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Simulating and predicting the development trends of the water–energy–food–ecology system in Henan Province, China

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ABSTRACT

The intricate interplay among water, energy, food, and ecology underscores the paramount importance of investigating water–energy–food–ecology (WEFE) systems to foster regional sustainable development. In this study, a dynamic simulation model for the WEFE system was formulated using system dynamics, probing alterations in resource supply, demand dynamics, and ecosystem responses to resource shifts. Utilizing Henan Province as a case study and factoring in resource scarcity and environmental pollution, five scenarios were crafted to forecast WEFE system developmental trajectories from 2005 to 2035. The findings revealed the following key insights: (1) Within each subsystem, the food supply–demand balance ratio maintained a robust level of approximately 4.0. Conversely, the water and energy supply–demand balance ratio remained below 1.0 throughout the study period, indicating a worsening trend in the annual misalignment between supply and demand. Carbon dioxide (CO_2) emissions are projected to surge by 103%, posing challenges for future CO_2 emission reduction efforts. (2) Among the various scenarios, the Green Development (GD) scenario emerged as pivotal for fostering a coordinated development of the WEFE system. Implementation of the GD scenario showcased a notable 38.1% improvement in the resource supply–demand ratio and a 26% reduction in CO_2 emissions. (3) Addressing ecosystem feedback, the reduction of carbon emissions emerges as a focal point for future ecological environment enhancement initiatives in Henan Province. Strategic emphasis should be placed on adjusting energy consumption and its structure to propel the healthy development of the ecological environment. This study serves as a guide for managing regional WEFE systems effectively.

1. Introduction

Water, energy, and food (WEF) constitute fundamental and strategic resources crucial for human survival, economic prosperity, and social advancement (Hoff, 2011). The security of WEF lies at the heart of the United Nations' 2030 Agenda for Sustainable Development. With the ongoing global population growth and a continuous rise in urbanization levels, there is a heightened demand for cultural, educational, and health services (Grinberga-Zalite and Zvirbule, 2022). Hyperactivity in production and daily life contributes to resource overconsumption (Marín-Beltrán et al., 2022). Research conducted by the National Intelligence Council indicates a projected increase of 40 %, 50 %, and 35 % in the demand for WEF, respectively, by 2030 (National Intelligence Council, 2012). This escalating demand highlights the intensifying contradiction between resource supply and demand. The substantial growth in WEF needs has profound implications for resource security, and mismanagement of these resources may inflict harm on interconnected systems (Karabulut et al., 2018). A striking example is the Aral Sea Basin, which has garnered international attention due to ecological crises stemming from inappropriate hydropower development and agricultural practices (Li et al., 2021b). Understanding the intricate and interconnected dynamics among WEF is imperative for achieving the goals of sustainable global development.

The WEF Nexus has garnered significant scholarly attention since the Bonn 2011 Conference. Initial research on the WEF Nexus primarily concentrated on security assessments (Tan et al., 2018), synergistic

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development (Zhou et al., 2019), and optimal management (Zhang and Vesselinov, 2017). As research progressed in depth, the content and scope gradually diversified, encompassing external factors such as the economy (Zhang and Xu, 2022), land (Siciliano et al., 2017), and climate (Sánchez-Zarco et al., 2020) within the WEF Nexus research framework. Derived from the WEF system, studies have explored land–water–energy–food and water–energy–food–climate systems.

The ecological environment functions as a vital substrate for the development and utilization of the three fundamental WEF resources. The production and consumption of WEF exert immense pressure on the ecological environment (Ding and Chen, 2022), diminishing its self-repair and regulatory capacity. This phenomenon adversely affects resource development and utilization, posing a threat to WEF security (Mirzaei et al., 2019), and establishes an undesirable cyclical state that hampers social development. Complex interactions and mutual constraints between WEF and the ecological environment exist (Liu et al., 2023). While some WEF Nexus studies have incorporated ecological environmental factors (Wen et al., 2022), they often integrated the ecological environment into the WEF system without considering it as a separate subsystem. Consequently, the linked ecological change effects on resource supply and demand were not thoroughly analyzed.Recognizing the crucial role of the ecological environment in ensuring WEF Nexus security (Qin et al., 2022), research on ecosystem feedback can assist decisionmakers in scientifically and effectively resolving the contradiction between resources, the environment, and social development. Therefore, it is imperative to treat the ecological environment as a distinct subsystem in the WEF Nexus and construct a research framework for the water–energy–food–ecology (WEFE) system.

Currently, research on WEFE systems predominantly focuses on system management strategy (Li et al., 2021a), vulnerability (Pan et al., 2022), and coupling, as well as coordinated development assessment (Ding and Deng, 2022). Research methods encompass the coupling coordination degree (Wang et al., 2021), Bayesian network models (Shi et al., 2020), and ecological cycle assessment (Del Borghi et al., 2022). Upon collating existing WEFE system research results, it becomes evident that the current focus primarily centers on the assessment of the present WEFE system development status, with few predictions for future simulation development. Considering the dynamic changes in management measures, it is essential to conduct relevant future forecasts to mitigate decision-making uncertainty and blindness (Zhou et al., 2023). Furthermore, most research on WEFE systems concentrates on the core relationships among WEF, neglecting research on ecosystem feedback effects. This oversight is not conducive to realizing WEFE system security under the conditions of coordinated development of the environment and society. Therefore, a systematic approach based on a holistic view of future dynamic predictions and feedback is imperative.

System dynamics (SD) emerges as a simulation and prediction method addressing multisystem problems through computer-assisted analysis. This simulation method employs feedback loops and causality to capture the dynamic behavior of systems over time (Mousavi et al., 2023), making it suitable for simulating medium- and long-term trends (Li et al., 2023). Scholars have successfully applied SD to the fields of water (Wang et al., 2022), energy (Feng et al., 2022), food (Ravar et al., 2020), and ecology (Zhang et al., 2023). Building upon these considerations, this study proposes a hypothesis, utilizing the SD model for dynamic prediction evaluation of WEFE systems. The study's outcomes will aid in determining the relationship between resource security and ecological conservation, offering scientific guidance for the coordinated development of WEFE systems.

Henan Province stands as one of the economic centers in central China, with relatively developed agriculture. However, per capita water resources in Henan Province are only about one-sixth of the national average, and nearly 58 % of energy consumption needs to be imported from outside the province. Concurrently, the deterioration of the ecological environment, such as air pollution, is becoming increasingly prominent (Yu et al., 2020), posing challenges to the development of the WEFE system and the realization of the goal of carbon neutrality and carbon peak. Urgently, simulation and prediction of WEFE system future development in Henan Province are necessary to explore policy schemes effectively improving the coordinated WEFE system development in the province and ensuring sustainable regional development. Based on this analysis, the main study objectives were as follows: (1) Utilize the SD model to analyze the complex interactions within the WEFE system and construct a dynamic WEFE system simulation model. (2) Compare the WEFE system development trend in Henan Province from 2005 to 2035 under different development scenarios, analyzing WEF resource supply and demand and ecosystem responses under resource changes. (3) Propose feasible suggestions for the future development of Henan Province.

2. Method and data

2.1. Research framework

The research framework comprises three main components(Fig. 1): structural system, SD model, and result analysis. Initially, the study constructed a WEFE system structure, encompassing the five major systems: water, energy, food, ecology, economy, and society. This structure clarified interactions among the systems from the perspective of resource supply and demand. Subsequently, the SD software Vensim was employed to portray interaction relationships between the systems. Different scenarios and model simulation periods were established for comprehensive simulation, and a series of tests were carried out on the model. Finally, the WEFE system was analyzed from various perspectives, and decision-making recommendations were derived from the model simulation results.

2.2. Study area

Henan Province, situated south of the North China Plain along the middle and lower reaches of the Yellow River, covers an area of 167 × 10^3 km^2, as illustrated in Fig. 2. The total population is 108.5 million, approximately 7.7 % of the national population. In this context, the mismatch between water and energy resource supply and demand in the region is more serious. Ecological security and resource shortages caused by resource consumption jointly restrict the future sustainable development of Henan Province. Concerning food, as a major agricultural province, Henan Province has maintained a high food security level, with its output accounting for about 10 % of the country's total food production (Niu et al., 2022). The annual food and agricultural by-product transfer from Henan Province is approximately 30 million tons, constituting around 17.6 % of the total food production in the province, providing a robust national food security guarantee (Gao et al., 2023).

Influenced by its position, Henan Province heavily relies on water consumption, with the provincial annual average water resource amounting to 40.35 billion m^3, which is only approximately 1.4 % of the national total. Among these, agricultural irrigation requires more than half of the water resources, and only 1.4 % of the water resources produce approximately 10 % of the country's food, creating a serious mismatch between water supply and demand. Some regions must exploit groundwater on a large scale, leading to a series of ecological and environmental problems such as ground subsidence and poor water quality.

Considering energy, coal is the primary energy source affected by resource endowment, creating a coal-based energy structure problem (Liu et al., 2016). The coal consumption proportion in Henan Province averaged as high as 78 % from 2005 to 2021. As the primary carbon dioxide (CO_2) emission source from energy consumption, coal utilization accounts for approximately 80 % or more of energy consumption CO_2 emissions. High coal consumption has intensified the CO_2 emissions problem in Henan Province, negatively impacting healthy local ecology development. Henan Province is rich in bioenergy, food crop straw

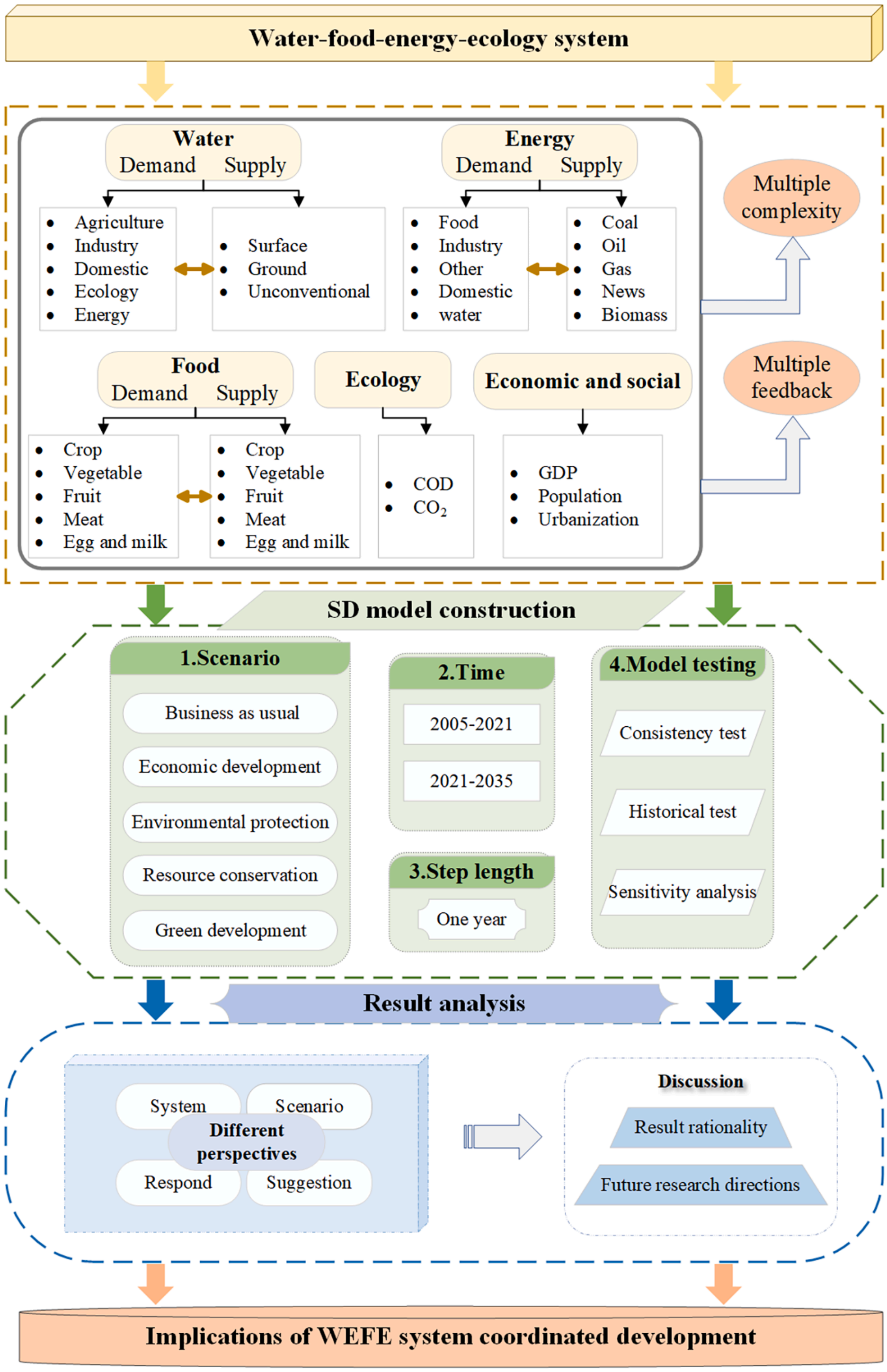

Fig. 1. Research framework diagram.

theoretical reserves are large, with crop straw resources increasing by 72 % between 2001 and 2020 (Li, 2022). The bioenergy industrial development potential is substantial. Without sacrificing food security, vigorously developing bioenergy can not only realize resourceful organic waste use, such as straw, thus improving the ecological environment, but also optimize the energy structure, achieving carbon peak, carbon neutrality, and environmental pollution control coordination.

2.3. *Model construction*

The WEFE system is intricate, encompassing factors like the economy, society, and industrial structure. The model presented in this paper, named WEFE-SD, is depicted in Fig. 3, showcasing the stock and flow diagram of WEFE-SD. The model is segmented into five subsystems: water, energy, food, ecology, and economic and social, represented in blue, orange, purple, green, and gray, respectively. These subsystems exhibit complex correlations, detailed as follows:

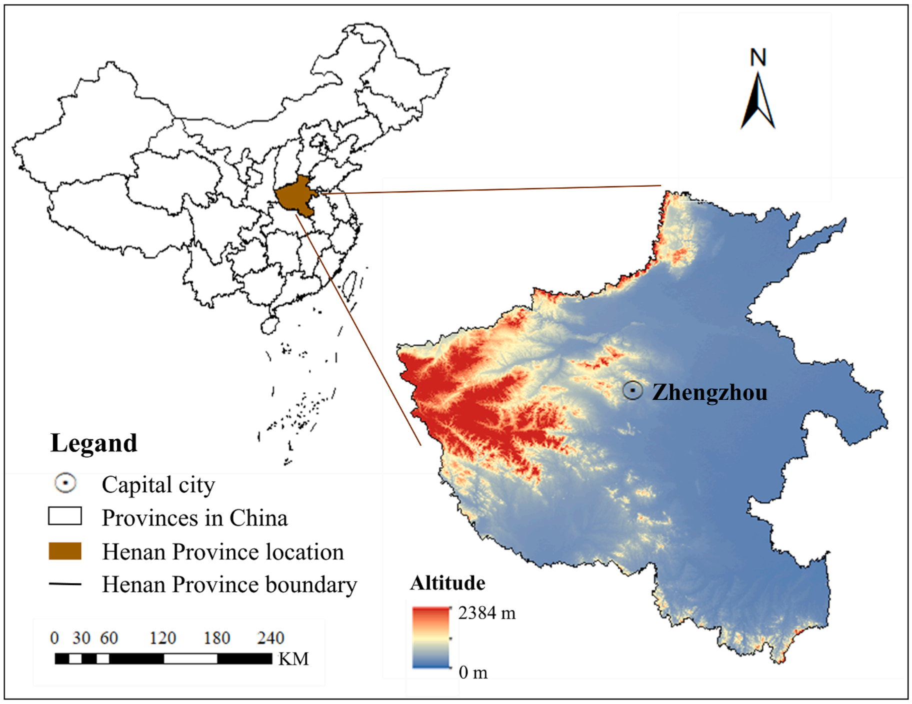

Fig. 2. Study area map.

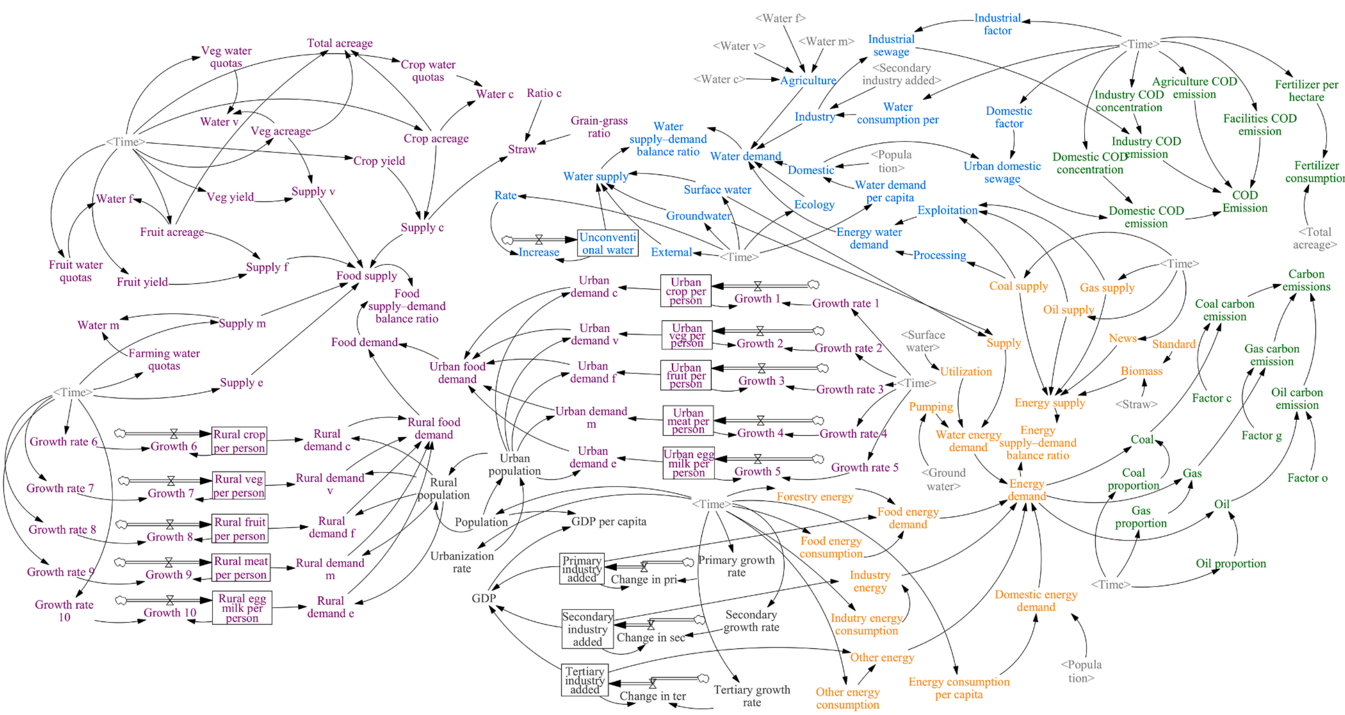

Fig. 3. The stock and flow diagram of WEFE-SD.

2.3.1. *Water subsystem*

The water subsystem incorporates water demand and supply. The water demand consists of five components, with the energy industry's water demand calculated separately for a more nuanced reflection of the energy subsystem's impact. The water demand calculation formulas are expressed in Equations (1)–(5):

$$WD = WD_{agriculture} + WD_{industry} + WD_{domestic} + WD_{ecology} + WD_{energy} \quad (1)$$

$$WD_{agriculture} = \sum_{i}(S_i \times WQ_{food-i}) \quad (2)$$

$$WD_{industry} = GDP \times WQ_{secondary} \quad (3)$$

$$WD_{domestic} = P \times WQ_{domestic} \quad (4)$$

$$WD_{energy} = \sum_{e}(ES_e \times WQ_{energy-e}) \tag{5}$$

where, WD is the water demand, and $WD_{agriculture}$, $WD_{industry}$, $WD_{domestic}$, $WD_{ecology}$, and WD_{energy} are the water demands for agriculture, industry, domestic use, ecology, and energy industries, respectively. S represents the area under agricultural cultivation, GDP is the gross domestic product, P is the permanent population, and ES is energy production. WQ_{food}, $WQ_{secondary}$, $WQ_{domestic}$, and WQ_{energy} are the water quotas for food, 10,000 yuan industrial value-added, and per capita water use for domestic and energy production, respectively. i and e represent different food and energy types, respectively.

The water supply is composed of three parts and is calculated using Equation (6):

$$WS = WS_{surface} + WS_{ground} + WS_{unconventional} \tag{6}$$

where, WS is the water supply, and $WD_{surface}$, WD_{ground}, and $WD_{unconventional}$ are the surface water, groundwater, and unconventional water resource supplies, respectively.

The water supply–demand balance ratio (W_R) gauges the equilibrium between water supply and demand, calculated as shown in Equation (7):

$$W_R = \frac{WS}{WD} \tag{7}$$

2.3.2. Energy subsystem

The energy subsystem comprises both energy demand and supply. Energy demand is dissected into five components and calculated using Equations (8)–(12):

$$ED = ED_{food} + ED_{industry} + ED_{other} + ED_{domestic} + ED_{water} \tag{8}$$

$$ED_{food} = \sum_{i} ED_{f-i} \tag{9}$$

$$ED_{industry/other} = \sum_{n}(GDP_n \times EC_n) \tag{10}$$

$$ED_{domestic} = P \times EC_{domestic} \tag{11}$$

$$ED_{water} = \sum_{k} ED_{w-k} \tag{12}$$

where, ED is the energy demand, and ED_{food}, $ED_{industry}$, ED_{other}, $ED_{domestic}$, and ED_{water} represent the energy demands for food systems, industry, other sectors, domestic use, and water utilization, respectively. ED_f is the energy demand for different food production types, EC is the industrial energy consumption in different sectors, $EC_{domestic}$ is the per capita domestic energy consumption, and ED_w is the energy consumption for different water use types. i, n, and k denote different food types, industries (secondary and tertiary), and water types, respectively.

Energy supply encompasses fossil fuels and new energy sources. Considering agricultural development in Henan Province, this study includes bioenergy, with calculation formulas detailed in Equations (13) and (14):

$$ES = ES_{coal} + ES_{oil} + ES_{gas} + ES_{news} + ES_{food} \tag{13}$$

$$ES_{food} = FS_c \times standard \tag{14}$$

where, ES is the energy supply, and ES_{coal}, ES_{oil}, ES_{gas}, ES_{news}, and ES_{food} represent the coal, oil, gas, new energy, and bioenergy supplies, respectively. FS_c is the crop yield, and *standard* is the straw standard coal coefficient.

The energy supply–demand balance ratio (E_R) gauges the balance between energy supply and demand, calculated as shown in Equation (15):

$$E_R = \frac{ES}{ED} \tag{15}$$

2.3.3. Food subsystem

The food subsystem involves both food demand and supply. Following the dietary recommendations outlined in the Dietary Guidelines for Chinese Residents (2022), a detailed consideration of the five food groups is undertaken, with calculation formulas provided in Equations (16)–(17):

$$FD = FD_c + FD_v + FD_f + FD_m + FD_e \tag{16}$$

$$FD_{c/v/f/m/e} = P \times FD_{per-i} \tag{17}$$

where, FD is food demand, and FD_c, FD_v, FD_f, FD_m, and FD_e represent crop, vegetable, fruit, meat, egg, and milk demands, respectively. FD_{per} is the per capita food demand and i represents different food types.

The food supply mirrors the demand, considering the availability of five different food types. Calculation formulas are detailed in Equations (18)–(19):

$$FS = FS_c + FS_v + FS_f + FS_m + FS_e \tag{18}$$

$$FS_{c/v/f} = S_{c/v/f} \times yield_{c/v/f} \tag{19}$$

where, FS is the food supply, and FS_c, FS_v, FS_f, FS_m, and FS_e represent crop, vegetable, fruit, meat, egg, and milk supply, respectively. S_c, S_v, and S_f are the crop, vegetable, and fruit agricultural acreages, respectively. $yield_c$, $yield_v$, and $yield_f$ are the crop, vegetable, and fruit unit yields, respectively.

The food supply–demand balance ratio (F_R) is employed to measure the equilibrium between food supply and demand, calculated as shown in Equation (20):

$$F_R = \frac{FS}{FD} \tag{20}$$

2.3.4. Ecology subsystem

In this study, we assess the impact on the ecological environment within different WEF systems. Chemical oxygen demand (COD) and CO_2 emissions are considered primary ecological subsystem indicators, with calculation formulas provided in Equations (21)–(24):

$$COD = COD_{agriculture} + COD_{industry} + COD_{domestic} + COD_{facilities} \tag{21}$$

$$COD_{industry/domestic} = WW_{industry/domestic} \times c_{industry/domestic} \tag{22}$$

$$CO_2 = CO_{2coal} + CO_{2oil} + CO_{2gas} \tag{23}$$

$$CO_{2coal/oil/gas} = ED_{coal/oil/gas} \times EF_{coal/oil/gas} \tag{24}$$

where, COD represents COD emissions, and $COD_{agriculture}$, $COD_{industry}$, $COD_{domestic}$, and $COD_{facilities}$ are the COD emissions from agriculture, industry, urban life, and centralized pollution treatment facilities, respectively. $WW_{industry}$ and $WW_{domestic}$ represent industrial and urban domestic sewage discharge, respectively, $c_{industry}$ and $c_{domestic}$ represent industrial and urban domestic sewage COD concentrations, respectively. CO_2 represents CO_2 emissions, and CO_{2coal}, CO_{2oil}, and CO_{2gas} are the CO_2 emissions from coal, oil, and natural gas, respectively. ED_{coal}, ED_{oil}, and ED_{gas} represent coal, oil, and gas consumption, respectively, EF_{coal}, EF_{oil}, and EF_{gas} are the CO_2 emission factors for coal, oil, and natural gas, respectively.

2.3.5. Economic and social subsystem

The economic and social subsystem encompasses GDP, population, and urbanization rate. Economic development relies on diverse resources, and shifts in economic and social factors, including population and urbanization rate, pose challenges for resources and the ecological environment. This study drew upon key planning documents, such as the New Urban Planning of Henan Province (2021–2035), the 14th Five-Year Plan for National Economic and Social Development of Henan Province, and the Outline of the Long-term Goals for 2035, to determine future population, urbanization rate, and other economic and social indicators specific to Henan Province.

2.4. Scenario settings

Henan Province grapples with significant water and energy shortages (Wang et al., 2016). China is marked by its classification as one of the 13 water-poor countries globally, while per capita water resources in the province are approximately one-sixth of the national average, indicating poor water resource endowment conditions. Additionally, around 58 % of the province's energy consumption in 2021 had to be imported from outside, reflecting a low energy self-sufficiency level. In light of planning documents like the Henan Province Four-Water Governance Plan (2021–2035) and Henan Province's 14th Five-Year Plan for Modern Energy Systems and Carbon/Peak Carbon Neutrality, and considering resource shortages and environmental pollution, five scenarios were devised to simulate and evaluate future development. These scenarios are compared by adjusting decision variables, with a total of 46 decision variables were selected for different scenarios simulation analysis. The scenarios are outlined as follows:

Scenario 1: Business as Usual (BAU) Scenario: Assumes unrestricted development with decision variables maintaining current trends.

Scenario 2: Economic Development (ED) Scenario: Focuses on bolstering economic growth based on BAU, involving higher GDP growth rates across sectors, increased population, and urbanization rate.

Scenario 3: Environmental Protection (EP) Scenario: Emphasizes ecological protection and restoration. Specifically, it controls groundwater overexploitation, promotes unconventional water growth, vigorously develops bioenergy to reduce fossil fuel dependence, and encourages green agricultural practices. It also considers sewage discharge coefficients, emission concentrations, and energy consumption structure changes.

Scenario 4: Resource Conservation (RC) Scenario: In response to concerns such as resource endowments, this scenario aims to optimize the resource supply–demand balance by controlling reasonable resource consumption. Aligned with relevant policy planning, the emphasis is on enhancing resource utilization, advocating sustainable practices such as water and energy conservation, fostering a rational diet, and promoting a conservation-oriented society. Within the water system, reductions are observed in groundwater supply, agriculture-related water quotas, water quotas per unit of industrial added value, and per capita domestic water quotas. The energy system targets reductions in industrial and per capita energy consumption. The food system concentrates on altering per capita food demand.

Scenario 5: Green Development (GD) Scenario: Prioritizes ecological environmental quality, ensuring resource safety, fostering balanced economic development, and integrating economic growth, environmental protection, and resource conservation. This approach aims to promote coupling and coordinated development of the WEFE system.

Given the extensive selection of decision variables, Table 1 highlights representative values for decision variables under the BAU scenario. Other scenarios exhibit variations based on these BAU decision variable values, as shown in Table 1.

2.5. Data sources

The water resources data in this study were sourced from the Water Resources Bulletin of Henan Province, encompassing total water resources, water demand, and water supply. Energy data primarily originated from the Statistical Yearbook of Rural China, covering industrial energy consumption and energy supply. Food data and socio-economic data were extracted from the Henan Provincial Statistical Yearbook and Statistical Yearbook of Rural China. Environmental data predominantly came from the China Environmental Statistical Yearbook. The relevant indicators for future scenarios were derived from pertinent development planning documents and reports, such as the 14th Five-Year Plan for National Economic and Social Development of Henan Province and the Outline of the Long-term Goals for 2035.

In this paper, the model's initial time was set as 2005, and the end time was 2035, with 2005–2021 representing the current year and 2022–2035 as the forecast period. The simulation step length of the model was set at 1 year.

Table 1
Major decision variable values and changes in 2035 under different scenarios.

System	Variable	BAU	ED	EP	RC	GD
Economic–Social	Secondary growth rate (%)	2	+100 %	–	–	+60 %
	Population (10^4 people)	10,620	+2%	–	–	–
	Urbanization rate (%)	65	+10 %	–	–	+10 %
Water	Groundwater (10^8 m^3)	102	–	–12 %	–12 %	–12 %
	Water consumption per (m^3/10^4 RMB)	14	–	–	–21 %	–21 %
	Water demand per capita (L/day/people)	170	–	–	–6%	–6%
Energy	Secondary energy consumption (10^4 tce/10^8 RMB)	0.52	–	–	–30 %	–30 %
	Energy consumption per capita (tce)	0.56	–	–	–10 %	–10 %
	Coal proportion (%)	56	–	–10 %	–	–10 %
Food	Crop yield (ton/ha)	7	–	+15 %	–	+15 %
	Veg water quotas (m^3/ha)	2000	–	–	–10 %	–10 %
	Rural meat per person (kg)	71	–	–	–8%	–8%
Ecology	Industrial factor	0.21	–	–15 %	–	–15 %
	Domestic COD emissions (mg/L)	70	–	–15 %	–	–15 %

3. Results

3.1. Model validation

The DSS test in the Vensim software assessed the model's structural consistency, confirming its coherence in variable settings, causality, and equation construction. Building on this, a historical test of the model was conducted by comparing the simulated and actual values of five representative variables—water demand (WD), food system energy demand (ED_{food}), food supply (FS), COD emissions (COD), and per capita GDP (PP GDP)—during 2005–2021 using Equation (25). Simultaneously, ecological water demand, coal supply, and other indices were subjected to sensitivity analysis.

$$\theta = \frac{|x' - x|}{x} \times 100\% \tag{25}$$

where θ represents the model error, $x^{'}$ is the simulated value, and x is the actual value.

The historical test results, depicted in Fig. 4, demonstrated that simulation accuracy for FS and PP GDP was great, with errors controlled within 1.5 %. Other variable errors were maintained within 3.5 %, indicating good agreement between the simulated and actual values in both numerical and historical trends. In alignment with prior research standards, an approximately 5 % error control is deemed effective (Bao et al., 2022).

The sensitivity analysis revealed that the majority of the indices were insensitive, indicating the overall stability and robustness of the SD model. The preliminary research results outlined above demonstrated that the WEFE-SD model, as constructed in this paper, successfully passed the consistency test, historical test, and sensitivity analysis. The model exhibits high precision, good representation, and effectiveness, making it suitable for practical simulation research.

3.2. WEFE system simulation results

3.2.1. Results analysis of water subsystem

Fig. 5(a) provides an overview of water demand by category. Agricultural water demand has remained steady at approximately 1.2 billion m^3 for several years, with a discernible downward trend in the water demand proportion annually. By 2025 and 2035, agricultural water demand is projected to constitute about 47 % and 40 % of total demand, respectively, making it the largest portion. Both industrial and domestic water demands exhibit a rising trend, reaching approximately 5 billion m^3 and 6.1 billion m^3 in 2025 and 2035, respectively (BAU scenario). Ecological water demand experiences a slight increase during the forecast period, reaching 4.5 billion m^3 by 2035, with the proportion stabilizing at over 15 %. Energy industrial water demand constitutes a relatively small proportion of the total water demand, ranging between 0.5 and 0.8 billion m^3. Among the various demand types, agricultural, industrial, and ecological water demands exhibit more significant changes between scenarios, varying by a maximum of 20–40 % by 2035. In contrast, domestic and energy industrial water demand values show less correlation with the scenarios, with no more than a 7 % increase or decrease between scenarios.

Fig. 5(b) illustrates water resource supply, primarily from surface water and groundwater. Surface water supply remains stable at around 8.5 billion m^3, while groundwater supply hovers around 10.5 billion m^3, collectively constituting over 85 % of the total supply during the forecast period. Unconventional water supply, although negligible compared to surface and groundwater, demonstrates a consistent growth trend, increasing from 1.9 billion m^3 in 2025 to 2.6 billion m^3 by 2035, reflecting a 37 % increase. Groundwater and unconventional water supply exhibit more significant variations between scenarios, with a maximum difference of 13–23 % by 2035. Conversely, surface water supply variations across different scenarios are not notably significant.

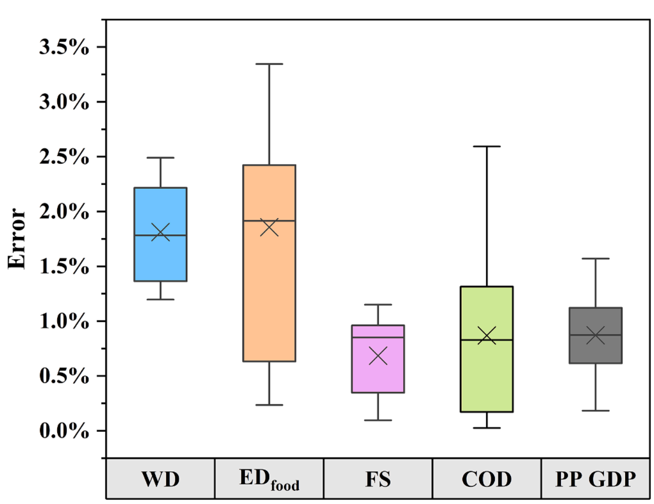

Fig. 4. Variable relative errors in the WEFE-SD model.

Fig. 5(c) depicts the water supply–demand balance ratio (W_R) in different scenarios, revealing a distinct downward trend in Henan Province. Over the 17-year status quo period, the W_R declined from 0.99 to 0.87. According to the forecast under the BAU scenario, the W_R is projected to decrease from 0.87 to 0.72 over the next approximately 15 years. In contrast to the average annual decline of 0.007 during the status quo period, the average annual decline over the forecast period increased to 0.011, raising concerns about future water security. The GD scenario, featuring an increase in unconventional water supply, exhibits the highest W_R by 2035 at 0.75. The order of W_R in other scenarios is RC > BAU > ED > EP. The smallest W_R in the EP scenario is only 0.67, demonstrating a potential difference of up to 0.08.

3.2.2. Results analysis of energy subsystem

Fig. 6(a) illustrates the demands for different energy types. Industrial energy demand demonstrates an upward trend, increasing from 190 million tce in 2025 to 225 million tce by 2035, marking an 18 % increase. Industrial energy demand comprises the majority of total energy demand, maintaining proportions of approximately 65 % and 61 % in 2025 and 2035, respectively. The energy demand from other sectors, similar to domestic energy demand, exhibits a rising trend. Domestic energy demand increased from 42 million tce to 59 million tce, representing a 40 % increase. Meanwhile, the energy demand for other sectors shows a 31 % increase. Energy demand for food systems and water utilization constitutes a relatively small proportion of the total demand, consistently below 3 % and 0.5 %, respectively. Industrial and other sector energy demands experience noticeable fluctuations with scenario changes. By 2035, the difference in industrial energy demand between scenarios could reach 272 million tce, while the difference in other sector energy demand could reach 24 million tce. In contrast, domestic, food system, and water use energy demands are less influenced by scenario changes, with fluctuations between scenarios remaining below 7 million tce.

Fig. 6(b) illustrates the supplies for different energy types, highlighting Henan Province's future reliance on coal and bioenergy. Coal supply is diminishing due to changes in the energy system, with projections of 46 million tce in 2025 and 36 million tce in 2035. The coal supply proportion in the total supply is expected to decrease to 45 % by 2035. Bioenergy experiences significant growth, anticipated to reach approximately 22 million tce by 2035. Oil supply has remained stable at 8.5–10.5 million tce, constituting approximately 12 % of the total energy supply. This new energy supply is projected to surpass 11 million tce by 2035, becoming an integral component of the total energy supply. Scenario changes notably impact coal, bioenergy, and new energy supplies, potentially creating a supply gap of up to 6 million tce. Oil and gas supplies vary significantly between different scenarios.

The energy supply–demand balance ratio (E_R) for different scenarios is depicted in Fig. 6(c). Over the study period, the E_R exhibited a downward trend, surpassing the decline observed in water resources. Under the BAU scenario, the E_R experiences an average annual decline of 0.026, approximately three times the average annual change in W_R. Notably, Henan Province's bioenergy developmental potential, driven by crop straw as the bioenergy basis, is substantial. The model projections indicate a 31 % increase in crop straw by 2035 compared to 2020, resulting in a relatively slower E_R decline of 0.014 over the forecast period. This decline is lower than the 0.035 average annual decline during the status quo period. In 2035, the order of E_R is GD > RC > EP > BAU > ED, with a maximum difference of 0.11.

3.2.3. Results analysis of food subsystem

Fig. 7(a) depicts the demand for food by category, revealing a continuous increase in total food demand. Essential for human life, crop

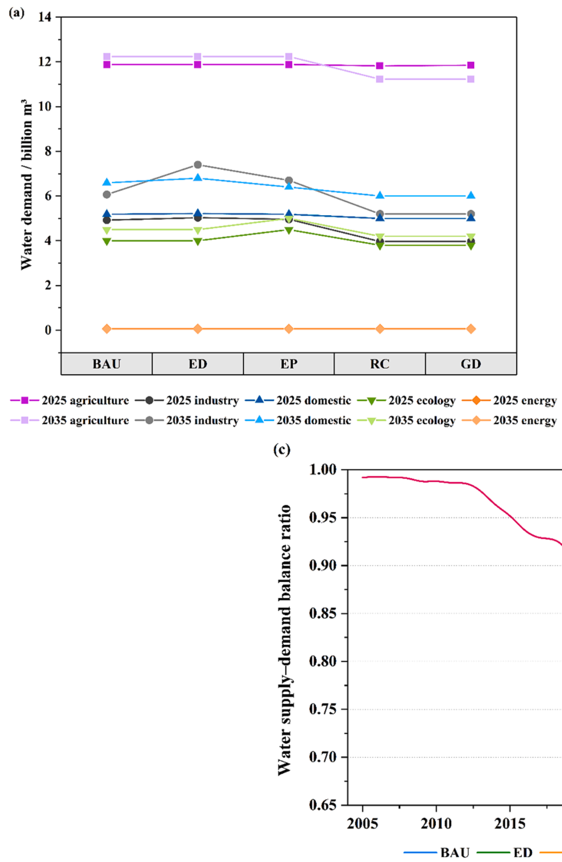

Fig. 5. Water subsystem simulation results.

demand consistently constitutes the highest proportion, hovering around 36 % for an extended period. By 2035, crop demand is projected to reach approximately 22 million tons, marking a 29 % increase from 2025. The demand for vegetables, accounting for 25 % and 22 % in 2025 and 2035, respectively, continues to rise despite a declining proportion. It is expected to grow from 11.5 million tons in 2025 to 14 million tons in 2035, reflecting a 22 % increase. The demand for fruit, meat, eggs, and milk is also on an upward trajectory, reaching 11, 8, and 6 million tons by 2035, with increases of 30 %, 60 %, and 36 %, respectively. Among the different demand types, crop and meat demands are significantly influenced by scenario changes, with crop demand in 2035 varying by up to 3.2 million tons between different scenarios, and meat demand varying by up to 1.6 million tons. However, the demand for vegetables, fruit, eggs, and milk remains relatively stable across different scenarios, fluctuating by no more than one million tons.

Fig. 7(b) illustrates the supply of various food types, with crops and vegetables representing a substantial proportion of the food supply. The crop supply proportion has consistently remained above 40 %, and the vegetable supply proportion above 43 %, exhibiting a clear growth trend. By 2035, the total supply of both is projected to reach 190 million tons, reflecting a 21 % increase. Fruit, meat, eggs, and milk supply remain relatively constant at approximately 17.5, 6.3, and 7.5 million tons, with declining proportions in the total supply. The proportions for these three categories are anticipated to be 8 %, 3 %, and 4 %, respectively, by 2035. Notably, crop and vegetable supply exhibit significant changes across scenarios, with crop supply fluctuating by 6 % and vegetable supply by 3 % under different scenarios. However, supplies of fruit, meat, eggs, and milk show less significant variation between scenarios.

Fig. 7(c) presents the food supply–demand balance ratio (F_R) values for different scenarios. Throughout the study period, the F_R remains above 1.0, indicating that food security concerns are more moderate compared to water and energy security. Despite fluctuations during the status-quo year, the F_R generally stabilizes at over 4.0. Per capita food demand statistics reveal a decline from approximately 322 kg/person in 2010 to 280 kg/person in 2018. This decline led to a substantial increase in F_R during 2010–2018, reaching 5.5. However, after 2018, per capita food demand rose to 390 kg/person by 2021, resulting in a decrease in F_R to around 4.0. Over the forecast period, F_R shows a fluctuating downward trend. In 2035, the order of F_R values, from highest to lowest, is GD > RC > EP > BAU > ED, with a 0.67 difference between the maximum and minimum values.

3.2.4. Results analysis of ecology subsystem

Fig. 8(a) displays the COD emissions for each scenario, revealing a significant downward trend in Henan Province from 2005 to 2035, with a sharp decline around 2015. This decline is attributed to the issuance of relevant documents in 2015, such as the Plan for the Management of Outstanding Environmental Problems in Agriculture (2015–2018). These documents effectively controlled pollution from agricultural sources, leading to a sudden decrease in COD emissions from 0.75 million tons to 0.02 million tons in just 1 year. Subsequently, total COD emissions stabilized in the 0.2–0.4 million ton range. By 2035, the magnitude of COD emissions under different scenarios follows the order ED > BAU > RC > EP > GD. Fluctuations between scenarios are not pronounced during the forecast period, with the maximum difference in COD emissions being only 0.07 million tons.

Fig. 8(b) presents the CO_2 emissions data for different scenarios, indicating an increasing trend under all scenarios. Total CO_2 emissions exhibit a fluctuating upward trend in the status quo year, with a slower growth rate, and CO_2 emissions in 2021 increase by only 30 % compared to those in 2005. Under the BAU scenario, CO_2 emissions grow at a faster rate over the forecast period, increasing by 56 % based on 2021 values and reaching 2.2 million tons. By 2035, the order of magnitude of CO_2

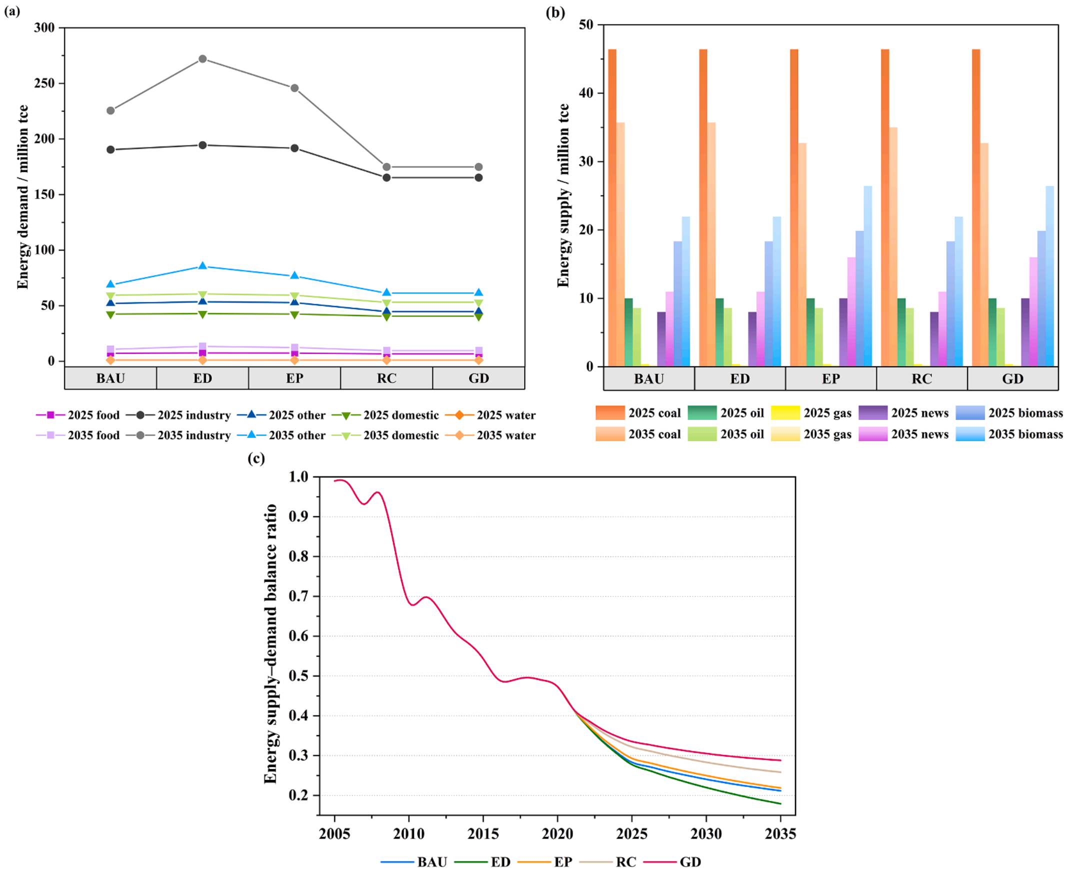

Fig. 6. Energy subsystem simulation results.

emissions from different scenarios is ED > BAU > EP > RC > GD. In the ED scenario, GDP increases by 23 % compared to the BAU scenario, leading to increased energy consumption and a subsequent 20 % rise in CO_2 emissions compared to the BAU scenario. Following an adjustment in energy consumption structure, CO_2 emissions in the EP scenario are reduced to 97 % of those in the BAU scenario. The RC scenario exhibits a more moderate CO_2 emission growth trend, with emissions by 2035 amounting to only 82 % of those in the BAU scenario. Therefore, controlling CO_2 source emissions, specifically energy consumption, proves more effective than solely adjusting the energy consumption structure. In the GD scenario, CO_2 emissions in 2035 increase by only 15 % compared to those in 2021, approximately 60 million tons less than in the BAU scenario, representing the lowest CO_2 emissions among the five scenarios.

3.3. Comprehensive scenario evaluation

Upon analyzing the differences in resource supply and demand balance ratios across scenarios, it is evident that complex and diverse influences shape these variations. Simultaneously, the ecological environment experiences distinct developmental trends driven by these factors. Fig. 9 portrays the changes in supply–demand balance ratios and emissions by 2035 for different scenarios, utilizing the BAU scenario as a baseline to compare dynamic projection results. As society develops in the BAU scenario, the demand for WEF rises in all areas, exacerbating the resource supply and demand contradiction and causing a decline in ecological environmental quality.

Under various policy controls, compared to the BAU scenario simulation results in 2035, the W_R changes in the ED, EP, RC, and GD scenarios are –4.1 %, –5.6 %, +1.4 %, and +4.2 %, respectively. The E_R experiences changes of –14.3 %, +4.8 %, +23.8 %, and +38.1 %, while the F_R sees changes of –3.7 %, +5.8 %, +9.5 %, and +15.6 %, respectively. COD emissions change by +3.8 %, –19.2 %, –3.9 %, and –23.1 %, and CO_2 emissions change by +18.3 %, –2.7 %, –18.0 %, and –26.1 %, respectively. The simulation results highlight that the E_R undergoes the most significant change, and the energy system is most affected by scenario variations.

The trend analysis reveals that the ED scenario, with an increased economic development rate, intensifies demand for WEF, putting more pressure on resource supplies and aggravating ecological environmental deterioration. The EP scenario indicates heightened investment in ecological protection, leading to increased water demand and decreased water supply, creating a more pronounced water resource supply and demand contradiction, while significantly improving ecological environmental quality. In the RC scenario, reduced demand for resources alleviates pressure on resource supply, improving the balance between supply and demand, albeit with a weaker effect on ecological environmental quality compared to the EP scenario. The GD scenario, comprehensively considering economic development, environmental protection, resource conservation, and other aspects, promotes coordinated resource and environmental development. Its adjustment effect on the resource supply and demand imbalance and ecological environmental deterioration surpasses that of other scenarios, providing a more robust guarantee for coordinated WEFE system development.

3.4. Ecology system responses under resource change

To a certain extent, resource utilization reflects human activity processes, wherein humans obtain resources for processing and utilization, significantly impacting the ecological environment (Dale et al., 2011). COD emissions dropped to 0.26 million tons in 2021, maintaining relatively low levels in the later period at approximately 0.2 million tons without significant change. Throughout the study period, major COD pollutant sources shifted significantly, as illustrated in Fig. 10 under the

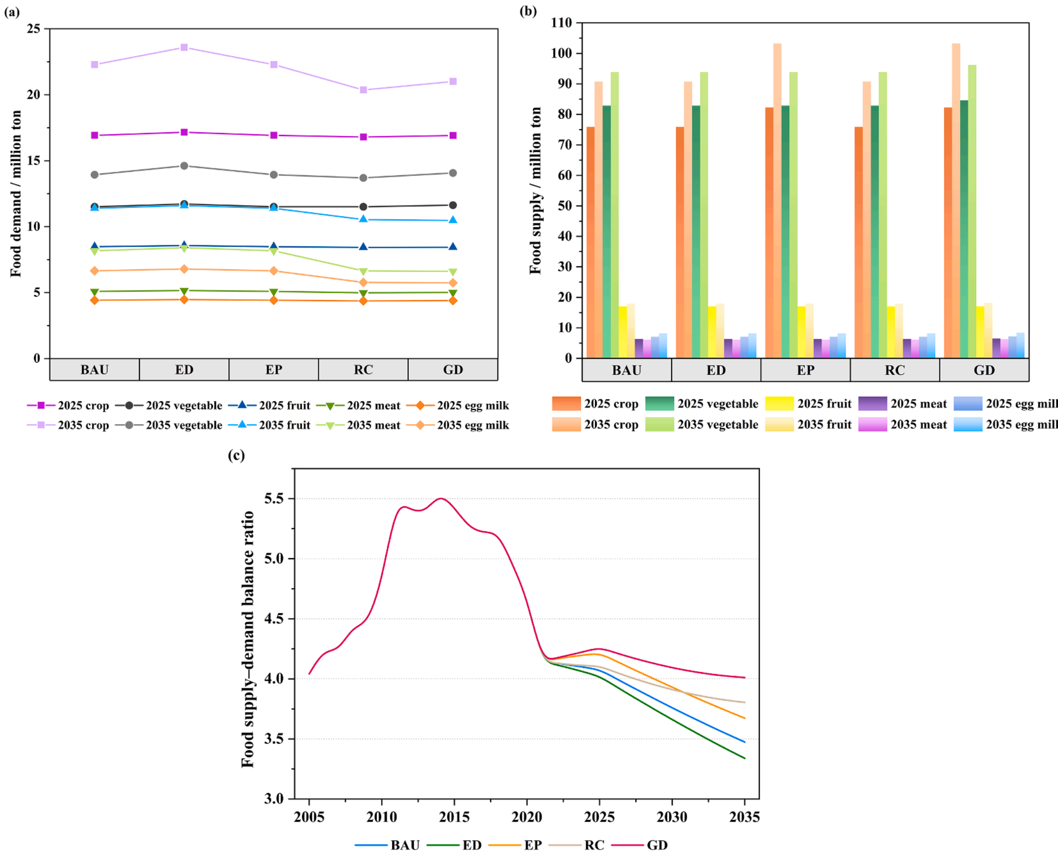

Fig. 7. Food subsystem simulation results.

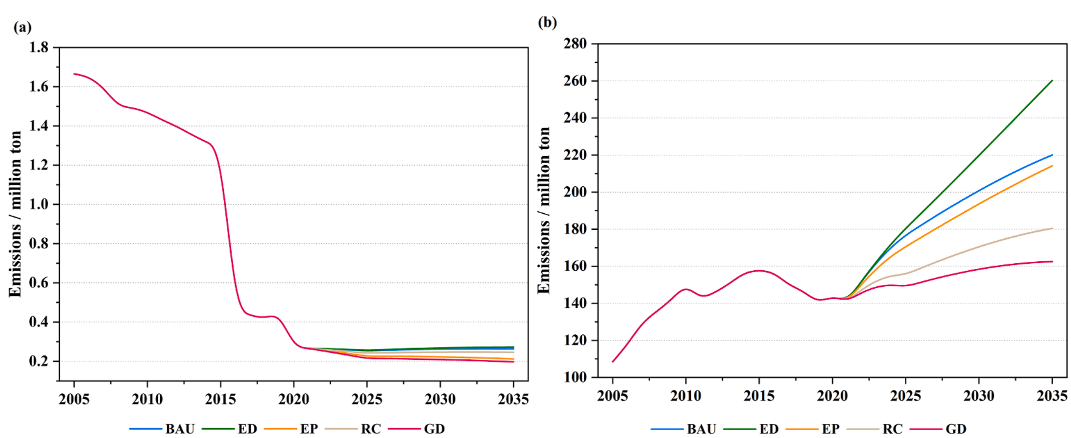

Fig. 8. Ecology subsystem simulation results.

BAU scenario.

From the pollution source perspective, the primary COD pollutant sources from 2005 to 2015 were agriculture and sewage, with livestock and poultry farming being the most significant agricultural pollutant sources, accounting for over 50 % of COD emissions. Following national policy influences, the pollution issue in the farming industry eased after 2015, leading to a significant decrease in COD emissions from agricultural sources. Simultaneously, the pollution source structure underwent a significant shift, with the primary pollutant source transitioning from agriculture to domestic sewage. The COD emissions proportion from domestic sewage to total emissions remained at approximately 93 % for many years. Future COD pollution control efforts should prioritize domestic sewage treatment, continually updating and reforming sewage treatment methods, improving water resource utilization rates, reducing sewage discharge, and safeguarding water resources and the ecological environment.

Ecological environmental improvement in Henan Province aims to reduce CO_2 emissions as a crucial focus. According to current academic research on factors influencing CO_2 emissions, the process involves various elements such as economy, population, energy, science, and technology (Zhao and Yu, 2013). Economic development determines the regional energy consumption structure and influences population changes. Human consumption, as the primary consumption source, significantly impacts CO_2 emissions (Liu and Yan, 2023). Over 80 % of China’s CO_2 emissions stem from fossil fuel production and consumption processes (Xu et al., 2020), making energy the primary source and a critical link between other influencing factors and CO_2 emissions. Fig. 11(a) illustrates the relationship between total energy consumption

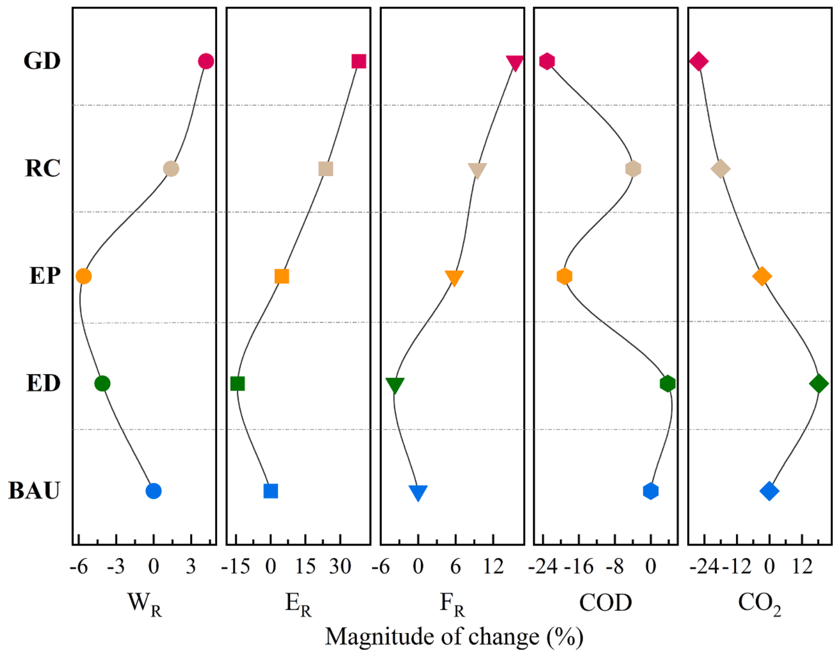

Fig. 9. Supply and demand balance ratio and emissions change amplitude in 2035 under different scenarios.

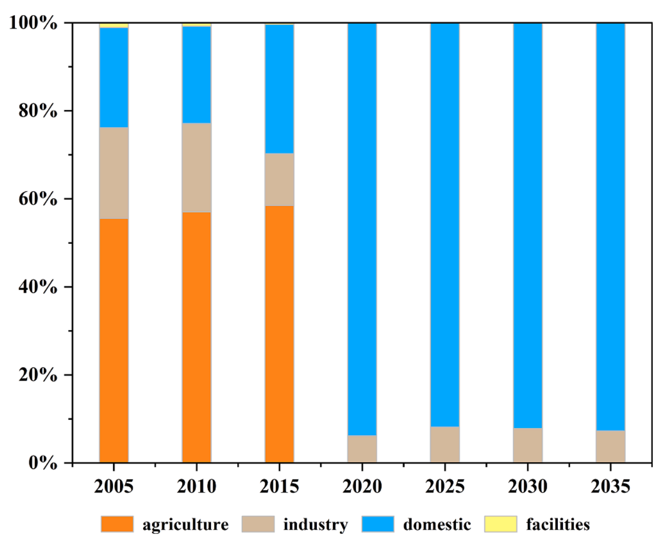

Fig. 10. COD emissions in the BAU scenario.

and CO_2 emissions from the study's simulation results. Without altering the energy consumption structure, the order of CO_2 emissions and energy consumption in the BAU, ED, and RC scenarios was ED > BAU > RC. There is a positive correlation between CO_2 emissions and energy consumption, and reducing energy consumption is conducive to achieving the carbon peak goal.

The energy consumption structure refers to the proportions of various energy sources in total energy. Among them, the use of non-renewable energy such as coal has an irreversible impact on the ecological environment and energy security (Kuriqi et al., 2020), particularly on carbon emissions. Fig. 11(b) depicts the RC and GD scenario energy consumption structures in 2035. According to the simulation results, the RC and GD scenario total energy consumptions were the same, but the energy consumption structures differed. In the RC scenario, coal, oil, and gas consumption accounted for 56 %, 22 %, and 11 % of the total consumption, respectively, while in the GD scenario, the figures were 51 %, 19 %, and 10 %, respectively. This indicates a decrease compared to the RC scenario, resulting in a CO_2 emission difference of approximately 18 million tons. Therefore, transitioning to an energy system based on renewable energy offers the dual advantage of reducing the environmental impact of greenhouse gas emissions, such as CO_2, and enhancing energy coverage and security (Kuriqi and Jurasz, 2022).

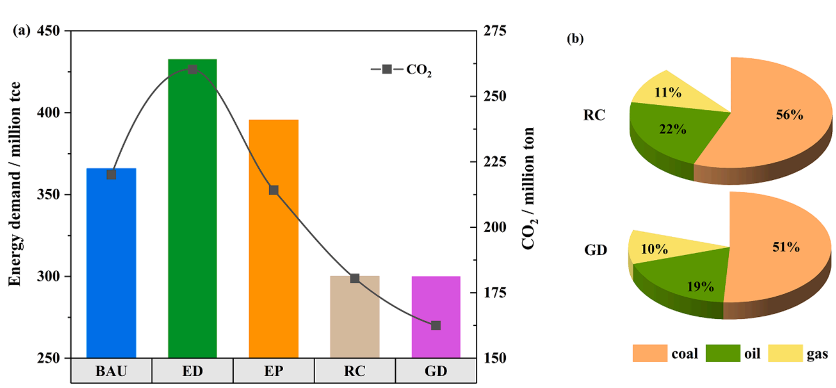

Fig. 11. CO_2 emission-related simulation results.

4. Discussion

4.1. Result rationality verification

In this study, the SD model is employed to predict the overall future development of the WEFE system in Henan Province, offering a new perspective on exploring regional sustainable development models. As no scholars have conducted relevant studies on the WEFE linkage system in Henan Province at the present stage, this study is validated by comparing existing separate system studies on water, energy, food, and ecology in Henan Province.

For instance, Ji et al. (2022) analyzed the future water resources carrying capacity of Henan Province, and their research results indicated that the contradiction between water resources supply and demand in Henan Province would become increasingly tense in the long run, aligning with our simulation results. They predicted that total COD emissions in Henan Province could reach 0.24 million tons by 2030. In comparison, the WEFE-SD model's simulation results in this study showed that COD emissions under the five scenarios would be 0.21–0.26 million tons by 2030, with the simulation error being less than 10 %. Zhao and Zhang (2020) constructed an energy revolution consumption model predicting that the total energy consumption in Henan Province would be controlled at about 2.6 million tons in 2035. Under an unreasonable development scenario, carbon emissions exhibited a significant upward trend between 2020 and 2035. Comparing these results with the WEFE-SD model's simulation in this study, the predicted carbon emissions also showed an upward trend, with an error of about 10 % compared to their total energy consumption results. This further underscores the accuracy and rationality of the findings in this study.

4.2. Policy suggestions

Coordinated development of the WEFE system necessitates reasonable double-constraint planning from supply and demand to promote sustainable regional development. The simulation results indicate that future water resource security in Henan Province will become increasingly constrained. Given that agricultural water demand accounts for the highest proportion of total water demand, the adoption of advanced agricultural water-saving technology is crucial to improving irrigation efficiency. Additionally, since supplying water resources across regions is challenging and water resource costs increase significantly in complex processes such as large-scale infrastructure construction (Zhao et al., 2017), promoting water-saving awareness and enhancing water utilization efficiency becomes paramount. Strengthening the development and utilization of unconventional water resources, improving renewable water resource supplies, and ensuring a supply and demand balance are essential efforts to address these challenges.

Energy serves as the driving force behind modern economic development. In the context of a realistic fossil energy shortage, Henan Province should expedite the upgrading and optimization of its energy structure. Leveraging its robust grain production capacity, the province should particularly focus on the development and utilization of new energy sources, such as bioenergy. Currently, bioenergy utilization stands at approximately 15 million tce, with the potential for a 70 % increase through initiatives like promoting straw energy. This underscores the imperative for Henan Province to continue and bolster its bioenergy development. Decisionmakers are advised to formulate detailed and feasible strategic plans for bioenergy, foster technological innovation in bioenergy production, and support the orderly development of the bioenergy industry.

As living standards continue to improve, the demand for nutritional food intensifies, accompanied by evolving dietary structures. While the current food security level is high, future challenges persist. Simulation results highlight that reducing demand significantly impacts the increase in the F_R. Therefore, alongside meeting nutritional and health requirements, promoting the concept of table-saving and constructing a food-saving society should be prioritized.

Furthermore, ecological issues resulting from resource changes, such as carbon emissions from non-renewable energy consumption, demand attention. To address these concerns, ecological protection measures, including clean energy replacement, promotion of low-carbon lifestyles, and reduction of groundwater extraction, should be implemented. These actions aim to enhance the ecological environment's quality and foster the coordinated development of the WEFE system in Henan Province.

4.3. Limitations and future research directions

The WEFE-SD model presented in this study comprehensively explores resource supply and demand, ecosystem response, and the interrelationship between WEFE, contributing to the coordinated development of the WEFE system. However, there are certain limitations in this study. Firstly, in quantifying ecological subsystems, only common indicators are considered. Future research should encompass a more comprehensive range of environmental indicators (e.g., green space coverage and solid waste disposal) to enhance model completeness. Secondly, the model neglects the impact of future climate change and extra-regional trade flows on the WEFE system. Future studies should comprehensively consider these factors and their interrelationships. Lastly, the simulation time step in this study is 1 year, future research can explore shorter time steps to improve the prediction accuracy of the SD model and facilitate more accurate policy implementation.

5. Conclusions

Coordinated development of the WEFE system is crucial for fostering sustainable regional growth. This study employed an SD model, considering various resource supply and demand factors, alongside ecological considerations, to construct a representative and effective WEFE-SD model. Five distinct scenarios were designed and simulated in Henan Province, yielding insights for promoting coordinated WEFE system development. The key conclusions are as follows:

(1) Regarding WEF resources, W_R and E_R exhibited a decline during the study period. In the BAU scenario, W_R and E_R are projected to be 0.72 and 0.21, respectively, by 2035, indicating an unbalanced state requiring external supply for equilibrium. F_R showed fluctuations but remained around 4.0, ensuring a balance between supply and demand. Ecological indicators revealed a significant decrease in COD emissions (84 %) but a rising trend in CO_2 emissions (103 %) by 2035, indicating a more challenging environmental situation.

(2) The ED scenario had adverse effects on resources and the environment. Compared to BAU, the ED scenario saw decreases in the W_R, E_R, and F_R by 4.1 %, 14.3 %, and 3.7 %, respectively. Simultaneously, COD and CO_2 emissions increased by 3.8 % and 18.3 %. The EP scenario improved environmental quality but intensified the water resource supply and demand contradiction, with the W_R of only 0.72. The RC scenario exhibited improved resource balance but less significant ecological improvement than the previous scenario. The GD scenario, considering economic, environmental, and resource aspects, played a pivotal role in enhancing WEFE system development and is more indicative of Henan Province.

(3) Domestic sewage emerged as the primary COD pollutant source during the forecast period. Therefore, in the pollutant control process, attention should be paid to the sewage discharge problem to realize dual water resource and ecological environmental protection. Energy is the primary CO_2 emission source, and changes in all aspects cause CO_2 emission fluctuations. From the energy consumption perspective, there is a positive correlation between CO_2 emissions and energy consumption. From the energy consumption structure perspective, the lower the fossil fuel proportion, the lower the CO_2 emissions. Controlling energy consumption and promoting energy-consumption structure transformation are effective CO_2 emission reduction measures.

(4) The constructed WEFE-SD model in this study demonstrates high

simulation accuracy, providing valuable insights into the intricate interplay between resource security and the ecological environment. Despite this success, it is essential to acknowledge existing limitations and areas for future exploration. Further research should delve into a more comprehensive consideration of the influencing factors within the WEFE system. The versatility of the model extends beyond this specific case, offering applicability to other research contexts. Decision-makers can leverage this model to address internal challenges in WEFE system development, enhancing policy formulation and strategic clarity.

CRediT authorship contribution statement

Minhua Ling: Conceptualization, Data curation, Methodology, Validation. **Tianxin Qi:** Conceptualization, Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Wei Li:** Conceptualization, Visualization, Writing – review & editing. **Lili Yu:** Data curation, Writing – review & editing. **Qinyuan Xia:** Supervision, Writing – review & editing.

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.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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