RESEARCH ARTICLE

Sustainable evaluation of the eco-economic systems in the π-shaped Curve Area of the Yellow River basin of China: a study based on the 3D ecological footprint model

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Abstract
Sustainable evaluation of the eco-economic systems is crucial to resolve the contradiction between environmental protection and economic development and promote healthy urban development. This paper constructed an SEC framework for sustainable development index (SDI) evaluation of the eco-economic systems in the π-shaped Curve Area in the Yellow River basin based on the 3D ecological footprint (EF) model. The study was conducted from three aspects: the capital utilization scale and equity during the ecological supply and demand process, the development efficiency and capacity of the eco-economic systems, and the relations between the systems embodied by the coordination and security evaluation. Also, the SDI and its influence mechanism were studied using the fully arrayed polygon diagram and geographic detector. Findings include the following: EF depth is higher in cities with poor natural resources, while EF size is higher in cities with vast territories and rich resources. The arrangement of EF depth and EF size presents nearly a reverse trend, and the consumption of capital flow and capital stock complements each other. Cities can be classified as heavy utilization type, moderate utilization type, mild utilization type, and low stock appropriation type. From 2005 to 2019, the area's SDI and the three aspects presented evident spatial heterogeneity and formed clusters. The role of government, energy consumption, scientific innovation, industrial structure, urbanization rate, population, economic level, and openness level impact SDI differently. This study proposed a new insight for the sustainability evaluation of eco-economic systems.

Keywords Sustainable development · 3D ecological footprint · Fully array polygon diagram · Geographic detector · Influence mechanism

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Highlights
- An "SEC" framework for evaluating the eco-economic system was proposed.
- The influence mechanism of sustainable eco-economy was explored using geodetector.
- The comprehensive sustainability was measured using the fully arrayed polygon diagram.
- Cities can be classified into four types based on their footprint size and footprint depth.

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Abbreviations

EF	Ecological footprint
ef	Ecological footprint per capita
EC	Ecological carrying capacity
ec	Ecological carrying capacity per capita
EPI	Ecological pressure index
SCI	System coordination index
HDI	Human development index
ED	Ecological deficit
ed	Ecological deficit per capita
ES	Ecological surplus
es	Ecological surplus per capita
SDI	Sustainable development index
NCS	Natural capital stock
FPD	Fully arrayed polygon diagram
GDP	Gross domestic product

Introduction

Urban agglomerations have become essential vehicles of urbanization and China's most dynamic and potential areas. However, urban agglomerations are also under dual pressures from environmental improvement and economic growth (Fang et al. 2017). In order to resolve the contradiction between ecological environment and economic development and promote the healthy development of urbanization, it is essential to evaluate the sustainability of eco-economic systems in urban agglomerations theoretically and practically. In October 2020, the State Council of China issued the "Outline of the Plan for Ecological Protection and High-quality Development of the Yellow River Basin," in which a development pattern of "five poles" was designed (Li et al. 2021). The π-shaped Curve Area is one of the poles located in the upper and middle reaches of the river basin and contains three regional-level urban clusters, and this paper attempted to study the sustainability of eco-economic systems in the π-shaped Curve Area through the construction of an "SCE" evaluation framework. An eco-economic system is a compound system formed by the interaction, interweaving, and interpenetrating between eco-system and economic system (Zhang 2020). The operation of eco-economic systems is the process of purposeful exploitation, scientific utilization, and rational allocation of natural resources by human beings. The existence of the eco-economic system proves that the increase in material wealth results from the combined effect of ecological and economic cycles (Jiang and Xu 1993) . The study of sustainable development requires a holistic perspective to coordinate the functioning of ecosystems and economic systems. For example, Yang and Cai (2020) constructed the ecological pressure index (EPI) and eco-economic coordination index to represent the relationship between the two systems. Peng et al. (2018) evaluated the sustainability level of the marine eco-economic system by constructing the vulnerability index and coordination index.

The fundamental contradiction of eco-economic systems is the infinite demand for natural resources of the economic systems with the growth-oriented mechanism and the finite resources supplied by ecosystems with the stable mechanism. As the optimal medium for linking ecological sustainability and economic sustainability, natural capital is the best indicator for evaluating sustainable development (Costanza and Daly 1992) . Pearce and Turner (1990) first introduced the concept of natural capital, and Daly (1994) defined the concept as the stock of natural resources and environmental assets that can provide valuable flows of goods and services in the present and future. The concept of ecological footprint (EF) was first proposed in order to study natural resource accounting

(Rees 1992). Wackernagel and Rees (1998) later refined EF as a quantitative measurement of capital utilization and a method for evaluating the impact of human activities on ecosystems. Many scholars have improved the EF method, but the research focus was still on the ecological deficit (ED) rather than the natural capital stock (NCS), so the "pseudo sustainability" could occur; that is, the surplus of EF is obtained by consuming a large amount of NCS, which is actually unsustainable. Niccolucci proposed a 3D EF model with apparent advantages over the traditional method. Theoretically, the 3D model realizes the classification of natural capital and takes the reduction in NCS as the standard for judging sustainability. Methodologically, the 3D model can indicate a physical quantity obtained by multiplying the EF size and EF depth, realizing the vertical expansion of EF. In terms of results, the EF size and depth can reflect intra-generational equity and inter-generational justice (Niccolucci et al. 2011). The 3D EF model emphasizes the critical role of NCS in maintaining the sustainable ecosystem and provides a new perspective for sustainable evaluation based on natural capital utilization. However, most of the existing research using the 3D EF model mainly focused on measuring the scale of capital utilization and proposing policy implications (Fang et al. 2018, Wu et al. 2021, Yang and Hu 2018. Few studies have extended this approach and applied it to the multidimensional evaluation of eco-economic systems. Due to the scarcity of natural capital, the inequitable allocation of natural capital can lead to the failure of environmental governance and aggravate the pollution transfer, which is not conducive to the sustainable development of eco-economic systems. The Gini coefficient is widely used to evaluate the equity of resource allocation. For example, Druckman and Jackson (2008) used the Gini coefficient to measure the inequity of resource consumption, Shu and Xiong (2018) adopted the Gini coefficient to measure the uneven spatial distribution of ecological carrying capacity (EC), and Chen et al. (2017) used the Gini coefficient to discuss the spatial inequality of CO_2 emissions generated by energy consumption in China from 1997 to 2014.

Besides the consideration of utilization scale and distribution fairness of natural capital, the systems' development efficiency and capacity should not be overlooked in the evaluation. The development efficiency represents the system's ability to transform ecological consumption into human well-being, and the combination of EF with the human development index (HDI) has been proved to be applicable and reliable for its estimation (Long et al. 2020). The relationship between the structure of a system and the features it exhibited can be studied using the diversity theory in both ecosystem and economic systems (Siegel et al. 1995; Tilman 1996). Ulanowicz (1986) argued that diversity is related to the development capacity and proposed a general theory of

the relationship between growth and development. Templet (1999) firstly realized the homogeneity between ecosystems and economic systems and analyzed the relationship between energy diversity and development capacity using the Ulanowicz formula. Due to the limitations of indicators, studies on development capacity were limited to ecosystems or economic systems. This paper argued that the capability evaluation should be extended to eco-economic systems as humans' influence on nature increased. To sum up, to get a more comprehensive understanding of the sustainable development of eco-economic systems, a multidimensional framework that includes the evaluation of capital utilization and distribution, development capacity and efficiency, and the relations between systems needs to be established.

Possible innovations of this paper were as follows: First, the selection of the research area was of practical significance to China's regional development. The Area is the birthplace of Chinese ethnic culture and an important frontier area. The east Area is connected with the southeast coast of China, which is conducive to undertaking the industrial transfer. The Area borders four agglomerations in the south, which is conducive to resource sharing, industrial support, and collaborative innovation, among clusters. The west Area is connected with the Eurasian Land Bridge, which is conducive to multilateral cooperation with Central Asian and Arab countries. The Area borders Mongolia in the north, which is conducive to constructing the China-Mongolia-Russia Economic Corridor. With these unique geographical advantages, the π-shaped Curve Area acted as a primary carrier of population and productivity in the Yellow River basin and a strong growth pole. Second, this paper constructed an "SCE" evaluation framework for the sustainable development of eco-economic systems from the perspectives of scale and equity evaluation of natural capital during the ecological demand and supply process, the efficiency and

capacity assessment that denoted development potential and development ability, and the coordination and security measurement that represented the relations between the systems (Fig. 1). Third, this paper adopted the fully arrayed polygon diagram (FPD) method to evaluate the sustainability level of eco-economic systems comprehensively, and its influence mechanism was explored using geographic detector.

Methods and data

Study area and data sources

The study area of this paper is the "π-shaped" Curve Area in the Yellow River basin that includes 17 cities in four provinces (Fig. 2). The data in this paper came from the China City Statistical Yearbook (National Bureau of Statistics 2005–2019), China Urban Construction Statistical Yearbook (Ministry of Housing and Urban-Rural Development 2005–2019), China Forestry and Grassland Statistical Yearbook (National Forestry and Grassland Administration 2005–2019), Shaanxi Statistical Yearbook (Shaanxi Provincial Bureau of Statistics 2005–2019b), Shanxi Statistical Yearbook (Shanxi Provincial Bureau of Statistics 2005–2019a), Ningxia Statistical Yearbook (Ningxia Hui Autonomous Region Bureau of Statistics 2005–2019), Inner Mongolia Statistical Yearbook (Inner Mongolia Autonomous Region Bureau of Statistics 2005–2019a), and Statistical yearbooks of 17 prefecture-level cities (Statistics Bureau of 17 Cities 2005–2019).

Methods

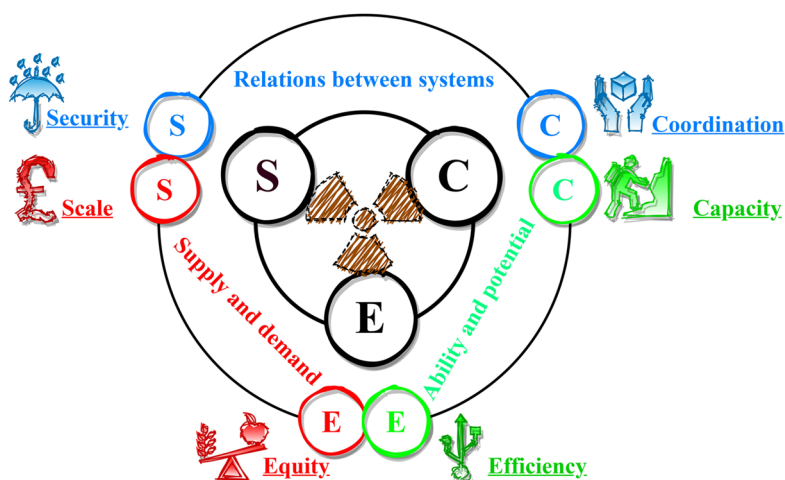This paper explored the spatiotemporal differences in sustainability levels through quantitative measures, and an "SEC"

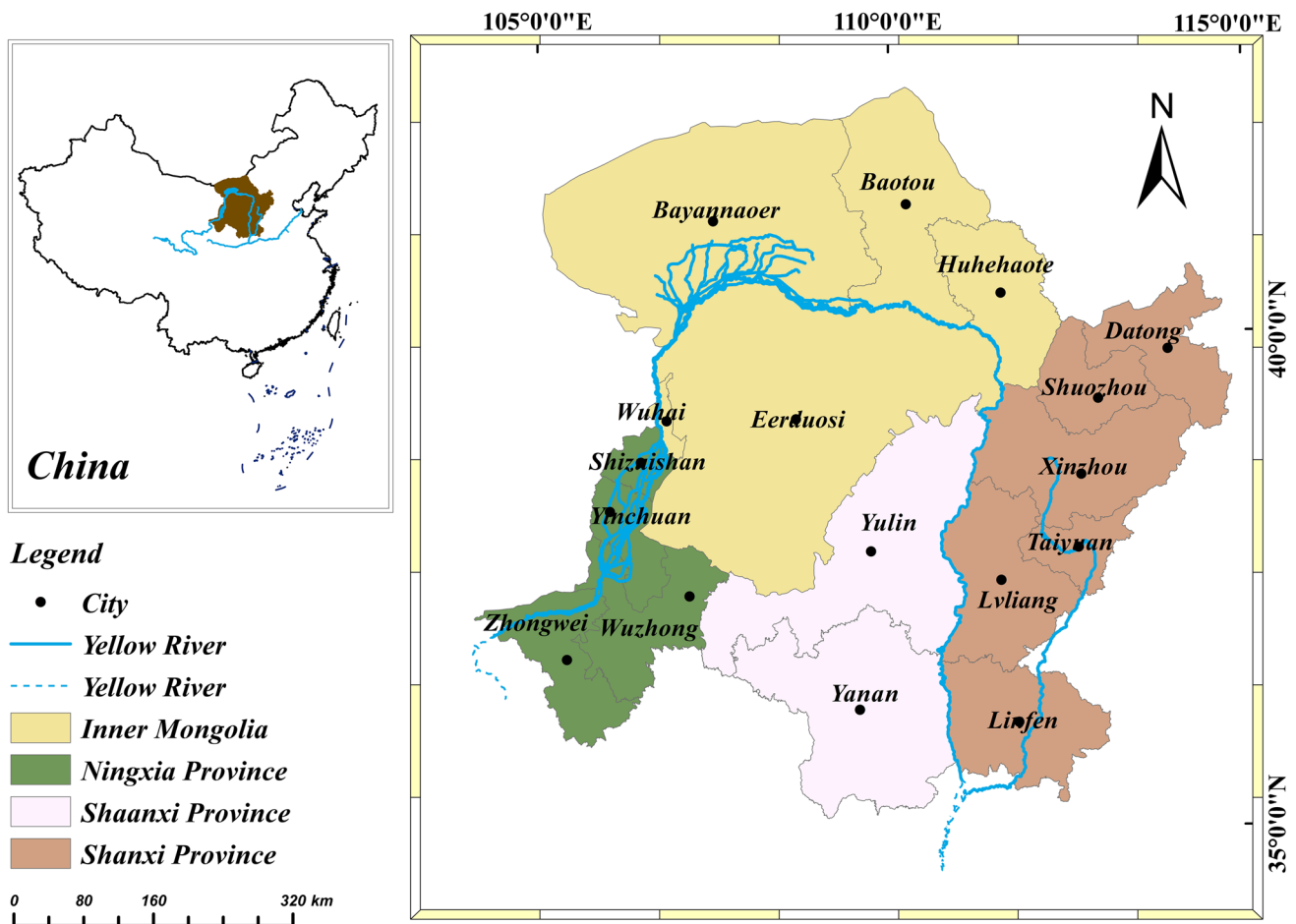**Fig. 1** The "SCE" evaluation framework of the eco-economic system

Fig. 2 The location of the π-shaped Curve Area in the Yellow River basin

evaluation framework was established based on the improved 3D EF model. The sustainability of eco-economic systems can be evaluated from three perspectives: the utilization scale and allocation equity of natural capital during the ecological demand and supply process, the development efficiency and development capacity of the systems, and the relationships between systems embodied by the system coordination index (SCI) and ecological pressure index (EPI). The measurement of "scale" was realized by calculating EF size and EF depth, which could signify the utilization of NCS and natural capital flow (NCF), respectively. The analysis of "equity" was based on the calculation of the Gini coefficient of EF size, and the assessment of "efficiency" focused on the relationship between satisfying human welfare and the size of occupied NCS. The evaluation of "capacity" was achieved by adopting the Ulanowicz formula, and the SCI and EPI were calculated to represent the system "coordination" and "security." This paper chose FPD and geodetector to study the comprehensive performance of the eco-economic systems and its influence mechanism.

Analysis of scale based on EF size and EF depth

This paper followed the method proposed by Sun and Wang (2022) to construct an improved EF model, and some improvements include the new addition to the traditional footprint account, localization of transformation factor, and refining the calculation method. Based on the improved 2D model, this paper calculated the EF size and EF depth using the following equations Fang and Heijungs 2012

$$EF_{depth} = 1 + \frac{ED}{EC} = 1 + \frac{\sum_i ED_i}{EC} = 1 + \frac{\sum_i max(EF_i - EC_i, 0)}{EC} \tag{1}$$

$$EF_{size} = \sum_i min(EF_i EC_i) \tag{2}$$

$$EF_{3D} = EF_{depth} \times EF_{size} \tag{3}$$

where i represents different land types, EF_{depth} is the ecological footprint depth, EF_{size} indicates the ecological footprint size, ED is the regional ecological deficit, and EC denotes ecological carrying capacity.

To characterize the occupancy of NCF when the footprint depth is at natural depth, the occupancy rate of capital flow (OR_{flow}) was introduced. See Eq. (4).

$$OR_{flow} = \frac{EF_{size}}{EC} \times 100\%, EF \leq EC \tag{4}$$

When the NCS was consumed, the utilization ratio of NCS to NCF (UR_{flow}^{stock}) was adopted to represent their relationship.

$$UR_{flow}^{stock} = \frac{EF - EF_{size}}{EF_{size}} = \frac{ED}{EC} = EF_{depth} - 1, EF > EC \tag{5}$$

Measurement of equity using Gini coefficient

The Gini coefficient of footprint size can be used to characterize the inequitable degree of NCF appropriation within a region (Fang and Heijungs 2012). In this paper, population, GDP, and water resources were given the same weight to comprehensively analyze the allocation equity (Yang et al. 2020).

$$G_{pop} = 2\sum_{i}^{n}\left(\lambda_{EF_{size,i}} \times \sum_{i}^{n}\lambda_{pop,i}\right) - \sum_{i}^{n}\left(\lambda_{EF_{size,i}} \times \lambda_{pop,i}\right) - 1 \tag{6}$$

$$G_{GDP} = 2\sum_{i}^{n}\left(\lambda_{EF_{size,i}} \times \sum_{i}^{n}\lambda_{GDP,i}\right) - \sum_{i}^{n}\left(\lambda_{EF_{size,i}} \times \lambda_{GDP,i}\right) - 1\# \tag{7}$$

$$G_{water} = 2\sum_{i}^{n}\left(\lambda_{EF_{size,i}} \times \sum_{i}^{n}\lambda_{water,i}\right) - \sum_{i}^{n}\left(\lambda_{EF_{size,i}} \times \lambda_{water,i}\right) - 1 \tag{8}$$

$$G_{comprehensive} = \frac{(G_{pop} + G_{GDP} + G_{water})}{3}, 0 \leq G_{EF_{SIZE}} \leq 1 \tag{9}$$

where G represents the Gini coefficient of EF size and $\lambda_{EF_{size,i}}$ is the ratio of EF size of e region i to the EF size of the whole area. $\lambda_{pop,i}$, $\lambda_{GDP,i}$, and $\lambda_{water,i}$ are the proportion of the population, GDP, and water resources of region i to the total population, GDP, and water resources of the whole area. $\sum_{i}^{n}\lambda_{pop,i}$, $\sum_{i}^{n}\lambda_{GDP,i}$, and $\sum_{i}^{n}\lambda_{water,i}$ are the cumulative proportion of the population, GDP, and water resources of region 1 to i to the total population, GDP, and water resources of the whole area.

Assessment of efficiency using capital utilization efficiency index

The Human Development Index (HDI) is a geometric mean of three equally weighted indices that account for human well-being: gross national income per capita, mean years of schooling and expected years of education, and life

expectancy at birth (McGillivray and White 1993). This paper calculated the ratio of the HDI to EF depth to denote the capital utilization efficiency (EFF).

$$EF_{depth}^* = \frac{EF_{depth}}{EF_{maxdepth}} \tag{10}$$

$$EFF = \frac{HDI}{EF_{depth}^*} \tag{11}$$

The HDI for prefecture-level cities were obtained from the China Human Development Report 2005 (UNPD China 2013c), Report 2007–2008 (UNPD China 2013d), Report 2009–2010 (UNPD China 2013b), Report 2013 (UNPD China 2013a), Report 2016 (UNPD China 2016), and 2019 (UNPD China 2019). HDI score of 0.8 was defined as the boundary between medium and high human development levels (Peng et al. 2015).

Evaluation of capacity based on development capacity index

According to the Ulanowicz formula, the development capacity of an ecosystem can be obtained by multiplying the ef by the EF diversity index (H) (Xu et al. 2003).

$$H = -\sum_{i=1}^{7} p_i \ln p_i \tag{12}$$

$$DCI = ef \times H \tag{13}$$

where DCI represents the development capacity of the eco-economic system, and p_i is the proportion of the EF of the land type i to the total footprint.

Analysis of coordination using system coordination index

The SCI can indicate the coordination degree between the eco-environment and socio-economic system (Yang and Cai 2020).

$$SCI = (EF_{3D} + EC)\sqrt{(EF_{3D}^2 + EC^2)} \tag{14}$$

The closer the SCI is to 1, the lower the degree of coordination. The closer the SCI is to 1.414, the higher the degree of coordination.

Evaluation of security using ecological pressure indicator

The EPI reflects the intensity of disturbance to the ecosystem caused by the consumption of resources, products, and services in human activities. This paper defined EPI as the ratio of 3D EF of renewable resources to the EC, and the

lower the value, the lower the ecological pressure (Zhao et al. 2006).

$$EPI = \frac{EF_{3D}}{EC} \qquad (15)$$

If EPI > 1, the supply of natural capital is under tremendous pressure. The lower the EPI, the better the ecological security.

Evaluation of comprehensive sustainability using FPD

The FPD method is a comprehensive multi-indicator evaluation method. The diagram can present both static indicators and depict dynamic trends, which improves the objectivity and accuracy of the study (Gao et al. 2015; Lu 2018; Pan et al. 2020). The normalization of evaluation indicators is obtained using Eq. (16).

$$S_i = \frac{(U_i - L_i)(X_i - T_i)}{(U_i + L_i - 2 * T_i)X_i + (U_i + L_i)T_i - 2U_iL_i} \qquad (16)$$

where U_i, L_i, and T_i represent the upper limit, lower limit, and critical value of X_i, respectively. S_i represents the normalized index value, and the sustainable development index (SDI) was calculated based on Eq. (17).

$$SDI = \frac{\sum_{i \neq j}^{i,j} (S_i + 1)(S_j + 1)}{2n(n-1)} \qquad (17)$$

where S_i and S_j represent individual index values. i, j = 1, 2, ….n, and $S_i \neq S_j$.

Explore the influence mechanism of system sustainability using geodetector

The geographic detector is a statistical method to detect spatial heterogeneity and reveal its driving forces (Feng et al. 2022, Wang and Xu 2017) . The factor detector is mainly used to detect the extent to which the independent variable explains the spatial variance of the dependent variable, as measured by the q value, where a higher value indicates a stronger explanatory power of the independent variable.

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} \qquad (18)$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2 \quad SST = N \sigma^2 \qquad (19)$$

where q is the power of determinant; N and N_h are the numbers of sample units in the entire region and the subregion; $h = 1,2 …, L$ is the number of secondary regions;

σ_h^2 and σ^2 are the variance of the samples in subregion h and the global variance of Y over the entire study region. SSW and SST are the within sum of squares and total sum of squares, respectively. The range of q is [0, 1].

This paper selected the following indicators to study the influence mechanism of SDI. Specifically, energy consumption, the proportion of expenditure on R&D in GDP, the ratio of the share of tertiary sector in GDP to the share of secondary sector in GDP, and population were used to denote ecological pressure, scientific and technological innovation, industrial structure, and ecological demand (Tang et al. 2021).GDP, urbanization rate, the share of foreign direct investment (FDI) in GDP, and the proportion of local government fiscal expenditure in GDP were adopted to indicate economic development level, urban development status, openness degree, and the influence of government (Sun &Wang 2021a, 2021b).

Results

Results of scale evaluation

In 2005, the EF depth of the Curve Area was 3.97. By 2019, the EF depth reached 5.16. The EF size per capita of the Curve Area did not significantly change and decreased from 0.73 ha per capita in 2005 to 0.69 ha per capita in 2019 (Fig. 3). In general, EF depth is generally higher in cities with poor natural resources (Fig. 4), where fossil fuels contribute the most to ED, making the EF depth affected by the degree of overshoot unfavorable. EF depth exceeded 1 in all cities, indicating that it has become common in the Curve Area to ensure socio-economic development at the expense of NCS overuse. EF size reflects the mobility of natural capital and the extent of NCF occupied by human activities. The distribution of EF size per capita was uneven, and geographically vast areas with rich natural resource endowments have higher EF per capita (ef) because of their relatively abundant biocapacity to support NCF, whereas in densely populated and resource-poor areas, ef is generally lower, and NCF is constrained. Eerduosi, Bayannaoer, Yulin, Wuzhong, Zhongwei, Huhehaote, and Yanan had relatively rich productive land, and the sum of their ef size accounted for 65.62% of the total ef size in the Curve Area. The ef size of provincial capitals and resource-based cities such as Wuhai, Taiyuan, Yinchuan, Shizuishan, Datong, Linfen, and Lvliang was less than 0.04 ha per capita due to their dense population and poor bio-productive land resources.

To explore the relations between NCF and NCS, each city's ef size and ef depth were normalized with the Z-score method and presented in a quadrant diagram with their medians as the baselines (Peng et al. 2015, Sun and Wang

**Fig. 3** The ef size and ef depth of the Curve Area
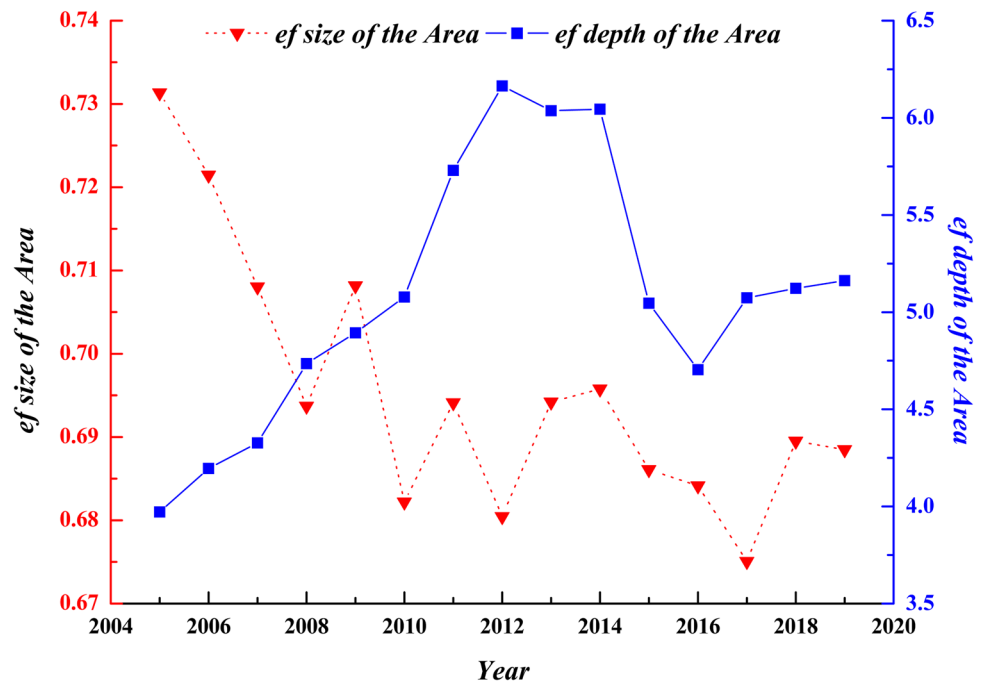
Fig. 4 The ef size and ef depth of 17 cities
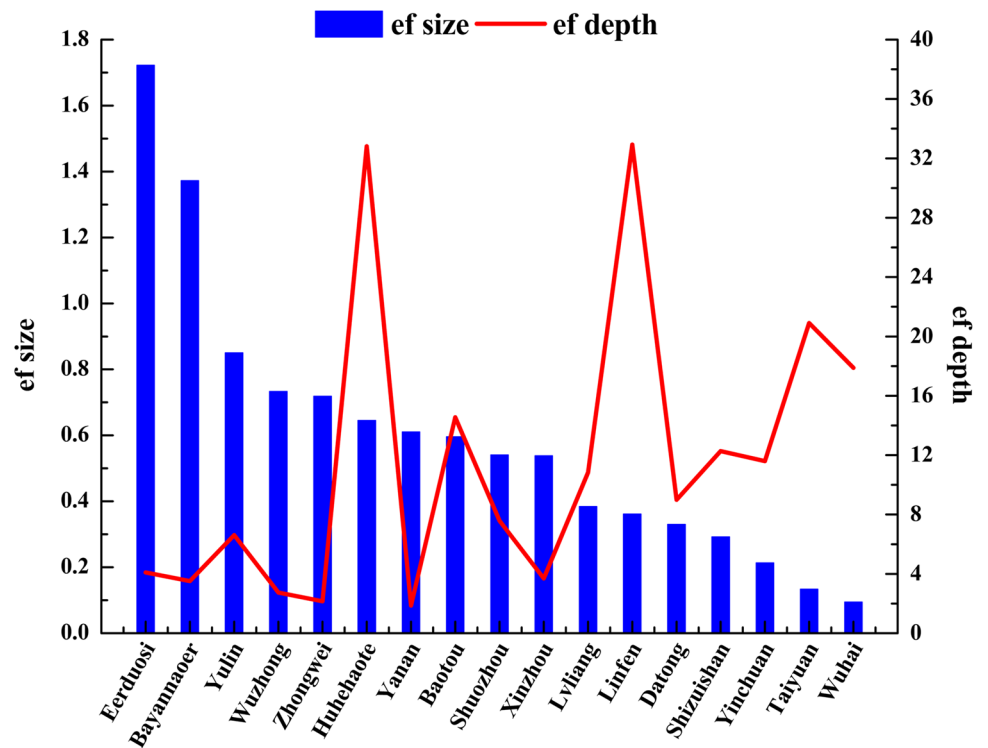
2021a) . Cities could be grouped into four types based on their positions in the quadrant diagram (Fig. 5). Cities in the first quadrant were defined as "heavy utilization type." High NCF and NCS consumption characterized this type, and Huhehaote and Baotou were of this type in 2019. Cites in the second quadrant belonged to the "moderate utilization type." This type was characterized by low NCF utilization

and high NCS consumption. In 2019, cities in this category included Linfen, Taiyuan, Yinchuan, Wuhai, Lvliang, and Shuozhou. Cities in the third quadrant were grouped as "mild utilization type." Low consumed NCF and NCS characterized this type, and Shizuishan, Xinzhou, and Datong were of this type in 2019. Cities in the fourth quadrant were defined as "low stock appropriation type" that occupy mostly

Fig. 5 Quadrant division of ef size and ef depth
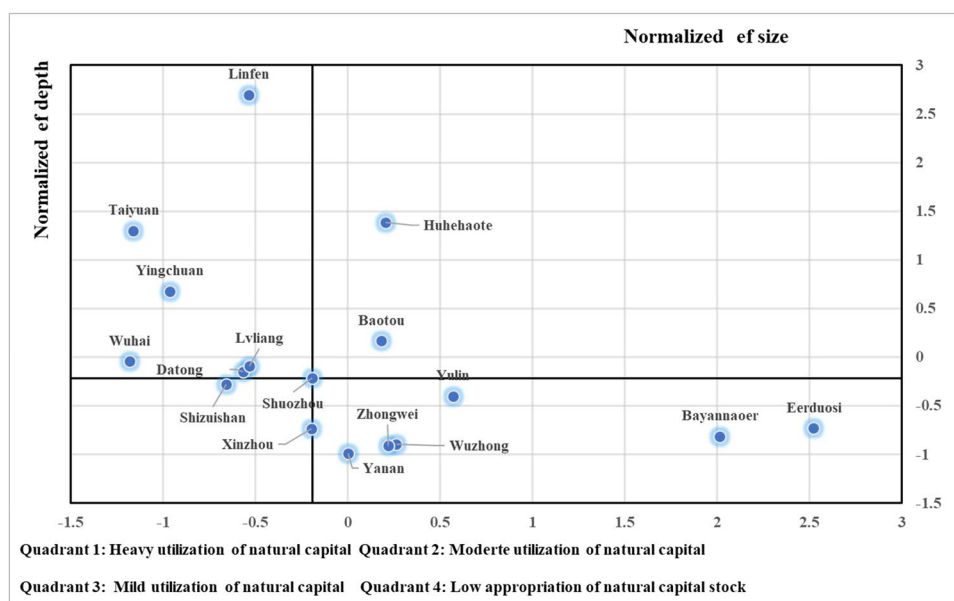
the NCF. In 2019, cities of this type included Eerduosi, Bay-annaoer, Yulin, Wuzhong, Zhongwei, and Yan'an. Although these cities had relatively large ef size, their environmental pressure was low due to good resource endowment and low stock consumption.

The OR_{flow} and UR_{flow}^{stock} in 2019 were calculated. High OR_{flow} areas were distributed in Huhehaote, Baotou, Bayan-naoer, Datong, Wuzhong, Linfen, and Zhongwei, where the occupancy rate reached over 85%, and the ecosystem was under tremendous pressure. Low OR_{flow} areas were distributed in Yan'an and Wuhai, with less than 50% occupancy rate. Cities with high UR_{flow}^{stock} were Linfen, Huhehaote, and Taiyuan, and the maximum value could reach 38.65. These areas overconsumed NCS to compensate for the NCF short-age, and the sustainability was weakest. Cities with low UR_{flow}^{stock} were Yanan, Zhongwei, Wuzhong, and Bayannaoer, and their sustainability was the strongest. The quadrant par-titioning and the conclusions drawn from formula calcula-tions were in high agreement, and the combination of the two provided intuitive information.

Results of equity analysis

During the study period, the population contribution Gini of the Area was relatively stable, increasing slightly from 0.23 in 2005 to 0.26 in 2019. The economic contribution Gini presented an overall downward trend, characterizing the increasing equity between economic development and the distribution of NCF. The water resources contribution Gini exceeded the warning line of 0.4, indicating the unbalanced allocation between water resources and natural capital, and the distribution of water resources was not the most crucial factor affecting the consumption of ecological resources

(Yang and Fan 2019, Yang et al. 2021). The comprehensive Gini decreased slowly from 0.38 in 2005 to 0.31 in 2019, indicating fairer consumption of natural capital in the Area (Fig. 6). The Gini of four provinces in the Area were also measured, and Ningxia Province had the highest compre-hensive Gini while Shaanxi Province experienced the lowest from 2005 to 2019.

Results of security and coordination assessment

The EPI and SCI were calculated using Eqs. 16 and 17. The EPI decreased from 1.80 in 2005 to 1.25 in 2019 (Fig. 7), representing an improvement in ecological security level from "very insecurity" to "quite security" (Wang et al. 2018). From the perspective of spatial differentiation, the EPI rak-ing was as follows: Wuhai > Shizuishan > Taiyuan > Huhe-haote > Yinchuan > Baotou > Shuozhou > Datong > Bayan-naoer > Wuzhong > Linfen > Zhongwei > Lvliang > Eerdu-osi > Xinzhou > Yulin > Yanan. The EPI was found to have significant spatial clusters (Global Moran Index of EPI = 0.434, Z-score = 2.796, P = 0.005), and the local Moran index indicated that the High-High clustering was centered in Shizuishan and Wuhai, while Yanan and Yulin were the centers of Low-Low clustering. Both Yanan and Yulin belong to Shaanxi Province, indicating that Shaanxi had the highest ecological security level compared to other provinces. Meanwhile, Wuhai and Shizuishan are the only two declining resource-based cities in the Area, and their high EPI may be related to their economic development mode of high energy consumption. Overall, the ecological pressure on the south bank of the Yellow River was lower than that on the north bank. Economic development is often at the expense of the ecological environment. This paper

Fig. 6 The Gini of NCF in the Curve Area from 2005 to 2019
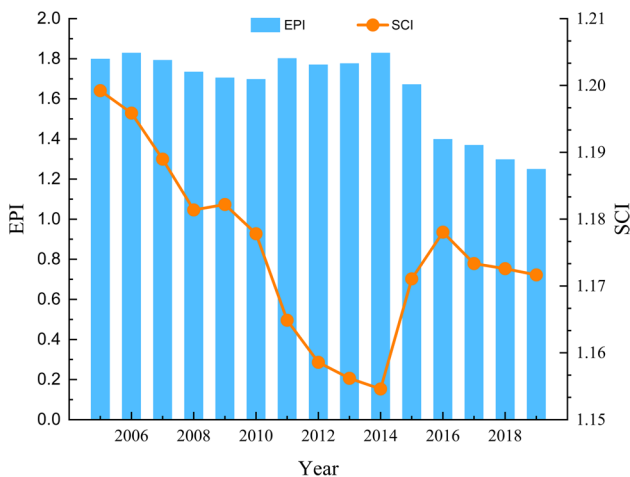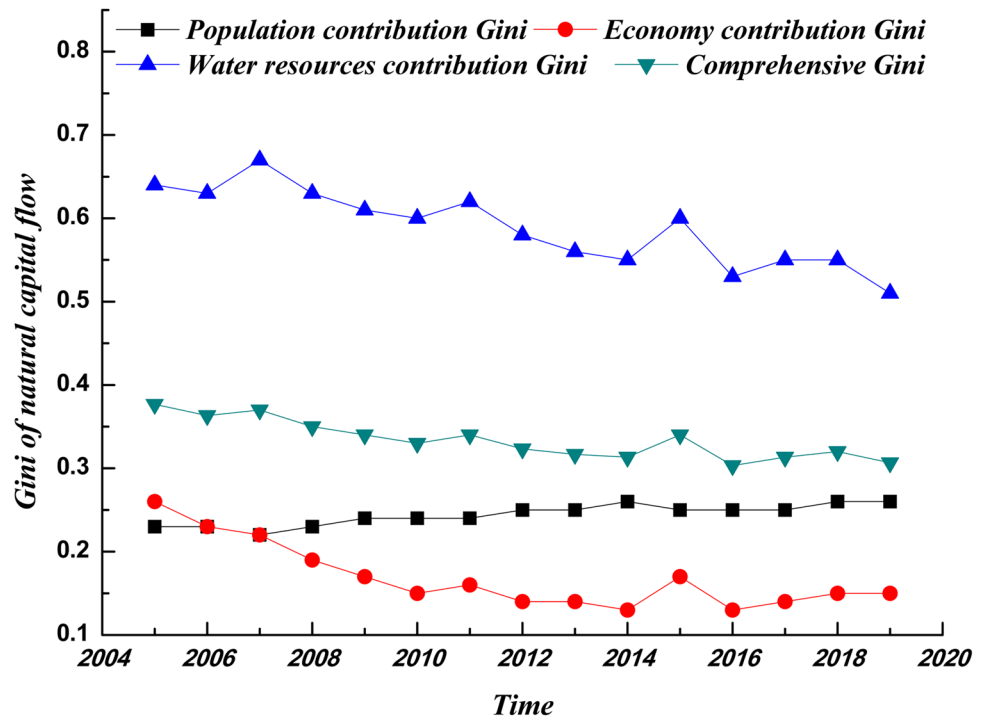
Fig. 7 The EPI and SCI of the Curve Area

used the SCI to reflect the coordination degree between the environment and economic development. The closer the SCI index is to 1.414, the higher the coordination is. SCI dropped from 1.20 in 2005 to 1.15 in 2014 and then recovered quickly and stabilized around 1.17 after 2017, presenting a V-shaped trend during the study period. The SCI ranking was as follows: Yanan > Zhongwei > Wuzhong > Xinzhou > Bayannaoer > Eerduosi > Yulin > Shuozhou > Datong > Yinchuan > Lvliang > Wuhai > Shizuishan > Baotou > Taiyuan > Linfen > Huhehaote. The SCI was generally higher on the south bank of the Yellow River than that on the north bank, and that of the east Area was lower than that of the

west. Notably, the EPI of the Area decreased after 2014 while the SCI increased, indicating a good momentum for regional development.

Results of efficiency and capacity analysis

The yearly HDI of the Area were all above 0.7 during the study period and were considered reaching "high development levels" (Bi et al. 2020). The order of EFF was as follows: Yanan > Zhongwei > Wuzhong > Bayannaoer > Xinzhou > Eerduosi > Yulin > Shuozhou > Datong > Yinchuan > Lvliang > Shizuishan > Baotou > Wuhai > Taiyuan > Huhehaote > Linfen. The top four cities, except Yanan, were all non-resource-based cities, indicating the relatively inefficient capital utilization in resource-based cities. Also, the ranking of DCI in the 17 cities was follows: Yanan < Taiyuan < Xinzhou < Zhongwei < Lvliang < Datong < Yinchuan < Wuzhong < Linfen < Wuhai < Yulin < Shuozhou < Shizuishan < Bayannaoer < Baotou < Eerduosi < Huhehaote. DCI is the product of EF diversity index and ef; therefore, the larger the ef, the higher the DCI, and similarly, the higher the diversity index, the higher the DCI. From 2005 to 2019, DCI presented an overturned V-shaped trend, increasing from 2005 to a peak in 2014 and then declining rapidly (Fig. 8). During the same time, the ef of the Area presented a similar development trend, while the diversity index decreased, suggesting that the development of capacity was at the cost of the increased ef. The DCI can be improved by increasing the ef or EF diversity or both of two simultaneously. However, since
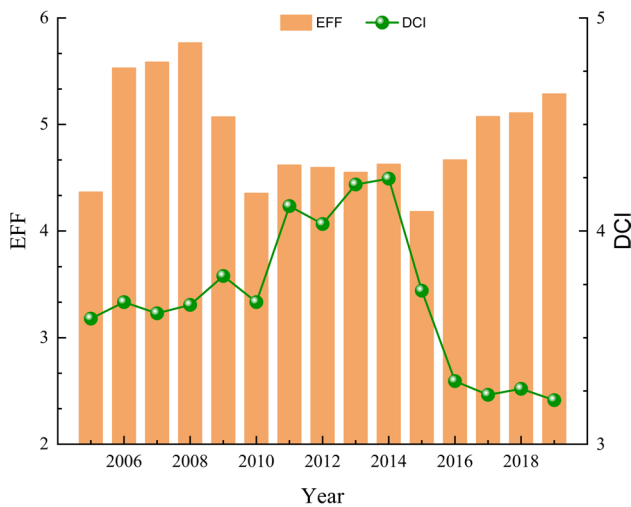
Fig. 8 The EFF and DCI of the Curve Area

most cities in the Area were in ED, the only way to further improve the development capacity of the eco-economic system is to diversify the ecologically productive land.

Results of the comprehensive evaluation

From 2005 to 2019, the SDI of the eco-economic system in the Area presented a W-shaped trend. The sub-indicators of SDI all fluctuated around the critical values, among which the security level has improved significantly. Shaanxi Province performed the best among the four provinces, with the SDI above 0.5, while Shanxi Province performed the worst, with the SDI below 0.2 (Fig. 9). The SDI of the central part of the Curve was significantly higher, and that of the south bank of the watershed was higher than that of the north bank. From the perspective of temporal evolution, most cities' SDI was stable or had improved, with Linfen consistently lagging behind (Fig. 10).

The influence mechanism of the SDI

This paper explored the influence mechanism of SDI using geodetector. The selected independent variables were divided into five levels through the natural breaks using ArcGIS, and all the factors passed the 1% significance test in 2005, 2010, 2015, and 2019, indicating that economic development, openness degree, population, industrial structure, urbanization,
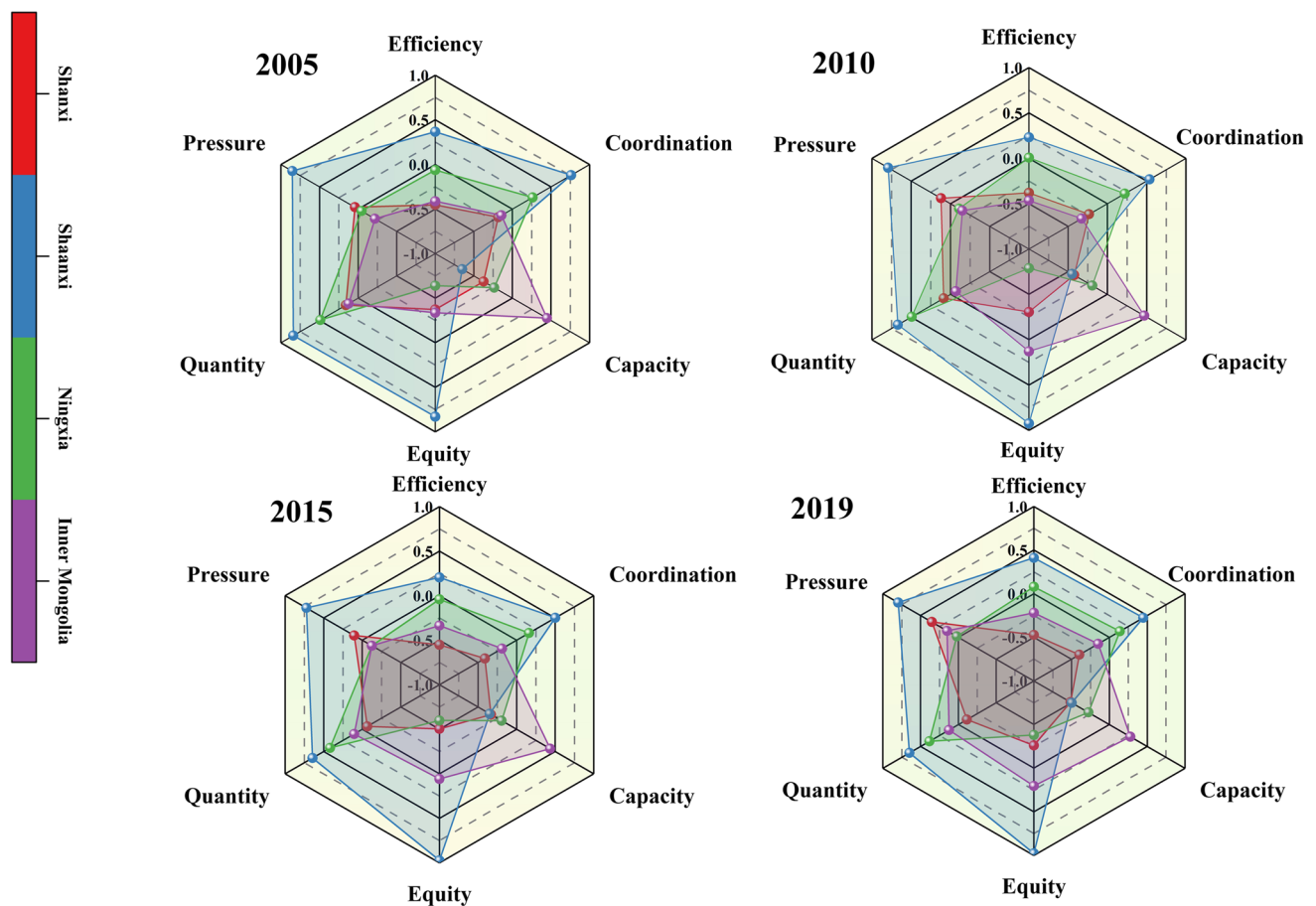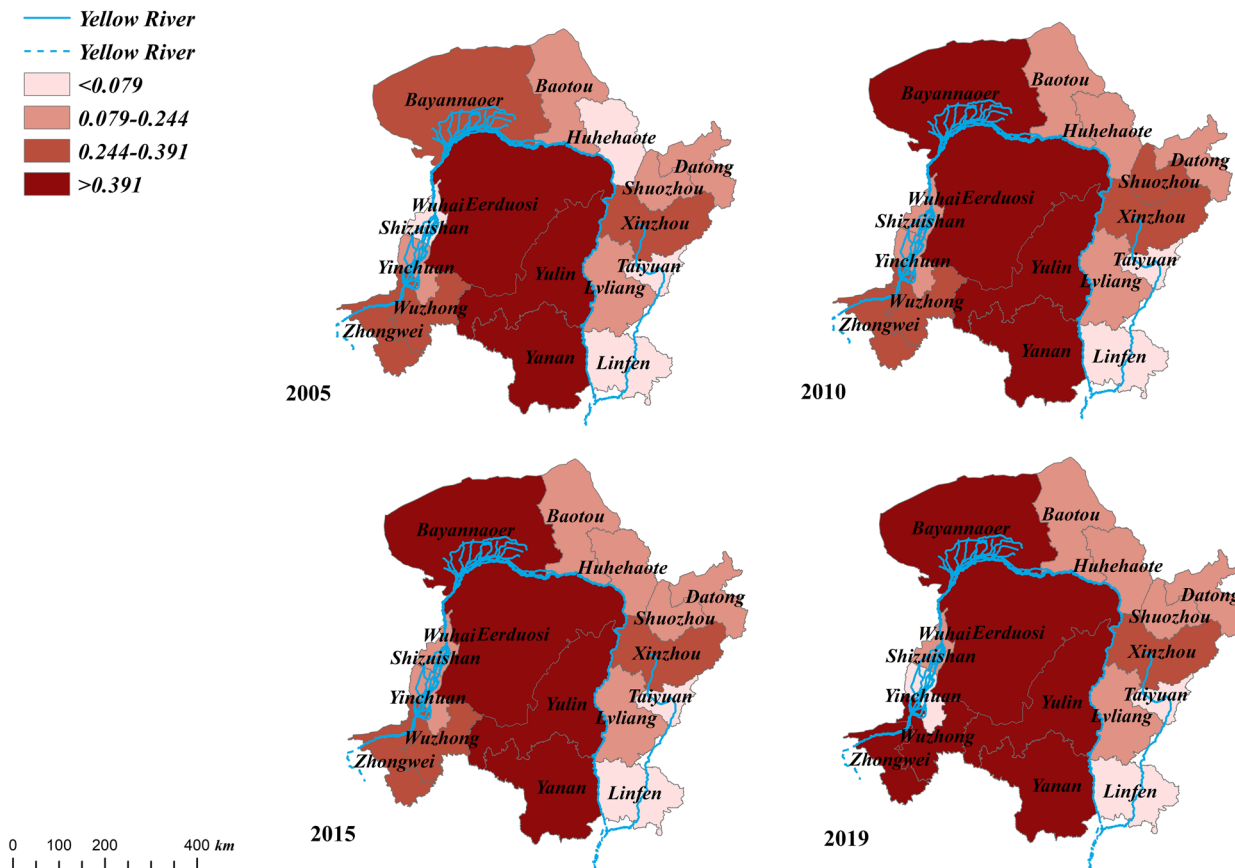

Fig. 9 The FPD of SDI of the four provinces in selected years

Sustainability of eco-economic system and its spatial differentiation

Fig. 10 The spatiotemporal differentiation of SDI in the Curve Area in selected years

energy consumption, and government influence all had an impact on the SDI (Table 1).

Discussion

Research on watersheds has evolved from study on economic growth to regional development, from analysis of causes to comprehensive planning, and from administrative areas

Table 1 Results of geodetector analysis

Factors	2005-q	2010-q	2015-q	2019-q
Economic development	0.335	0.032	0.051	0.256
Openness degree	0.663	0.492	0.385	0.479
Population	0.578	0.611	0.537	0.524
R&D investment	0.456	0.497	0.638	0.311
Industrial structure	0.256	0.344	0.624	0.358
Urbanization rate	0.437	0.428	0.245	0.208
Energy consumption	0.419	0.799	0.540	0.166
Government influence	0.373	0.799	0.202	0.338

to natural systems. In this process, the importance of the functional positioning of geographic units and the spatial patterns they represent for macroeconomic control has emerged, which is the focus of the study of watersheds from an economic geography perspective, namely, the spatial differentiation patterns. This paper described the spatiotemporal characteristics of the SDI in the Curve Area based on an "SEC" evaluation framework. Specifically, the S-E represented the utilization Scale and allocation Equity during the ecological supply and demand process. The E-C indicated the development efficiency and capacity of the systems, the C-S denoted the relationships between systems embodied by the coordination and security level, and the performance of these sub-indicators presented apparent spatial heterogeneity. As a natural watershed landscape, the economic system and ecosystem of the Yellow River are holistic, and the fluidity of the river drives spatial linkages and resource sharing through upstream and downstream and between the north and south banks. However, the division of administrative units has led to the lack of systematism and integrity in the basin's economic layout, resource management, and institutional patterns. Based on the understanding of the uneven

and heterogeneous development of eco-economic systems, integrated management and synergistic research should be given priority, and the driving force of collaboration in the Area should be the improvement of SDI, which requires the participation of multiple parties of policies, resources, markets, and economies under the framework of integrated management.

Analyzing the utilization level and spatial pattern of NCF and NCS is an essential basis for promoting the optimal utilization and allocation of natural capital. During the study period, the Area was in a state of capital deficit, with varying degrees of deficit and changing trends within the region. The dependence of socio-economic development on natural capital was still difficult to change in the short term and faced the double pressure of economic growth and environmental protection. This paper found that EF depth is generally higher in cities with poor natural resources, while EF size is higher in districts with vast territories and rich resource endowments. This was consistent with the findings of Wu et al. (2021) that the consumption of NCS and NCF was roughly complementary. This paper classified cities into four types based on their EF size and EF depth. Cities of "heavy utilization type" are the samples of the resource curse in China since their over-exploitation of resources has restricted the development space and functions and even dragged down the economic development. Cities of "moderate utilization type" have high NCS depletion and medium levels of natural capital utilization. Cities of "mile utilization types" have relatively high levels of economic development and low levels of natural capital utilization. The low depletion of NCS in the fourth category is relative to their higher NCF occupation; in fact, once NCS declines, the sustainability diminishes. Most industries in the Curve Area are at the low end of the industrial chain, and their major problem in capital utilization is the high resource input and environmental cost. For example, resource-based cities such as Datong, Linfen, Yulin, and Huhehaote have been exporting non-renewable resources, such as coal and petroleum, to the other parts of China for a long time, which is the main reason for their declining NCS. A comprehensive discussion that combines capital utilization types, city types, and the differentiation of SDI can contribute to refined and differentiated management strategies.

Exploring the influence mechanism of SDI and quantifying the effect of the influencing factors can enhance the identification of evaluation results and policy pertinence. The role of government, energy consumption, scientific innovation, industrial structure, urbanization rate, population, economic level, and openness level impact SDI differently. The population can characterize ecological pressure. Its influence on SDI has decreased since 2010, which might be induced by the increasing contradiction between demand and supply in the labor market, disappearing demographic

dividend, and employment transfer in the context of urban–rural integration. The influence of economic growth on SDI fluctuated at low levels. In the long run, it is the mode of economic growth and resource utilization efficiency that determines sustainable development fundamentally. The influence of industry structure and R&D investment on SDI has increased by 2015. Industrial structure upgrading and scientific innovation can improve energy efficiency and labor productivity and lead to low consumption and low emission development, which could explain the decreased influence of energy consumption on SDI after 2010. Urban development is unsustainable at the cost of environmental quality and ecological balance. Although the impact of urbanization on SDI has decreased, the Area still should be alert to the negative effects induced by agglomeration strategies such as the policy of strong capitals. Government influences the spatial differentiation of SDI mainly from two directions: development planning and environmental regulation. With the introduction of integrated management programs for water, land, and other resources and the formulation of related bills, feedback effects on the Area's industrial layout and development pattern are formed. As a "visible hand," government implements appropriate macro-control intervention when development is in disorder and gives proper incentives through supervision when development is orderly. The influence of the government on SDI was far greater in 2010 than other factors, which may be because while the financial crisis was spreading, China's economy was experiencing a shift in growth rate and structural adjustment. In this process, the government gave full play to the role of the "visible hand" and implemented fiscal and monetary policies to minimize the negative impact of market failure on the eco-economic system. The impact of openness degree on SDI was significant in 2005, which might be due to the low admission standards that attract foreign investment and that FDI was primarily interested in high-return polluting industries. The increased influence of openness degree in 2019 could be related to the improved capacity to utilize foreign capital, and the government has appropriately raised the entry threshold and guided green investment. The synergy of the "opening up to the outside world" strategy can be promoted by analyzing the functional location of the Yellow River basin, Yangtze River basin, and the Pearl River basin, forming inter-basin interaction and complementarity to the south, strengthening the extension of the Belt and Road to the north, and planning the mode of collaboration with corresponding regions and other countries.

The limitations of this paper were in the following aspects: The Gini coefficient of footprint size can only compare the relative inequities of capital occupation, but cannot reflect the absolute differences between regions, and the Gini coefficient calculated by the geometric method always has lower values, which could affect the accuracy of evaluation.

Besides, this paper did not analyze the supply and demand of natural capital on different land types, did not measure the specific impact of NCS consumption on EC and land productivity, and did not consider the transfer effect of cross-regional trade on natural capital, all of which need to be addressed in future research. Also, the transformation relationship between NCS and NCF, the specific impact of reduced NCS on ecosystem service functions, and the ecological threshold of NCS depletion were all directions for further research in the future. It should be noted that this paper only calculated the NCS depletion compared to previous years. If a widely accepted method of measuring natural capital stock (similar to the perpetual inventory method of estimating physical capital stock in economics) can be established, it will further promote the quantification of sustainable development research.

Conclusions and policy implications

Sustainable evaluation of the eco-economic systems is crucial to resolve the contradiction between environmental protection and economic development and promote healthy urban development. This paper constructed an SEC framework for evaluating the sustainability of the eco-economic system in the Curve Area of the Yellow River Basin from 2005 to 2019. Specifically, the capital utilization scale and distribution equity, development efficiency and capacity, and system coordination and security were analyzed based on the 3D EF approach. Also, the SDI and its influence mechanism were investigated through FPD and geodetector, respectively. The results of this paper proposed a new insight for the sustainability evaluation and provided important policy implications.

The main finding includes the following: First, during the study period, the Area was in a state of capital deficit, with varying degrees of deficit and changing trends within the region. The dependence of socio-economic development on natural capital was still difficult to change in the short term and faced the double pressure of economic growth and environmental protection. The SDI of the eco-economic system in the Area presented a W-shaped trend during the study period, characterized by spatial unevenness and relative stability. The SDI of the central part of the Curve was significantly higher, and the SDI of the south side of the watershed was higher than that of the north. Second, the scale and equity evaluation found that the arrangement of EF depth and EF size presents nearly a reverse trend, and the consumption of NCS and NCF complements each other. Cities can be classified as heavy utilization type, moderate utilization type, mild utilization type, and low stock appropriation type according to their EF size and EF depth. The decreased comprehensive Gini from 2005 to 2019 indicated fairer consumption of natural capital

in the Area, and Ningxia Province had the highest average comprehensive Gini while Shaanxi Province experienced the lowest. The efficiency and capacity evaluation found that the EFF of resource-based cities was relatively lower than that of non-resource-based cities, and the improvement of DCI in the Curve Area required more diversified utilization of ecologically productive land. The security and coordination evaluation found that the EPI on the south bank of the Yellow River was lower than that on the north bank. The SCI was generally higher on the south bank of the Yellow River than that on the north bank, and the SCI of the east Curve Area was lower than that of the west Area. Third, the role of government, energy consumption, scientific innovation, industrial structure, urbanization rate, population, economic level, and openness level were found to impact SDI differently.

This paper proposed the following suggestions for sustainable eco-economic systems in the Area. First, establish an inter-governmental coordination mechanism for the synergistic development of the Area. At the same time, the top-level design should be strengthened to promote the flow of resource elements, especially talents and technologies, so that the cooperation among cities can be thoroughly carried out to maximize the benefits. Second, the dynamic balance between supply and demand of natural capital is the basic condition to maintain regional sustainable development. From the perspective of the supply of natural capital, regional development can reduce the NCS consumption by increasing investment in natural capital and improving EC, while carrying out structural reform on the supply side to enhance the adaptability and flexibility of supply to demand. From the perspective of the demand for natural capital, the government should guide the improvement of consumption structure and reduce the consumption of products with high energy consumption and high resource occupation and at the same time, change the economic growth model, promote the transformation of industrial structure, and accelerate the formation of an efficient and economical economic growth mode with low inputs, low energy consumption, and low emissions. It is worth noting that, considering the obvious spatial heterogeneity of natural capital utilization and its driving mechanism, integrated and fine-grained zoning management becomes the key to achieving sustainable regional development. In a word, based on the resource endowment and the strategic advantages of "Western development "and "One Belt One Road," the Curve Area should rationally utilize resources, promote industrial upgrading, develop emerging industries, and avoid falling into the trap of "resource curse." Third, the government should moderately strengthen environmental regulation and develop differentiated regulation policies. Instead of implementing overly strict regulations, the ecological carrying capacity could be improved by understanding cities' comparative advantages.

Declarations

Ethics approval There is no data collected from human subjects.

Consent to publish The work was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the publish.

Consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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