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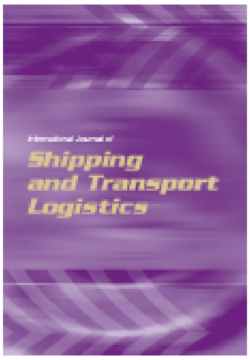

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Analysis of the differences and spatial-temporal dynamic evolution of the environmental sustainability of the Yangtze River Economic Belt in China

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Abstract: The Yangtze River Economic Belt (YREB) is a pioneering example of ecological civilisation construction in China; thus, the environmental sustainability of the YREB is important for advancing China's national level of environmental sustainability. To achieve this goal, we propose an evaluation index system to measure the environmental sustainability levels of the 11 provinces and cities in the YREB and analyse their upper, middle and lower regional differences and spatiotemporal dynamic evolution characteristics according to an integration of Dagum's Gini coefficient decomposition method, kernel density estimation, Moran's I and the Markov chain. The results show that during the period from 2003 to 2020, the following occurred: first, the average environmental sustainability level of the YREB steadily increased. Second, the difference in the environmental sustainability level of the entire YREB decreased, whereas the intraregional- and interregional differences were the sources of differences in the environmental sustainability of the YREB. Third, there was no significant spatial correlation between the environmental sustainability levels of the regions.

Keywords: environmental sustainability; evaluation; regional differences; dynamic evolution; Yangtze River Economic Belt; YREB.

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1 Introduction

Despite China's rapid economic development [China's gross domestic product (GDP) reached 17.79 trillion US dollars and thus ranked second in the world and accounted for 16.87% of the world's total economy in 2023], the country's extensive economic growth model continues to accelerate resource consumption and pollutant emissions, thus resulting in serious environmental pollution and ecological damage (He et al., 2018; Qin et al., 2021; Zhang and Chen, 2021). The Yangtze River Economic Belt (YREB) is among the regions with the widest coverage and strongest economic development in China; thus, the region's fragile ecosystem, scarce water resources and other environmental pollution problems cannot be ignored (Ji and Zhang, 2023). Therefore, establishing a resource-saving and environmentally friendly society in the YREB must be accelerated to contribute to the environmental sustainability of the region and even the country. What is the status of environmental sustainability in the YREB? What are the differences and spatiotemporal dynamic evolution characteristics? This information is essential to help the YREB build a high-quality development demonstration base and even improve China's environmental sustainability.

In recent years, a central feature of environmental planning and policy has been environmental sustainability (Nketiah et al., 2024; Roy and Gow, 2018), which is increasingly becoming a concern for academics and practitioners (Zuccotto et al., 2024). The mainstream approach to measuring environmental sustainability is to construct an evaluation index system (Zhou et al., 2006a). Many institutions and scholars have constructed comprehensive evaluation systems for environmental sustainability at the global, national, regional and industrial sectoral levels (Liu, 2007; Chen et al., 2023; Roboredo et al., 2016; Cheng et al., 2020; Kim et al., 2022). However, in most studies, indicators of environmental sustainability were developed by drawing on existing evaluation frameworks, which lack consideration of economic, social and environmental differences and features in different regions. Moreover, traditional assessments have focused mainly on geographically independent regions and are not applicable to this case study because the YREB covers 11 provinces and cities in close proximity, thereby making accurate and comprehensive measurement of the environmental sustainability level of the YREB difficult. Some studies have noted that scientifically measuring environmental sustainability and monitoring its dynamic status can inform the sustainable development of cities (Zhang and Chen, 2021). In addition, most previous studies explored regional distribution differences in environmental sustainability from the perspective of qualitative analysis. Concerning regional differences and the dynamic evolution of environmental sustainability, although qualitative analysis has made valuable contributions, there is still a lack of scientific, structural, and quantitative explanations that can quantify the magnitude of regional differences and identify their sources.

To close this research gap, in this study, we do the following: first, we follow the 'pressure effect-state change-problem solving' logic to build an evaluation index system for the environmental sustainability of the YREB. Specifically, in accordance with the pressure-state-response (PSR) model, which was proposed by the Organization for Economic Cooperation and Development, we combine government documents and important speeches related to the development of the YREB and the high-frequency indicators used in the literature. Second, using the panel data of 11 provinces and cities in the YREB from 2003 to 2020, we assess the environmental sustainability of the YREB via the entropy weight method and grey incidence analysis. Third, from the perspectives of the upper, middle and lower regions, we comprehensively analysed the characteristics and reasons for regional differences and the spatiotemporal dynamic evolution features of YREB environmental sustainability by combining Dagum's Gini coefficient decomposition method, kernel density estimation, Moran's I and the Markov chain.

This study has several main contributions. First, to evaluate the environmental sustainability of the YREB, we propose an index system based on the PSR model and constructed by integrating characteristics and high-frequency indicators. The characteristics indicators are used to describe regional characteristics and are selected by reviewing government documents and important conference speeches related to the development of the YREB. High-frequency indicators are derived from academic research results. Integrating these indicators makes the index system more suitable for assessing the environmental sustainability of the YREB. Second, we uncover the magnitude and sources of regional environmental sustainability differences in the YREB from three dimensions: overall, intraregional and interregional differences. Third, on the basis of the distribution characteristics of the neighbouring provinces and cities in the YREB, we incorporate spatial correlation analysis to reveal the spatial distribution features of environmental sustainability in the YREB and reveal the dynamic evolution features of environmental sustainability from the temporal, spatial and transfer probability dimensions.

The remainder of this study is organised as follows: Section 2 reviews the related literature on sustainability as a general concept and environmental sustainability and compares and analyses existing studies. Section 3 describes the construction process and evaluation steps of the YREB environmental sustainability index system. Section 4 explores the regional differences in environmental sustainability and the spatial and temporal dynamics of the YREB. Section 5 presents the results and discussion. Section 6 provides conclusions, theoretical and practical implications, research limitations, and potential future studies.

2 Literature review

2.1 Research on sustainability

Sustainability, which has three pillars (economic, social and environmental), is widely regarded as an important means of creating and sustaining high-quality development (Yin et al., 2023). There are currently two main bodies of literature concerning sustainability. The first focuses on evaluating sustainability at different regional levels and multidimensional spatial scales. For example, Smetana et al. (2016) applied the regional sustainability assessment methodology (RSAM) based on resource capital and its internal and external transfers to analyse the relative sustainability of subnational regions. Phillis et al. (2017) used the fuzzy evaluation model to measure and rank the sustainability level of 106 cities worldwide. Yang et al. (2017) proposed a linear dimensionless coordinate system for evaluating sustainable urban development in China; using this system, the authors revealed the status quo of sustainability in 287 cities across the eastern, central, and western regions. Li and Yi (2020) used the coupling coordination model to assess the sustainability of nine central cities in China from a regional perspective. Adamo et al.

(2022) relied on the analytic hierarchy process (AHP) and the 10-point scale to evaluate the sustainability level of 103 cities in Italy with 45 SDGs; the results indicated that the sustainability levels across Italy differ greatly.

Table 1 Comparison of previous studies on sustainability

Research contents and perspectives	*References*	*Index construction method or basis*	*Index evaluation method*	*Object of measurement*
Evaluation of sustainability at different regional levels and multidimensional spatial scales	Phillis et al. (2017)	Refers mainly to the index system of past scholars	Fuzzy evaluation model	Measured and ranked the sustainability level of 106 cities worldwide
	Yang et al. (2017)	Combined urban ecological cost and social, economic, and environment benefits	Linear dimensionless method	Revealed the status quo of sustainability in 287 cities across the eastern, central, and western regions in China.
	Li and Yi (2020)	Major literature reviews on sustainable development	Coupling coordination model	Assessed the sustainability of nine central cities in China
	Adamo et al. (2022)	Sustainable development goals in the 2030 Agenda	A hybrid methodology based on the AHP and the 10-point scale	Evaluated the sustainability level of 103 cities in Italy
Temporal or spatial dynamic evolution features	Wang and Yu (2021)	According to the development goals set out in the 2019 Sustainable Development Report	Principal component analysis	Calculated the level of sustainable agricultural development in China from 2007 to 2018 and revealed the spatiotemporal evolution characteristics of sustainability
	Zhong et al. (2021)	Combined with the idea of strong sustainability	Additive aggregation method	Spatiotemporal assessment of the regional
	Khodakarami et al. (2023)	Indicator-based approach in building a sustainability assessment framework	An integrated framework of spatial modelling and multicriteria decision-making analysis	Assessed urban spatial sustainability

With the continuous development of sustainability evaluation research, scholars have begun to explore the differences in sustainability and the dynamic spatiotemporal evolution features thereof among different regions at different times. For example, Yin et al. (2023) explored the spatial distribution differences in urban sustainability in the Yangtze River Delta Urban Agglomeration (YRDUA) and reported that the northern YRDUA (heavy industrial area) performs well in terms of economic but not environmental sustainability and that the southwestern YRDUA (high-density forest area) performs better in terms of environmental sustainability than it does in terms of economic or social sustainability. Zhong et al. (2021) assessed the regional sustainability of 66 counties in the Yangtze River Delta (YRD) in China and reported autocorrelations and diverse aggregation characteristics among counties. Wang and Yu (2021) revealed that sustainable agricultural development in China from 2007 to 2018 tended to attenuate from west to east and that the southwest and northwest provinces were polarised. Khodakarami et al. (2023) developed a spatially-based sustainability assessment and reported that the central parts of a city were more sustainable than the urban periphery. Table 1 provides an analysis of the differences among existing studies on sustainability in terms of several dimensions.

In summary, despite the significant contributions of previous studies on sustainability, research regarding the specific analysis of regional differences and the dynamic evolution characteristics of sustainability from the perspectives of the economic, social, and environmental pillars has been limited. The environmental dimension is considered the foundation of the economic and social aspects, and it is very important to study sustainability from an environmental perspective (Usubiaga-Liaño and Ekins, 2021b; Tóthová and Heglasová, 2022). Nevertheless, few studies have been conducted on regional differences and dynamic evolution characteristics from the perspective of environmental sustainability. Moreover, most studies have been limited to using qualitative analysis to study the distribution characteristics of sustainability in time and space, whereas quantitative methods for revealing the origins of regional sustainability differences and spatiotemporal evolution mechanisms are lacking.

2.2 Assessment of environmental sustainability

Environmental sustainability is a key global challenge that has attracted increasing attention because of climate change, pollution and declining biodiversity (Zuccotto et al., 2024), especially in terms of comprehensive measurement (Usubiaga-Liaño and Ekins, 2021a). Currently, the evaluation index system is the most common approach for assessing environmental sustainability (Zhou et al., 2006a). Scholars have employed various approaches for constructing indicator systems for assessing environmental sustainability (Wang et al., 2013b; McBride et al., 2011; Zhou et al., 2006a). The evaluation results can provide quantitative environmental information for decision makers for performance monitoring, policy progress assessment, benchmark comparison and decision making (Esty et al., 2005).

Many achievements have been made in assessing environmental sustainability at different spatial scales. At the country level, Yale and Columbia Universities collaborated to develop the environmental sustainability index (ESI) in 2005. The ESI integrates 76 variables into 21 indicators via the PSR model, which is employed to monitor natural resources, environmental stress, environmental management capacity, and global participation (Liu, 2007). The ESI has sparked extensive discussions in the academic community and has been widely applied to assess environmental sustainability at the national level (Siche et al., 2008). Babcicky (2013) verified the architecture of the ESI by using the PSR model and exploratory factor analysis; additionally, the authors reported that the performance of the index is inconsistent and that economically developed countries and thus the weighting methods used by the index reflect a potential bias. Therefore, the authors constructed a reweighted index (equivalised ESI) to improve the index's measurement qualities. Additionally, the environmental sustainability gap (ESGAP) framework is also used to assess environmental sustainability; the framework uses two environmental sustainability indices [the strong environmental sustainability index (SESI) and the strong environmental sustainability progress index (SESPI)] (Sato et al., 2024). Sato et al. (2024) applied the ESGAP framework and reported that Japan has not experienced significant changes in terms of aggregate environmental sustainability throughout the 2011–2017 period. At the regional level, Lee et al. (2023) stated that the existing research handles only the regional heterogeneity of inventor data at a single scale; they then introduced a general computational framework for spatially explicit environmental sustainability assessment based on a multiregional hybrid modelling approach. Zhang and Chen (2021) calculated the degree of environmental sustainability and the degree of coupling coordination among different dimensions of 17 cities in Shandong and reported that the level of environmental sustainability was poor in Shandong because of lagging social and economic development. At the industry level, Cheng et al. (2020) constructed a four-dimensional index system, evaluated the industrial environment of the Nansha Industrial Base of Guangzhou and discovered that the environmental sustainability of the industrial base generally showed a progressive development trend. Goyal et al. (2018) quantitatively measured and compared the environmental sustainability of the supply chain in the Indian steel industry through the graph theory method, and the results indicated that the environmental sustainability of the steel industry significantly improved during the study period. This study compares previous studies on environmental sustainability in several dimensions, as shown in Table 2.

As shown in Table 2, although studies on environmental sustainability assessment have made several achievements, most are based on existing assessment frameworks that do not consider regional economic, social and environmental differences or characteristics in different regions where natural resources, environmental pressure and social response vary by region (Huang et al., 2008) and cannot reveal the temporal and spatial correlation of environmental sustainability in multiple adjacent regions. Additionally, the assessment methods of environmental sustainability are generally the same and are essentially the composite indices obtained through normalisation, weighting and the aggregation of indicators. However, owing to the ambiguity of sustainability, the lack of strict definitions and the ambiguity of some components, there are still subjective factors that may exaggerate or reduce the contributions of some indicators. Moreover, studies on regional differences and dynamic evolution characteristics from the perspective of environmental sustainability are still lacking, and most of the previous studies used qualitative analysis methods. There is a lack of scientific, structural and quantitative explanations for quantifying the magnitude of regional differences and identifying their sources.

Table 2 Comparison of previous studies on environmental sustainability

Research contents and perspectives	*References*	*Index construction method or basis*	*Index evaluation method*	*Object of measurement*
Country level's environmental sustainability	Babcicky (2013)	PSR model	Factor analysis of ESI indicators was performed to redetermine the weights	120 countries
	Sato et al. (2024)	Environmental sustainability gap framework	Weighting and aggregation	Assessing the environmental sustainability in Japan
Regional level's environmental sustainability	Lee et al. (2023)	Integrating existing databases and ecosystem modules at each scale	A general computational framework for spatially explicit environmental sustainability assessment based on a multiregional hybrid modelling approach	Illustrative example of corn production in two regions.
	Zhang and Chen (2021)	Referring to the index system of the past scholars	Linear aggregation operator	Environment sustainability of 17 cities in Shandong
Industry level's environmental sustainability	Cheng et al. (2020)	Three-line environmental governance policy	Full permutation polygon synthetic indicator (FPPSI)	Industrial environment sustainability of the Nansha Industrial Base of Guangzhou
	Goyal et al. (2018)	Conducting a literature review to identify the driving factors of environmental sustainability	Graph theory method	Environmental sustainability of the supply chain in the Indian steel industry

2.3 Research methods

To comprehensively assess the environmental sustainability of the YREB and analyse the differences and spatiotemporal dynamic evolution of regions, this study attempts to integrate various methods to build a more logical, authoritative and rational environmental sustainability index system and analyse the spatiotemporal dynamic characteristics. To facilitate an effective and appropriate evaluation of environmental sustainability, ensuring that the index system is comprehensive and hierarchical is crucial (Bao et al., 2001). Moreover, maintaining the policy orientation of environmental sustainability is important (Wang et al., 2013b). Therefore, this study used the PSR model as a basis, followed the logic of 'pressure effect-state change-problem solving', and ensured the hierarchical structure of the assessment framework. Moreover, we compile and analyse environmental sustainability assessment indicators from previous studies and select high-frequency indicators to ensure the comprehensiveness of the assessment framework. Moreover, we obtained characteristic indicators from government documents and important conference speeches pertaining to the development of the YREB to ensure that the assessment framework aligns with the strategic planning of the region's development.

Because the entropy weight method has significant advantages in excluding the impact of subjective factors and measuring the amount of information (Zou et al., 2006), the method is used in this study to identify the weight of each evaluation index to avoid subjectivity in the evaluation indicators. In addition, the indicators of each target layer are vectors in the multidimensional space of environmental sustainability. If the results are calculated directly via linear addition, the contributions of some indicators will be exaggerated or reduced (Huang et al., 2008). Grey correlation analysis is thus combined with the entropy weight method to evaluate the environmental sustainability of the YREB.

Variation coefficients, the Theil index, the Gini coefficient, σ convergence and β convergence are usually used to study regional distribution differences (Xin and Chen, 2019). However, these methods do not consider the distribution of subsamples (Lv et al., 2021); fail to decompose the source and contribution degree of regional differences; and explain dynamic evolution processes, such as changes, stratification, and polarisation in regional distribution differences. Because Dagum's Gini coefficient decomposition method can be used to quantitatively calculate and analyse the degree of regional differences in geographical phenomena (Cheng et al., 2016), it was employed in this study to analyse the differences in environmental sustainability across the various YREB regions.

The YREB covers 11 provinces and cities located close to one another, and the spatial correlation among provinces must be considered. To reflect the spatiotemporal distribution of the absolute differences and dynamic evolution characteristics of the environmental sustainability of the YREB, kernel density estimation, Moran's I and a Markov chain are integrated with Dagum's Gini coefficient decomposition method in this study. The advantages of kernel density estimation, which investigates the non-equilibrium distribution, are that the form of the function can be set arbitrarily and that the distribution of indicator data is less restricted than traditional parameter estimation methods (Sun and Li, 2015). Spatial correlation involves global and local correlations. Moran's I is used to analyse interregional correlations (Wang et al., 2021). The global Moran's I index can characterise whether the study area has spatial correlation, while the local Moran's I is used to verify the existence of local clustering effects (Hong et al., 2017). The Markov chain is used for spatiotemporal analysis (Cui et al., 2021) and describes trends from the past to the present and the future (Arsanjani, 2018). The Markov chain studies the dynamic evolution characteristics of environmental sustainability in different periods from time and space dimensions (Yang et al., 2019).

In short, to compensate for the differences in environmental sustainability among the 11 provinces and cities in the YREB, help the YREB build a high-quality development demonstration base, and promote the sustainable development of the YREB and China, this paper aims to integrate the PSR model, YREB environmental sustainability policy documents, important speeches and high-frequency indices to construct the logic, rationality and authority of the YREB environmental sustainability index system; apply the entropy method and grey correlation analysis to evaluate the environmental sustainability levels of the 11 provinces and cities in the YREB during 2003–2020; and analyse the upper, middle and lower regional differences in the YREB and spatiotemporal dynamic evolution characteristics by using an integration of Dagum's Gini coefficient decomposition method, kernel density estimation, Moran's I and the Markov chain.

3 Index system construction and assessment of the environmental sustainability of the YREB

3.1 Study area: YREB

The YREB covers 11 provinces and cities across the eastern, central and western regions of China. The relationship between geographical proximity is shown in Figure 1. The YREB occupies an area of approximately 2.05 million square kilometres and contains more than 40% of China's population and GDP (Wang and Xu, 2020). The YREB is among the regions with the largest coverage area, the strongest economic development strength and the largest strategic support role in China and serves as a leading demonstration area of high-quality development (Zhou et al., 2016). The YREB is home to 30% of China's petrochemical industry and 40% of the country's cement industry, thus resulting in significant atmospheric pollution emissions. In 2017, the emissions of sulphur dioxide, nitrogen oxides and dust in the YREB were 3,219,600 tons, 4,410,100 tons and 2,274,900 tons, respectively, accounting for 36.78%, 35.03% and 28.57% of national emissions, respectively[1]. With the in-depth implementation of China's high-quality development strategy, under the strategic goal of prioritising ecology and green development, clarifying the environmental sustainability status of the YREB is very important to improve the level of environmental sustainability in China.

Figure 1 Adjacent regional relationships among the 11 provinces and cities in the YREB (see online version for colours)

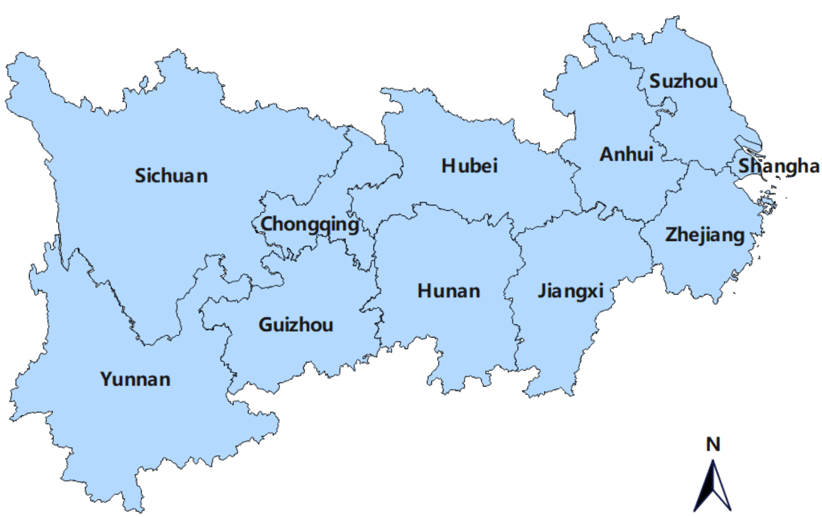


Table 3 Characteristic indicators and sources

No.	*Indicators*	*Corresponding documents*
1	The proportion of class I to III water	A; B; C; D
2	Population density	C
3	Urbanisation level	A; D
4	The number of water resources	A; B; D
5	Chemical oxygen demand	A; B; D
6	Ammonia nitrogen emission	A; B; D
7	Sulphur dioxide emission	A; C; D
8	The ratio of days with good or excellent air quality	C; D
9	Industrial solid waste generation	A; C
10	Chemical fertiliser use	A; C
11	Pesticide use	A; C
12	Soil erosion control area	A; B; D
13	Geological disaster prevention	A; B
14	Industrial wastewater discharge	B; D
15	Afforestation area	C; D
16	Forest coverage ratio	C; D
17	Harmless treatment rate of domestic garbage	C; D
18	Smoke (powder) emission	A; C
19	Industrial waste gas emission	A; B
20	GDP per capita	C;-
21	Arable land coverage	D
22	Wetland area	A; B; D
23	The proportion of industrial pollution control input in GDP	A; C; D
24	Soil erosion area	A; B
25	Biodiversity	A; C; D
26	The amount of articulate matter emissions	A; B; C; D
27	Nitrogen oxide concentration	A; C; D
28	Acid rain frequency	A; D
29	Heavy metal pollution	A; B; D

3.2 Evaluation index system construction for the environmental sustainability of the YREB

To highlight the regional characteristics of the YREB and avoid the subjective and arbitrary selection of evaluation indicators, we adopted the PSR model, which is commonly used in environmental quality assessment, as the protocol layer. The economy, society, resources and environment constitute the solution layer. Then, we compile the corresponding indicators for the protocol and solution layers by integrating the following two methods: concerning the characteristic indicators, to ensure that the indicator system conforms to Chinese national strategic guidance and closely revolves around the development features of cities in the YREB, this study adopts the method employed by Ke et al. (2020); this method selects characteristic indicators from government documents and important conference speeches related to the development of the YREB. This study collected the 'Guideline for Developing the YREB Based on the Golden Waterway' (document A) (which was released in 2014), important speeches that were delivered at the 'Symposium on comprehensively accelerating the development of the YREB' (document B) (which was held in 2020), the 'Ecological Development Report of the YREB 2019–2020' (document C), and the 'Ecological Environment Protection Plan of the YREB' (document D) (which was released in 2017). We then identified the paragraphs related to the environment and manually screened out the indicators directly related to environmental sustainability, as shown in Table 3.

Concerning the high-frequency indicators, we consulted articles published in the Web of Science database between 1987 (when the concept of environmental sustainability was coined) and 2022. Studies on environmental sustainability assessment were accurately identified by preliminarily filtering topic options via queries and Boolean operators. The initial search returned 711 publications. To ensure the quality of the indicator selection, only 'journal articles', 'reviews' and 'online publications' written in English were selected as the units of analysis, thus resulting in 705 papers retained for further analysis. Another round of manual selection was subsequently conducted on these articles, thus ultimately resulting in a sample of 63 publications. The environmental sustainability assessment indicators used in these papers were then compiled, and indicators that were used five or more times were classified as high-frequency indicators. The specific high-frequency indicators and references are described in Table 4.

Table 4 High-frequency indicators and sources

Rank no.	*Indicators*	*References*
1	Carbon dioxide emission	Boggia and Cortina (2010), Gonzalez-Garcia et al. (2018), Athanassiadis et al. (2018), Zhong et al. (2021), Wang et al. (2013a, 2013b), Buzási and Jager (2020), Moldan et al. (2012), Mcbride et al. (2011), Pan and Kao (2009), Olafsson et al. (2014), Cook et al. (2017), Dong and Hauschild (2017), Chandrakumar and McLaren (2018), Shen et al. (2022), Liao et al. (2020) and Li et al. (2021)
2	Forest coverage ratio	Dash (2011), Roboredo et al. (2016), Saeed and Ahmad (2021), Moldan et al. (2012), Pan and Kao (2009), Olafsson et al. (2014), Cook et al. (2017), Zhang et al. (2017), Wu and Wu (2012), Dong and Hauschild (2017), Zhao et al. (2021), Shi et al. (2021), Che et al. (2021) and Hong et al. (2019)
3	Nitrogen oxide concentration	Dash (2011), Gonzalez-Garcia et al. (2018), Athanassiadis et al. (2018), Wang et al. (2013a, 2013b), Saeed and Ahmad (2021), Moldan et al. (2012), Olafsson et al. (2014), Cook et al. (2017), Zhang et al. (2017), Zhou et al. (2006a), Zheng and Bedra (2018), Liao et al. (2020) and Liu (2007)
4	Sulphur dioxide emission	Dash (2011), Gonzalez-Garcia et al. (2018), Zhong et al. (2021), Wang et al. (2013a, 2013b), Moldan et al. (2012), Olafsson et al. (2014), Zhang et al. (2017), Zhou et al. (2006a), Zheng and Bedra (2018), Liao et al. (2020), Shi et al. (2021) and Liu (2007)

Table 4 High-frequency indicators and sources (continued)

Rank no.	*Indicators*	*References*
5	The amount of articulate matter emissions	Gonzalez-Garcia et al. (2018), Athanassiadis et al. (2018), Wang et al. (2013a, 2013b), Saeed and Ahmad (2021), McBride et al. (2011), Olafsson et al. (2014), Cook et al. (2017), Dong and Hauschild (2017), Shen et al. (2022), Zheng and Bedra (2018), Li et al. (2021) and Huang et al. (2020)
6	Per capita water consumption	Boggia and Cortina (2010), Sogut and Erdogan (2022), Gonzalez-Garcia et al. (2018), Athanassiadis et al. (2018), Wang et al. (2013a), Moldan et al. (2012), Mcbride et al. (2011), Olafsson et al. (2014), Dong and Hauschild (2017), Chandrakumar and McLaren (2018), Bjørn et al. (2020) and Huang et al. (2020)
7	Park green area	Wang et al. (2013a, 2013b), Buzási and Jager (2020), Saeed and Ahmad (2021), Cheng et al. (2020), Zhou et al. (2006b), Zheng and Bedra (2018), Li and Li (2017), Li et al. (2018), Shi et al. (2021) and Yi et al. (2019)
8	Biodiversity	Dash (2011), Mcbride et al. (2011), Cheng et al. (2020), Olafsson et al. (2014), Cook et al. (2017), Wu and Wu (2012), Dong and Hauschild (2017), Li and Li (2017), Zhao et al. (2021) and Liu (2007)
9	Industrial wastewater discharge	Athanassiadis et al. (2018), Zhong et al. (2021), Zhang et al. (2017), Li and Li (2017), Liao et al. (2020), Li et al. (2018), Shi et al. (2021), Yi et al. (2019) and Che et al. (2021)
10	Industrial solid waste generation	Dash (2011), Sogut and Erdogan (2022), Gonzalez-Garcia et al. (2018), Athanassiadis et al. (2018), Saeed and Ahmad (2021), Olafsson et al. (2014), Cook et al. (2017), Li and Li (2017) and Che et al. (2021)
11	Industrial solid waste disposal	Dash (2011), Gonzalez-Garcia et al. (2018), Wang et al. (2013a), Cheng et al. (2020), Zhou et al. (2006b), Li et al. (2018), Shi et al. (2021) and Yi et al. (2019)
12	Urbanisation level	Boggia and Cortina (2010), Wang et al. (2013b), Wu and Wu (2012), Shen et al. (2022), Zhou et al. (2006b), Li and Li (2017) and Huang et al. (2020)
13	The ratio of days with good or excellent air quality	Aryampa et al. (2021), Sogut and Erdogan (2022), Wang et al. (2013a), Cheng et al. (2020), Wu and Wu (2012), Zheng and Bedra (2018) and Liu (2007)
14	Ozone concentration	Gonzalez-Garcia et al. (2018), Wang et al. (2013a), Moldan et al. (2012), McBride et al. (2011), Dong and Hauschild (2017), Chandrakumar and McLaren (2018) and Zheng and Bedra (2018)
15	The proportion of class I to III water	Aryampa et al. (2021), Sogut and Erdogan (2022), Wang et al. (2013a), Cheng et al. (2020), Wu and Wu (2012) and Liu (2007)
16	Per capita energy consumption	Wang et al. (2013a), Buzási and Jager (2020), Olafsson et al. (2014), Zhou et al. (2006b) and Huang et al. (2020)
17	Chemical fertiliser use	Dash (2011), Olafsson et al. (2014), Cook et al. (2017), Zhou et al. (2006b) and Liu (2007)

Table 4 High-frequency indicators and sources (continued)

Rank no.	*Indicators*	*References*
18	Area of nature reserve	Dash (2011), Moldan et al. (2012), Cook et al. (2017), Dong and Hauschild (2017), Zhou et al. (2006b)
19	Harmless treatment rate of domestic garbage	Wang et al. (2013a), Cheng et al. (2020), Zhou et al. (2006b), Liao et al. (2020) and Shi et al. (2021)
20	Wastewater treatment	Cheng et al. (2020), Olafsson et al. (2014), Cook et al. (2017), Li et al. (2018) and Zhao et al. (2021)
21	Vehicle density	Dash (2011), Wang et al. (2013b), Zhou et al. (2006b), Liu (2007) and Hong et al. (2019)
22	Carbon monoxide concentration	Gonzalez-Garcia et al. (2018), Athanassiadis et al. (2018), Buzási and Jager (2020), McBride et al. (2011) and Cook et al. (2017)
23	The direct economic losses of natural disasters	Dash (2011), Pan and Kao (2009), Dong and Hauschild (2017), Chandrakumar and McLaren (2018) and Zhao et al. (2021)

Finally, the characteristic and high-frequency indicators were merged, and duplicate indicators were eliminated. In accordance with the principles of objectivity, scientific integrity, representativeness and availability of data, 30 indicators were ultimately selected.

The environmental system is large and complex, and environmental sustainability is not only dependent on natural resources but also influenced by many social and economic indicators, such as human activities, environmental benefits and social responses (Esty et al., 2005; Du et al., 2006). In this study, in accordance with the PSR model, environmental pressure, environmental status, and social response are treated as the protocol layer, while economy, society, resources, and environment are treated as the solution layer; also, in accordance with the PSR model, an evaluation index system for the environmental sustainability of the YREB is constructed. The protocol layer follows the 'pressure effect-state change-problem solving' logic, which well explains 'why it happened', 'what happened' and 'how to do it'; this logic is the underlying logic of building the YREB environmental sustainability evaluation index system in this study. Environmental pressure stems from the environmental pollution and ecological damage generated by human activities (Yao et al., 2019; Xi et al., 2015). To maintain the structure of the environment without qualitative changes or damage to the environment, human economic and social activities must be carried out under the premise of not exceeding the bearing capacity of the environment (Morshed et al., 2024). From the perspective of the economy, society, resources and the environment, economic losses, population growth, resource consumption and pollution caused by natural disasters all damage and disturb the environment, thereby resulting in environmental pressure, which raises the question of 'why it happened'. Environmental states represent the results of interactions between an environmental system and its environment at a specific time stage. Moreover, environmental status is the life-supporting system that humans and other organisms rely on and can thus affect the environmental carrying capacity of a region (Raven and Wagner, 2021; Wang et al., 2022). The pressure of human social and economic activities on the ecosystem changes the state of the environmental system. From the dimensions of the economy, resources and environment, such changes include changes in gross domestic product, urbanisation level, resources or vegetation stock, and air and water quality; these changes can be a good answer to the question 'what happened?' Social response refers to the social model with basic skills, attitudes and networks that promote an effective response to environmental challenges (Wang et al., 2015); i.e., social response is the action taken by human beings to improve environmental sustainability. To achieve environmental sustainability, we should also consider 'man's contribution to nature' rather than 'nature's contribution to man' (Washington and Maloney, 2020). In other words, people should not only protect nature but also be more active in constructing and using nature to establish a coordinated and efficient artificial ecosystem. Geological disaster prevention, afforestation, the establishment of nature reserves, soil erosion control, pollution control, etc., answer the question of 'how to do this'. The specific evaluation indicator system is described in Table 5. To quantify all the factors reasonably, we categorise each indicator as either a positive index ('Positive') or a negative index ('Negative') according the indicator's characteristics.

Table 5 YREB environmental sustainability evaluation index system

Protocol layer	*Solution layer*	*Index layer*	*Attributes*
Environmental pressure	Economy	The direct economic losses of natural disasters (X_{i1})	Negative
	Society	Population density (X_{i2})	Negative
	Resources	Per capita water consumption (X_{i3}),	Negative
		Per capita energy consumption (X_{i4})	
	Environment	Chemical oxygen demand (X_{i5})	Negative
		Ammonia nitrogen emission (X_{i6})	
		Sulphur dioxide emission (X_{i7})	
		Smoke (powder) emission (X_{i8})	
		Carbon dioxide emission (X_{i9})	
		Chemical fertiliser use (X_{i10})	
		Pesticides use (X_{i11})	
		Industrial wastewater discharge (X_{i12})	
		Industrial waste gas emission (X_{i13})	
		Industrial solid waste generation (X_{i14})	
Environmental status	Economy	GDP per capita (X_{i15})	Positive
		Urbanisation level (X_{i16})	
	Resources	The number of water resources (X_{i17})	Positive
		Forest coverage ratio (X_{i18})	
		Arable land coverage (X_{i19})	
		Wetland area (X_{i20})	
		Park green area (X_{i21})	
	Environment	The proportion of days with good or excellent air quality (X_{i22})	Positive
		The proportion of class I to III water (X_{i23})	

Table 5 YREB environmental sustainability evaluation index system (continued)

Protocol layer	*Solution layer*	*Index layer*	*Attributes*
Social response	Society	Geological disaster prevention (X_{i24})	Positive
	Resources	Afforestation area (X_{i25})	Positive
		Area of nature reserve (X_{i26})	
	Environment	Soil erosion control area (X_{i27})	Positive
		Industrial solid waste disposal (X_{i28})	
		Harmless treatment rate of domestic garbage (X_{i29})	
		The proportion of industrial pollution control input in GDP (X_{i30})	

3.3 Environmental sustainability evaluation steps and methods based on the integration of the entropy weight method and grey correlation analysis

The process for assessing the environmental sustainability of the YREB is divided into the four steps described below. The parameters used in the assessment process are listed in Table 6.

Table 6 Parameters for assessing environmental sustainability

Notation	*Description*
i	The i^{th} province
j	The j^{th} indicator
m	The number of provinces (m = 11)
n	The number of indicators (n = 30)
X_{ij}	The initial value of the j^{th} indicator for the i^{th} province
X'_j	The standardised result of the j^{th} indicator for the i^{th} province
max[X_{ij}]	The maximum values of the X_{ij}
min[X_{ij}]	The minimum values of the X_{ij}
P_{ij}	The proportion of the i^{th} province in the j^{th} indicator
E_j	The entropy of the j^{th} index
W_j	The weight of the j^{th} indicator of the i^{th} province
k	The k^{th} protocol layer (k = 1, 2, 3)
$R_i(k)$	The score of the k^{th} protocol layer for the i^{th} province
$R_0(k)$	The optimised vector including the maximum value of environmental status and social response index and the minimum value of environmental pressure
ρ	The resolution coefficient (ρ = 0.5)
$\xi_i(k)$	The grey correlation coefficient of the k^{th} protocol layer for the i^{th} province
CEI_i	The value of environmental sustainability of the i^{th} province ($0 \le CEI_i \le 1$)

Step 1 Standardisation: since the magnitude of the difference between indices is large, normalising the data before evaluation is necessary. The initial matrix of the environmental sustainability evaluation index is set as $(X_{ij})_{m*n}$ ($1 \leq i \leq m$, $1 \leq j \leq n$), where m and n indicate the number of provinces and the number of indicators, respectively. In this study, $m = 11$, and $n = 30$.

The standardisation of positive indicators is based on the following calculation formula:

$$X'_{ij} = \frac{X_{ij} - \min\left(X_{ij}\right)}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)} \quad (1)$$

The standardisation of negative indicators is based on the following calculation formula:

$$X'_{ij} = \frac{\max\left(X_{ij}\right) - X_{ij}}{\max\left(X_{ij}\right) - \min\left(X_{ij}\right)} \quad (2)$$

Step 2 Calculate the information entropy of the index; the formula is:

$$E_j = -\frac{\sum_{i=1}^{m} P_{ij} \ln P_{ij}}{\ln m} \quad (3)$$

The calculation method for P_{ij} is as follows:

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}} \quad (4)$$

Step 3 Calculate the entropy weight of each indicator and obtain the scores of each protocol layer. The specific calculation formula is as follows:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^{n} \left(1 - E_j\right)} \quad (5)$$

$$R_i(k) = \sum_{j=1}^{n} W_{kj} X'_{ij} \quad (6)$$

The greater W_j is, the more useful the information of the j^{th} indicator, and vice versa.

Step 4 Measure the grey correlation coefficient. First, the maximum value of the environmental status and social response index and the minimum value of the environmental pressure are taken as the optimised vector $R_0(k) = (x_0(1), x_0(2), x_0(3))$ for environmental sustainability, where 1, 2 and 3 represent the environmental status, environmental pressure and social response of the protocol layer, respectively. The correlation coefficient between the protocol layer and the optimal vector in each region is subsequently calculated. Finally, the average correlation degree of each protocol layer is calculated as the degree of environmental sustainability. The specific formula is defined as follows:

$$\xi_i(k) = \frac{\min_k \min_i \left|R_0(k) - R_i(k)\right| + \rho \max_k \max_i \left|R_0(k) - R_i(k)\right|}{\left|R_0(k) - R_i(k)\right| + \rho \max_k \max_i \left|R_0(k) - R_i(k)\right|}, \tag{7}$$

$$CEI_i = \frac{1}{3}\sum_{k=1}^{3} \xi_i(k) \tag{8}$$

The greater the value of CEI_i is, the better the environmental sustainability of the province.

4 Analysis of regional differences and spatiotemporal dynamic evolution features

4.1 Regional difference analysis of the environmental sustainability of the YREB via Dagum's Gini coefficient decomposition method

In this study, we divide the YREB into three regions, namely, the upper, middle and lower regions, to analyse the differences in environmental sustainability across regions. The upstream regions include Chongqing, Sichuan, Guizhou, and Yunnan; the middle region includes Jiangxi, Hubei, and Hunan; and the downstream areas include Shanghai, Jiangsu, Zhejiang, and Anhui. We then adopt Dagum's Gini coefficient decomposition method to analyse regional differences in environmental sustainability. The parameters of the regional differences are listed in Table 7.

Table 7 Parameters of Dagum's Gini coefficient decomposition method

Notation	*Description*
q	The number of regions ($q = 3$)
m_i	The number of provinces in the i^{th} region; $i = 1, 2, 3$, referring to the upper, middle and lower regions
CEI_{ij}	The environmental sustainability of the j^{th} province in the i^{th} region of the YREB
μ	The mean value of regional environmental sustainability
G	The differences in the environmental sustainability of the YREB ($G = G_w + G_{mb} + G_l$))
G_{ii}	The Gini coefficient of the environmental sustainability for the i^{th} region
G_{it}	The Gini coefficient of the environmental sustainability between the i^{th} and t^{th} regions
μ_i	The mean value of the regional environmental sustainability of the i^{th} region
μ_t	The mean value of the regional environmental sustainability of the t^{th} region
G_w	The intraregional environmental sustainability difference
G_{mb}	The interregional net environmental sustainability difference
G_l	The transvariation intensity

The overall Gini coefficient of the YREB's environmental sustainability is denoted by G, which refers to the differences in the environmental sustainability of the YREB; the formula for G is as follows:

$$G = \frac{\sum_{i=1}^{q}\sum_{n=1}^{q}\sum_{j=1}^{m_i}\sum_{r=1}^{m_t}\left|CEI_{ij} - CEI_{tr}\right|}{2m^2\mu} \tag{9}$$

The Gini coefficient of environmental sustainability for the i^{th} region is set as G_{ii}, which is calculated via the following formula:

$$G_{ii} = \frac{\sum_{j=1}^{m_i}\sum_{r=1}^{m_i}\left|CEI_{ij} - CEI_{ir}\right|}{2m_i^2\mu_i} \tag{10}$$

The Gini coefficient of environmental sustainability between the i^{th} and t^{th} regions is denoted by G_{it}, the formula for which is as follows:

$$G_{it} = \frac{\sum_{j=1}^{m_i}\sum_{r=1}^{m_t}\left|CEI_{ij} - CEI_{tr}\right|}{m_i m_t\left(\mu_i + \mu_t\right)} \tag{11}$$

The total Gini coefficient of environmental sustainability in the YREB is divided into three components: intraregional environmental sustainability difference (G_w), interregional net environmental sustainability difference (G_{mb}) and transvariation intensity (G_l); that is, G denotes the sum of G_w, G_{mb} and G_l (or, $G = G_w + G_{mb} + G_l$). G_l refers to the contribution that affects the total differences due to the existence of cross terms when dividing subgroups; this component is used to identify phenomena overlapping between regions (Liu, 2019). The formula for G_w is as follows:

$$G_w = \sum_{i=1}^{q} G_{ii}\frac{m_i^2\mu_i}{m^2 u} \tag{12}$$

The approach to calculating G_{mb} is as follows:

$$G_{mb} = \sum_{i=2}^{q}\sum_{t=1}^{i-1} G_{it}\left(\frac{m_i m_t u_t}{m^2 u} + \frac{m_t m_i u_i}{m^2 u}\right)D_{it} \tag{13}$$

The approach to calculating G_l is as follows:

$$G_l = \sum_{i=2}^{k}\sum_{t=1}^{i-1} G_{it}\left(p_i s_t + p_t s_i\right)\left(1 - D_{it}\right) \tag{14}$$

where $p_i = \frac{m_i}{m}$, $s_i = \frac{m_i u_i}{mu}$; D_{it} denotes the relative impact of environmental sustainability between the i^{th} and t^{th} regions and is calculated as $D_{it} = \frac{d_{it} - p_{it}}{d_{it} + p_{it}}$; d_{it} denotes the mathematical expectation obtained by summing all sample values in the i^{th} and t^{th} regions that satisfy $CEI_{ij} - CEI_{tr} > 0$ and is calculated as $d_{it} = \int_0^{\infty} dF_t(y)\int_0^{y}(y-x)dF_i(y)$, where $F_i(y)$ and $F_t(x)$ refer to the cumulative density distribution functions of environmental sustainability for the i^{th} and t^{th} regions, respectively; and p_{it} represents the mathematical expectation obtained by summing all sample values in the i^{th} and t^{th} regions that satisfy $CEI_{tr} - CEI_{ij} > 0$ and is calculated as $p_{it} = \int_0^{\infty} dF_t(y) \int_0^{y} (y-x) dF_i(y)$.

Notably, the value of G falls between 0 and 1. The closer the G value is to 0, the smaller the difference in environmental sustainability among all provinces in the YREB. Conversely, the closer the G value is to 1, the greater the difference in environmental sustainability among all provinces in the YREB. The closer G_w, G_{mb} and G_l are to 1, the greater the contribution rate to the overall difference in the YREB. Conversely, the closer G_w, G_{mb} and G_l are to 0, the smaller the contribution to the overall difference in the YREB.

4.2 Dynamic evolution characteristics analysis of the environmental sustainability of the YREB by using kernel density estimation and Moran's I

In this study, the dynamic evolution characteristics of the environmental sustainability of the YREB are analysed in the following three steps:

Step 1 Temporal dynamics analysis

The specific formula for kernel density estimation is as follows:

$$f(CEI) = \frac{1}{mh} \sum_{i=1}^{m} K\left[\left(CEI_i - \overline{CEI}\right)/h\right] \tag{15}$$

where $K[*]$ represents the kernel function, which is usually a symmetric unimodal probability density function; h denotes the bandwidth that determines the smoothness of the estimated density function (Li, 2021); and $\overline{CEI}$ denotes the mean value of environmental sustainability. Here, we present the development level, polarisation trend, and spatial differences in environmental sustainability in the YREB visually through 3D kernel density maps. Therefore, the distribution location reveals the level of environmental sustainability, whereas the distribution pattern describes the spatial differences and polarisation characteristics of environmental sustainability. In addition, the distributed ductility analyses the magnitude of spatial differences between the province with the highest level of environmental sustainability and other provinces.

Step 2 Spatial dynamics analysis

The approaches for calculating the global and local Moran's I are as follows:

$$I = \frac{\sum_{i=1}^{m} \sum_{j \neq i}^{m} w_{ij} \left(CEI_i - \overleftarrow{CEI}\right)\left(CEI_j - \overleftarrow{CEI}\right)}{S_1^2 \sum_{i=1}^{m} \sum_{j \neq i}^{m} w_{ij}} \tag{16}$$

$$I_i = \frac{(x_i - \bar{x})}{S_2^2} \sum_{j=1}^{m} w_{ij} \left(x_j - \bar{x}\right). \tag{17}$$

where I denotes the global Moran's I; I_i denotes the local Moran's I; w_{ij} denotes the spatial weight matrix; and S_1^2 and S_2^2 are the variances of environmental sustainability, which are calculated as $S_1^2 = \frac{1}{m}\sum_{i=1}^{m}(CEI_i - \overleftarrow{CEI})^2$ and $S_2^2 = \frac{1}{m}\sum_{j=1}^{m}(CEI_j - \overleftarrow{CEI})^2$. The value of I or I_i ranges from –1 to 1. When $I > 0$ (or $I_i > 0$), it indicates that environmental sustainability presents a positive spatial correlation between all provinces (or between certain provinces) of the YREB, and the greater the value is, the greater the spatial correlation. When $I < 0$ (or $I_i < 0$), it denotes a negative spatial correlation between all provinces (or between certain provinces) of the YREB, and the smaller the value is, the stronger the spatial difference. When $I = 0$ or $I_i = 0$, the space is random. Notably, which spatial weight matrix is selected will affect the result of Moran's I. Commonly used spatial weight matrices include the spatial contiguity matrix (A), geographic distance weight matrix (B) and economic weight matrix (C). Obtaining comprehensive and accurate results from the perspective of a single weight matrix is difficult. Thus, in combining matrices B and C, this study validates the spatiality of environmental sustainability by using the product of matrices B and C as the spatial weight matrix.

Step 3 Transition probability analysis

In this study, the transition probability is used to reveal the specific transition patterns of environmental sustainability in the YREB and each region. Before the Markov matrix is calculated, determining the transfer states is necessary. The main partitioning methods of the transition state include subjective partitioning, equal interval partitioning, quantile partitioning and natural breakpoint partitioning (Li, 2021). As mentioned above, the environmental sustainability of the YREB is different. For ease of comparison, we divide the status of the YREB and each region in the same way so the quartile is selected for division. Then, the environmental sustainability of the YREB is grouped into low-level (I), medium-low-level (II), medium-high-level (III), and high-level (IV) quartiles. Finally, the transfer probabilities of the four states are calculated.

The probability that the YREB and each region will transition from the initial state i at time i to state j at time $t + 1$ is:

$$p_{ij} = \frac{\sum_{t=0}^{T} N_{ij}}{\sum_{t=0}^{T} N_i} \quad (18)$$

where N_i denotes the number of provinces in state i and N_{ij} denotes the number of provinces transitioning from state i at time t to state j at time $t + 1$. The values of p_{ij} range from 0 to 1. The more p_{ij} tends to 0, the smaller the probability of a state transition of environmental sustainability; that is, the more environmental sustainability tends to a stable state. Conversely, the greater the value of p_{ij} tends to 1, the greater the probability of a state transition of environmental sustainability; that is, the greater the degree of environmental sustainability tends to fluctuate. When $p_{ij} = 0$, none of the provinces in state i have undergone a transition, thus indicating a stable state of environmental sustainability. When $p_{ij} = 1$, it suggests that provinces in state i have transitioned to state j, thus indicating a phenomenon of varying degrees of upwards or downwards transitions in environmental sustainability.

5 Results and discussion

5.1 Data sources

Considering the completeness, availability, and validity of the data, the required data are collected as much as possible. The data used in this paper for the assessment indicators of environmental sustainability were derived from the China Statistical Yearbook on the Environment, China Energy Statistical Yearbook, Bulletins on the State of the Ecological Environment, Statistical Yearbook of each province, and China's carbon accounting database from 2003 to 2020. The specific sources are shown in Table 8. For missing data from individual years, the interpolation method was applied.

Table 8 Sources of assessment indicators for environmental sustainability

Doc sources	*Specific source*	*Indicators*
China Statistical Yearbook on Environment	Natural disasters and environmental accidents	The direct economic losses of natural disasters
	Atmospheric environment	Sulphur dioxide emissions
	Atmospheric environment	Smoke (powder) emissions
	Rural environment	Pesticide use
	Rural environment	Chemical fertiliser use
	Natural ecology	Soil erosion control area
	Environmental investment	The proportion of industrial pollution control input in GDP
China Energy Statistical Yearbook	General survey	The per capita energy consumption
Bulletins on the State of the Ecological Environment	Atmospheric environment	The proportion of days with good or excellent air quality
	Water environment	The proportion of Class I to III water
Statistical yearbook of each province	Discharge situation of industrial wastewater	Chemical oxygen demand
	Discharge situation of industrial waste gas	Ammonia nitrogen emissions
	Discharge situation of industrial wastewater	Industrial wastewater discharge
	Discharge situation of industrial waste gas	Industrial waste gas emissions
	Discharge situation of industrial solid waste	Industrial solid waste generation
	Treatment and utilisation of industrial solid waste	Industrial solid waste disposal

Table 8 Sources of assessment indicators for environmental sustainability (continued)

Doc sources	*Specific source*	*Indicators*
China's Carbon Accounting Database	List of provincial emissions	Carbon dioxide emissions
China Statistical Yearbook	Population	Population density
	Resources and environment	Per capita water consumption
	Resident life	GDP per capita
	Urban, rural, and regional development	Urbanisation level
	Resources and environment	The amount of water resources
	Resources and environment	Forest coverage ratio
	Resources and environment	Arable land coverage
	Resources and environment	Wetland area
	Resources and environment	Park green area
	Resources and environment	Geological disaster prevention
	Resources and environment	Afforestation area
	Resources and environment	Area of nature reserve
	Resources and environment	Harmless treatment rate of domestic garbage

5.2 Evaluation results and analysis of the environmental sustainability of the YREB

According to the evaluation index system and formulas (1)–(8) depicted in Section 3, the environmental sustainability assessment results of the 11 provinces in the YREB and the upper, middle and lower regions were obtained, as shown in Figures 2 and 3. The results show that from an overall perspective, the average environmental sustainability of the YREB increased from 0.589 to 0.632, thus exhibiting a steady upwards trend from 2003 to 2020. The values of the four levels of environmental sustainability of the YREB are less than 0.551, 0.551 to 0.604, 0.604 to 0.663, and greater than 0.663, which correspond to levels I–IV, respectively. The higher the level is, the greater the degree of environmental sustainability. Therefore, in 2003, there were five provinces at level I, one province at level II, and three provinces at level III of environmental sustainability in the YREB. In addition, there were two provinces at level IV. In 2020, there were four provinces at level IV, three provinces at level III, one province at level II, and three provinces at level I of environmental sustainability in the YREB. In general, the level of environmental sustainability in the YREB is evolving from low and medium-low levels to medium-high and high levels. Consistent with the conclusions of Zhou et al. (2021), the environmental sustainability of the YREB is stable and good mainly because in the past 18 years, China has prioritised the restoration of the ecological environment of the Yangtze River. Ecological environmental protection has undergone watershed change in terms of improving the effectiveness of environmental governance and promoting environmental sustainability. For example, the Yangtze River Valley shelterbelt system[2] was constructed, the level of green technology innovation[3] was improved, and a series of related strategic arrangements were implemented to improve the environment[4] (Liu et al., 2022; Zhou et al., 2021; Yan et al., 2021).

This trend reflects not only the improvement in the environmental quality of the YREB but also the gradual increase in the degree of coordination between regional economic development and environmental protection. The YREB is transforming from the traditional development mode of high energy consumption and high pollution to the development mode of a green, low-carbon and circular economy. The in-depth implementation of industrial structure adjustment, energy conservation and emission reduction, and ecological restoration has provided strong support for the sustainable development of the YREB environment. However, since the outbreak of COVID-19 in 2019, the level of environmental sustainability in these provinces has decreased significantly, thus indicating that COVID-19 has adversely affected the environment, economy and society. For example, the epidemic has significantly increased medical waste and disposable protective equipment pollution, thus causing significant environmental pressure; economic contraction has also directly reduced environmental investment. COVID-19 has also exposed the challenges and problems facing environmental protection. We still need to continue strengthening environmental protection work and promote the coordinated development of the economy, society and environment.

From a regional perspective, the environmental sustainability of the three regions of the YREB showed varying degrees of fluctuation. This confirms the view of regional economic theory; that is, different regions have different resource endowments (Behrens and Thisse, 2007), and different regions have different strategies for environmental regulation, energy conservation, emission reduction, and pollution prevention and control, as well as different behaviour choices and implementation efforts, thus showing obvious regional differences in environmental sustainability levels. The environmental sustainability of the middle region was greater than that of the upper region, whereas that of the upper region was greater than that of the lower region. The average annual growth rate downstream was –0.109, thus indicating a downwards trend. The upper and middle regions presented an upwards trend. Additionally, the average annual growth rate in the upstream region was 0.977, which was higher than the average annual growth rate of 0.445 in the midstream region. The lower regions of Shanghai, Jiangsu and Zhejiang showed downwards trends and thus require increased attention. The provinces and cities in the upper and middle regions exhibited an increasing trend. The urban agglomeration in the middle region, as the core region that promotes the rise of the central region and drives the development of the YREB, not only fully uses the integrated advantages of ecological factors (such as mountains, water, forests, fields and lakes) but also adopts decision-making measures (such as the implementation plan of the 14th Five-Year Plan) for developing an urban agglomeration in the middle region of the YREB, thereby complying with the requirements of green development and promoting the sustainable development of the environment in the middle region. The lower region of the YREB has a large industrial scale and a high demand for energy in industrial development. The irrational industrial structure and layout in the earlier stages of development have caused the prominent ecological problems of accumulation, superposition and potential, thus making it difficult to improve environmental sustainability in the short term. In addition, the upper region of the YREB has a superior natural environment, large and sparsely populated areas, a relatively low degree of industrialisation, and strong ecological restoration capacity, thus realising growth in environmental sustainability.

Figure 2 Environmental sustainability of the provinces and cities in the YREB (see online version for colours)

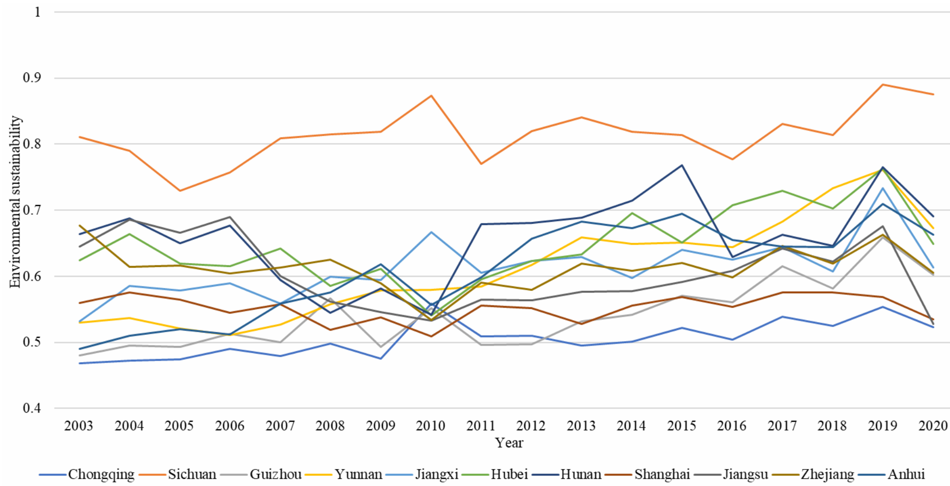
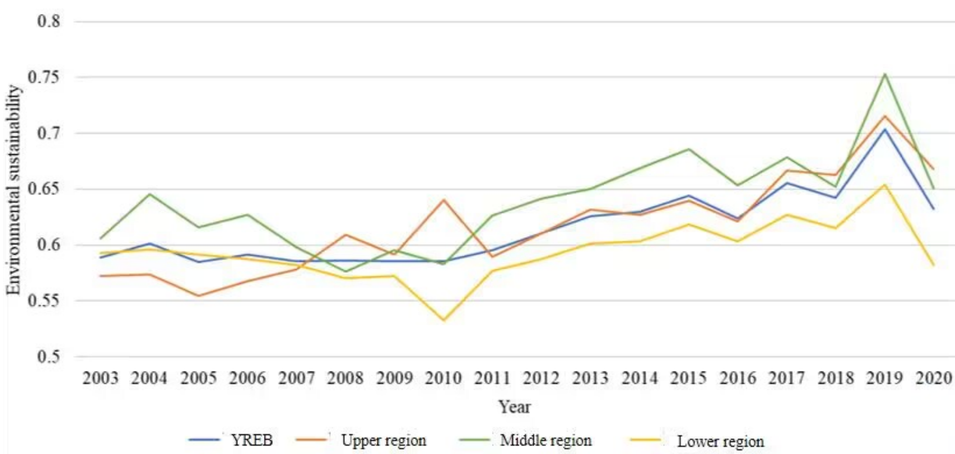


Figure 3 Environmental sustainability of the YREB and its upper, middle, and lower regions (see online version for colours)



5.3 Analysis of differences in environmental sustainability across various YREB regions

5.3.1 Overall difference

Using the methods proposed in Section 4, G, G_w, G_{mb} and G_l were obtained, as described in Table 9, which shows the sources and contributions of the overall differences in the environmental sustainability of the YREB from 2003 to 2020. The average annual Gini coefficient of the YREB was 0.073. Overall, G exhibited a fluctuating downwards trend, thus indicating that the difference in environmental sustainability in the YREB is gradually narrowing. Except for 2010, 2019 and 2020, the contribution rate of G_l was consistently the highest, whereas the contributions of G_w and G_{mb} were relatively balanced. Therefore, intraregional and interregional differences are the main origins of overall differences in environmental sustainability. The contribution of G_w remained stable without significant fluctuations, and the average annual contribution was 28.314%. Before 2009, the contribution of G_{mb} showed a declining trend, whereas after 2009, G_{mb} fluctuated continuously. The fluctuation trend of the contribution rate of G_l was completely opposite to that of G_{mb}, and there was an inverse fluctuation relationship with G_{mb}. Therefore, the results indicate that before 2009, G_{mb} was caused mainly by extremely high environmental sustainability in certain provinces within certain regions, whereas other provinces within other regions had extremely low environmental sustainability, thus resulting in significant polarisation. Nevertheless, after 2009, interregional differences were composed mainly of interregional net differences, and this polarisation trend weakened. In summary, the change trajectory of regional environmental sustainability differences in the YREB not only reflects the effectiveness of policy interventions and regional development strategies but also reveals the importance of continuously strengthening environmental protection and promoting balanced regional development in the future.

Table 9 Sources and contributions of the difference in environmental sustainability in the YREB

Year	*Overall difference (G)*	*Intraregional difference (G_w)*		*Interregional net difference (G_{mb})*		*Transvariation intensity (G_l)*	
		Source	*Contribution degree (%)*	*Source*	*Contribution degree (%)*	*Source*	*Contribution degree (%)*
2003	0.094	0.028	29.724	0.013	13.543	0.053	56.734
2004	0.087	0.024	27.787	0.025	28.699	0.038	43.514
2005	0.073	0.02	27.367	0.023	31.24	0.03	41.393
2006	0.079	0.022	27.943	0.021	26.923	0.035	45.134
2007	0.073	0.02	26.748	0.007	9.345	0.047	63.908
2008	0.063	0.02	31.251	0.015	24.364	0.028	44.385
2009	0.072	0.021	28.669	0.009	12.318	0.042	59.013
2010	0.072	0.02	27.157	0.042	59.15	0.01	13.693
2011	0.063	0.017	26.724	0.017	27.148	0.029	46.128
2012	0.075	0.021	27.431	0.019	25.147	0.036	47.422
2013	0.079	0.024	29.816	0.017	21.478	0.039	48.707
2014	0.077	0.022	28.497	0.022	28.259	0.033	43.245
2015	0.071	0.021	29.131	0.022	30.679	0.029	40.19
2016	0.063	0.018	29.033	0.017	26.803	0.028	44.166
2017	0.058	0.017	28.618	0.018	29.968	0.024	41.414
2018	0.065	0.018	27.864	0.017	26.398	0.03	45.739
2019	0.071	0.019	26.543	0.031	43.384	0.021	30.074
2020	0.078	0.023	29.353	0.031	40.158	0.024	30.489
Mean	0.073	0.021	28.314	0.02	28.056	0.032	43.63

5.3.2 Regional differences

The intraregional and interregional Gini coefficients of environmental sustainability in the three regions from 2003 to 2020 are shown in Table 10.

1. Intraregional differences: during the study period, the average Gini coefficient of environmental sustainability in each region was 0.044, 0.053 and 0.072 in the upper, lower and middle regions of the YREB, respectively. This finding indicates that the difference in environmental sustainability in the upper region was smaller than that in the lower region, whereas the difference in environmental sustainability in the lower region was smaller than that in the middle region. From a regional perspective, the Gini coefficient in the upper region fluctuated continuously and exhibited an overall upwards trend, thus indicating that the differences in environmental sustainability within the upper region were constantly changing and tended to expand. This may be due to the combined effects of geographical, economic or policy factors in the upper region, which lead to differences and challenges in environmental management and sustainable development strategies, thus expanding the differences in environmental sustainability. The Gini coefficient in the middle region also fluctuated continuously, but there was an overall downwards trend, thus suggesting that the differences in environmental sustainability in the middle region are decreasing, thus showing a positive trend. The Gini coefficient in the lower region exhibited an overall downwards trend (the Gini coefficient decreased from 0.118 in 2003 to 0.051 in 2020), thus demonstrating that the difference in environmental sustainability in the lower region is gradually narrowing, thus reflecting that the imbalance in the internal sustainable development of this region is effectively improved and regulated.
2. Interregional differences: according to Table 10, the interregional Gini coefficients from high to low were the midstream-downstream of the YREB, the upstream-midstream of the YREB and the upstream-downstream of the YREB. The Gini coefficient fluctuation between the upper and middle regions of the YREB increased to the highest value of 0.098 in 2009 and then began to decrease slightly, thus indicating that the difference in environmental sustainability between the upper and middle regions first increased but then decreased, with an overall slight expansion. The Gini coefficient between the upper and lower regions of the YREB decreased to the minimum value of 0.03 in 2009 and then began to fluctuate and rise, thus suggesting that the regional environmental sustainability difference between the upper and middle regions gradually narrowed in the early period but began to expand later. The Gini coefficient of the middle and lower regions of the YREB decreased gradually during the fluctuation, thus indicating that the difference between the middle and lower regions of environmental sustainability narrowed. In summary, the differences in environmental sustainability between different regions and their changing trends are the result of the interweaving effects of multiple factors. In the future, we should continue to strengthen regional exchanges and cooperation and jointly explore more efficient and sustainable environmental governance models to achieve an overall improvement in environmental sustainability nationwide.

Table 10 Intraregional and interregional Gini coefficients of environmental sustainability in the YREB

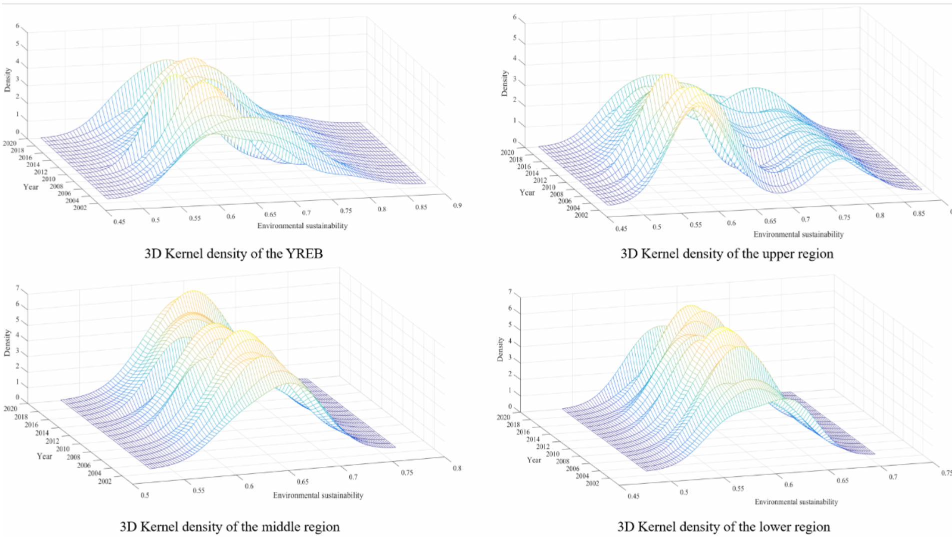
Year	*Intraregional Gini coefficients*			*Interregional Gini coefficients*		
	The upper region	*The middle region*	*The lower region*	*Upstream-midstream*	*Upstream-downstream*	*Midstream-downstream*
2003	0.048	0.068	0.118	0.063	0.116	0.115
2004	0.035	0.059	0.108	0.06	0.118	0.105
2005	0.026	0.052	0.09	0.046	0.101	0.093
2006	0.031	0.063	0.088	0.06	0.104	0.091
2007	0.031	0.022	0.11	0.03	0.106	0.101
2008	0.098	0.021	0.036	0.078	0.08	0.033
2009	0.011	0.118	0.031	0.098	0.03	0.098
2010	0.096	0.048	0.017	0.09	0.092	0.049
2011	0.029	0.095	0.016	0.089	0.041	0.077
2012	0.02	0.11	0.035	0.096	0.053	0.094
2013	0.02	0.115	0.053	0.096	0.053	0.099
2014	0.039	0.106	0.039	0.096	0.063	0.089
2015	0.041	0.093	0.041	0.085	0.064	0.078
2016	0.028	0.091	0.032	0.078	0.047	0.075
2017	0.028	0.088	0.021	0.073	0.04	0.073
2018	0.096	0.032	0.021	0.084	0.087	0.037
2019	0.009	0.097	0.041	0.075	0.071	0.088
2020	0.105	0.026	0.051	0.082	0.099	0.064
Mean	0.044	0.072	0.053	0.077	0.076	0.081

5.4 Analysis of the dynamic evolution of environmental sustainability in the YREB

5.4.1 Temporal evolution characteristics

To visually demonstrate the development level, polarisation trend and spatial differences in environmental sustainability, we generated 3D kernel density maps of environmental sustainability in the YREB and its three regions. The window width was determined via the formula $h = 0.9SeN^{0.2}$, where Se represents the standard deviation of the observed value of the random variable and N represents the number of provinces within the region (Yan and Hou, 2015). However, since the data used in this work are panel data, calculations based on this formula would result in different window widths for different years, thus making 3D kernel density maps of environmental sustainability incomparable across different years (Li, 2021). Hence, we adopted the annual window width for the entire sample of environmental sustainability data provided by Stata 16.0, and the window width of the 3D kernel density maps was finally determined to be 0.0586. Finally, 3D kernel density maps were generated for the YREB, upper region, middle region, and lower region, as shown in Figure 4.

Figure 4 3D kernel density maps of environmental sustainability (see online version for colours)



From the viewpoint of regional distribution:

1 The upper region of the YREB exhibited a trend towards a rightward shift in environmental sustainability, with a right-trailing trend. This trend indicates that there are provinces with higher environmental sustainability levels in the upper region; this finding is consistent with the assessment results of environmental sustainability. The environmental sustainability of Sichuan was between 0.73 and 0.89, which is far ahead of that of other provinces and has maintained a stable development. The distribution of environmental sustainability exhibited a bimodal pattern, thus indicating significant development disparities among provinces in the upstream region and a trend towards multilevel differentiation. Moreover, the width of the peaks showed an overall trend of expansion, thus suggesting that the difference in environmental sustainability in the upper region is expanding.

2 During the research period, the peaks in the middle region tended to increase overall, whereas the peak width tended to decrease, and there was a right-shifting trend. This observation shows that the level of environmental sustainability in the middle region is gradually increasing and that the differences within the region are narrowing.

3 In the lower region of the YREB, there was a leftward shift in the distribution of environmental sustainability, with a significant decline in environmental sustainability in the lower region. The peaks display a U-shaped distribution from 2011 to 2017, and the width of the peaks varies with fluctuations, thereby showing an overall decreasing trend, thus indicating that the difference in environmental sustainability in the lower region narrowed.

Overall, the environmental sustainability of the YREB exhibited the following characteristics:

1 In terms of distribution location, the distribution centre of YREB environmental sustainability was constantly shifting towards the right, thus indicating a rising trend in the level of environmental sustainability across different regions.

2 The distribution of environmental sustainability in the YREB showed a right-trailing trend, thus suggesting the presence of provinces with a high level of environmental sustainability.

3 From the peak perspective, the peak of the environmental sustainability distribution in the YREB showed an increasing trend, thus indicating that the level of environmental sustainability in the YREB generally improved from 2003 to 2020. Moreover, the shape of the peaks became narrower, thus demonstrating that the disparity between environmental sustainability in different regions generally narrowed.

4 In terms of the number of wave peaks, the distribution of environmental sustainability in the YREB from 2003 to 2020 exhibited only a single peak, which was not steep, thus indicating that there was no apparent polarisation trend in the environmental sustainability of the YREB. Therefore, the environmental sustainability of the YREB showed a simultaneous increase in the overall level and narrowing of regional disparities.

5.4.2 Spatial evolution characteristics

According to formulas (16) and (17) depicted in Section 4.2, the global Moran's I and local Moran's I of environmental sustainability in the YREB and three regions were calculated. From the perspective of the whole sample, no significant spatial correlation of environmental sustainability was detected except in 2010, when these provinces had a weak positive spatial correlation. Owing to space constraints, the data are omitted. From the perspective of regions, apart from the lower region, which had a weak negative spatial correlation with environmental sustainability in 2009 and 2016, there was no significant spatial correlation in other regions in each year. The results of the local Moran's I indicate that there was no significant local spatial correlation of environmental sustainability in each region. This finding suggests that no apparent spatial correlation of environmental sustainability existed among the three regions possibly because they each face different challenges and adopt different strategies when promoting environmentally sustainable development; alternatively, these regions may be affected by socioeconomic and geographical environmental factors that are unique to their respective regions, and they may fail to form effective environmental management cooperation mechanisms or share successful experiences of sustainable development, thereby limiting improvements in environmental performance to specific regions. In addition, forming a cross-regional positive spillover effect is difficult.

5.4.3 Transition probability analysis

The quartiles of environmental sustainability were calculated, and the first, second and third quartiles were 0.551, 0.604 and 0.663, respectively. Therefore, we divided the states of environmental sustainability into four categories: less than 0.551, 0.551 to 0.604, 0.604 to 0.663 and greater than 0.663, which represent levels I, II, III, and IV of environmental sustainability, respectively. Finally, the transition probabilities were measured, and the results are shown in Table 11, in which diagonal numbers represent the probability of no change in state from t to t+1, whereas the off-diagonal numbers indicate the probabilities of state changes from t to t+1. For example, 0.681 indicates that from t to t+1 years, the probability that the environmental sustainability of the YREB will remain at level I is 0.681.

Table 11 Markov transition probability matrix of environmental sustainability

		I	*II*	*III*	*IV*
YREB	I	0.681	0.298	0	0.021
	II	0.229	0.521	0.229	0.021
	III	0.022	0.152	0.587	0.239
	IV	0.022	0.043	0.217	0.718
The upper region	I	0.8	0.2	0	0
	II	0.363	0.364	0.273	0
	III	0	0.286	0.571	0.143
	IV	0	0	0	1
The middle region	I	0	0.75	0	0.25
	II	0.182	0.455	0.273	0.091
	III	0.053	0.105	0.526	0.316
	IV	0	0.059	0.412	0.529
The lower region	I	0.5	0.5	0	0
	II	0.222	0.593	0.185	0
	III	0	0.15	0.65	0.2
	IV	0.111	0.111	0.333	0.445

In the YREB and its three regions, the diagonal elements were greater than the off-diagonal elements, and the probability of transitioning to the adjacent type was greater than the probability of transitioning to the non-adjacent type. As a result, the environmental sustainability in the three regions of the YREB was more likely to remain stable. Additionally, the state transfer of environmental sustainability in the YREB exhibited the characteristics of club convergence, which shows that regions with a high level of environmental sustainability tend to have stronger stability, and regions with a low level of development have relatively stronger mobility. The possible reason for this result is that regions with high levels of environmental sustainability tend to have a longer period of investment and accumulation in environmental protection, thus resulting in a relatively stable environmental protection infrastructure and relatively stable institutional systems. Such historical accumulation makes them more resilient in the face of external shocks. In contrast, regions with low environmental sustainability levels may face a variety of challenges and uncertainties, such as a lack of resources, serious environmental pollution, and weak economic foundations, which make developing effective long-term strategies for environmental management difficult and which increase the volatility of their environmental sustainability.

6 Conclusions and implications

6.1 Conclusions

In accordance with the PSR environmental policy model, an evaluation indicator system for the environmental sustainability of the YREB was constructed by using two sources: characteristic indicators and high-frequency indicators. The entropy weight method and grey relational analysis were subsequently employed to evaluate the environmental sustainability of the 11 provinces and three regions in the YREB from 2003 to 2020. Dagum's Gini coefficient decomposition method was applied to decompose the differences in the environmental sustainability of the three regions of the YREB. Kernel density estimation and Moran's I were employed to analyse the evolution trend of environmental sustainability from the viewpoint of time and space. Finally, a Markov chain was used to calculate the transition probability of environmental sustainability across different states. In summary, we draw the following conclusions from the evaluation results, regional difference analysis and dynamic evolution of environmental sustainability in the YREB:

1 The analysis of the environmental sustainability assessment revealed that the environmental sustainability of regions in the YREB fluctuated to varying degrees from 2003 to 2020. The environmental sustainability of the middle region was greater than that of the upper region, whereas the upper region had greater environmental sustainability than did the lower region. The environmental sustainability in both the upstream and midstream regions improved, especially in the upstream region, where resource advantages and policy deployment have significantly driven regional environmental sustainability. This finding reflects not only the improvement in the environmental quality of the YREB but also the gradual strengthening of the coordination between regional economic development and environmental protection.

2 From the difference analysis of environmental sustainability, we observed the following:

   a The difference in environmental sustainability in the YREB showed a fluctuating declining trend. Both intraregional and interregional differences were the main origins of overall differences in environmental sustainability in the YREB.

   b The differences in environmental sustainability in the middle, the lower and upper regions (ranked from large to small) were as follows: the differences in the upper region showed an expanding trend. The differences in environmental sustainability between regions ranked from large to small were as follows: midstream to downstream, upstream to midstream, and upstream to downstream. The difference between the upper and middle regions was slightly greater. This change trajectory not only reflects the effectiveness of policy interventions and regional development strategies but also reveals the importance of continuously strengthening environmental protection and promoting balanced regional development in the future.

3 The dynamic evolution of environmental sustainability can be described as follows:
   a From a temporal viewpoint, the overall level of YREB environmental sustainability indicated a dynamic trend of continuous improvement and simultaneous narrowing of regional disparities. The level of environmental sustainability in the upper and middle regions increased, and there was multilevel differentiation in the upper region.
   b At the spatial level, there was no significant spatial correlation or local spatial correlation in the YREB or in its three regions.
   c From the perspective of transfer probability analysis, the environmental sustainability of the upper, middle and lower regions of the YREB exhibited varying degrees of upwards or downwards transition tendencies in terms of environmental sustainability.

   Nevertheless, there was a greater likelihood of maintaining stability in the environmental sustainability of the YREB and each region. An in-depth analysis of these changes and the reasons behind them can provide strong support for formulating more accurate and effective environmental protection and sustainable development strategies.

6.2 Theoretical and practical implications

On the theoretical side, we studied the YREB and discussed the development status of its environmental sustainability. The YREB is a pioneering example of high-quality economic development and ecological civilisation construction, thus making the YREB highly representative in terms of realising environmental sustainability. Research on the environmental sustainability of the YREB is of great theoretical and practical importance; this research not only provides data support for improving regional environmental sustainability but also presents valuable insights for other regions to emulate. Second, we establish an evaluation index system for environmental sustainability by combining characteristic and high-frequency indicators. This study provides a systematic and comprehensive approach to quantifying the environmental sustainability of the YREB, thereby enriching and expanding the literature on regional environmental sustainability assessment. Moreover, by delving into the differences in regional environmental sustainability, we identified the key sources of environmental sustainability disparities in the YREB, thereby offering a theoretical basis for coordinating regional environmental policies and expanding the literature on the quantitative analysis of regional differences in environmental sustainability. Finally, quantifying and visualising the trends in environmentally sustainable development in the YREB helps identify potential patterns and pathways for transforming environmental sustainability. This study provides feasible and valuable suggestions for future research on the mechanisms of environmental sustainability transformation.

On the managerial side, there was no significant spatial correlation between the YREB and its three regions; this finding implies that there is still no cooperative relationship between the regions in terms of environmental sustainability. As a result, regional governments and businesses can strengthen collaboration to achieve win-win effects in terms of resource sharing, technological innovation, and market expansion, which can collectively address challenges in environmental sustainability. For instance, regional governments and businesses can collaborate on technological innovation and conduct joint research and development of environmentally friendly technologies. Sharing expertise, equipment, and research experience accelerates innovation and promotes the adoption of new technologies. Moreover, the decomposition analysis of regional differences suggests that both intraregional and interregional differences are the main factors contributing to differences in environmental sustainability in the YREB. Therefore, the government can establish a regional collaborative development mechanism for the upper, middle and lower regions of the Yangtze River to narrow the development differences in environmental sustainability within and between regions. For example, an environmental information sharing platform could be established for the YREB, and digital technologies should be employed to share environmental monitoring data, environmental assessment reports and other information in various regions to keep abreast of environmental governance in each region. Furthermore, the in-depth analysis of the Markov probability transition matrix identifies the probabilities of transitions between different environmental sustainability states, thereby providing support and reference for decision makers to anticipate changes and develop corresponding intervention measures in advance. For example, the government can formulate appropriate plans and policies to proactively respond to transitions in different states and apply intervention measures in a timely manner to ensure the protection of environmental sustainability. Moreover, by understanding the transition probabilities between different environmental sustainability states, enterprises can plan and allocate resources more effectively to improve environmental sustainability.

6.3 Research limitations and future studies

This study has several limitations and shortcomings: first, there is a lack of in-depth research on the spatial correlation of environmental sustainability in the YREB regions. Moreover, there is a lack of discussion on the causes and consequences of environmental sustainability. In the future, the mechanism of causality can be further studied via econometric models. Second, emerging environmental issues (such as microplastic pollution, nuclear effluent discharges, and digital pollution) have been insufficiently considered. In the future, these emerging environmental issues can be considered when selecting indicators to evaluate the level of environmental sustainability more comprehensively. Finally, there is a lag in the sample data used in this paper. In the future, we can continue to collect and update the latest data. Additionally, in accordance with the research findings, which show that the environmental sustainability of various regions has declined significantly since 2019, we can continue to explore the differences and spatiotemporal dynamic evolution of the environmental sustainability of the YREB in the three stages before, during and after the outbreak of COVID-19.

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Notes

1 The data came from the 'Bulletin on the State of the Ecological Environment' of each province.

2 In 1989, China launched the first phase of the shelterbelt system in the Yangtze River Basin with a planned afforestation of 6.484 million hectares. The second phase of the project (2001–2010) plans to afforest 6.484 million hectares. In the third phase of the project (2011–2020), the planned afforestation is to be performed on 5.3021 million hectares. Over the past 30 years, 11.84 million hectares of forest have been planted.

3 According to the Y02 category in the Cooperative Patent Classification (CPC) jointly developed by the European Patent Office (EPO) and the US Patent and Trademark Office (USPTO), the following information was obtained from the incoPat global patent database: From 2003 to 2020, the number of green patent applications in the YREB increased from 4,408 to 135,129.

4 China has issued a series of documents and reports, such as the 'Guideline for Developing the YREB Based on the Golden Waterway' and the 'Outline of the Development Planning of the YREB', which prioritise environmental restoration in the development of the YREB, enhancing the effectiveness of environmental governance and promoting the sustainable development of the environment.