

Assessing the Coordination of Regional Water and Soil Resources and Ecological Environment System Based on Development Rate Characteristics

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Assessing the coordination of regional water and soil resources and ecological environment system based on development rate characteristics

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Abstract

The coordinated development of land and water resources and the ecological environment is essential to regional sustainable development. In view of the current rapid development of information science, the coordination degree of eco-environmental systems has been evaluated from the perspective of development rate. Taking the major grain-producing areas in China as an example, this study used information entropy to determine the weights of various indicators and introduced the average annual growth rate to characterize the development rates of indicators. Through an improved dynamic coupling and coordination model, the coupling and coordination indices of the system and subsystems of land and water resources with the ecological environment were obtained. These indices were analyzed and compared with those generated from raw data. The results showed that during the study period, the land and water resources and the ecological-environmental system had a relatively low coupling, with reluctant coordination, and had a relatively low level of coordinated development. Compared with the results based on raw data, the development rate method yielded similar results on the coupling of subsystems. For the analysis of trends, the method using development rate characteristics better reflected the overall coupling of the system, as well as the coordination of the system when considering the range of relative changes. Therefore, evaluation results based on development rate characteristics can, to a certain degree, better help decision-makers timely understand the coordinated development of the land and water resources and the ecological-environmental system.

Keywords Development rate characteristics·Index system·Information entropy·Coupling index·Coordination index

1 Introduction

The ecological environment is a composite system consisting of the nature, society, and the economy. The rapid expansion of urbanization has disrupted the balance of the ecological environment to a certain extent. When the degree of disruption exceeds the carrying capacity of the system, human societies become more impeded than facilitated. Therefore, with the frequent occurrences of various natural disasters, the quality of the ecological environment has received more attention. A growing number of studies on this aspect have been conducted, with significant findings.

Most of these studies emphasize eco-environmental risk assessment. In view of the rapid development of Pakistan's pharmaceutical industry, Muhammad et al. (1997) used the risk quotient to perform an eco-environment risk assessment of industrial wastewater production during pharmaceutical processes. Ning et al. (2013) used Thematic Mapper (TM) remote-sensing imagery to perform layered algebraic calculations to quantitatively analyze the ecological risks and spatial-temporal trends of land use. Based on the role of wetlands in regional development and environmental protection, Jiang et al. (2017) analyzed the risks that plateau wetland degradation and disappearance posed to society and the ecological environment. Using screened environmental pollutants, Tian et al. (2020) discussed the ecological risk to China's Yellow Sea large marine ecosystem. Based on rough sets, composite indices, and catastrophe theory, Gao et al. (2019) evaluated ecological security and its driving factors under the rapid development of islands. Xiang et al. (2020) addressed the role of forest ecosystems in protecting the ecological environment. To remove the influences of weighting uncertainty on the evaluation results, they used an unweighted cloud model in the evaluation study of forest ecosystems. Sun and Loh (2019) conducted research on regional sustainable development based on ecological efficiency – an indicator for scientifically evaluating performance recognized by international organizations and research institutions. Aiming at developing key strategies to tackle ecological problems, Galina et al. (2019) developed and examined the universal ethical principles of individual-based ecological and cultural innovation models. They discussed the legal relevance of the equal coexistence of people and nature and the sustainable development of interacting ecosystems, economies, and production. David et al. (2018) used caves with relatively simple species compositions as an example to study the survival of biological populations in the

changing ecological environment. Stepanova et al. (2018) focused on the status of the ecological environment and determined its impacts on human health by examining the metal levels in children. Li et al. (2020) analyzed the association between the intensity of human activities and ecosystems from the perspective of ecosystem service values. By addressing the index system as an important tool for evaluating the ecological environment, Chang et al. (2019) proposed the ‘ecological-factor conceptual framework’ – based on ecological hierarchy networks – as a way to construct an index system. This method showed superiority in the quantitative analysis of the impacts of various indicators on the ecological environment. Qing and Wang (2019) adopted a ‘driving force–pressure–state–impact–response’ framework to construct an evaluation index system and used the TOWA-GA hybrid operator for the dynamic evaluation of eco-environmental quality.

In summary, in a society where the economy, information, and urbanization are rapidly developing, there are relatively few studies on the ecological environment based on development rate changes, but these can give rise to a range of ecological and environmental problems. Therefore, it is necessary to understand the coordinated development capability of the ecological-environmental system based on the development rates of various indicators. Taking the major grain-producing areas in China as an example, this study used the average annual growth rate to describe the development rates of various indicators of land and water resources and the ecological-environmental system. The coupling coordination index of the system was used for the dynamic evaluation of its level of positive development. In comparison with the results from evaluating raw data, the relationships and interactions between the society, economy, resources, and the ecological environment of the study area were analyzed. Our findings provide a reference for understanding and improving the current state and developmental trends of the ecological environment.

2 Study area

The coordinates of the study area are 43°25′-53°33′N and 121°11′-135°05′E. The study area is the northernmost and highest-latitude commodity grain base (Fig. 1). The percent contribution of the study area to China’s Gross domestic product (GDP) dropped from 2.95% in 2003 to 1.82% in 2018, and its overall economic development relatively lagged. The average

annual water use efficiency of the study area was 39.76%, which was higher than the national average (21.64%). Water resources in the study area were relatively abundant. However, the average annual surface water and groundwater use efficiencies were 81.13% and 18.19%, respectively, which were 25% lower and 26% higher than the corresponding national levels, indicating relatively large disparities in the use of water resources. As a commodity grain base, grain yield of the study area almost doubled between 2003 and 2017. Major indicators of agricultural production have also shown continuously growing trends. The area of cultivated land, the effective irrigation area, and the amount of chemical fertilizer application (expressed in elemental form) increased by 34.77%, 185.63%, and 99.77%, respectively. The yield per unit area of rice, corn, and soybean –the major grain crops – increased by 7.04% and 10.37% and decreased by 10.94%, respectively. These increases in per unit yield contributed little to the surge in overall production.

Thus, under the influences of the regional economy and the development and use of land and water resources, the stability and direction of development of the ecological-environmental system in the study area have undergone changes. There is a need to conduct a systematic analysis of land and water resources and the ecological-environmental system in order to explore policy measures to maintain the virtuous cycle of the ecological environment and facilitate the coordinated development of people and the ecological environment.

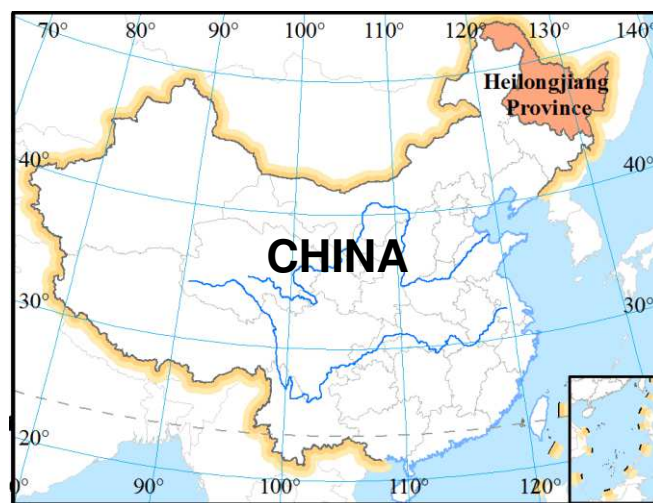


Fig. 1 Study area

3 Research methods

3.1 Construction of an index system

At present, land and water resources and the ecological environment are generally analyzed by establishing an evaluation index system. In this study, the indices selected are scientific, systematic, comparable, and accessible in principle. Given the structure of the large, composite ecological-environmental system, it was divided into four interdependent subsystems: resource (B₁), society (B₂), economy (B₃), and the ecological environment (A), based on which an evaluation index system was established. In view of the actual situation of the study area, for the resource subsystem, this study considered the ability to regulate, the extent of consumption, and the availability of land and water resources. Six representative indicators were selected: per capita water consumption (C₁), per capita land area (C₂), groundwater use ratio (C₃), surface water use ratio (C₄), proportion of cultivated land (C₅), and water consumption intensity (C₆). For the society subsystem, in consideration of the natural development of the population and its resource demands, living standards, urbanization level, status of societal development, and food security, six representative indicators were selected: population density (C₇), urbanization rate (C₈), per capita GDP (C₉), per capita grain yield (C₁₀), rate of natural increase (C₁₁), and Engel coefficient (C₁₂). For the economy subsystem, in consideration of energy production and consumption, the proportion of agriculture in the economy, the ability to withstand natural disasters, the resource carrying capacity, and the agricultural productivity, seven representative indicators were selected: proportion of agriculture in the regional economy (C₁₃), elasticity coefficients of energy production and consumption (C₁₄, C₁₅), water consumption per unit GDP (C₁₆), GDP per unit area (C₁₇), grain yield per unit area (C₁₈), and irrigation area coverage (C₁₉). For the ecological environment subsystem, in consideration of human pressures on land and water resources and air quality, five representative indices were selected: air pollution index (C₂₀), pollution load per unit area of cultivated land (C₂₁), load of industrial wastewater per unit area of land (C₂₂), per capita industrial exhaust emission (C₂₃), and eco-environmental water use (C₂₄). Furthermore, as society has given more and more attention to ecological quality, investment in environmental governance per unit GDP (C₂₅) was calculated to characterize the ability to mitigate

environmental degradation. In this study, indicators of the resource, society, economy, and ecological environment subsystems were directly related to the stable development of eco-environmental quality and were all positive indicators.

Details of the index system are listed in Table 1.

Table 1 Indicators for evaluating land and water resources and the ecological-environmental system

| Subsystem | Indicator | Formula | Meaning of indicator |
|-------------------------------|--|--|---|
| Resource (B ₁) | Per capita water consumption (C ₁) | Water resource consumption/population size (10 ⁴ m ³ /person) | Ability to regulate water resources |
| | Per capita land area (C ₂) | Total land area/population size (hm ² /person) | Ability to regulate land resources |
| | Groundwater use ratio (C ₃) | Groundwater use/total volume of groundwater (%) | Extent of consumption of groundwater resources |
| | Surface water use ratio (C ₄) | Surface water use/total volume of surface water (%) | Extent of consumption of surface water resources |
| | Proportion of cultivated land (C ₅) | Area of cultivated land/total land area (%) | Cultivation intensity |
| | Water consumption intensity (C ₆) | Water resource use/total land area (10 ⁴ m ³ /hm ²) | Availability of land and water resources |
| Society (B ₂) | Population density (C ₇) | Population size/regional land area (person/hm ²) | Resource demand |
| | Urbanization rate (C ₈) | Population in urban areas/population size (%) | Level of urban development |
| | Per capita GDP (C ₉) | Regional GDP/population size (\$10 ⁴ /person) | Level of societal development |
| | Per capita grain yield (C ₁₀) | Grain yield/population size (t/person) | Food security |
| | Rate of natural increase (C ₁₁) | Birth rate - Death rate (‰) | Status of the natural development of the population |
| | Engel coefficient (C ₁₂) | Food expenditure/total expenditure (%) | Living standard |
| Economy (B ₃) | Proportion of agriculture in the regional economy (C ₁₃) | Agriculture GDP/regional GDP (%) | Status of economy |
| | Elasticity coefficient of energy production (C ₁₄) | Average growth rate of total energy production/average growth rate of the economy (%) | Sustainability of energy production |
| | Elasticity coefficient of energy production consumption (C ₁₅) | Average growth rate of total energy consumption/average growth rate of the economy (%) | Sustainability of energy consumption |
| | Water consumption per unit GDP (C ₁₆) | Water resource use/regional GDP (m ³ /\$) | Carrying capacity of water resources |
| | GDP per unit area (C ₁₇) | Regional GDP/total land area (m ³ /\$) | Carrying capacity of land resources |
| | Grain yield per unit area (C ₁₈) | Grain yield/total area of cultivated land | Agricultural productivity |

| | Irrigation area coverage (C ₁₉) | (t/hm ²) Effective irrigation area/total area of cultivated land (%) | Ability to withstand natural disasters |
|--|---|--|---|
| | Air pollution index (C ₂₀) | Number of days of air quality below grade II standard/365 days (%) | Status of air quality |
| | Pollution load per unit area of cultivated land (C ₂₁) | (Fertilizer application (in elemental form) + pesticide application + amount of plastic film used)/total area of cultivated land (t/hm ²) | Agriculture pressure on the environment |
| Ecological environme nt system(A) | Load of industrial wastewater per unit area of land (C ₂₂) | Load of industrial wastewater/total land area (10 ⁴ t/hm ²) | Industrial pressure on the environment |
| | Per capita industrial exhaust emission (C ₂₃) | Industrial exhaust emission/population size (10 ⁴ m ³ /person) | Exhaust gas pressure on the environment |
| | Eco-environmental water use (C ₂₄) | Ecosystem water consumption/water resource consumption (%) | Ecological pressure on the environment |
| | Investment in environmental governance per unit GDP (C ₂₅) | Investment in environmental governance/regional GDP (%) | Ability to mitigate environmental degradation |

3.2 Data sources

The raw data of the index system in this study were taken from Heilongjiang Statistical Yearbook (2013-2018), Heilongjiang Agriculture Yearbook (2003-2019), and China Statistical Yearbook on the Environment (2003-2018).

3.3 Determination of weight of each indicator

In this study, much uncertainty arose from the processing of the selected statistical data. Based on the advanced theory of quantifying information uncertainty, information entropy (Shannon, 1948) was calculated to determine the weight of each indicator. The greater the information provided by the data, the smaller the information entropy. Based on this relationship, key data reflecting the important aspects and the order of eco-environmental quality were explored to evaluate and analyze land and water resources and the ecological-environmental system. The steps to calculate it are as follows:

Step 1: Standardization of indices

Set the sample set as $\{x_{ij}^* | i=1,2,L,n; j=1,2,L,p\}$, where x_{ij}^* is the value of index i of the j^{th} year, and n, p are the number of indices and length of the time series, respectively.

$$x'_{i,j} = \frac{x_{ij}^* - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

where x_{\max} , x_{\min} represent the maximum and minimum values of each index, and $r'_{i,j}$ is the standardized value of each index.

Step 2: Calculation of the entropy of each indicator

According to the principles of information entropy, the entropy of each index was determined:

$$E_i = -\frac{1}{\log p} \sum_{j=1}^p x_{ij} \log x_{ij}$$

$$x_{ij} = \frac{1 + x'_{i,j}}{\sum_{j=1}^p (1 + x'_{i,j})} \quad (2)$$

where E_i is the entropy value of the i^{th} index.

Step 3: Calculation of the weight for each indicator

The greater the value of the entropy weight of the index, the less it influences the ecological environment:

$$d_i = \frac{1 - E_i}{n - \sum_{i=1}^n E_i} \quad (3)$$

where d_i is the weight of the i^{th} index.

3.4 Determination of average annual growth rate of indicators

During the study period, relatively large differences in the rates of change between various indicators had considerable effects on the trends of the continuous development and expansion of land and water resources and the ecological environment of the study area. Using 2003 as the base year, average annual growth rate (compounded annually) was calculated for the indicators to reflect their development rate characteristics. Further, through the calculation methods established in this study, the coupling coordination index of the system and subsystems was generated based on the average annual growth rate. This provided an additional measure of the level of positive development of the system:

$$r_{i,k+2003} = (\sqrt[k]{x'_{i,k+2003} / x'_{i,2003}} - 1) \times 100\% \quad (4)$$

3.5 Construction of an evaluation model of land and water resources and the ecological-environmental

system

The land and water resources and the ecological-environmental system is influenced by external and internal factors of the subsystems to varying degrees, as these subsystems often differ in terms of the level and stage of development. To achieve overall positive development of the system, ideas for the development of composite systems were applied, and coupling and coordination indices were used to evaluate the level and stage of development of the system. The coupling index was calculated as the rate of change of the evolution equations of different systems, which characterized the dynamic relationships between different interacting systems. The coordination index was calculated from the static index and dynamic index describing the level of comprehensive development of the system, and it characterizes the level of positive development of different interacting systems.

3.5.1 Determination of the coupling and coordination indices of subsystems

The coupling index is a quantitative indicator that reflects the dynamic relationships between different systems. This study used a dynamic coupling model to determine the included angle (C_i) (radians) between development rates of different subsystems. The greater the value of C_i , the higher the coupling degree between systems. The smaller the value of C_i , the lower the coupling degree between systems. This helped analyze the interactions and development patterns of different subsystems. The details are as follows:

$$C_i = \arctan(V_A / V_{B(i)}) \quad (5)$$

$$V_A = df(A) / dt, \quad V_{B(i)} = df(B(i)) / dt, \quad i=1,2,3$$

where $f(A)$ and $f(B(i))$ are the evolution equations of the ecological environment subsystem and other subsystems, respectively. To derive the evolution equations of subsystems, based on the discrete data of the developmental level of each subsystem $F(x)$ (see equation 6), this study used the fitting function in the cftool toolbox of MATLAB to obtain the evolution equations and fitting curves of each subsystem:

$$F(A) = \sum_{i=1}^k d_i x_{ij}, \quad F(B) = \sum_{i=1}^k d_i x_{ij}, \quad j = 2003, \dots, 2018 \quad (6)$$

where k is the number of indices of the subsystem.

The coordination index (D) reflects the influences of the coupling degree of the interactions between subsystems on the composite system, and is a quantitative indicator of the level of positive development of the composite system. After the normalization of the coupling index and the comprehensive development level (T_i), the projection of the coupling index on the comprehensive development level was determined as the coordination index (D). The closer the value of D to 1, the higher the degree of coordination between composite systems. The closer the value of D to 0, the lower the degree of coordination between composite systems. The equations are shown as follows:

$$\begin{aligned} D_i &= T'_i \cdot C'_i \cdot \cos(C_i) \\ T_i &= F(A) + F(B(i)) \end{aligned} \quad (7)$$

where C'_i and T'_i are the normalized values of the coupling index of subsystems, and comprehensive development level of subsystems, respectively.

3.5.2 Determination of the coupling and coordination indices of the system

Using the capacity coupling coefficient model in physics (Illingworth, 1996) to integrate the coupling index of subsystems, the coupling index of the system (C) was obtained. Integrating the calculation of the coordination index of the subsystems, the coordination index of the system (D) was determined. The equations are as follows:

$$\begin{aligned} C &= \arctan(V_T / V_C) \\ D &= T'_N \cdot C_N \cos(C) \\ V_T &= df(T') / dt, \quad V_C = df(C') / dt \\ C' &= (C_1 \times C_2 \times C_3) / \sqrt[3]{C_1 + C_2 + C_3} \\ T' &= F(A) + \sum_{i=1}^3 F(B(i)) \end{aligned} \quad (8)$$

where C_N and T'_N are the normalized values of the coupling index of the system, and comprehensive development level of the system, respectively.

3.6 Classification of the land and water resources and the ecological-environmental system

Combining the methods of determining the coupling and coordination indices, a median split procedure (Li et al. 2012; Wang et al. 2015) was done to classify the levels of coordination and development of the land and water resources and the

ecological-environmental system, as shown in Table 2.

Table 2 Classification of evaluation of the land and water resources and the ecological-environmental system

| Coupling index classification | | | Coordination index classification | | |
|-------------------------------|--------------------|--------------------------------|-----------------------------------|------------|---|
| Level | Range | Meaning | Level | Range | Meaning |
| I | $(-\pi/2, -\pi/4]$ | System in lowly coupled stage | I | (0, 0.2] | System in imbalance and a declining stage |
| II | $(-\pi/4, 0]$ | System in antagonistic stage | II | (0.2, 0.4] | System with reluctant coordination |
| III | $(0, \pi/4]$ | System in adjustment stage | III | (0.4, 0.8] | System with moderate coordination |
| IV | $(\pi/4, \pi/2]$ | System in highly coupled stage | IV | (0.8, 1] | System with high coordination |

4 Results

The weight of each indicator was calculated from the raw data of the study area obtained from 2003-2018, using equations (1)-(3). The average annual growth rate of each indicator of the study area from 2004-2018 was calculated using equation (4). The coupling and coordination indices of the land and water resources and the ecological-environmental system, based on the average annual growth rate of each indicator, were calculated using equations (5)-(8) (see Table 3).

4.1 Coupling index of the land and water resources and the ecological-environmental system

As seen in Table 3, during the study period, the coupling index of the ecological environment and resource subsystems in the four levels was 53.33%, 13.33%, 6.67%, and 26.67%, and was mainly in level I. This finding indicates that these two subsystems were in a less coupled stage and weakly interacted with each other. The coupling index of the ecological environment and society subsystems in the four levels was 26.67%, 13.33%, 46.67%, and 13.33%, respectively, and was mainly in level III. This indicates that these two subsystems were mainly in an adjustment stage and relatively strongly interacted with each other. The coupling index of the ecological environment and economy subsystems in the four levels was 46.67%, 6.67%, 0%, and 46.67% and was mainly in level I and IV. This indicated that these two subsystems exhibited two central tendencies and switched between low and high-coupling stages, as well as between strong and weak degrees of interaction with each other. The coupling index of the entire ecological-environmental system in the four levels was 6.67%, 60%, 33.33%, and 0% and was mainly in level II. This indicated that the system was in an antagonistic stage, with weakly

interacting subsystems.

4.2 Coordination index of the land and water resources and the ecological-environmental system

During the study period, the coordination index of the ecological environment and resource subsystems in the four levels was 86.67%, 13.33%, 0%, and 0%. The coordination index of the ecological environment and society subsystems in the four levels was 93.33%, 6.67%, 0%, and 0%. The coordination index of these subsystem pairs was highly concentrated in level I, indicating an imbalance and a declining stage. The harmony and consistency of the subsystems reached the worst level. The coordination index of the ecological environmental system in the four levels was 26.67%, 46.67%, 26.67%, and 0% and was mainly in level II. The system was in a stage with reluctant coordination, indicating a relatively low level of positive development. In summary, both the subsystems and the system suggested a relatively poor level of coordination and orderly development of the land and water resources and the ecological-environmental system in the study area.

Table 3 Coupling and coordination indices of the land and water resources and the ecological-environmental system based on average annual growth rate (2004-2018)

| Year | | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|------|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| E-R | Coupling | -0.14 | -1.29 | 0.73 | 1.40 | -0.86 | -1.30 | -0.24 | 1.53 | -0.99 | -1.49 | -1.52 | 1.42 | -1.52 | -0.94 | 0.97 |
| | Coordination | 0.00 | 0.00 | 0.14 | 0.08 | 0.10 | 0.01 | 0.28 | 0.03 | 0.09 | 0.00 | 0.00 | 0.10 | 0.00 | 0.05 | 0.20 |
| E-S | Coupling | 0.01 | -1.15 | -0.44 | -1.21 | -1.53 | -0.40 | 0.42 | 1.44 | 1.30 | 0.41 | 0.33 | 0.39 | -1.26 | 0.15 | 0.03 |
| | Coordination | 0.15 | 0.05 | 0.24 | 0.03 | 0.00 | 0.30 | 0.51 | 0.11 | 0.25 | 0.56 | 0.43 | 0.09 | 0.00 | 0.06 | 0.00 |
| E-E | Coupling | -0.54 | -1.51 | 1.55 | -1.55 | 1.56 | 1.48 | 1.50 | 1.54 | -1.56 | 1.27 | 1.54 | -1.43 | -1.54 | -1.29 | -1.09 |
| | Coordination | 0.28 | 0.00 | 0.01 | 0.00 | 0.00 | 0.06 | 0.05 | 0.02 | 0.00 | 0.17 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 |
| ESS | Coupling | -0.30 | 0.32 | -0.25 | -1.08 | -0.16 | 0.31 | -0.12 | -0.44 | 0.22 | -0.54 | -0.14 | 0.38 | 0.70 | -0.03 | -0.14 |
| | Coordination | 0.42 | 0.47 | 0.26 | 0.00 | 0.32 | 0.45 | 0.35 | 0.21 | 0.49 | 0.16 | 0.00 | 0.30 | 0.29 | 0.25 | 0.18 |

5 Discussion

Coupling and coordination indices of the subsystems and the system was calculated from the raw data of the study area using equations (5)-(8). These indices were then compared with the results calculated based on the development rate characteristics (see Figs. 2 and 3). Figure 2 shows the results of the comparison of the coupling index trends. Figure 3 shows the results of the comparison of the coordination index trends.

5.1 Comparison of the coupling index of the land and water resources and the ecological-environmental

system

The range of change of the coupling index of the three subsystem pairs based on the raw data was 2.95, 3.0, and 2.91, respectively (Fig. 2). The range of change based on development rate characteristics was 3.06, 2.97, and 3.13, respectively. The difference in the range of change between the two calculation methods was 3.85%, 0.8%, and 7.4%, respectively, which was relatively small. Development rate characteristics can be directly used to analyze the coupling of subsystems.

The range of change of the coupling index of the entire system, calculated based on raw data and development rate characteristics, was 0.06 and 1.79, respectively. This difference between the two calculation methods was relatively large. The trend based on development rate characteristics was more apparent, and it encompassed the values based on raw data. Therefore, when analyzing the coupling of the entire system, the calculation method based on development rate characteristics can be good for understanding the trends in mutual influences between subsystems. The coupling index of the system can be reflected by the expected means and other relevant data processing methods. In addition, while performing the data summary, the influences of the basic units on all indices were removed, so that the extent of change reflected the strength of the influences of various indicators on the land and water resources and the ecological-environmental system. Based on development rate characteristics, the indicators with the greatest influences were C_{14} in the economy subsystem, C_{11} in the society subsystem, C_{18} in the economy subsystem, C_{25} in the ecological environment subsystem, C_{22} in the ecological environment subsystem, C_{23} in the ecological environment subsystem, C_{15} in the economy subsystem, and C_4 in the resource subsystem. Based on raw data, the top five indicators were C_{12} in the society subsystem, C_{22} in the ecological environment subsystem, C_{11} in the society subsystem, C_9 in the society subsystem, and C_{18} and C_{17} in the economy subsystem. Factors with main influences based on development rate characteristics were more numerous and diverse and might lead to a greater degree of change in the coupling index of the entire system. Given the results in section 4 showing that the entire system was in an antagonistic stage with relatively weak coordination, calculations based on development rate characteristics are conducive to more clearly analyzing the degree of interaction and the harmony and consistency of the system.

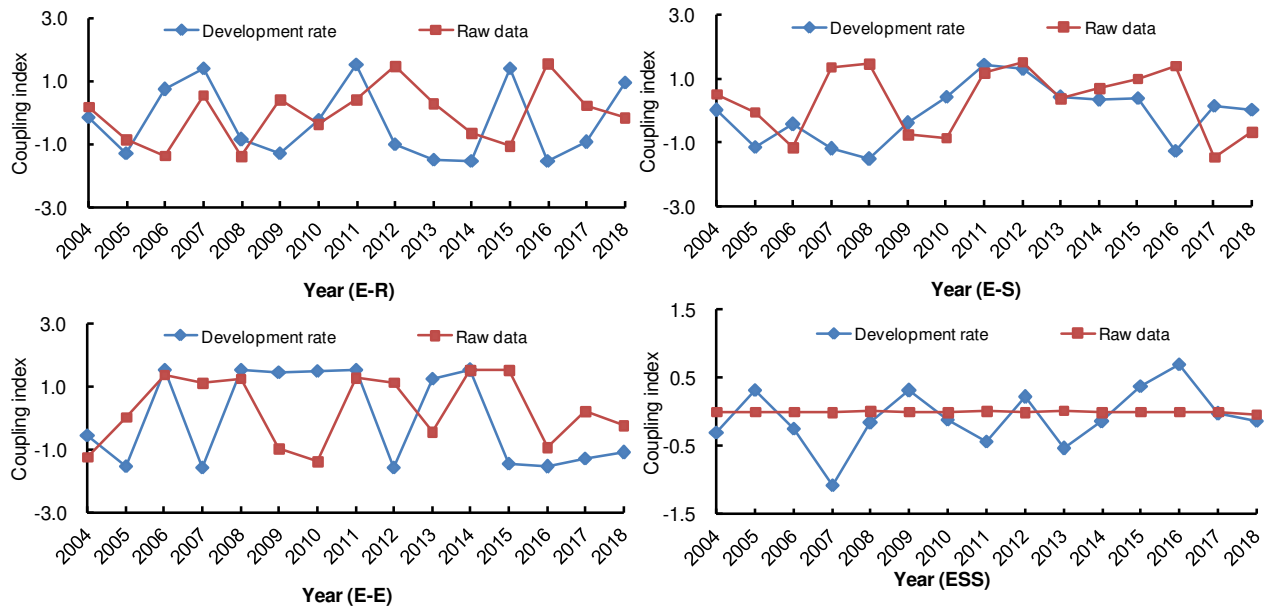


Fig. 2 Comparison of the coupling index trends calculated based on raw data and development rate characteristics (annual average growth rate)

5.2 Comparison of the coordination index of the land and water resources and the ecological-environmental system

The range of change of the coordination index of the three subsystem pairs and the system based on raw data was 0.54, 0.57, 0.43, and 1.0, respectively (Fig. 3). Range of change based on development rate characteristics was 0.28, 0.56, 0.28, and 0.49, respectively. The ranges of the changes based on raw data were greater than those based on development rate characteristics. The coordination index was calculated using the coupling index and the comprehensive development level. Given the results in section 4 showing a relatively low level of positive interactions for the subsystems and the system, calculations based on development rate characteristics showed a smaller range of change and better reflected the system's coordination. Moreover, when the range of change based on development rate characteristics exhibited a relatively great difference, so did the one based on raw data in later stages of development. Therefore, as the land and water resources, society, economy, and ecological environment of the study area keep developing rapidly, there is a need for timely evaluation of the coordination of regional land and water resources and the ecological-environmental system, in order to promote the positive

development of society and the ecological environment. The trends over time of the dynamic development of subsystems and whole systems can be understood based on development rate characteristics, which conveniently allow managers to adjust policies pertaining to the management of land and water resources, thereby enabling the ecological environment to provide better services to the sustainable development of human societies.

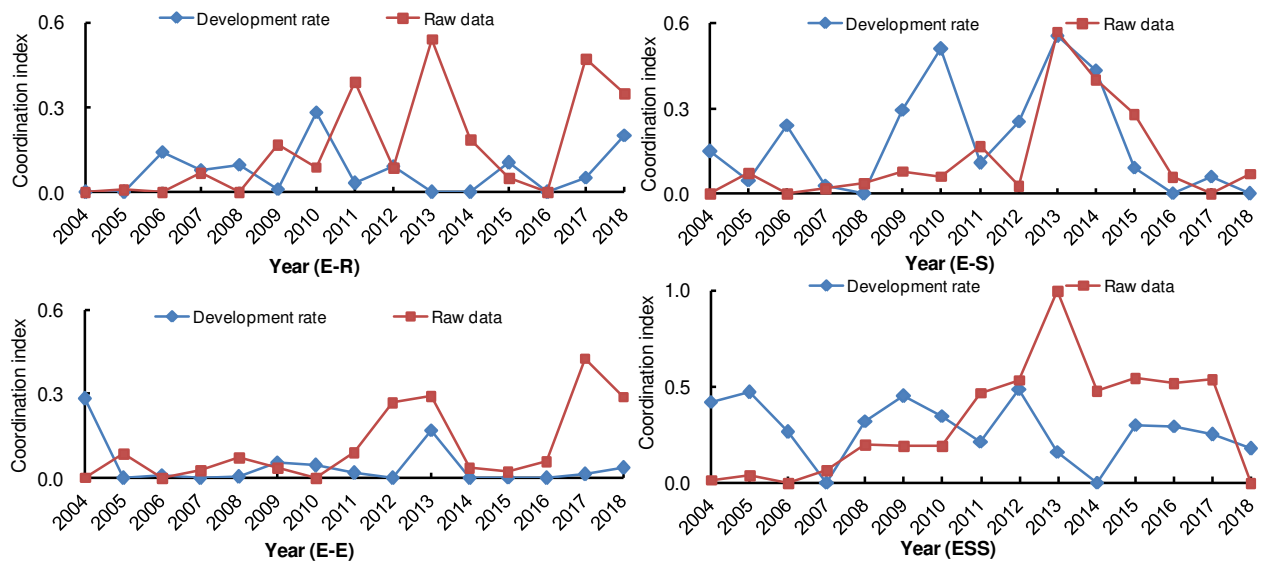


Figure. 3 Comparison of the coordination index trends calculated based on raw data and development rate characteristics

6 Conclusion

Based on the current state of socioeconomic development of the study area, this study established an evaluation index system from the aspects of resources, society, economy, and the ecological environment. Based on improving the dynamic coupling and coordination model, the coordination of the land and water resources and the ecological environmental system of the major grain-producing areas was evaluated from the perspective of development rate characteristics. The ecological environment–resource subsystem was less coupled and was in an imbalanced and declining stage. The ecological environment–society subsystem was adjusting and was in an imbalanced and declining stage. The ecological environment–economy subsystem switched between high and low degrees of coupling and was in an imbalanced and declining stage. The entire system had a relatively low degree of coupling with reluctant coordination. In summary, the level of coordination and orderly development of the land and water resources and the ecological-environmental system of the

study area was relatively poor. Compared with the evaluation results based on raw data, the development rate method yielded relatively small differences when calculating the degree of the coupling of subsystems. When analyzing the coupling of the entire system, calculation methods based on development rate characteristics could better highlight the trends of strengths of influences between subsystems. In addition, this method is conducive to timely evaluating the coordination of the land and water resources and the ecological-environmental system, which can enable decision-makers to conveniently plan and manage land and water resources and the ecological environment.

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Compliance with Ethical Standards

Conflict of Interest None

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Figures

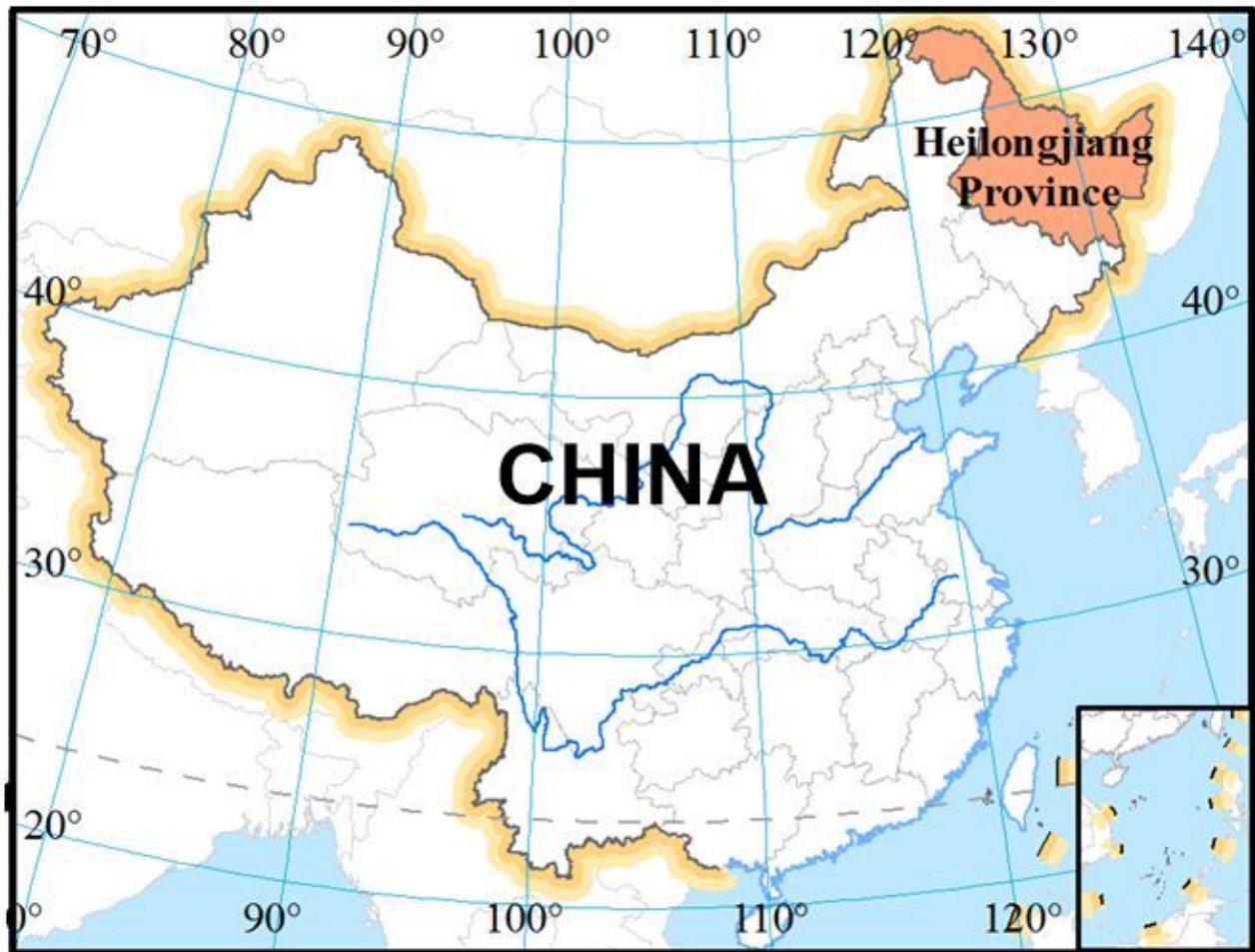


Figure 1

Study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

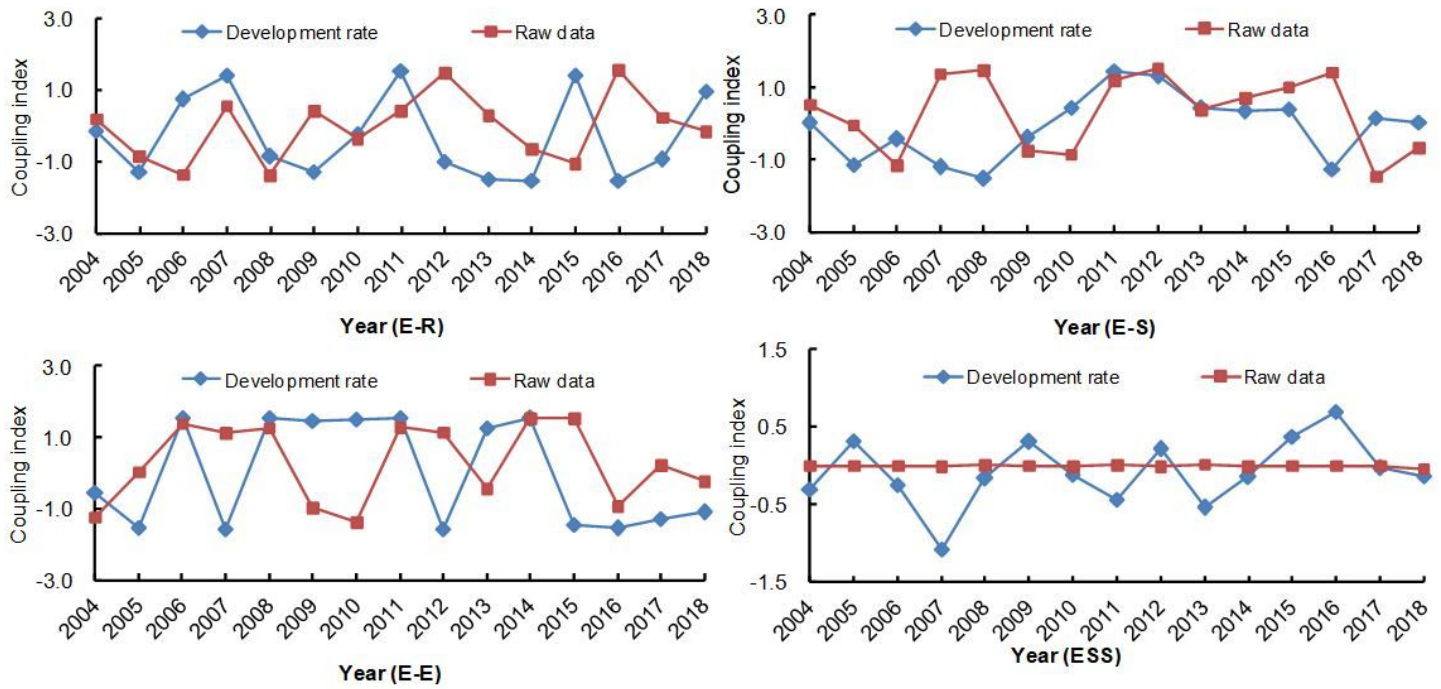


Figure 2

Comparison of the coupling index trends calculated based on raw data and development rate characteristics (annual average growth rate)

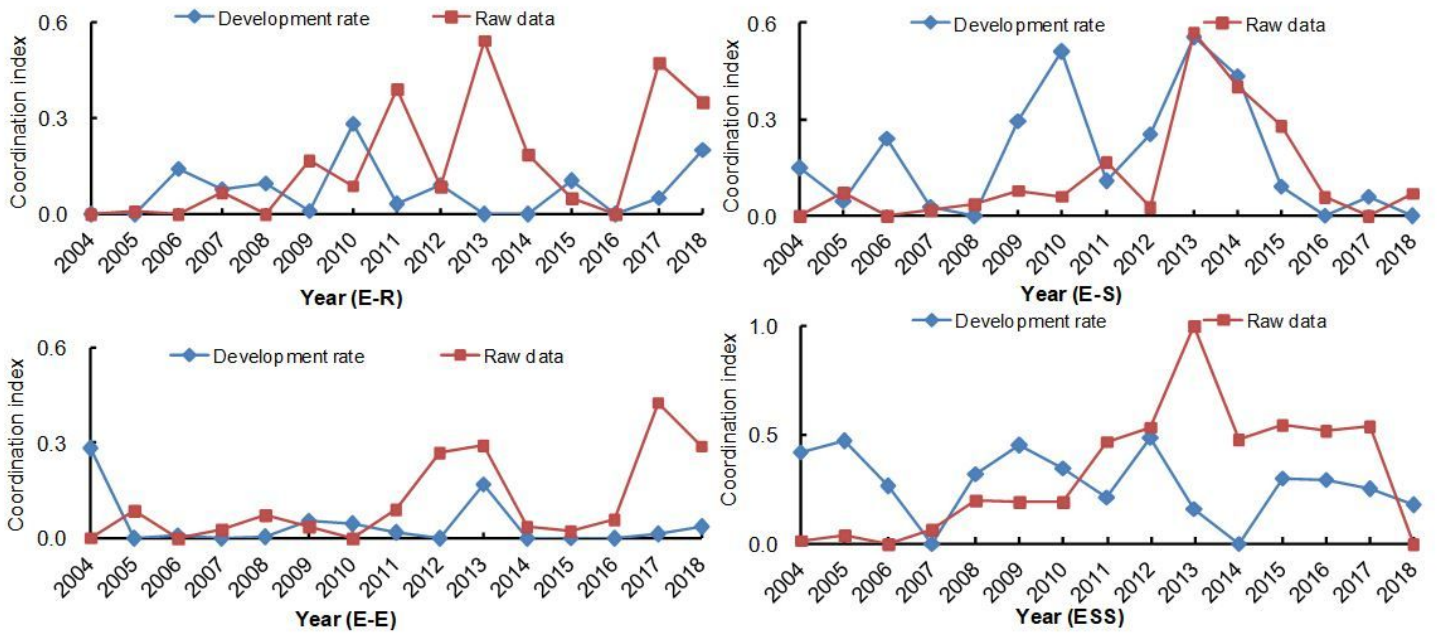


Figure 3

Comparison of the coordination index trends calculated based on raw data and development rate characteristics