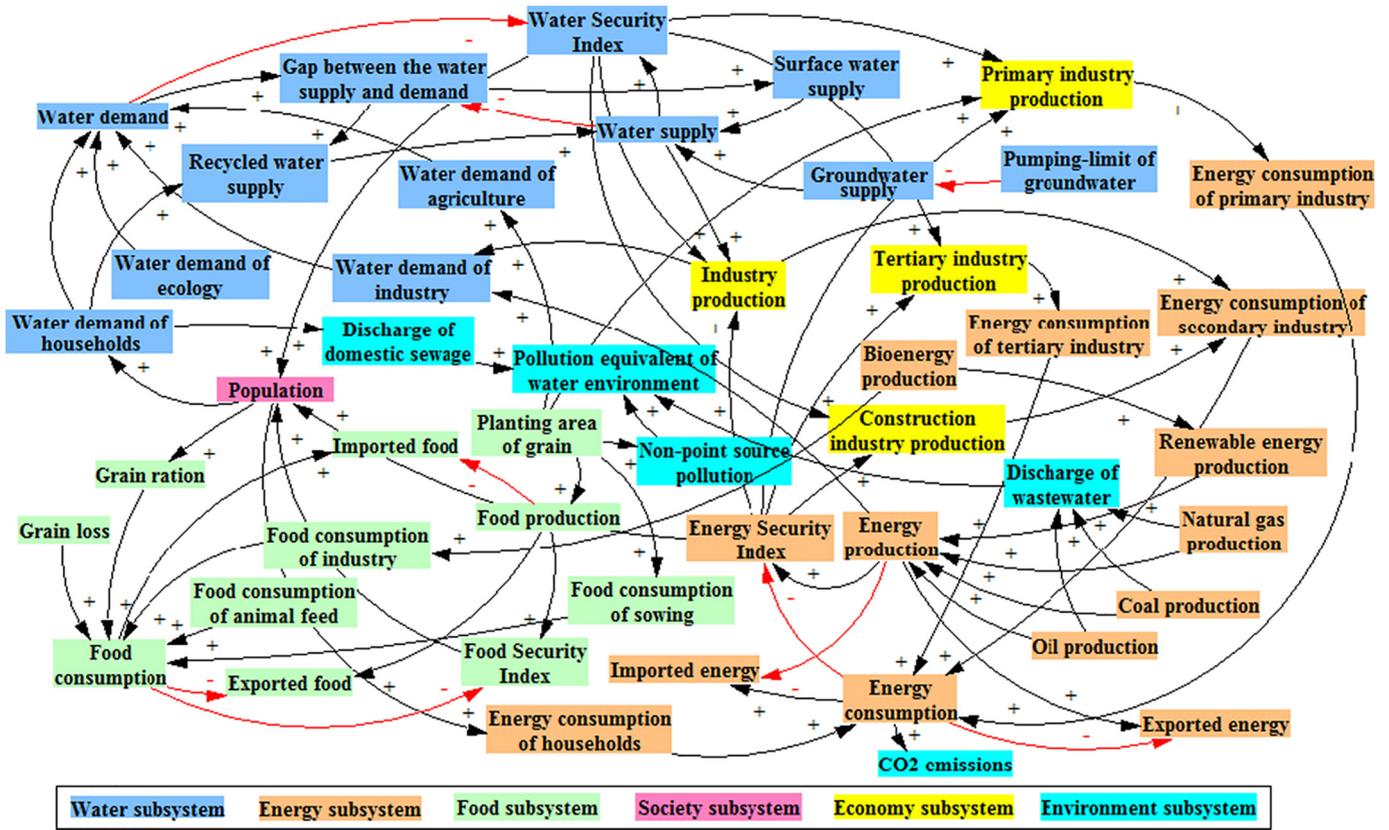


Fig. 2. Causal loop diagram for the water-energy-food nexus system of resource-based regions.

through the energy demand for urban and rural households. The society subsystem is related to the energy subsystem through the energy demand for primary, secondary, and tertiary industries.

2.2.3. Food subsystem

In the food subsystem, the supply side is composed of production of corn, rice, beans and wheat, and the demand side is divided into five sectors: animal feed, industry, grain ration, grain loss and sowing. The energy subsystem is related to the food subsystem through the crop demand for production of bioenergy (fuel ethanol). As an alternative fuel, fuel ethanol can be mixed with gasoline in a certain proportion to produce ethanol gasoline, thereby reducing the consumption of oil, but its production requires consumption of corn and water resources, which leads to interrelation of the energy, water and food subsystems. The society subsystem is related to the food subsystem through the food demand for grain rations of urban and rural households.

2.2.4. Society subsystem

For the society subsystem, the urban population and rural population are selected as the research objects. Water, energy and food are the three essential resources for human survival. Exploitation and processing of natural resources are the leading industries in RBRs. The single economic structure leads to a single employment structure. When the resources are exhausted, problems of lay-offs and unemployment will occur, resulting in population loss. Whether the supplies of water, energy and food can meet social needs will directly affect regional population change. Therefore, in this study, the Water Security Index, Energy Security Index and Food Security Index are taken as limiting factors (Eq. (1)) of population change to reflect the impacts of the water subsystem, energy subsystem and food subsystem on the society subsystem (Bernard and David, 2018; Purwanto et al., 2019; Ravar et al., 2020).

$$\frac{dP}{dt} = SI_{WEF} \cdot cr_p \cdot P \tag{1}$$

$$SI_{WEF} = IF \text{ THEN ELSE}(\text{MIN}(SI_W, SI_E, SI_F) \geq 100, 1, \text{MIN}(SI_W, SI_E, SI_F)/100) \tag{2}$$

where P is the total population (people), cr_p is the change rate of population, SI_{WEF} is the Resources Security Index of water-energy-food, SI_W is the Water Security Index, SI_E is the Energy Security Index, and SI_F is the Food Security Index.

2.2.5. Economy subsystem

For the economy subsystem, the output values of primary industry, secondary industry and tertiary industry are selected as the research objects. Water and energy are important strategic resources for social and economic development. The import of resources from outside the region will increase the cost of resource use, and will make the development of the region vulnerable to external shocks. If the supplies of water and energy resources cannot meet social needs, the economic development of the region will be affected. Therefore, in this study, the Water Security Index and Energy Security Index are taken as limiting factors (Eq. (3)) of economic growth to reflect the impacts of the water subsystem and energy subsystem on the economy subsystem (Chen and Chen, 2020; Yang et al., 2019).

$$\frac{dOV_i}{dt} = SI_{WE} \cdot gr_i \cdot OV_i \tag{3}$$

$$SI_{WE} = IF \text{ THEN ELSE}(\text{MIN}(SI_W, SI_E) \geq 100, 1, \text{MIN}(SI_W, SI_E)/100) \tag{4}$$

where OV_i is the output value of primary industry, secondary industry or tertiary industry (yuan), gr_i is the growth rate of output value, and SI_{WE} is the Resources Security Index of water-energy.

2.2.6. Environment subsystem

For the environment subsystem, the pollutant equivalents of water environment and CO₂ emissions are selected as the research objects. The pollutant equivalent is a comprehensive index, which allows aggregating different types of pollutants according to their environmental and health impacts by assigning a specific coefficient representing their respective damage of each pollutant (Zhang et al., 2018b). The pollutant equivalent (Eq. (5)) can be calculated according to scientific method provided by China's Ministry of Environmental Protection, which comprehensively considers each pollutant's impact on ecological system, toxicity on organism and technical feasibility to remove (Yang and Wang, 1998). The discharge of domestic sewage, the non-point source pollution caused by grain-planting activities, and the discharge of wastewater from energy production processes will increase the pollutant equivalents of water environment. Chemical oxygen demand and ammonia nitrogen are selected as typical pollutants in the calculation process of the pollutant equivalent of households and energy production. Total phosphorus and total nitrogen are selected as typical pollutants in the calculation process of the pollutant equivalent of grain planting. Pollutant equivalent value of typical pollutant is shown in Table 1. The consumption of coal, oil and natural gas, the import of electricity and the production of fuel ethanol will increase CO₂ emissions. The environment subsystem establishes relationships with the energy subsystem, food subsystem and society subsystem based on the processes described above.

$$A_p = \sum_{i=1}^n \frac{Q_i}{W_i} \tag{5}$$

where A_p is the pollutant equivalents, Q_i is the emissions of pollutant i (kg), W_i is the pollutant equivalent value of pollutant i (kg), and n is the number of pollutants.

2.3. Model validation

To ensure that the model can truly reproduce the behavior of the system, the SD model should be validated before it is put into use. After the SD model was used for simulation, several representative variables were selected for the test. The simulation results were compared with historical data. The relative error (Eq. (6)), coefficient of determination (Eq. (7)) and discrepancy coefficient (Eq. (8)) were used to judge the reliability of the SD model.

$$M = \left| \frac{S_i - O_i}{O_i} \right| \times 100\% \tag{6}$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (S_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O}_i)^2} \tag{7}$$

$$U_0 = \frac{\sqrt{\sum_{i=1}^n (S_i - O_i)^2}}{\sqrt{\sum_{i=1}^n S_i^2} + \sqrt{\sum_{i=1}^n O_i^2}} \tag{8}$$

Table 1
Pollutant equivalent value of typical pollutant.

Pollutant	Pollutant equivalent value (kg)
Chemical oxygen demand	1
Ammonia nitrogen	0.8
Total phosphorus	0.25
Total nitrogen	0.8

where M is the relative error, S_i is the simulated value, O_i is the historical value, \bar{O}_i is the average of historical values, R^2 is the coefficient of determination, U_0 is the discrepancy coefficient, and n is the number of historical values.

3. Case study

3.1. Study area

Daqing is a resource-based region located in Heilongjiang Province, Northeast China (Fig. 3), covering 22,161 km², and is characterized by a temperate continental monsoon climate. Daqing is not only the location of the largest oil field in China, but is also an advanced city for grain production. After years of high-intensity mining, the ability to guarantee the city's energy supply gradually declined. The production of oil decreased from 4495.10 × 10⁴ t in 2005 to 3400.03 × 10⁴ t in 2017. The extensive mode of production has caused the soil fertility to decrease, and the grain yield is not high. The grain type has gradually shifted to higher income-producing, higher water demanding varieties. In addition, Daqing City is located in the noncontributing area of the Songnen Plain, and water resources are relatively scarce. The regional volume of water resources per capita is only 714 m³, below the standard required (1000 m³) for a region to maintain economic and social development (Alcamo et al., 2007). The urban water supply mainly comes from water diversion from the Nenjiang River and groundwater exploitation. With the rapid development of the social economy and the continuous increase of the urbanization level, both water shortages and environmental pollution have become increasingly prominent. These have become the main bottlenecks restricting energy and food production. To provide an effective collaborative management scheme for the water, energy and food sectors and enable Daqing City to export more energy and food for the country, the need to conduct in-depth research on the WEFN of RBRs is urgent.

The Sankey diagram of water, energy and food flows of Daqing in 2017 is shown in Fig. 4. In terms of water supply, surface water accounted for 73.63% of the total, followed by groundwater (24.80%) and recycled water (1.57%). In terms of water withdrawal, agriculture accounted for 75.62% of the total, followed by industry (15.90%), households (6.21%) and ecology (2.27%). In terms of energy supply, oil accounted for 73.61% of the total, followed by imported energy (17.83%), natural gas (8.09%) and new energy (0.47%). In terms of energy consumption, industry accounted for 88.49% of the total, followed by tertiary industry (8.05%), households (2.37%), agriculture (1.04%) and construction (0.05%). The exported energy is composed of oil (95.02%) and natural gas (4.98%). In terms of food production, corn accounted for 76.45% of the total, followed by rice (19.11%), beans (4.10%) and wheat (0.34%). The imported food is composed of wheat (97.92%) and beans (2.08%). In terms of food consumption, animal feed accounted for 37.10% of the total, followed by industry (33.79%), grain ration (22.69%), grain loss (4.72%) and sowing (1.70%). The exported food is composed of corn (83.57%) and rice (16.43%).

From the perspective of the WEFN, energy-related water withdrawal and food-related water withdrawal accounted for 12.77% and 70.82% of the total water withdrawal (25.60 × 10⁸ m³), respectively. Water-related energy consumption and food-related energy consumption accounted for 0.38% and 0.45% of the total energy consumption (3548.21 × 10⁴ tce), respectively. Energy-related food consumption was 0 t, because the production of fuel ethanol did not start until 2020.

3.2. WEFN-Daqing model

3.2.1. Model boundary and data sources

In this study, considering the availability of data and the practicability of research results, we used the administrative area of Daqing as the model boundary. The simulation period was from 2005 to 2030 with annual time steps. The period of the model identification and verification

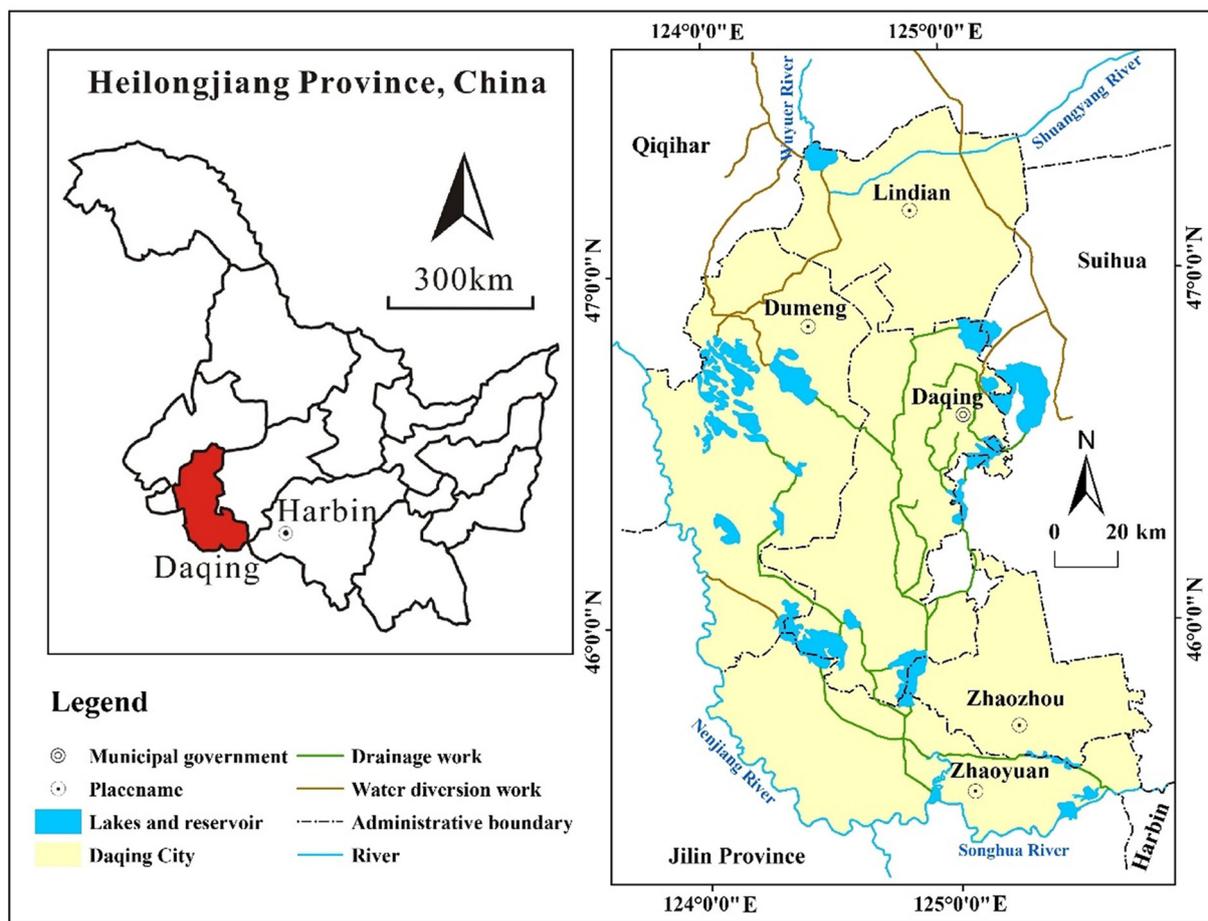


Fig. 3. Map of Daqing City.

period was from 2005 to 2017. The prediction period was from 2018 to 2030. The basic data and related parameters of the WEFN system mainly came from the Bureaus of Statistics, Water Resources, Energy, Grain and Environmental Protection. Some of the research data were obtained from field investigation of typical irrigation areas and petrochemical enterprises. The main variables and functions of the WEFN-Daqing model are summarized in Table A.1 (Appendix A). The stock and flow diagram of each subsystem is shown in Figs. A.1–A.6 (Appendix A).

3.2.2. Future scenarios

Scenario analysis was used in the WEFN-Daqing model to predict future supply and demand of WEF. To simulate the impacts of the resources development plans designed by different government departments on the WEFN system, five scenarios were proposed. Detailed information on each of the schemes is shown in Table 2. The scheme for business as usual (BAU) can reflect the development trend of the WEFN system without significant changes in the economic development model, and its result is the basis for comparative analysis of other scenarios. The scheme for the development of bioenergy (BIO) aims to simulate and predict the development plan of bioenergy in Daqing (Daqing Municipal Bureau of Energy, 2018). Based on the results of the multi-objective optimization model (Appendix B), a scheme for adjustment of the production structure (APS) is proposed, which focuses on adjustment of the supply side of energy and food. The parameters of energy and food resources are set according to the sustainable development plan of the Daqing oilfield (Daqing Oilfield, 2015) and the development plan of modern agriculture in Daqing (Daqing Municipal Bureau of Agriculture and Countryside, 2017). The scheme for strengthening the development of water and food resources

(SDWF) focuses on the adjustment of the supply side of water and food. The SDWF scenario refers to the 14th five-year development plan of water conservancy (Daqing Municipal Bureau of Water Affairs, 2019) and the 14th five-year development plan of the planting industry in Daqing (Daqing Municipal Bureau of Agriculture and Countryside, 2019). The scheme for saving WEF resources (SWEF) focuses on adjusting the demand side of the WEFN system. The parameters in the SWEF scenario are assumed based on related research papers (Lin et al., 2019a; Ravar et al., 2020). By simulating these scenarios, the direct and indirect impacts of each scenario on different sectors can be compared and assessed.

4. Results and discussion

4.1. Model validation

The validation results of the WEFN-Daqing model are presented in Figs. 5–6. Based on comparison of the simulations with historical data for the period 2005–2017, the simulation results of eight representative variables show good agreement with observations, both in terms of absolute numbers and historical trends. The relative error of each indicator in the model is no more than 10%, which falls within the acceptable range (Yang et al., 2019; Wang et al., 2021). The R^2 values are close to 1, which reveals that there are no significant differences between the simulated and historical data (Purwanto et al., 2021). The U_0 values are close to 0, which indicates that the behaviors of the WEFN system can be accurately simulated (Naderi et al., 2021). The WEFN-Daqing model can be used to predict the development trend of the WEFN system and provide support for scenario analysis.

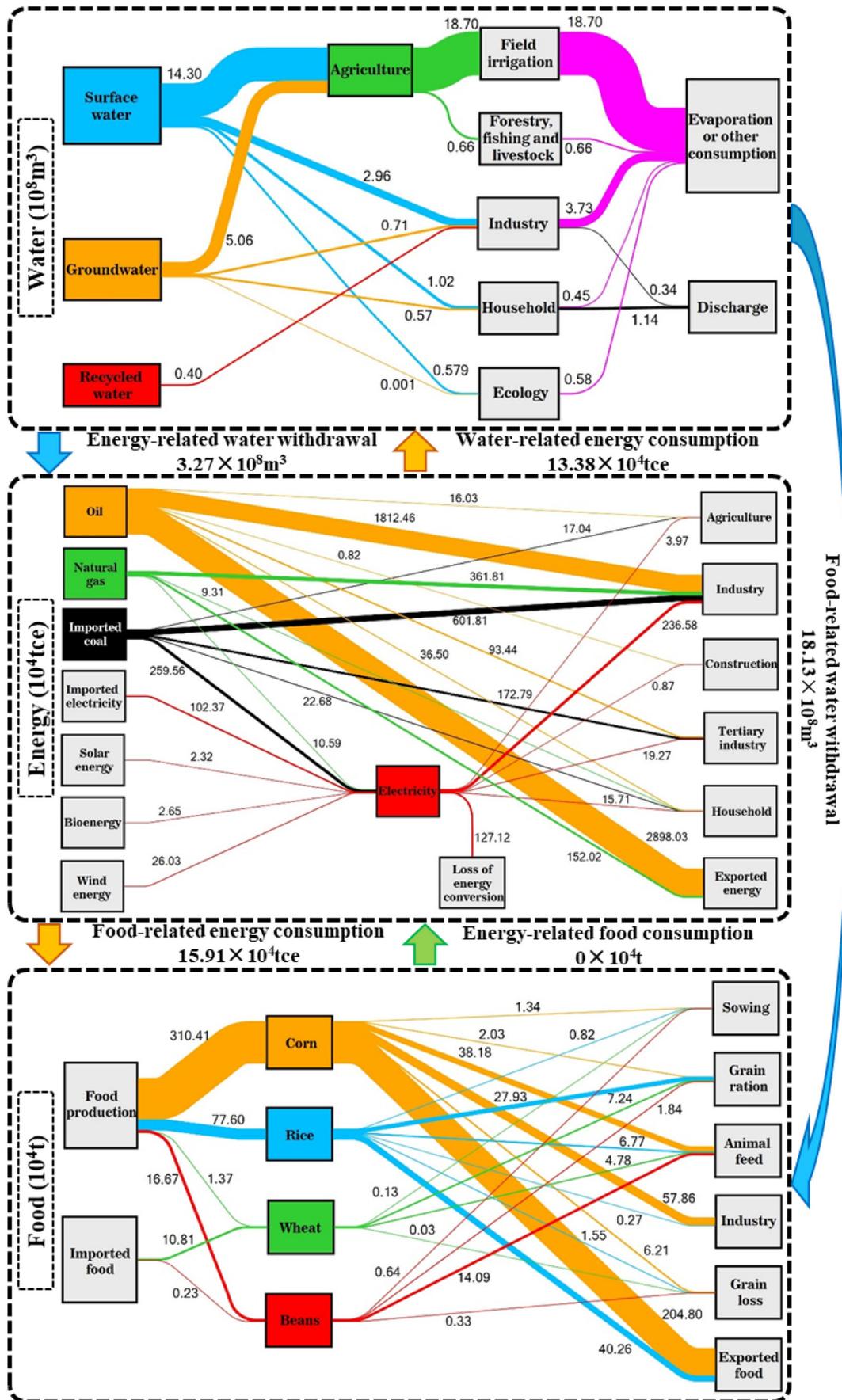


Fig. 4. Sankey diagram of water, energy and food flows of Daqing in 2017.

Table 2
Future scenarios in the WEFN-Daqing model.

Full name of scenario	Abbreviation	Main assumptions
Business as usual	BAU	The parameters in the BAU scenario are set according to the 14th five-year development plan of Daqing and the development law from 2005 to 2017.
Development of bioenergy	BIO	Referring to the development plan of bioenergy in Daqing, fuel ethanol is produced from 2020 onward, with an annual output of 30×10^4 t.
Adjustment of production structure	APS	The planting areas of corn, rice, wheat and beans in 2030 are set at 41.86×10^4 hm ² , 11.89×10^4 hm ² , 348.48 hm ² and 14.14×10^4 hm ² respectively, and oil and natural gas production in 2030 are set at 2672.15×10^4 t and 67.11×10^8 m ³ respectively. The data of other forecast years are obtained by interpolation.
Strengthening development of water and food resources	SDWF	Compared with BAU, the surface water supply, groundwater supply and reuse rate of domestic sewage are increased by 10%, and the grain yield per unit area is increased by 10%.
Saving WEF resources	SWEF	The water efficiencies in grain production, oil and gas exploitation and thermal power generation are increased by 10%, and the energy efficiencies in water resources development, grain production and industrial production are increased by 10%. In addition, water, energy and food consumption per capita is reduced by 10%.

4.2. Simulation results under different scenarios

4.2.1. Comparison of scenarios

Five scenarios were simulated by the WEFN-Daqing model. In this study, the balance of supply and demand for resources and the

development trends of society, the economy and the environment were analyzed to intuitively reveal the impacts of the five plans on the future development of the WEFN system.

(1) Balance analysis of supply and demand for water

The Water Security Index for different scenarios is shown in Fig. 7. In the BAU scenario, the Water Security Index decreases from 78.96% in 2018 to 76.40% in 2030. The gap between water supply and demand increases from 6.74×10^8 m³ in 2018 to 8.17×10^8 m³ in 2030. Overall, the Water Security Index in the APS scenario first increases and then decreases, whereas the Water Security Index in other scenarios shows a downward trend. The order of the Water Security Index is SDWF > SWEF > APS > BAU > BIO. The Water Security Index in the BIO scenario is lower than that in the BAU scenario after 2020, because the production of fuel ethanol increases the water demand of Daqing. After adjustment of the energy production structure, the water demand for oil and gas exploitation in the APS scenario is higher than that in the BAU scenario. With the increasing proportion of upland crop area and the decrease of rice planting area, the water demand for grain irrigation is effectively decreased (Fig. 8), such that the Water Security Index in the APS scenario is larger than that in the BAU scenario. The surface water supply, groundwater supply and reuse rate of domestic sewage in the SDWF scenario are increased by 10%, which can greatly alleviate the water shortage problem in Daqing. The Water Security Index in the SDWF scenario is always the largest. By improving the water efficiency in the processes of food and energy production and enhancing residents' awareness of water conservation, the water demand for energy and food production and residential water consumption are decreased, which can effectively increase the Water Security Index in the SWEF scenario.

(2) Balance analysis of supply and demand for energy

The Energy Security Index for different scenarios is shown in Fig. 9. In the BAU scenario, the Energy Security Index decreases from 148.56% in 2018 to 114.00% in 2030. Overall, the Energy Security

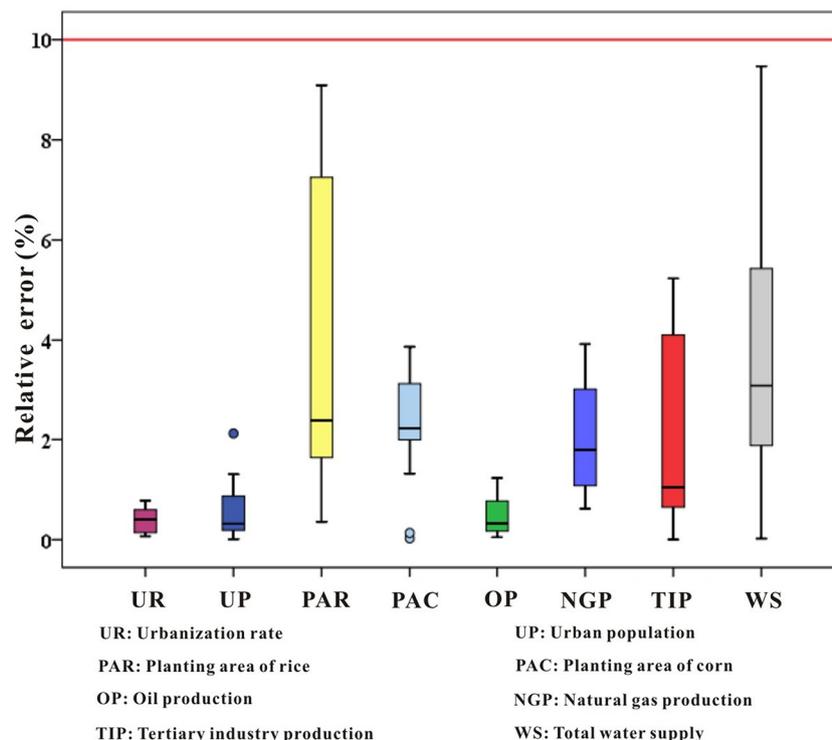


Fig. 5. Relative error of representative variables in the WEFN-Daqing model.

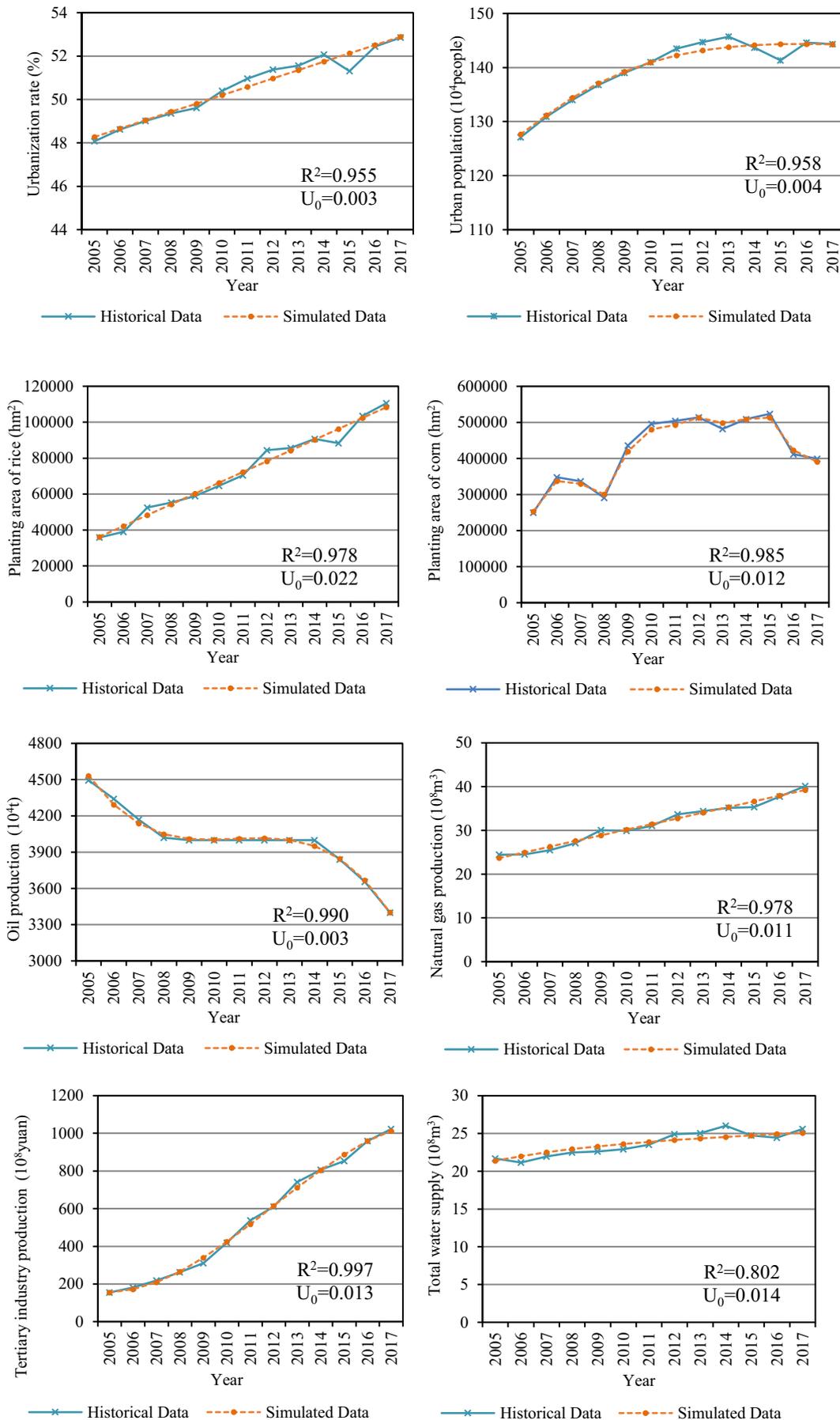


Fig. 6. Comparison of model simulations with historical data.

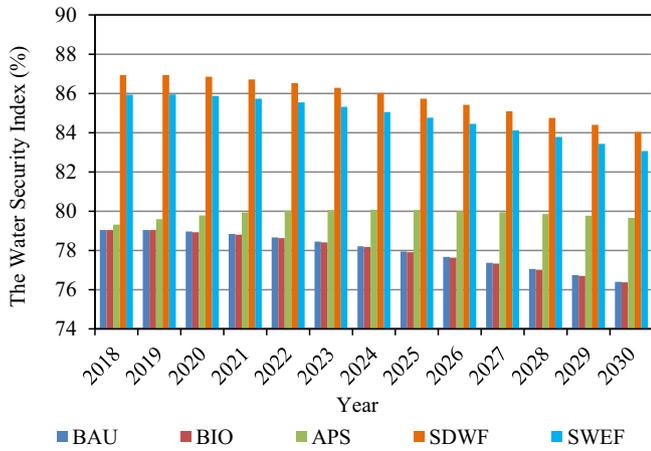


Fig. 7. The Water Security Index for different scenarios.

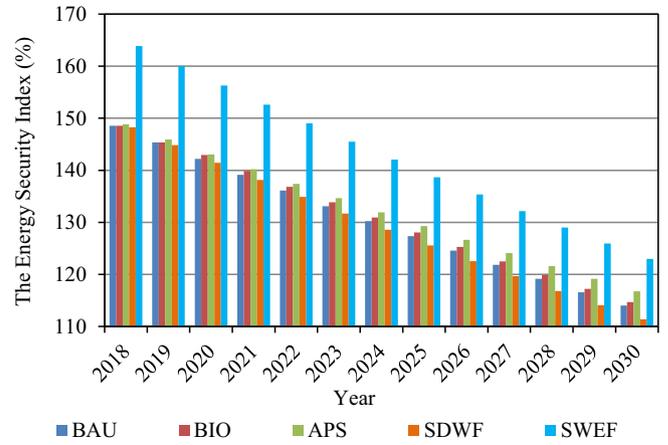


Fig. 9. The Energy Security Index for different scenarios.

Index in the five scenarios shows a downward trend. The order of the Energy Security Index is SWEF > APS > BIO > BAU > SDWF. The import and export of energy for different scenarios are shown in Fig. 10. The Energy Security Index in the BIO scenario improves after 2020, which is due to the fact that the production of fuel ethanol starts in Daqing in 2020. Fuel ethanol can replace some oil products, thereby reducing oil consumption and increasing the self-sufficiency rate of oil (Fig. 11). After adjustment of the energy production structure, the Energy Security Index in the APS scenario is higher than that in the BAU scenario. The export of oil and natural gas is increased with the increase of their production. With the increase of water supply, the energy consumption for water extraction, treatment, distribution, drainage and wastewater reuse in the SDWF scenario is increased. The improvement of the Water Security Index effectively promotes the development of society and the economy, resulting in an increase in the consumption of oil, natural gas, coal and electricity. The Energy Security Index in the SDWF scenario is decreased compared with the BAU scenario. By improving the energy efficiency in the process of water resources development, grain production and industrial production and enhancing residents' awareness of energy conservation, energy consumption is decreased, which can effectively increase the Energy Security Index in the SWEF scenario. The export of oil and natural gas is increased, and the import of coal and electricity is decreased.

(3) Balance analysis of supply and demand for food

The Food Security Index for different scenarios is shown in Fig. 12. In the BAU scenario, the Food Security Index decreases from 235.54% in

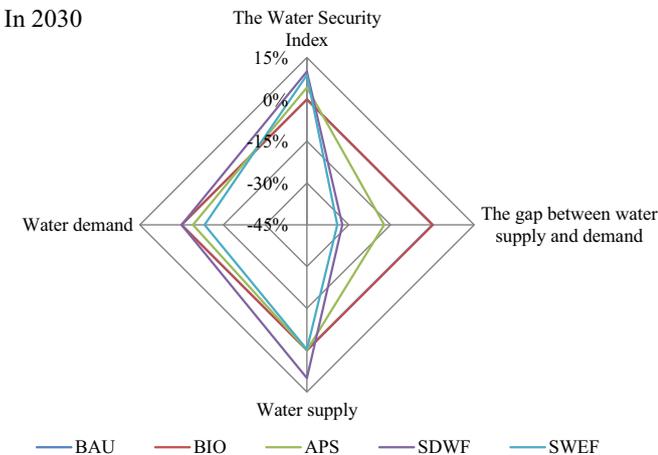


Fig. 8. Impacts of the different scenarios on indicators of the water subsystem.

2018 to 229.36% in 2030. Overall, the Food Security Index in the five scenarios shows a downward trend. The order of the Food Security Index is SDWF > SWEF > APS > BAU > BIO. The import and export of food for different scenarios are shown in Fig. 13. The Food Security Index in the BIO scenario decreases significantly after 2020, which is because the production of fuel ethanol begins in Daqing in 2020. The production of fuel ethanol consumes a large amount of corn, which reduces the self-sufficiency rate and export of corn. After the adjustment of the food production structure, the planting area of corn is increased, and the planting areas of rice, wheat and beans are decreased. Compared with the BAU scenario, the Food Security Index in the APS scenario is increased, and the self-sufficiency rates of rice, wheat and beans are decreased accordingly (Fig. 14). The Food Security Index in the SDWF scenario is always the largest. The increase of grain yield per unit area effectively improves the Food Security Index. The export of corn, rice and beans is increased, and the import of wheat is decreased. The enhancement of residents' awareness of food conservation reduces the consumption of grain ration, which makes the Food Security Index in the SWEF scenario larger than that in the BAU scenario.

(4) Development trends of society, economy and environment

GDP (Gross Domestic Product) per capita is an important indicator to measure the development of a regional economy. In the BAU scenario, the GDP per capita increases from 10.48×10^4 yuan in 2018 to 15.87×10^4 yuan in 2030. As shown in Fig. 15, the GDP per capita in the five scenarios shows an upward trend. The order of the GDP per capita is SDWF > SWEF > APS > BAU > BIO, which shows that the APS, SDWF and SWEF scenarios represent effective ways to improve the GDP per capita. Carbon dioxide (CO₂) emissions and the pollutant equivalents of water environment are important indicators to measure the impacts of human activities on the environment. In the BAU scenario, CO₂ emissions increase from 0.86×10^4 t in 2018 to 0.91×10^4 t in 2030. CO₂ emissions in the five scenarios show an upward trend. The order of the GDP per capita is SDWF > APS > BAU > BIO > SWEF, which shows that the BIO and SWEF scenarios represent effective ways to reduce CO₂ emissions. The pollutant equivalents of water environment in the five scenarios show a downward-upward trend. The order of the pollutant equivalent is SDWF > BAU > BIO > APS > SWEF, which shows that the APS and SWEF scenarios represent effective ways to reduce the pollutant equivalents of water environment.

4.2.2. Comprehensive evaluation of scenarios

In this study, the indicators of the WEFN system in the BAU scenario were taken as a benchmark. By analyzing the relative change of the indicators in the other four scenarios in 2030, comprehensive evaluation of the scenarios could be realized.

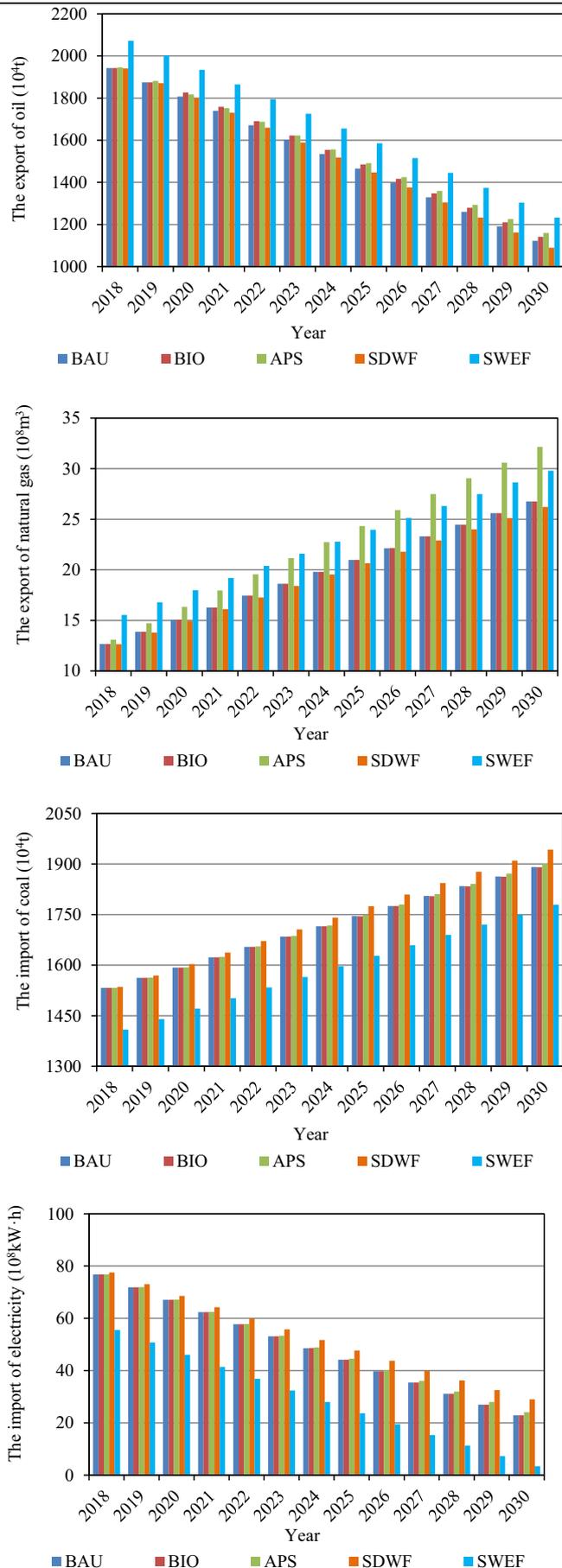


Fig. 10. Import and export of energy for different scenarios.

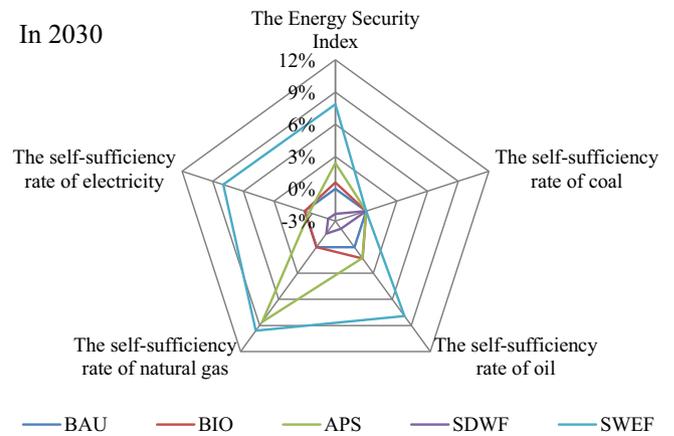


Fig. 11. The self-sufficiency rate of energy for different scenarios.

Comparing the predicted results of the different scenarios (Table 3) reveals that the production of fuel ethanol in the BIO scenario reduces CO₂ emissions, but requires the consumption of large amounts of corn and water (Fig. 16). The adjustment in the APS scenario alleviates the pressure of social development on water resources and increases the production of food, oil and natural gas resources. The measures taken in the SDWF scenario not only increase the water supply, food production and GDP per capita, but also increase the CO₂ emissions and energy consumption for water resources development. The improvement of the utilization efficiency of water, energy and food resources in the SWEF scenario can effectively reduce the demand for resources, increase GDP per capita, and reduce the pollutant equivalents of the water environment and CO₂ emissions.

In summary, the APS scenario and the SWEF scenario not only improve the security of WEF resources, but also reduce pollution of the water environment by human activities, which is conducive to promoting the coordinated development of the WEFN system. In addition, decision-makers can determine resource management objectives based on the actual situation, and combine the above scenarios to give full play to the advantages of the different scenarios and to overcome the disadvantages, so as to improve the comprehensive benefits of the WEFN system.

5. Practical suggestions

Based on the simulation research of the WEFN-Daqing model, the following suggestions are put forward (Fig. 17).

- (1) With the continuous development of the social economy and the steady improvement of people's living standards, the consumption

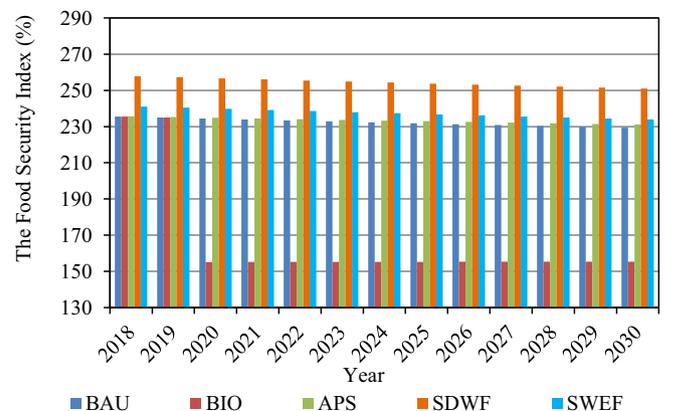


Fig. 12. The Food Security Index for different scenarios.

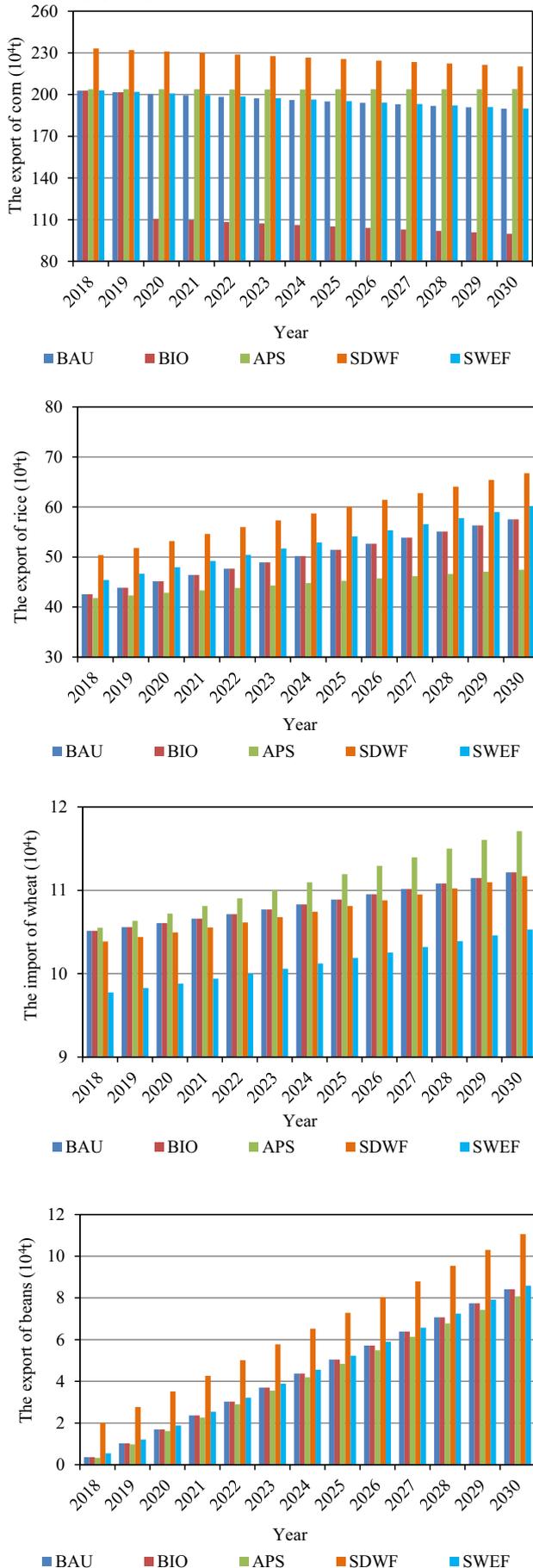


Fig. 13. Import and export of food for different scenarios.

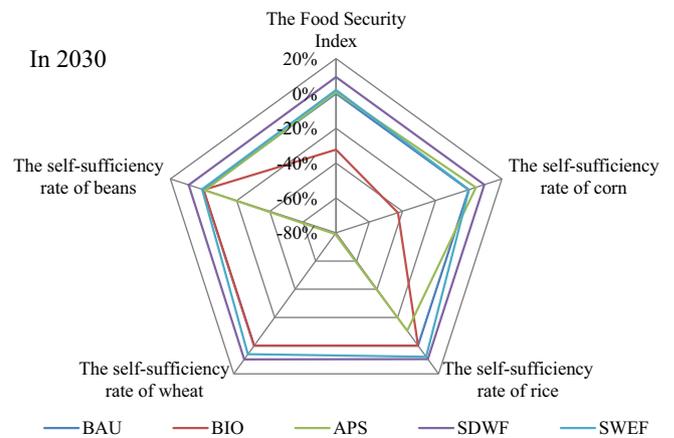


Fig. 14. The self-sufficiency rate of food for different scenarios.

of WEF resources continues to increase, resulting in the gradual increase of pressure on the resource supply. The simulation of the SWEF scenario shows that improving the efficiency of resource utilization can reduce water demand by 8.25%, energy consumption by 7.29%, food consumption by 1.95%, pollutant equivalents of water environment by 6.70% and CO₂ emissions by 9.02% in 2030. Therefore, improving the efficiency of resource utilization and building a conservation-minded society are fundamental ways to alleviate the contradiction between the supply and demand of resources.

- (2) Daqing City is a typical resource-based region. It is necessary to stabilize the production of oil and natural gas by means of strengthening exploration, promoting technological innovation, reducing cost and increasing efficiency. Combining the advantages of regional resources, the industrial structure should be adjusted. Wind energy, photovoltaics, bioenergy and other new energy industries should be vigorously developed. Industries with high energy and water consumption should be upgraded to control the rapid growth of energy and water consumption. As a modern agricultural demonstration zone, structural reform of the agricultural supply-side should be promoted. To improve the yield and quality of grain, it is necessary to further optimize the planting structure of grain and popularize advanced cultivation modes. The simulation of the APS scenario confirms that adjusting the production structure is an effective way to promote the coordinated development of the WEFN system. In addition, it is necessary to combine industrial characteristics and regional resource advantage characteristics, adopt measures suited to local conditions, rationally lay out related industries, reduce the cost of resource utilization, and improve economic benefits.
- (3) Based on the balance analysis of supply and demand for resources, the contradiction between supply and demand for water resources is the main factor that restricts the coordinated development of the WEFN system in Daqing. The simulation of the SDWF scenario shows that increasing the water supply can reduce the gap between water supply and demand by 32.32% and increase the ratio of water supply to demand from 76.40% to 84.03% in 2030. Strengthening the development of water resources can effectively alleviate the problem of water shortage. Daqing City is located in the noncontributing area of the Songnen Plain. There are no natural rivers in the area. Surface water resources are relatively scarce. The area of groundwater overexploitation needs further treatment, and the reuse rate of domestic sewage is low. Therefore, it is necessary to increase the construction investment into water conservancy projects, improve the development and utilization of extraneous water resources and unconventional water resources, and rationally exploit groundwater resources. At the

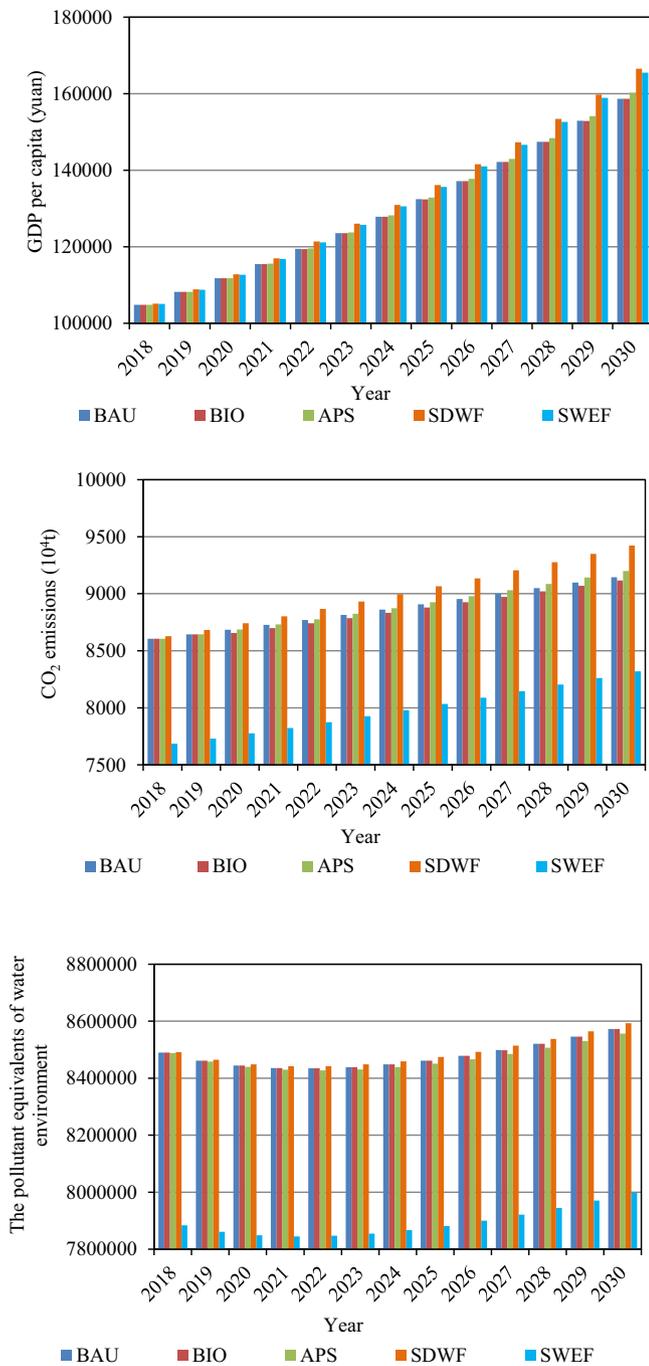


Fig. 15. Social, economic and environmental indicators for different scenarios.

same time, the energy efficiency in the process of water resources development should be improved to promote the coordination of the water-energy nexus.

- (4) Corn ethanol is an ideal form of bioenergy. Compared with gasoline, fuel ethanol can be burned completely, which can significantly reduce the emission of harmful substances in automobile exhaust, thereby reducing environmental pollution (Demirbas, 2009). However, the consumption of a large amount of corn will cause a sharp rise in food prices in the international market (Naylor et al., 2007), which in turn will cause fluctuations in the prices of livestock products and other related agricultural products. At the same time, in the case of limited arable land, expansion of the corn planting area will inevitably reduce the planting areas of other crops (Zhang et al., 2018a). The simulation result of the BIO

Table 3
Impacts of the different scenarios on indicators of the water-energy-food nexus system.

Scenario	BAU	BIO	APS	SDWF	SWEF
Water Security Index	0.00%	-0.04%	+4.26%	+9.99%	+8.71%
Energy Security Index	0.00%	+0.59%	+2.40%	-2.32%	+7.86%
Food Security Index	0.00%	-32.25%	+0.76%	+9.42%	+1.99%
GDP per capita	0.00%	NE	+0.97%	+4.94%	+4.30%
CO ₂ emissions	0.00%	-0.31%	+0.59%	+3.02%	-9.02%
The pollutant equivalents of water environment	0.00%	NE	-0.19%	+0.23%	-6.70%
The gap between water supply and demand	0.00%	+0.18%	-17.29%	-32.32%	-34.13%
The export of oil	0.00%	+1.73%	+3.35%	-2.91%	+9.85%
The export of natural gas	0.00%	NE	+20.18%	-2.06%	+11.41%
The import of coal	0.00%	NE	+0.54%	+2.75%	-5.91%
The import of electricity	0.00%	NE	+5.16%	+26.85%	-85.02%
The export of corn	0.00%	-47.41%	+7.44%	+16.05%	+0.10%
The export of rice	0.00%	NE	-17.46%	+16.00%	+4.59%
The export of beans	0.00%	NE	-3.98%	+31.47%	+2.07%
The import of wheat	0.00%	NE	+4.42%	-0.40%	-6.11%

green = increase in variable, yellow = decrease in variable, blue = no effect or negligible effect (NE) on the variable.

scenario shows that the production of fuel ethanol can reduce the ratio of food supply to demand from 229.36% to 155.39% in 2030, which has a great impact on food security in Daqing. The production scale of fuel ethanol should be strictly controlled. In addition, agricultural residues such as straw and livestock manure can be fully utilized to develop rural biogas and compressed fuel, and to promote the utilization of biomass for power generation.

- (5) The production process of energy and food is usually accompanied by the generation and discharge of pollutants. These pollutants enter the surface water and form regional non-point source pollution. Some pollutants infiltrate into the groundwater, which poses a serious threat to the water environment. The discharge of domestic sewage is increasing year by year, and environmental protection issues have become increasingly severe. The simulation results of five different scenarios confirm that economic growth will increase the pollutant equivalents of water environment to varying degrees. It is necessary to promote the standardized management of wastewater discharge of industrial enterprises and centralized control of water pollution in industrial agglomeration areas. The construction of urban sewage treatment facilities and pipe networks should be accelerated. Treated domestic sewage can be used for cooling water in thermal power plants and water supply for ecological landscapes. Agricultural non-point source pollution should be controlled. The utilization rate of fertilizers and pesticides should be improved. Planting crops with low fertilizer requirements and outstanding environmental benefits should be given priority in the areas where groundwater is vulnerable to pollution. The reuse rate of industrial water should be increased. The management of oil extraction wastewater should be further strengthened to ensure its reuse after advanced treatment. It is necessary to ensure the safety of drinking water sources, strengthen the prevention and control of water pollution in the drainage basin, remediate urban black-colored and odorous water bodies, and protect the wetland ecosystems.

6. Conclusions and prospects

RBRs have made significant contributions to the social and economic development of the nations. The long-term and high-intensity development of resources put tremendous pressure on WEF resources and the ecological environment. Exploring the WEFN of RBRs is the key to making informed decisions about regional sustainable development. In this study, a feedback model for the WEFN of RBRs was developed using a SD approach. Taking Daqing, a typical energy and grain production base in

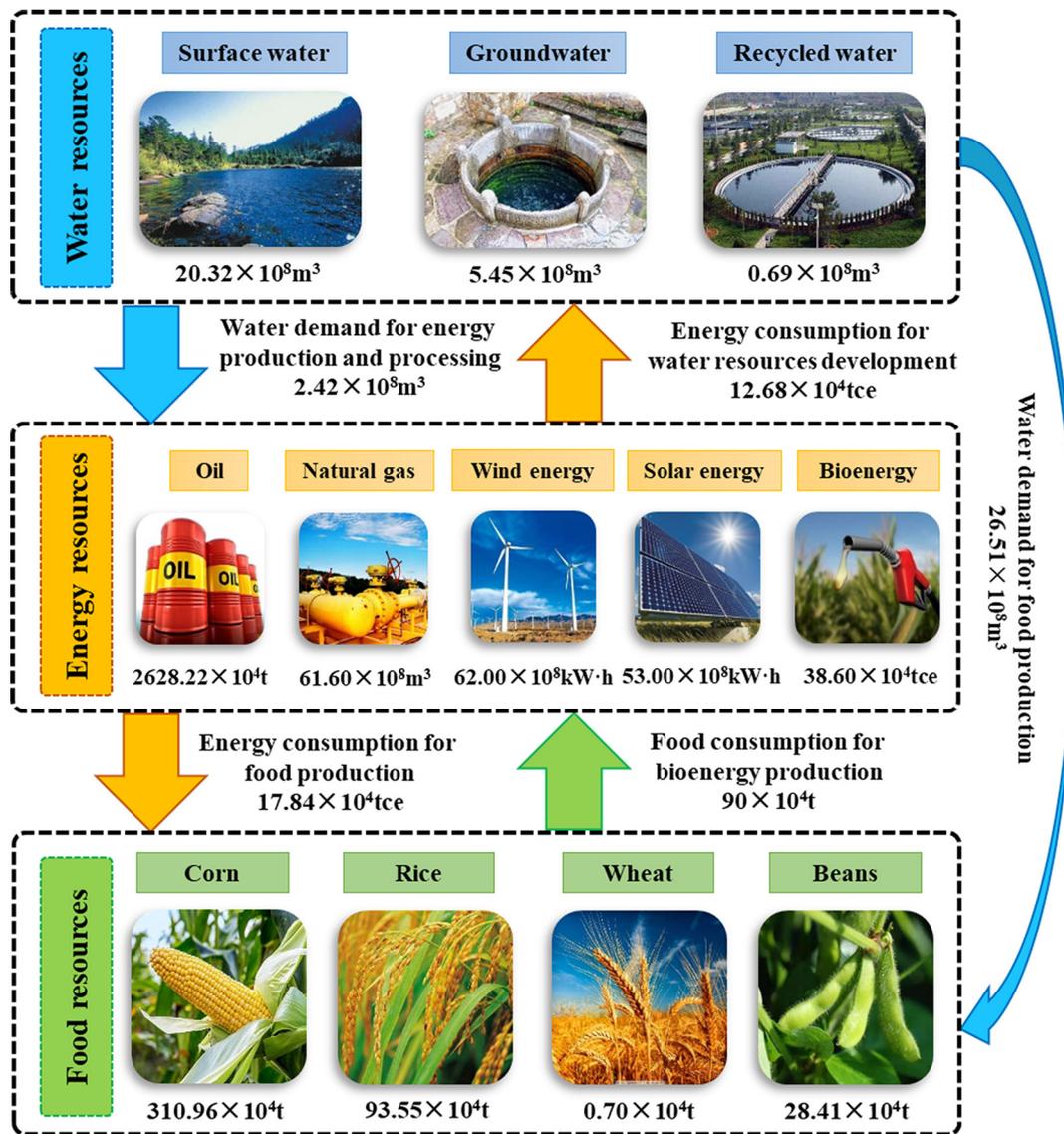


Fig. 16. The water-energy-food nexus of the scheme for the development of bioenergy in 2030.

China, as an example, scenario analysis was applied to explore the impacts of real policies on the WEFN system. After comparisons of the simulation results, we put forward practical suggestions for the coordinated development of the WEFN system. The main conclusions are as follows.

Comparing the predicted results of the BAU, BIO, APS, SDWF and SWEF scenarios reveals that the APS and SWEF scenarios not only improve the security of WEF resources, but also reduce the pollution of the water environment by human activities, which is conducive to improving the overall benefits of the WEFN system.

To further promote the coordinated development of the WEFN system in Daqing, it is necessary to improve the efficiency of resource utilization and explore the potential to save resources. Industrial structure should be adjusted and optimized in accordance with the characteristics of regional resources in Daqing. The construction investment of water conservancy projects should be increased. The development of extraneous water resources and unconventional water resources should be improved. The production scale of fuel ethanol should be strictly controlled. Comprehensive utilization of agricultural residues should be further promoted. The construction of ecological civilization should be taken seriously. Prevention and control of water pollution should be strengthened.

Some suggestions for SD model improvement in future steps are as follows:

- (1) Economic policies are an important means of resource management. It is suggested that economic models of the WEFN system can be developed in the next stage. The impacts of different economic policies can be evaluated through price mechanisms.
- (2) The WEFN model is used to simulate the impacts of different development plans on the WEFN system. However, the implementation of these plans may have additional costs, such as technology innovation, trade market and social costs. It is suggested that a follow-up study could further analyze the difficulty and costs of various measures to improve the feasibility of decision-making.
- (3) To facilitate the collection of data and avoid the impacts of missing data on this study, the food subsystem in the WEFN model only includes grain crops, such as corn, rice, wheat and beans. Meat, vegetables and other foods were not considered. It is suggested that the WEFN model can be further improved by expanding the food types included.
- (4) Short-term prediction of the WEFN system was carried out, and the impacts of climate change on the supply and demand sides

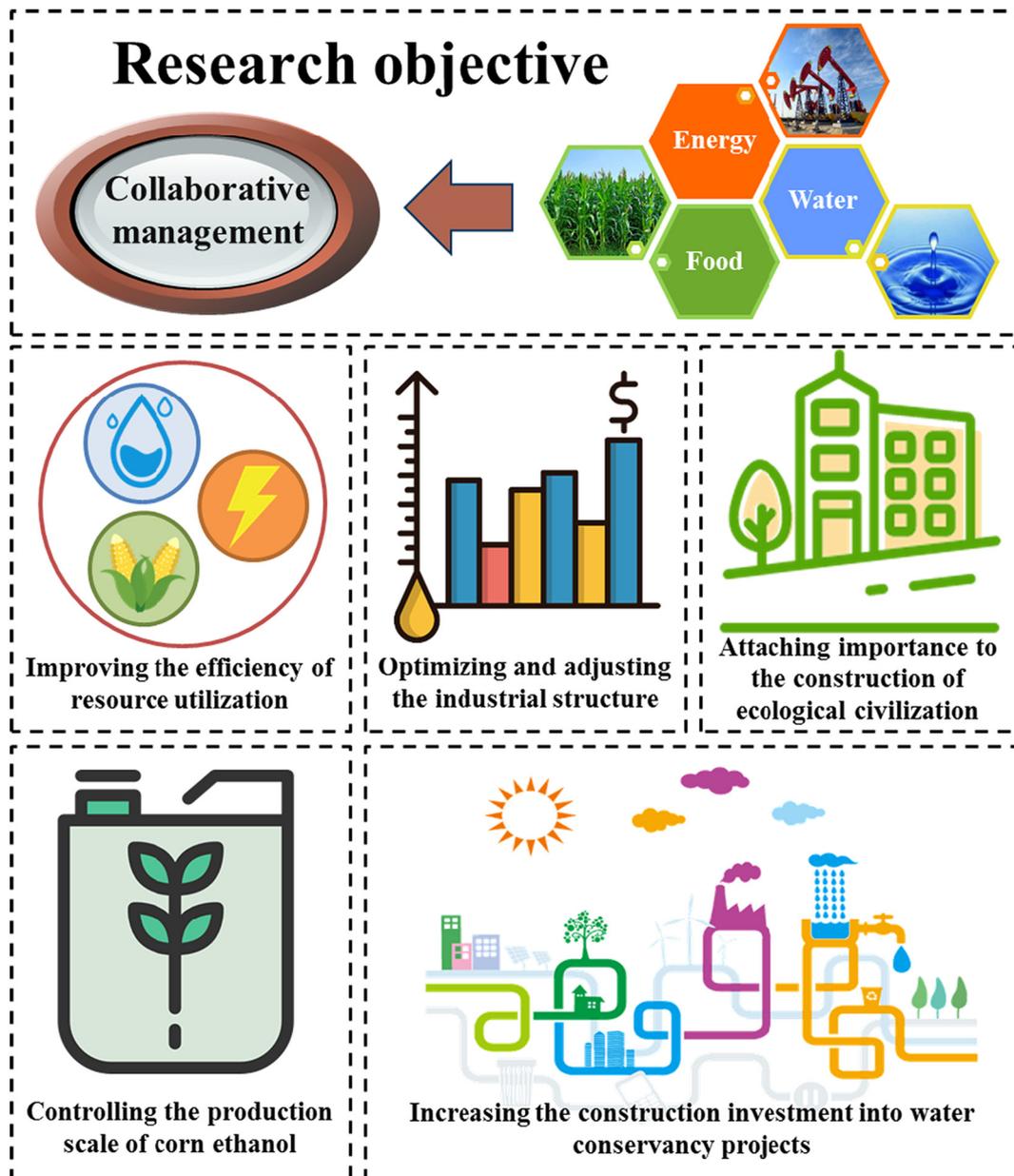


Fig. 17. Practical suggestions for coordinated development of the water-energy-food nexus system in Daqing.

of the WEFN were not given special consideration. It is suggested that in the next stage, research on the response of the WEFN system to different climate scenarios could be carried out to enhance the ability of regions to adapt to climate change and to provide a scientific basis for decision-makers to formulate collaborative management strategies.

CRediT authorship contribution statement

Chuanlei Wen: Conceptualization, Methodology, Software, Writing – original draft. **Weihong Dong:** Writing – review & editing, Project administration. **Qichen Zhang:** Investigation, Data curation. **Nannan He:** Validation. **Tong Li:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2021.150497>.

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