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Water–Energy–Food Nexus in the Yellow River Basin of China under the Influence of Multiple Policies

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Abstract: The water–energy–food (WEF) nexus constitutes a pivotal aspect of regional ecological protection and high-quality development. The exertion of multiple WEF-related policies would engender both synergies and trade-offs within the WEF nexus. However, a quantified framework that integrates the impact of multiple WEF-related policies with conventional WEF nexus assessments and simulations is currently lacking. This study quantified the WEF nexus in the Yellow River basin (YRB) of China under the influence of multiple policies, calculated the current and future WEF scores under different policy combination scenarios using the improved entropy weight method, the auto-regressive integrated moving average (ARIMA) model, and the linear optimization method. The results revealed the following: (1) From 2000 to 2020, WEF overall scores and subsystem scores were substantially increased with spatial heterogeneity. (2) Scenario analysis indicated that policy implementation would generally accelerate WEF score improvements in each city, yet embracing all policies simultaneously was not optimal for each city. (3) The spatial heterogeneity in policy impacts was also found in the YRB, with higher trade-offs in the upper reaches of cities, and higher synergies in the middle and lower reaches of cities. To attain high-quality development within the YRB, the related policies' implementation should consider the regional disparities and enhance the optimization of resource allocation across the regions.

Keywords: water–energy–food; multi-policy impacts; scenario analysis; the Yellow River basin; China

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1. Introduction

Water resources, energy, and food are the "slow factors" of the human–earth system [1] and the essential elements for sustainable development [2,3]. The rational allocation and utilization of water, energy, and food have largely decided the stability of the ecosystem, thus providing key ecosystem services to meet human well-being standards [4]. However, maintaining the security of water, energy, and food resources has become more challenging [5–7], owing to the global population growth and the transition of human activities, as well as the impact of threats like pandemics, floods, and wars. A scientific understanding of the dynamic evolution and functional mechanisms of these three elements is therefore essential.

Water resources, energy, and food are also highly interconnected elements. The synergies and trade-offs among the three elements tend to be evident in socio-economic activities. The shift from traditional "silo" approaches to the integrated "nexus" approaches began in the 1980s and has since evolved through three distinct stages [8,9]. Firstly, the food–energy nexus [10], the water–energy nexus [11], and the water–food nexus [12] were launched during the 1980s and early 2000s. Subsequently, the water–energy–food (WEF) nexus has been highlighted since the Bonn Conference [13]. As critical materials for socio-economic activities, the WEF nexus not only received considerable academic attention but also considered policy frameworks for sustainable development [14,15]. In the late 2010s, the scope of the WEF nexus was expanded to additional elements like water–energy–food–ecosystem (WEFE), water–energy–food–land (WEFL), and water–energy–food–carbon (WEFC) [14,16,17]. Ecosystems are regarded as the foundation of the WEF nexus, and WEFE is usually proposed to meet the Sustainable Development Goals. The WEFE nexus research mainly focuses on the connection of ecosystem services such as water yield, energy generation, and food production [6,18,19]. For the studies of WEFL or WEFC, the tight relationships between WEF and land use and carbon emission were conducted due to the carrier role of the land element in WEF, and the carbon effects in WEF industrial activities [20,21]. Therefore, the WEFL, WEFC, and WEFE nexus can be considered as extensions of the WEF nexus in specific scenarios. The WEF nexus, which combines natural and socio-economic attributes, can be regarded as the core of the linkage between ecological protection and high-quality socio-economic development.

Previous studies have explored the WEF nexus in both theoretical and practical aspects. In theory, the conceptual framework of the WEF nexus and the internal relationship among the three subsystems were well-studied [22,23]. The connections, synergies, trade-offs, and optimal management approaches related to the WEF nexus in varied scales were suggested to achieve the Sustainable Development Goals [8,15,24,25]. In practice, the coupling status and influencing factors of the WEF nexus were evaluated in multiple ways [26–29]. Additionally, simulations of the WEF nexus were carried out to provide quantitative support for the regional future sustainable development policymaking [30–35]. However, the quantitative framework that incorporates the trade-offs and synergies among the WEF nexus is still lacking, limiting the scientific understanding of the regional WEF nexus.

In China, a plethora of policies related to the WEF nexus have been introduced by different government departments. Most of these policies are narrowly focused and emphasize the optimization of specific elements within the WEF nexus. Simultaneously implementing multiple policies may result in trade-offs among other elements within the WEF nexus, hindering the maximization of overall benefits [36]. Previous studies have elucidated the WEF nexus relationships and presented the regional WEF characteristics across different scales [37–41]. Nevertheless, few studies have quantitatively incorporated the synergies and trade-offs among WEF-related policies into the WEF nexus framework.

As the cradle of Chinese civilization, the Yellow River basin (YRB) plays a pivotal role in water resources supply, energy production, and food security. It encompasses the Huang-Huai-Hai Plain, Fenwei Plain, and Hetao irrigation area, which serve as important food production areas and rich reserves of hydropower, coal, oil, and natural gas resources, thereby boosting the economy of the northern regions of China. Nonetheless, the YRB still faces significant challenges. Firstly, the YRB region contends with severe water scarcity, presenting a substantial challenge to its sustainable development. Per capita water resource in the YRB only reaches 45% of China's average level [42]. Secondly, the escalating demand for WEF caused by population growth and economic development has resulted in a mounting imbalance between supply and demand [43]. Thirdly, although a range of policies has been implemented for WEF management in the YRB, discernible trade-offs and inefficiencies persist in policy governance [44]. Hence, to achieve ecological protection and high-quality development goals, it is urgent to pay attention to maximizing the integrated benefits of WEF in the YRB.

To fill these knowledge gaps, we proposed a novel quantitative analytical framework based on policy trade-offs and synergies, and our framework was applied to a WEF nexus simulation and policy optimization in the YRB. The present study aims to (1) analyze the interactions and relationships between WEF policies; (2) evaluate the current state of the WEF nexus; and (3) simulate the impacts of different policy combinations on the WEF nexus. The findings can provide a new perspective to understanding policy-based WEF nexus and propose tailored policy combinations to achieve the ecological protection and high-quality development of the YRB.

2. Materials and Methods

2.1. Research Area

The YRB is in the northern part of China, covering an area of 7.95×10^5 km^2 and flowing through nine provinces and 70 cities (Figure 1). Although some of the cities have relatively minor connections to the Yellow River basin from a physical geography perspective, all cities were emphasized in the critical role of policy development and management for the ecological protection and high-quality development of the YRB in national policies and regulations. Therefore, all 70 cities are included in this study.

The YRB has a pivotal strategic position in the overall development of the country, as it hosted 13.26% of China's GDP, and 15.52% of China's total population by 2020. The YRB is also known for China's raw coal and grain production area, accounting for 66.89% and 18.16% of the country, respectively, by 2019 [45]. However, the YRB comprises mostly arid and semi-arid areas with relatively scarce water resources, accounting for only 2.75% of the country by 2019 [45].

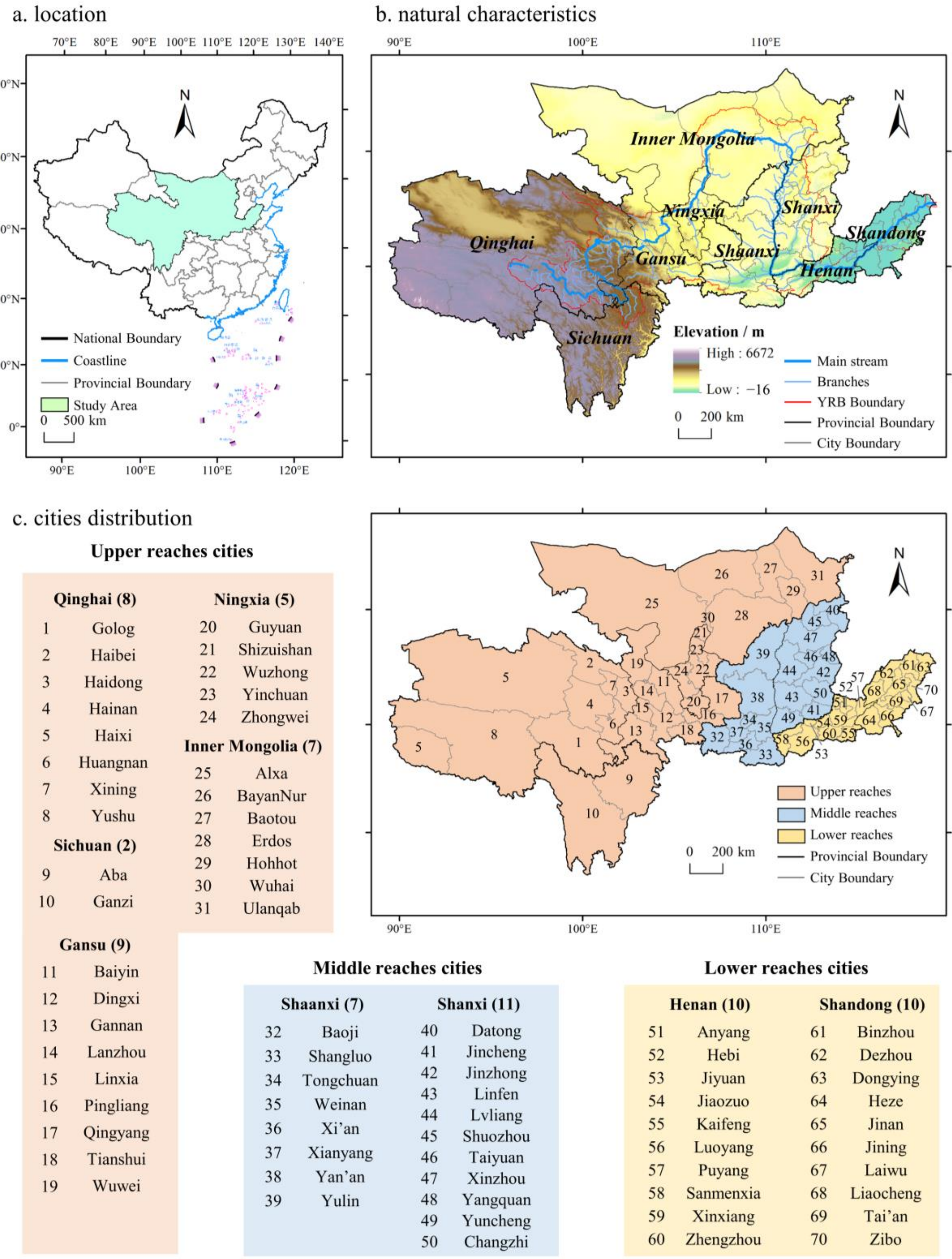
There is significant spatial heterogeneity in the upper, middle, and lower reaches of the YRB, leading to spatial mismatches within the WEF system. The upper reaches involving Qinghai, Sichuan, Gansu provinces, the Ningxia Hui autonomous region, and the Inner Mongolia autonomous region are mainly water source conservation and clean energy areas. Nevertheless, the majority of the upper reaches lie west of the 400 mm isohyet, encountering challenges related to potential over-exploitation of water resources [29]. Furthermore, the higher elevations in the upper reaches and insufficient cumulative temperatures pose constraints on the development of agriculture. The middle reaches involving Shaanxi and Shanxi provinces primarily serve as energy production and ecological conservation areas. However, the vulnerability of the regional ecological environment necessitates an urgent transition from traditional energy production and economic development. The lower reaches involving Henan and Shandong provinces are characterized as grain production and urban development areas. Although the downstream areas exhibit a more accelerated economic development process than the upper reaches and middle reaches, historical patterns of rough development and excessive resource consumption have seriously impacted the ecological environment. Consequently, areas in the lower reaches face the imperative challenge of effecting a green transformation in agriculture and quick economic development under the constraints of water resources.

2.2. Policy Review and Theoretical Framework

2.2.1. Historical Policy Review in the YRB

Over the past two decades, China has been committed to protecting, managing, and enhancing the YRB. Many policies, plans, and projects (hereafter collectively referred to as policies) have been implemented (Figure 2), ranging from localized management to systemic strategies. In this study, the policy framework can be classified into four categories: overall, water, energy, and food governance. For overall policies, the earliest planning initiative "Model Yellow River" project planning was established in 2003, followed by the development of the "Yellow River Basin Comprehensive Planning" a decade later. From 2020, there has been a notable increase in policies related to the YRB. The "Yellow River Protection Law of the People's Republic of China" was enacted in 2022, further emphasizing the protection and restoration of the ecological integrity of the entire basin. Water-related policies have been important. However, the focus of content has transformed from water resource engineering, such as the "Xiaolangdi Water Control Hub" and the "South-to-North Water Diversion Project", to comprehensive governance and specialized planning. These endeavors have played a pivotal role in sand consolidation [46], soil erosion mitigation [47], and agricultural development [48]. Energy-related policies have been mainly focused on the sustainable development of resource-based cities and modern energy systems. Food-related policies have been mainly listed in national planning to emphasize sustainable and green agricultural development. In addition, "Guiding Opinions of the State Council on Establishing the Functional Zones for Grain Production and the Protected Zones for

Production of Major Agricultural Products" was released in 2017 to indicate the important role of the YRB in China's food security.



Upper reaches cities

Qinghai (8)	
1	Golog
2	Haibei
3	Haidong
4	Hainan
5	Haixi
6	Huangnan
7	Xining
8	Yushu

Sichuan (2)	
9	Aba
10	Ganzi

Ningxia (5)	
20	Guyuan
21	Shizuishan
22	Wuzhong
23	Yinchuan
24	Zhongwei

Inner Mongolia (7)	
25	Alxa
26	BayanNur
27	Baotou
28	Erdos
29	Hohhot
30	Wuhai
31	Ulanqab

Gansu (9)	
11	Baiyin
12	Dingxi
13	Gannan
14	Lanzhou
15	Linxia
16	Pingliang
17	Qingyang
18	Tianshui
19	Wuwei

Middle reaches cities

Shaanxi (7)	
32	Baoji
33	Shangluo
34	Tongchuan
35	Weinan
36	Xi'an
37	Xianyang
38	Yan'an
39	Yulin

Shanxi (11)	
40	Datong
41	Jincheng
42	Jinzhong
43	Linfen
44	Lvliang
45	Shuozhou
46	Taiyuan
47	Xinzhou
48	Yangquan
49	Yuncheng
50	Changzhi

Lower reaches cities

Henan (10)	
51	Anyang
52	Hebi
53	Jiyuan
54	Jiaozuo
55	Kaifeng
56	Luoyang
57	Puyang
58	Sanmenxia
59	Xinxiang
60	Zhengzhou

Shandong (10)	
61	Binzhou
62	Dezhou
63	Dongying
64	Heze
65	Jinan
66	Jining
67	Laiwu
68	Liaocheng
69	Tai'an
70	Zibo

Figure 1. Location of the YRB in China (**a**), natural characteristics of the YRB (**b**), and city distribution in the YRB (**c**).

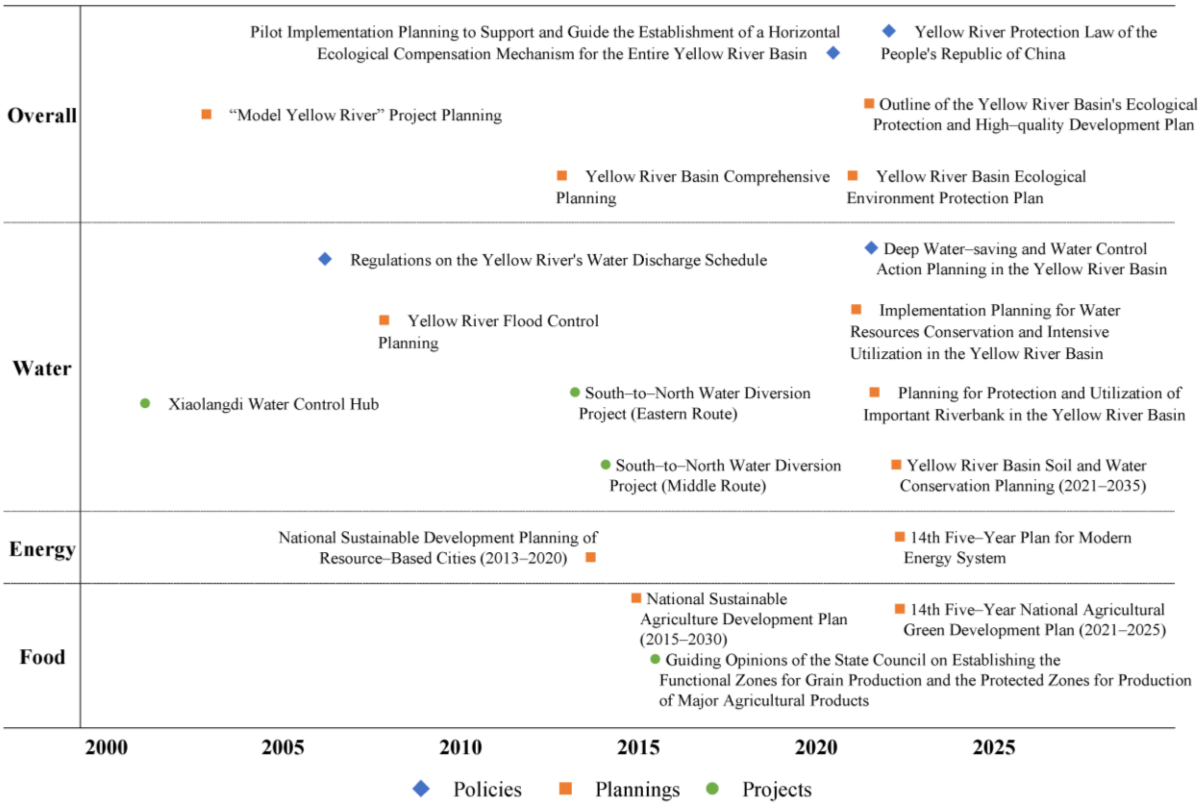


Figure 2. Policies related to water, energy, and food in the YRB.

2.2.2. Theoretical Framework

WEF is a system interwoven with both natural and social systems, characterized by openness, complexity, uncertainty, and hierarchy [29,49]. The synergies and trade-offs of the WEF nexus are embedded in the lifecycle of WEF-related industrial activities [50], which consists of both inner-subsystem processes and inter-subsystem processes (Figure 3). For the water resources subsystem, water resources consume energy in multiple processes such as collection, transmission, and wastewater treatment. In addition, activities such as groundwater protection and regional soil and water conservation impose limitations on the scale and intensity of energy development, as well as food production and processing. For the energy subsystem, the diversity and aggregate quantity of energy supply benefits from the inclusion of water energy provided by water resources and biomass energy derived from agricultural and animal husbandry wastes. However, this integration alters the water resources consumption structure, and accelerates the strain on pollution treatment in both water and energy subsystems. Moreover, activities such as fossil energy development and the construction of new energy projects often encroach on agricultural and livestock production space. For the food subsystem, the lifecycle of food resources consumes water and energy during production, circulation, consumption, and recycling. Furthermore, extensive agricultural practices contribute to elevated water and carbon footprints, thereby intensifying the demands on pollution treatment within the water and energy subsystems.

2.2.3. Trade-Offs and Synergies of WEF Nexus

Based on the theoretical framework, the outlined WEF policies in the 14th Five-Year Plans of 70 cities in nine provinces were listed from the perspectives of production, circulation, consumption, and recycling (Table 1). The policies for each subsystem were strategically selected using the following approach: (1) Policy identification: extracting policies related to water, energy, and food from the 14th Five-Year Plans of each province and city in the YRB. (2) Policy categorization: organizing policies according to the lifecycle of WEF-related industrial activities, with similar policies consolidated to avoid redundancy.

(3) Frequency analysis: by analyzing the frequency of the consolidated policies, the five most frequently mentioned policies in each subsystem were selected as representative of the WEF policies in the YRB.

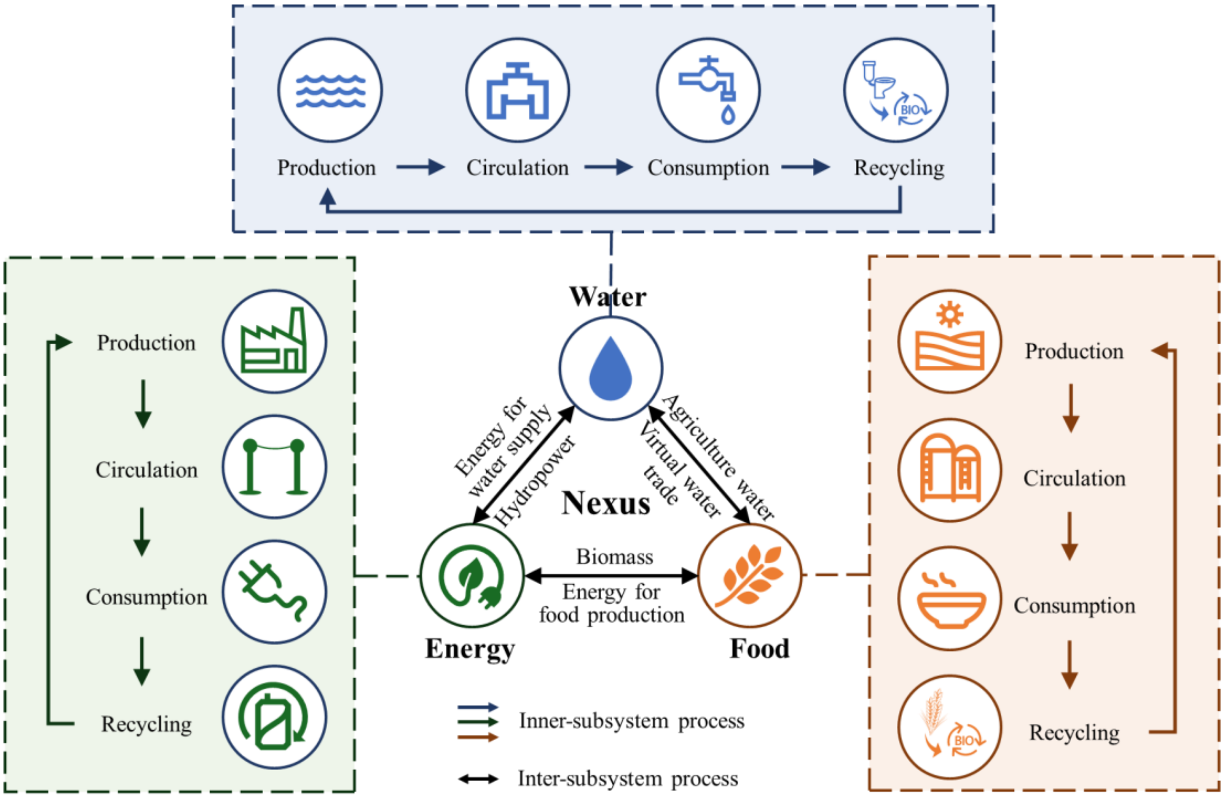


Figure 3. Interaction mechanisms of WEF system.

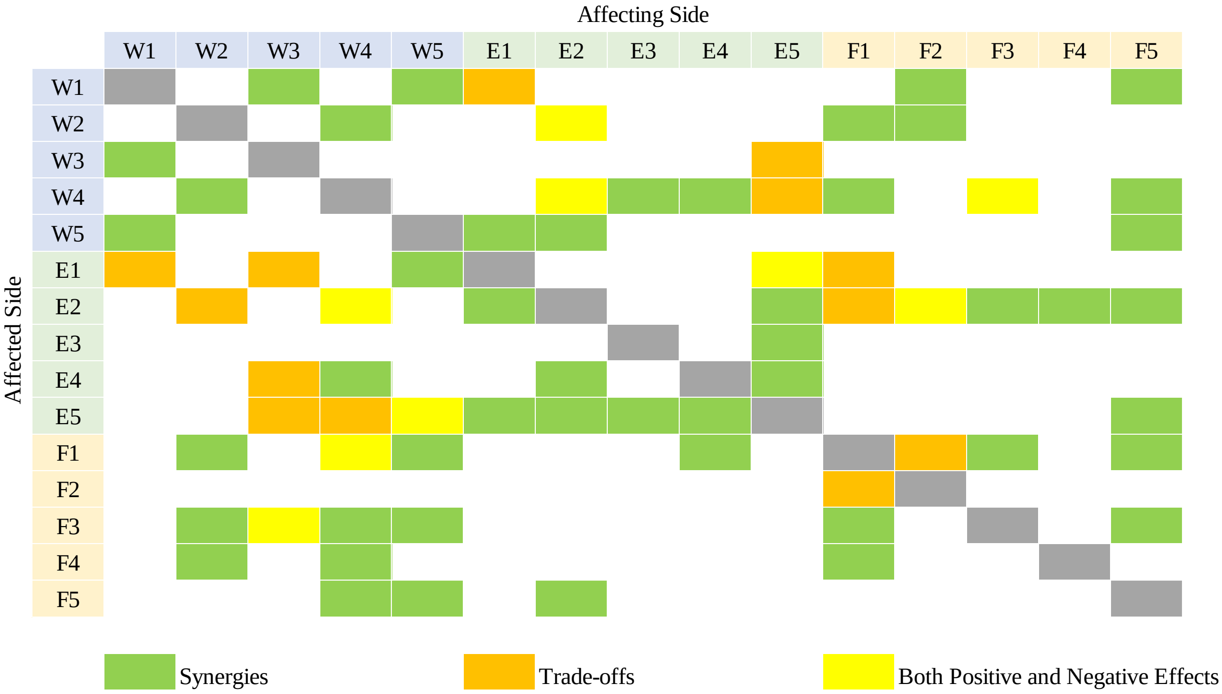
Table 1. Policies in WEF system based on the 14th Five-Year Plans at a city level.

Subsystems	Dimensions		Policy Goals
Water	Production	W1	Securing the safety of centralized drinking water sources
	Circulation	W2	Optimizing the pattern and efficiency of water allocation
	Consumption	W3	Controlling the quantity and intensity of water resource utilization
		W4	Improving the efficiency of water resource utilization
	Recycling	W5	Strengthening water pollution prevention
Energy	Production	E1	Optimizing the intensity and efficiency of energy extraction
		E2	Developing clean energy
	Circulation	E3	Optimizing the pattern and efficiency of energy allocation
	Consumption	E4	Improving the efficiency of energy utilization
	Recycling	E5	Reduction of carbon footprints and energy waste pollution
Food	Production	F1	Securing the quantity and quality of arable land
		F2	Grain for Green, and keeping grassland–animal balance
		F3	Ensuring food supply security and price stability
	Circulation		-
	Consumption	F4	Enhancing the added value of agricultural products
	Recycling	F5	Enhancing agricultural waste reuse capacity

Note: policies related to food circulation were not common in the 14th Five-Year Plans of each city, so they were not listed in this paper.

For the water resources subsystem, the corresponding policies focus on water resource protection, allocation, conservation, use efficiency improvement, and pollution prevention. For the energy subsystem, the corresponding policies focus on developing clean energy, improving the efficiency of energy development, allocation, utilization, and reducing carbon footprints and pollution. For the food subsystem, the corresponding policies focus on guaranteeing arable land and food security, enhancing agricultural added value, and resource utilization of agricultural waste. Overall, the objectives of all the selected policies are consistent with the overall goals of ecological preservation and high-quality development of the YRB.

Interactions among the implemented policies can bring about three outcomes, including synergies, trade-offs, or both positive and negative effects. Overall, the relationship among WEF policies is dominated by synergies. It is noted that partial trade-off relationships and both positive and negative effects were found between the energy and water subsystems and between the energy and food subsystems. Specifically, trade-offs between energy development and utilization (E1, E2, E4, E5), water resources protection (W1, W2, W3, W4), and arable land protection (F1) are evident. Trade-offs and relationships with both positive and negative effects also exist within the food subsystem (F1, F2, F3) (Figure 4). The trade-offs are a challenge in achieving the goal of ecological protection and high-quality development in the YRB.



Affecting Side

Affected Side

	W1	W2	W3	W4	W5	E1	E2	E3	E4	E5	F1	F2	F3	F4	F5
W1	▨		🟩		🟩	🟧						🟩			🟩
W2		▨		🟩			🟨				🟩	🟩			
W3	🟩		▨							🟧					
W4		🟩		▨			🟨	🟩	🟩	🟧	🟩		🟨		🟩
W5	🟩				▨	🟩	🟩								🟩
E1	🟧		🟧		🟩	▨				🟨	🟧				
E2		🟧		🟨		🟩	▨			🟩	🟧	🟨	🟩	🟩	🟩
E3								▨		🟩					
E4			🟧	🟩			🟩		▨	🟩					
E5			🟧	🟧	🟨	🟩	🟩	🟩	🟩	▨					🟩
F1		🟩		🟨	🟩				🟩		▨	🟧	🟩		🟩
F2											🟧	▨			
F3		🟩	🟨	🟩	🟩						🟩		▨		🟩
F4		🟩		🟩							🟩			▨	
F5				🟩	🟩		🟩								▨

🟩 Synergies 🟧 Trade-offs 🟨 Both Positive and Negative Effects

Figure 4. Interactive relationships among WEF policies.

2.3. WEF System Evaluation

2.3.1. WEF Indicator Framework

Based on previous WEF valuation studies [29,43] and the theoretical framework of production–circulation–consumption–recycling (Figure 3), we chose 24 indicators involved with three types: aggregate, structure, and benefit, to construct the evaluation system. The aggregate indicator reflects the stock and consumption of resources across various stages of the industrial lifecycle, the structure indicator primarily describes the production and consumption structure of resources, and the benefit indicator measures the production and utilization efficiency of resources. For the water subsystem, indicators were designed to evaluate the total amount, structure, efficiency, and environmental impacts of water production and consumption. For the energy subsystem, indicators were designed the same way as the water subsystem. For the food subsystem, indicators were designed to evaluate the total amount, structure, and efficiency of food production. The economic contributions and environmental impacts in the food subsystem were also taken into account (Table 2).

Table 2. WEF evaluation framework.

Subsystem	Dimensions		Evaluation Indicator	Indicator Type	Attribute	Weight
Water	Production	w1	Per capita water resource (m^3/person)	Aggregate	+	0.317
		w2	Proportion of groundwater supply (%)	Structure	−	0.012
		w3	Water production coefficient (%)	Benefit	+	0.034
	Circulation	w4	Water Resource self-sufficiency rate	Structure	+	0.374
	Consumption	w5	Per capita water use (m^3/person)	Aggregate	−	0.014
		w6	Water pressure (%)	Structure	−	0.043
		w7	Proportion of ecological water (%)	Structure	+	0.142
		w8	Water use per unit of GDP (m^3)	Benefit	−	0.012
	Recycling	w9	Per capita wastewater discharge (t/person)	Aggregate	−	0.022
		w10	Wastewater discharge rate (%)	Benefit	+	0.029
Energy	Production	e1	Per capita electricity production (kW·h/person)	Aggregate	+	0.328
	Circulation	e2	Electricity self-sufficiency rate (%)	Structure	+	0.365
	Consumption	e3	Per capita electricity consumption (kW·h/person)	Aggregate	−	0.036
		e4	Per capita energy consumption (ton of SCE/person)	Aggregate	−	0.061
		e5	Proportion of oil consumption (%)	Structure	−	0.041
		e6	Energy consumption per unit of GDP (10,000 tons of SCE/100 million yuan)	Benefit	−	0.075
	Recycling	e7	Per capita Industrial waste gas emission (t/person)	Aggregate	−	0.023
		e8	Industrial waste gas emission rate (%)	Benefit	+	0.070
Food	Production	f1	Per capita food production (kg/person)	Aggregate	+	0.171
		f2	Per capita meat production (kg/person)	Aggregate	+	0.222
		f3	Proportion of effective irrigated area (%)	Structure	+	0.235
		f4	Food production per unit area(kg/ha)	Benefit	+	0.128
	Circulation		-			
	Consumption	f5	Engel's coefficient	Benefit	−	0.008
	Recycling	f6	Comprehensive utilization rate of livestock and poultry manure (%)	Benefit	+	0.236

Note: SCE is the abbreviation of "standard coal equivalent"; indicators related to food circulation were not listed in this paper, owing to the lack of related policies and data at the city level.

2.3.2. Methodology for Determining Weights

Previous research has typically adopted the entropy method [5,39], the combination weighting method based on game theory [51], and the analytic hierarchy process (AHP) [52] to judge the weighting of each indicator. Given the substantial geographic variation within the study area, this study employed the improved entropy weight method to mitigate the potential impact of extreme values in determining indicator weights. According to the "three sigma rule", values that exceed two or three standard deviations from the mean can be identified as extreme values [53]. In regional studies, values that exceed two standard deviations can be regarded as outliers [54,55]. Therefore, the values that exceed two standard deviations are calculated as two standard deviations in this study.

$$x'_{ijk} = \begin{cases} \dfrac{x_{ijk} - \overline{x_i}}{\sigma_i}, \left| \dfrac{x_{ijk} - \overline{x_i}}{\sigma_i} \right| \leq 2 \\ -2, \dfrac{x_{ijk} - \overline{x_i}}{\sigma_i} < -2 \\ 2, \dfrac{x_{ijk} - \overline{x_i}}{\sigma_i} > 2 \end{cases} \tag{1}$$

where x_{ijk} represents the indicator's value i in city j of year k, $\overline{x_i}$ represents the mean value of indicator i, and σ_i represents the standard deviation of indicator i. Weight determination is subsequently conducted using the processed data through the entropy weight method [56]. The evaluation score of WEF is the arithmetic mean of the three subsystems.

2.4. Scenario Setting

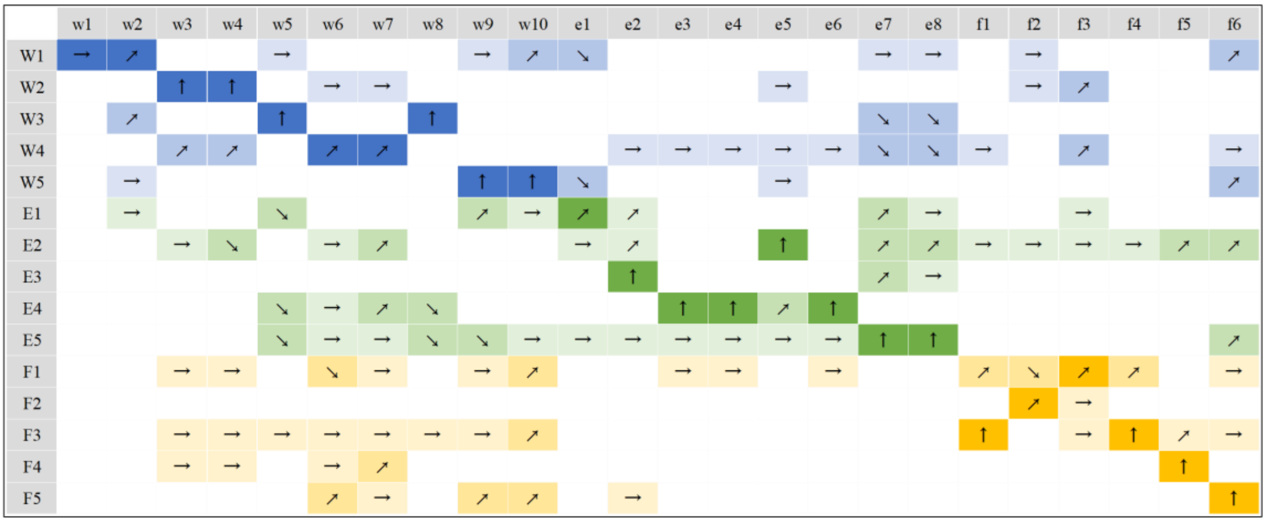
2.4.1. Correlation between Policies and Evaluation Indicators

The impacts of each policy on evaluation indicators can be further analyzed based on the trade-offs and synergies among WEF policies. The impacts of policies on evaluation indicators can be categorized into four types. In addition to them being high-related, low-related and not related, there is another relation type in which a policy can be inner-related with its sub-indicators. Furthermore, the trend of the impact of the policies on the evaluation indicators was categorized into four types, namely, very high increasing trend, increasing trend, maintaining trend, and decreasing trend (Table 3).

Table 3. Relationships between policies and evaluation indicators.

Dimension	Type	Description
Policies' impact on indicators	Inner-related High-related Low-related Not related	The indicator belongs to the policy goal The indicator doesn't directly belong to the policy goal but is highly related The indicator is slightly related to the policy goal The indicator has nothing to do with the policy goal
Impact trends	Very high increasing trend Increasing trend Maintaining trend Decreasing trend	The exertion of the policy can highly increase the indicator's value The exertion of the policy can moderately increase the indicator's value The exertion of the policy can have little change on the indicator's value The exertion of the policy can decrease the indicator's value

The relationships between policies and evaluation indicators were analyzed by integrating the literature and an expert grading method [57,58]. Water policies have high impacts on the water indicators, showing increasing and maintaining trends. Conversely, the impacts of water policies on energy and food indicators are all lower. The trends of water policies on energy indicators show decreasing and maintaining trends, while increasing or maintaining impact trends are found between water policies and food indicators. Energy policies have high impacts on the water indicators and energy indicators. The trends of energy policies on water indicators demonstrate decreasing or maintaining trends, while increasing or maintaining impact trends are found between energy policies and energy indicators.. Food policies exhibit low impacts on the water indicators and energy indicators, with maintaining or increasing trends, whereas significant impacts are found between food policies and food indicators, exhibiting increasing trends (Figure 5).



	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	e1	e2	e3	e4	e5	e6	e7	e8	f1	f2	f3	f4	f5	f6
W1	→	↗			→				→	↗	↘						→	→		→				↗
W2			↑	↑		→	→								→					→	↗			
W3		↗			↑			↑									↘	↘						
W4			↗	↗		↗	↗					→	→	→	→	→	↘	↘	→		↗			→
W5		→							↑	↑	↘				→									↗
E1		→			↘				↗	→	↗	↗					↗	→			→			
E2			→	↘		→	↗				→	↗			↑		↗	↗	→	→	→	→	↗	↗
E3												↑					↗	→						
E4					↘	→	↗	↘					↑	↑	↗	↑								
E5					↘	→	→	↘	↘	→	→	→	→	→	→	→	↑	↑						↗
F1			→	→		↘	→		→	↗			→	→		→			↗	↘	↗	↗		→
F2																				↗	→			
F3			→	→	→	→	→	→	→	↗									↑		→	↑	↗	→
F4			→	→		→	↗																↑	
F5						↗	→		↗	↗		→												↑

Policies' impact on indicators

🟦 🟩 🟨 Inner-related 🟦 🟩 🟨 High-related 🟦 🟩 🟨 Low-related □ □ □ Not related

Impact trends

↑ Very high increasing trends ↗ Increasing trends → Maintaining trends ↘ Decreasing trends

Figure 5. Impacts of WEF policies on indicators.

2.4.2. Implementation of Scenario Analysis

The linear optimization method was applied to quantify the synergistic and trade-off effects among various WEF policies. For indicators affected by policies showing very high increasing trends, it is assumed that the values of these indicators increase by 2% per year as a result of policies; for indicators affected by policies showing increasing trends or decreasing trends, it is assumed that the values of these indicators increase or decrease by 1% per year as a result of policies; and for indicators affected by policies showing maintaining trends, it is assumed that the values of these indicators do not change as a result of policies [56,57]. The cumulative impact of different policies on a given indicator was calculated by multiplying their effects. The core formulas of this algorithm is presented as follows:

$$\mathrm{Score_j} = \mathbf{I} \times \mathbf{P_{W1}} \times \mathbf{P_{W2}} \times \cdots \times \mathbf{P_{F5}} \times \mathbf{W} \tag{2}$$

$$\begin{cases} \mathbf{P_{W1}} = \begin{cases} \mathrm{diag}(\alpha_{\mathrm{W1,w1}}, \alpha_{\mathrm{W1,w2}}, \cdots, \alpha_{\mathrm{W1,f5}}), \text{if policy W1 is adopted} \\ \mathrm{diag}(1, 1, \cdots, 1), \text{if policy W1 is not adopted} \end{cases} \\ \mathbf{P_{W2}} = \begin{cases} \mathrm{diag}(\alpha_{\mathrm{W2,w1}}, \alpha_{\mathrm{W2,w2}}, \cdots, \alpha_{\mathrm{W2,f5}}), \text{if policy W2 is adopted} \\ \mathrm{diag}(1, 1, \cdots, 1), \text{if policy W2 is not adopted} \end{cases} \\ \cdots \\ \mathbf{P_{F5}} = \begin{cases} \mathrm{diag}(\alpha_{\mathrm{F5,w1}}, \alpha_{\mathrm{F5,w2}}, \cdots, \alpha_{\mathrm{F5,f5}}), \text{if policy F5 is adopted} \\ \mathrm{diag}(1, 1, \cdots, 1), \text{if policy F5 is not adopted} \end{cases} \end{cases} \tag{3}$$

$$\mathbf{I} = (\mathrm{w_1}, \mathrm{w_2}, \cdots, \mathrm{f_6}) \tag{4}$$

$$\mathbf{W} = (\mathrm{W_{w1}}, \mathrm{W_{w2}}, \cdots, \mathrm{W_{f6}})^{\mathrm{T}} \tag{5}$$

$$\text{s.t. } \alpha_{\mathrm{W1,w1}}, \alpha_{\mathrm{W1,w2}}, \cdots, \alpha_{\mathrm{F5,f5}} > 0 \tag{6}$$

The objective function of the model is Formula (2). The objective, $Score_j$, predicts the WEF score in city j at the end of the 14th Five-Year Plan. $\boldsymbol{I}$ represents the indicators' matrix, where the basic value of 24 indicators in city j is incorporated (Equation (4)). $\boldsymbol{W}$ represents the weight matrix that is determined using the improved entropy weight method (Equation (5)). Because $\boldsymbol{I}$ and $\boldsymbol{W}$ are determined in Section 2.3, they are considered as the constants. The decision variables are the 15 policy-affecting matrixes, $\boldsymbol{P}_{W1}$, $\boldsymbol{P}_{W2}$, . . . , and $\boldsymbol{P}_{F5}$. Each of the policies is optional to exert according to different scenarios. Each policy-affecting matrix is a diagonal matrix of order 24, corresponding to the impacts of 15 policies on 24 indicators (Equation (3)). If the policy is adopted, the elements of the matrix are the quantified WEF policies' impacts on indicators derived from Figure 5. For example, element $\alpha_{\mathrm{W1,w1}}$ means the quantified impact of policy W1 on indicator w1. If the policy is not adopted, the policy-affecting matrix is a unit matrix. The constraints are the elements of policy-affecting matrixes (Equation (6)), and each element should be positive.

Three scenarios were defined in this study. The baseline scenario (S1) assumed no policy interventions in the current developmental context, which was conducted using the auto-regressive integrated moving average (ARIMA) model [56]. The optimal scenario (S2) aimed to identify policy combinations maximizing the WEF score. The 14th Five-Year Plan-based scenario (S3) adhered to policy combinations specified in municipal and provincial 14th Five-Year Plans. Calculations for each scenario were performed using R software (version 4.2.2).

2.4.3. Comparison between Different Scenarios

The difference degree (DD) is a statistics concept which compares the disparity of data [59]. In this study, DD was used to compare different scenarios within the YRB, which can be divided into the absolute difference degree (ADD) and the relative difference degree (RDD). According to the scenario setting, S1 focuses on the WEF score without policy intervention, which acts as a comparison scenario, while S2 and S3 focus on the impacts of policies on WEF scores. Hence, by analyzing the differences between S2 and S1, as well as

S3 and S1, how policy combinations under different scenarios (theoretical optimal versus actual planning) impact WEF scores can be explored.

The ADD is the difference between the two scenario scores.

$$\text{ADD}_{21} = \text{S2} - \text{S1} \tag{7}$$

$$\text{ADD}_{31} = \text{S3} - \text{S1\#} \tag{8}$$

The RDD calculation indicates the percentage increase in the WEF score when policies are implemented:

$$\text{RDD}_{21} = \frac{\text{S2} - \text{S1}}{\text{S1}} \tag{9}$$

$$\text{RDD}_{31} = \frac{\text{S3} - \text{S1}}{\text{S1}} \tag{10}$$

2.5. Data Sources

Data used in this study mainly include regional spatial data and statistical data related to water resources, energy, and food (Table 4). Because data for some indicators have not yet been updated, this study covers the period from 2000 to 2020. Notably, due to the changes in administrative boundaries, data during 2000 to 2003 in Wuzhong were used to replace the missing data of Zhongwei, and data from Jinan during 2019 to 2020 were used to replace the missing data of Laiwu. Additionally, the linear interpolation method was used to estimate the specific missing data in certain years. For absent indicators in specific regions, we replaced them with the average values from nearby cities within the same province.

Table 4. Data description and sources.

Data	Description	Source
Spatial data	Administrative division data and elevation data	Data Centre for Resource and Environ-mental Sciences (https://www.resdc.cn/ (accessed on 7 May 2023))
Socio-economic data	Data about population, GDP, and territorial area	China Statistical Yearbook (2001–2021)
Water resources data	Data about precipitation, water resource production and consumption, water pollution, and recycling	China Statistical Yearbook for Regional Economy, Water Resources Bulletins for provincial (2001–2021)
Energy data	Data about energy production and consumption, pollution, and recycling related to energy industry	China City Statistical Yearbook, China Regional Statistical Yearbook, China Energy Statistical Yearbook, Statistical Bulletin of National Economic and Social Development for city (2001–2021), City-level spatio-temporal energy consumption datasets for China (2000–2017)
Food data	Data about food production and consumption, agricultural pollution, and recycling	China Regional Statistical Yearbook, Statistical Yearbook for provincial (2001–2021)

3. Results

3.1. WEF Scores

From 2000 to 2020, there were noticeable upward trends observed in the scores of the water subsystem, the energy subsystem, the food subsystem, and the overall WEF system (Figure 6). For the water subsystem, the region in the upper reaches consistently achieved higher scores than the other regions. In particular, cities in the Qinghai and Sichuan provinces had higher scores, where the water resources are abundant and the natural environment has been well-preserved. Conversely, lower scores were observed in the cities of Ningxia, Inner Mongolia, and Shaanxi provinces (Figure 6(a1–a3)). For the energy subsystem, Inner Mongolia, northern Ningxia, and northern Shaanxi had higher scores than other regions in 2000, which were traditional energy aggregation areas (Figure 6(b1)). By 2020, rapid growth was observed in Sichuan and southern Qinghai due to the exploitation of renewable energy sources, forming two areas with high scores in the energy subsystem (Figure 6(b3)). For the food subsystem, scores showed a steady increase, with higher scores in the lower reaches, particularly in Shandong, which benefits from flat terrain and favorable hydrothermal conditions conducive to agricultural development. Conversely, lower scores were found in the upper reaches, particularly in Qinghai (Figure 6(c1–c3)). Overall, the scores of the WEF system consistently increased in the YRB. Three regions had relatively higher scores, including the Qinghai and Sichuan provinces, the Inner Mongolia–Northern Ningxia–Northern Shaanxi region, and Shandong (Figure 6(d1–d3)).

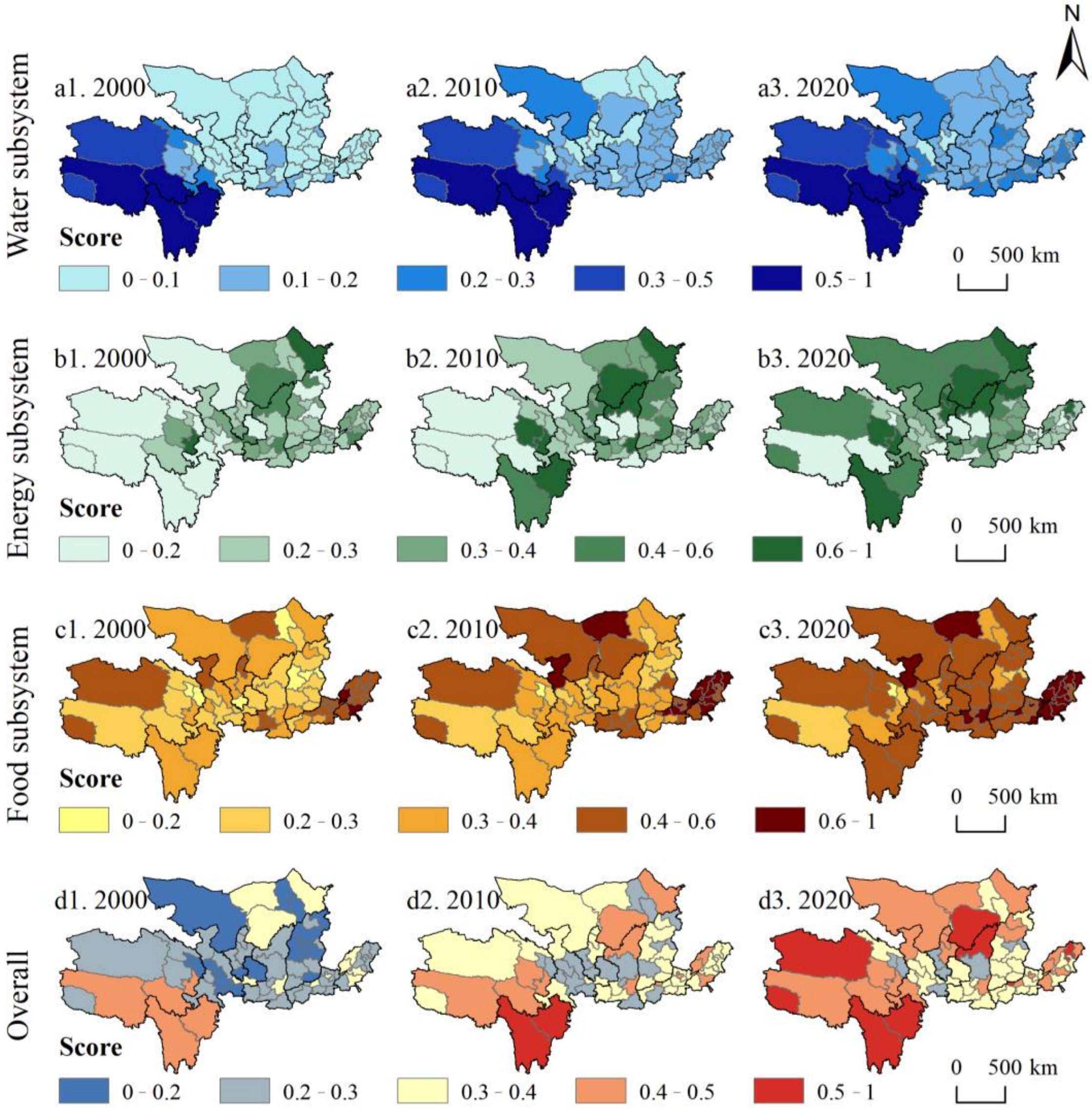


Figure 6. Spatial distributions of scores of water subsystem (**a1**–**a3**), energy subsystem (**b1**–**b3**), food subsystem (**c1**–**c3**), and overall score (**d1**–**d3**) in the YRB from 2000 to 2020.

3.2. Policy Choices and Scenario Predictions

3.2.1. Policy Adoption

For the policies adopted in S2, no city adopted all 15 policies (Figure 7a). Water-related policies were adopted less than energy-related and food-related policies in the cities of the YRB. Cities in the middle and lower reaches largely adopted all water, energy, and food policies, while in the upper reaches of the city, only policies W2 and W4 were predominantly adopted. This is mainly due to the trade-offs in water-related policies being relatively more in number than the energy-related or food-related policies. Additionally, according to Figures 3 and 5, the exertion of policy W3 may constrain the energy subsystem development.

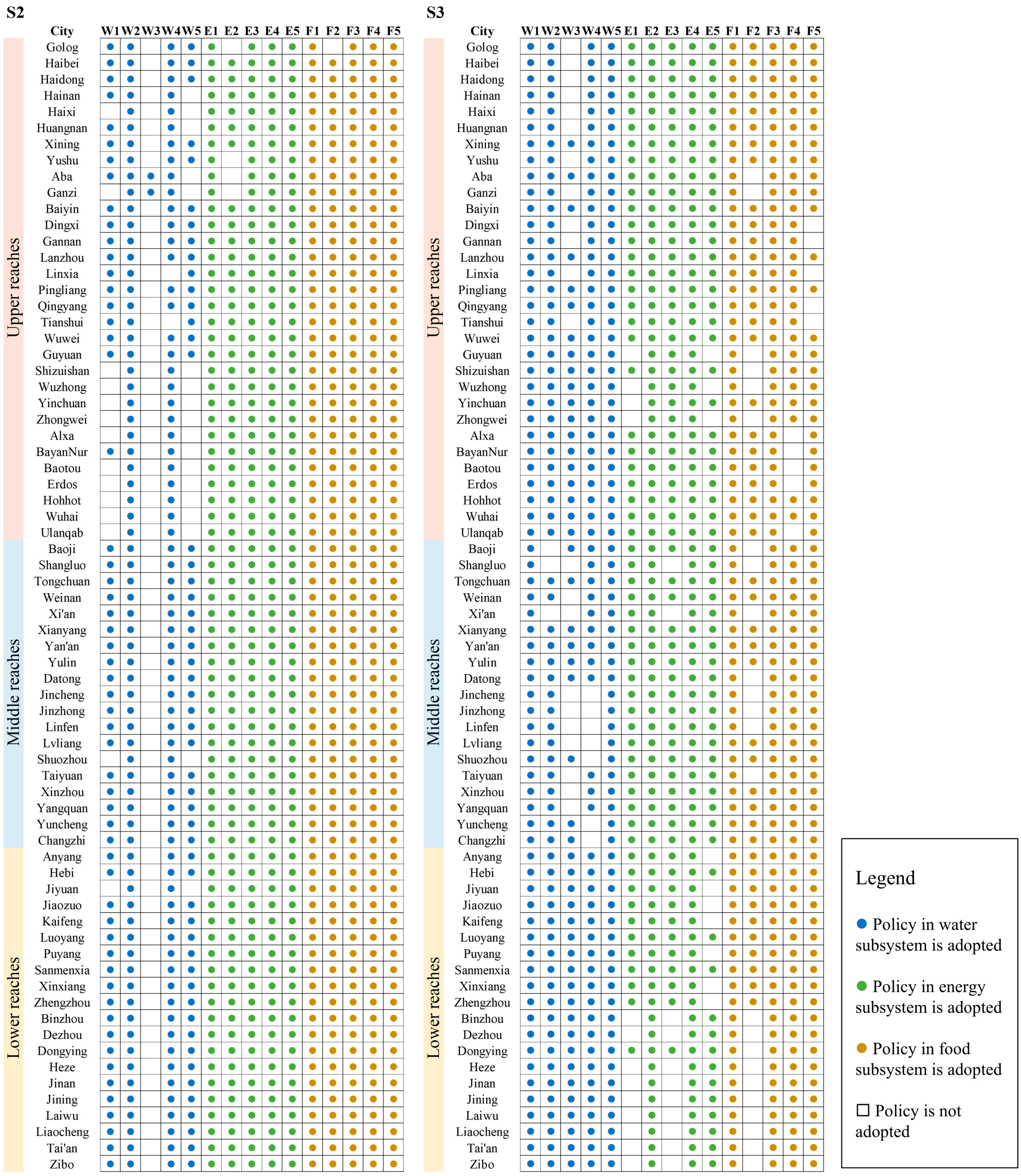


Figure 7. Policy choices in scenario 2 and scenario 3; the dotted cell means the corresponding policy was chosen.

For the policy adoption in S3, 14 cities implemented all policies in the 14th Five-Year Plan (Figure 7b). Policy selections varied significantly across different regions of the YRB. Cities in the upper and middle reaches tended not to adopt policy W3 but tended to adopt all energy policies in the 14th Five-Year Plan, while those in the lower reaches were relatively inclined toward all water policies, but not policy E1 and E3 (Shandong province) or E5 (Henan province). Additionally, Haibei, Haidong, Qingyang, Xinzhou, Weinan, and Yangquan exhibited policy choices in S3 that were identical to those in S2. The policy choices of other cities between S3 and S2 had high similarities. Although the urban development status constrained the exertion of some policies, most cities still had room for optimizing their current policy goals.

3.2.2. Scenario Prediction

Compared with the scores of the WEF system in the baseline (2020), each city shows an increasing trend in scores across all scenarios (Table 5). For S1, a significant increase occurs in the cities of the upper reaches, while a few cities located in the middle and lower reaches, such as Yan'an, Yulin, Xinzhou, Hebi, Jiyuan, and Laiwu, also have clear increases. For S2, each city's prediction score exhibits a surge higher than that of the baseline, especially in the cities of Gansu. Instead of only one city's WEF score (Ganzi) over 0.6 in the baseline, 14 cities' WEF scores are over 0.6 in S2. For S3, the predicted scores for each city are higher than those in S1, but lower than those in S2. A significant increase also occurs in cities in the upper reaches. A total of 11 cities' WEF scores are over 0.6 in S3, slightly less than that of S2.

Table 5. Prediction scores in different scenarios.

City	Baseline	S1	S2	S3	City	Baseline	S1	S2	S3
Golog	0.482	0.553	0.617	0.615	Xi'an	0.360	0.379	0.446	0.444
Haibei	0.374	0.420	0.467	0.467	Xianyang	0.389	0.406	0.471	0.470
Haidong	0.287	0.360	0.401	0.401	Yan'an	0.296	0.376	0.435	0.434
Hainan	0.488	0.577	0.639	0.636	Yulin	0.525	0.592	0.659	0.658
Haixi	0.515	0.571	0.621	0.613	Datong	0.360	0.431	0.481	0.478
Huangnan	0.459	0.496	0.547	0.545	Jincheng	0.380	0.448	0.508	0.505
Xining	0.214	0.271	0.306	0.306	Jinzhong	0.366	0.400	0.455	0.452
Yushu	0.443	0.501	0.555	0.552	Linfen	0.325	0.370	0.421	0.418
Aba	0.622	0.664	0.725	0.722	Lvliang	0.381	0.441	0.506	0.503
Ganzi	0.673	0.680	0.744	0.740	Shuozhou	0.415	0.460	0.502	0.498
Baiyin	0.375	0.445	0.503	0.502	Taiyuan	0.281	0.311	0.358	0.357
Dingxi	0.377	0.466	0.539	0.527	Xinzhou	0.459	0.545	0.615	0.615
Gannan	0.498	0.559	0.636	0.624	Yangquan	0.286	0.315	0.357	0.357
Lanzhou	0.309	0.365	0.426	0.426	Yuncheng	0.365	0.368	0.419	0.418
Linxia	0.316	0.388	0.449	0.437	Changzhi	0.329	0.375	0.421	0.419
Pingliang	0.392	0.473	0.537	0.536	Anyang	0.369	0.404	0.460	0.457
Qingyang	0.304	0.389	0.447	0.447	Hebi	0.438	0.505	0.574	0.573
Tianshui	0.281	0.364	0.422	0.409	Jiyuan	0.500	0.578	0.646	0.640
Wuwei	0.458	0.525	0.601	0.600	Jiaozuo	0.408	0.415	0.473	0.470
Guyuan	0.277	0.356	0.393	0.385	Kaifeng	0.388	0.416	0.478	0.475
Shizuishan	0.404	0.416	0.456	0.445	Luoyang	0.338	0.399	0.457	0.457
Wuzhong	0.433	0.469	0.516	0.492	Puyang	0.394	0.429	0.491	0.488
Yinchuan	0.430	0.491	0.552	0.531	Sanmenxia	0.327	0.393	0.448	0.447
Zhongwei	0.281	0.332	0.364	0.354	Xinxiang	0.372	0.418	0.475	0.472
Alxa	0.409	0.447	0.496	0.484	Zhengzhou	0.341	0.378	0.438	0.435
BayanNur	0.477	0.468	0.522	0.519	Binzhou	0.579	0.620	0.694	0.678
Baotou	0.349	0.422	0.463	0.454	Dezhou	0.443	0.482	0.551	0.543
Erdos	0.546	0.578	0.647	0.640	Dongying	0.488	0.550	0.628	0.624
Hohhot	0.360	0.420	0.466	0.461	Heze	0.417	0.452	0.520	0.512
Wuhai	0.382	0.411	0.459	0.449	Jinan	0.388	0.400	0.464	0.460
Ulanqab	0.499	0.553	0.618	0.612	Jining	0.393	0.408	0.470	0.463
Baoji	0.371	0.403	0.464	0.461	Laiwu	0.388	0.498	0.576	0.572
Shangluo	0.372	0.404	0.468	0.461	Liaocheng	0.485	0.507	0.575	0.562
Tongchuan	0.360	0.423	0.480	0.480	Tai'an	0.401	0.444	0.515	0.508
Weinan	0.470	0.473	0.547	0.547	Zibo	0.372	0.405	0.467	0.462

3.3. Difference Degrees Analysis

For ADD_{21}, at the basin scale, the higher increased score area in S2 was found in the lower reaches of the YRB, and the lower increased score areas in S2 were found in the northwestern parts of the YRB. At the city scale, however, the higher increase areas of the

WEF score were relatively scattered (Figure 8a). For RDD_{21}, 63 out of 70 cities had over a 10% increase than S1 (Figure 8b). Higher increased percentage areas were mainly in Gansu and the middle and lower reaches of the YRB, and lower increased percentage areas were mainly in the western part and lower part of the YRB.

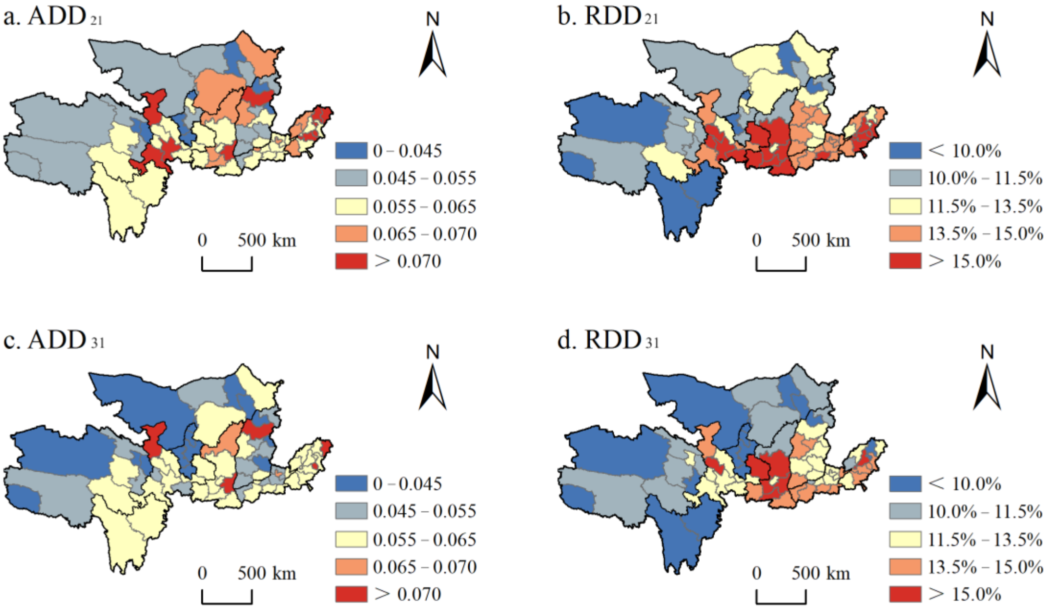


Figure 8. Difference degree between S1 and S2 (**a**,**b**) and S1 and S3 (**c**,**d**).

For ADD_{31}, at the basin scale, the higher increased score areas in S3 were found in the middle and lower reaches of the YRB. At the city scale, the increased score level in most cities of S3 exhibited a lower level than that of S2. The higher increase areas of the WEF score in S3 were more scattered than S2, and the lower increase areas of the WEF score in S3 were relatively scattered in the upper and middle reaches of the YRB (Figure 8c). For RDD_{31}, the increased percentage level in most cities in the upper and lower reaches of S3 exhibited a lower level than that of S2, whereas the increased percentage in most cities in the middle reaches of S3 retained the same level of S2 (Figure 8d).

4. Discussion

4.1. Spatio-Temporal Differences of WEF Nexus

The spatial patterns of the WEF score in the YRB showed significant spatial agglomeration (Figure 6). Generally, the spatio-temporal disparity of the WEF score is related to natural environment, resource endowment, and socio-economic development. In the YRB, the natural environment and resource endowment have determined the differences of the WEF nexus at the basin scale (Figure 1). Socio-economic development altered this difference [60]; for instance, cities in Henan and Shandong possess fewer advantages in terms of water resources and energy endowment, but both provinces are relatively developed economically in the Yellow River basin region. Furthermore, we also found that resource utilization or management also affected the spatio-temporal differences between the WEF score. Specifically, by regulating related human activities, with an increase in clean energy consumption and a decrease in coal consumption, the WEF score was altered. As evidenced by cities in Inner Mongolia, whose WEF score had significantly increased over two decades, resource utilization optimization brought about alterations.

The disparity in the natural environment, resource endowment, and socio-economic development also affected the score in each subsystem differently. For the water subsystem, areas with abundant water resources and that are less affected by humans mainly contributed to higher water subsystem scores [61]. Also, the improvement of the water resources consumption structure and sewage processing ability were indispensable socio-economic factors for the increase in the water resources score in the YRB [29]. For the energy subsystem, though the resource endowment of traditional energy was the primary factor of the energy subsystem score in the early stages, improved energy production capacity facilitated the energy subsystem development in the upper reaches [62,63]. The variety of energy exploitation is conducive to promoting regional energy resilience. For the food subsystem, flat terrain and favorable hydrothermal conditions constitute the basis for agricultural development [64], while socio-economic factors boosted the surge in food subsystem scores. With the farmland protection policy, the efficiency of grain production in the study area has generally improved. In addition, China's poverty alleviation policy [65], changes in rural livelihoods [66], and the utilization of agricultural waste resources [67] have improved the food subsystem in all aspects of industrial activities.

4.2. Differentiated Policies Adoption for WEF Optimization

The WEF score in each city increases with the adoption of multiple policies (Table 5). However, the policy combination that optimizes the WEF score varies among areas (Figures 7 and 8). Cities in the upper reaches have larger variations in policy adoptions in S2 than other cities (Figures 7 and 8). These differences mainly arise from the more pronounced geographic constraints. Cities in the upper reaches mostly located on the northwest side of the "Hu Line", with more fragile ecology conditions, fewer resources, and a lower environment carrying capacity, are more suitable for specialized policies [68]. In addition, limited human activities also give rise to more trade-offs in policy adoption, especially in Qinghai, Sichuan, Ningxia, and Inner Mongolia (Figure 8a,b). Cities in the middle reaches have the least incongruent policy combinations between S2 and S3, revealing more synergistic effects in policy adoptions than others (Figures 7 and 8). However, there are some differences in policy combinations for S3 among cities in the middle reaches (Figure 7, Table 5). This can be attributed to differentiated zonal characteristics from north to south in the middle reaches [68]. In our case, the 14th Five-Year Plan of each city in the middle reaches differs according to its natural condition and resource endowment. Cities in the lower reaches also have some differentiated policy adoptions between S2 and S3, such as W3, E1, E3, E5, and F2 (Figure 7). The primary reason for this incongruity is the trade-off between the water resource consumption structure optimization and the energy system burden [69]. Although implementing energy policies rather than water policies can increase the WEF overall score in theory, natural resources and economic foundations reveal that implementing water policies is more practical in reality [70,71]. In addition, the difference in policy choices between S2 and S3 in the lower reaches is also caused by a mismatch in regional development orientation. If a food policy (F2) were exerted in the lower reaches, a major grain-producing region and a key area for China's new urbanization, the area may face potential hindrances to its economic growth [38,72]. Hence, differentiated policy adoptions were found between S2 and S3 in cities in the lower reaches.

To achieve ecological protection and high-quality development in the YRB, the regional differences in the YRB should be fully considered. For the cities in the upper reaches, it is imperative to prioritize ecological security and promote the WEF nexus development. Based on the policies outlined in the 14th Five-Year Plan, there is room for more emphasis on the control of energy extraction and carbon emission while mitigating water resource deficits [73]. For the cities in the middle reaches, there is a need to match energy transition with the ecological environment [29]. Specifically, for the hilly and gully areas of the Loess Plateau, gully land consolidation projects and agricultural geographical engineering could be implemented to achieve sustainable land use and ensure regional food security [74,75]. For the cities in the lower reaches, it is necessary to comprehensively enhance the quality and resilience of WEF development based on the foundation of new urbanization. Trade-offs between water and energy subsystems should be fully considered. Furthermore, the optimization of resource allocation between regions should also be strengthened [76,77]. For example, in response to the high water-consuming demand for socio-economic development in the middle and lower reaches of the Yellow River basin, the equitable development of the basin's WEF nexus can be promoted by adopting ecological compensation for the regions in the upper reaches [78,79]. By alleviating the mismatch among water, energy, and food elements, the coordinated development of water–energy–food resources in the basin can be facilitated.

4.3. Shortcomings and Prospects

This study is theoretical and innovative in terms of the novelty of the research perspective and the applicability of the research results. A quantitative analysis framework was proposed from the perspective of trade-offs and synergies among water, energy, and food policies. The research results clearly provided a policy combination for the optimal development of the water–energy–food system in the Yellow River basin, which is highly practical. However, the study has several drawbacks. Firstly, constrained by some data at the city level that has not been updated, the WEF score evaluation was only updated to 2020. Secondly, the improved entropy method applied in the study is an objective weighting approach; the weight determined by the data distribution cannot reveal the importance of order in reality. Moreover, the differentiated WEF-developing inclination among different cities in the YRB is also neglected by adopting the same weight. Thirdly, the scenario analysis conducted in this research utilized a combination of the ARIMA model and the linear optimization method, which is typically employed for short-term forecasting models [80].

Further investigations into quantitative WEF relationships in the YRB are needed to explore the following aspects. Firstly, a multi-source dataset can be incorporated to update and enrich the WEF evaluation system, thus creating a longer time-series simulation and analysis. Secondly, a better method to tailor weights more effectively in WEF evaluations has yet to be explored. Thirdly, the methodology of WEF policy analysis and optimization can be applied in more areas, thus providing more implications for WEF management.

5. Conclusions

In the context of ecological protection and high-quality development, enhancing the WEF nexus in the YRB is a vital approach to sustainable human development. In this study, we analyzed interactions and relationships among policies within the WEF policy framework, evaluated the WEF score, and forecasted multi-policy impacts of various policy scenarios within the YRB. It drew the following conclusions: (1) Through the lifecycle of industrial activities, there are inner-subsystem processes and inter-subsystem processes in the WEF nexus, causing three kinds of policy mutual influence results: synergy, trade-off, and both positive and negative effects. (2) Within two decades, WEF overall scores and subsystem scores in the YRB have increased, influenced by natural circumstances, resource endowment, the economy, resource utilization, or management. (3) In terms of WEF scores forecasted at the end of 14th Five-Year Plan, the optimal policy combination in each city was to not adopt all policies, and the policy combination of the 14th Five-Year Plan-based scenario in most cities were not completely in accordance with that of the optimal value scenario, yet both scenarios in each city had more conspicuous increases than the baseline scenario. In the context of the YRB, and particularly in the cities of the upper and middle reaches, it is advisable to adopt a localized approach that considers the specific circumstances of each city and focuses on protecting and developing key resources.

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