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Application of Geographic Information System to Sensing Strength and Potentiality of Ecological Industrialization in China's Huai River Ecological Economic Belt

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Ecological industrialization is a new path for ecological economic zones to obtain both ecological and economic results. Potentiality and strength respectively present the possibility and reality of ecological industrialization, and the unity of the two determines the effectiveness of ecological industrialization construction. Thus, the scientific monitoring and evaluation of the unity between ecological industrialization strength and potentiality are very important for the healthy construction of ecological industrialization in ecological economic zones. We used geographic information systems (GISs) to construct an architecture for monitoring the unity between ecological industrialization strength and potentiality. On the basis of this, the unity between ecological industrialization strength and potentiality in China's Huai River Ecological Economic Belt (CHREEB) was evaluated, its spatiotemporal evolution process was analyzed, its influencing factors and roles were explored, and measures to promote the orderly and healthy development of ecological industrialization were proposed. The results have validated the effectiveness of the GIS-based monitoring system for ecological industrialization development: (1) there appeared phenomena such as insufficient potentiality and spatial differentiation in the unified development in CHREEB at present; (2) the reduced ecological resources, insufficient technology, and different regional factor combinations were the main reasons for the unfavorable results of the unified development; and (3) regular monitoring, differentiated strategies, and an integrated development system are effective in promoting the unified development. In this study, we provided information and decision-making assistance for the government to formulate countermeasures to promote the high-quality development of ecological industrialization.

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1. Introduction

With rapid socio-economic development worldwide, problems such as resource shortages, environmental pollution, and wealth inequality have become prominent,[1,2] leading to global ecological and social risks.[3,4] Most ecological economic zones are typically regions with fragile ecology and backward economic development.[5] When ecological problems are entangled with developmental problems, risks increase. Thus, how to curb poverty while protecting the environment in the ecological economic zones of developing countries worldwide is currently a focus of research and debate.

As a developing country, China consistently explores scientific solutions for environmental protection and economic development in its ecological economic zones.[6] The construction of China's Huai River Ecological Economic Belt (CHREEB) began in 2018, and the belt is intended to be a fine belt for China's ecological civilization construction in river basin areas.[7] The region has a dense river network, has a relatively fragile ecosystem, and is lagging in terms of economic development. Local governments and residents have been actively exploring a win–win path between ecological protection and economic development since the early part of this century.

Ecological industrialization is an appropriate developmental path for ecological economic zones according to their ecological advantages. Although ecological industrialization has achieved remarkable construction results,[8] various problems have inevitably emerged, such as weak top-level design,[6] excessive or lagging development,[9,10] and imbalanced regional development.[11] The essential cause of the ecological industrialization construction problem is that managers and builders lack a clear grasp of its state and needs. Therefore, there is an urgent need for scientific, systematic, and operable research on the construction of ecological industrialization.

Although many laws on ecological industrialization construction have been explored by some scholars from the perspectives of concept definition,[12] feasibility assessment,[13,14] measurement of development results,[8,15] determination of influencing factors,[16,17] and selection of development models,[18] the unified development between the potential possibility and actual development results of ecological industrialization has not been paid sufficient attention in the existing studies. These findings do not easily reflect the effectiveness of ecological industrialization construction.

The geographic information system (GIS) is a technical system that, supported by computer software and hardware, inputs, stores, updates, displays, maps, comprehensively analyzes, and applies various geographic information in a certain format according to spatial distribution and attributes.[19] GIS is widely used to analyze and process various phenomena and processes distributed within a certain geographical area, solve complex planning, decision-making, and management problems, and provide good assistance for the development of human civilization.[20,21]

Therefore, the GIS technology was used to monitor the unities between ecological industrialization strength and potentiality in 25 cities of CHREEB, and then to evaluate the unities and analyze their spatiotemporal evolution process and causes. On the basis of this, well-directed policy recommendations were proposed for enhancing the unified development between ecological industrialization strength and potentiality in each city (Fig. 1).

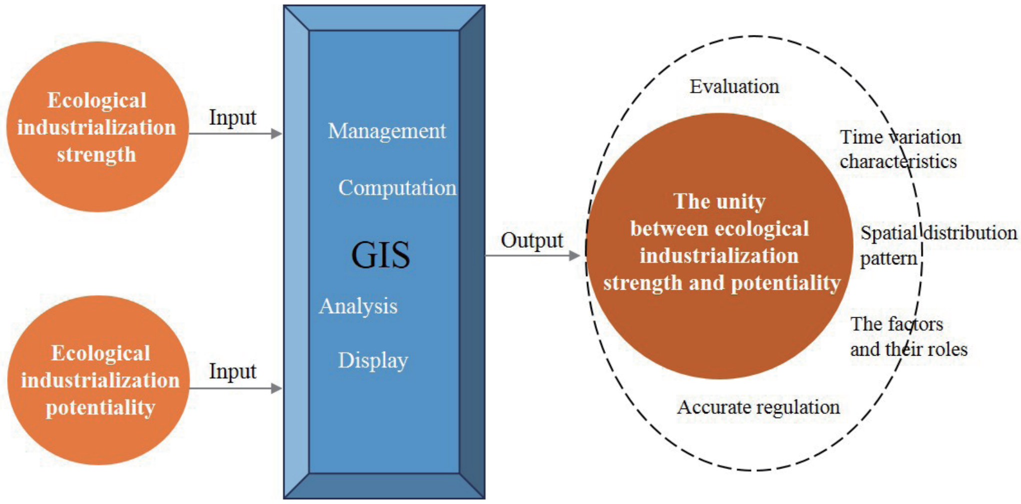

Fig. 1. (Color online) Architecture of GIS-based monitoring system for the unity between ecological industrialization strength and potentiality.

The rest of this study is as follows: Research methods and materials are presented in Sect. 2. The assessment results and reasons for the unity between ecological industrialization strength and potentiality are analyzed in Sect. 3. A discussion is provided in Sect. 4. The overall research is summarized and recommendations for further research are provided in Sect. 5.

2. Materials and Methods

2.1 Research methods

2.1.1 Connotation of unity between ecological industrialization strength and potentiality

Ecological industrialization transforms free ecological resources into ecological commodities to maintain or increase their value.[15] Essentially, it combines ecological construction and industrial economy to ensure economic and ecological results for society as a whole.[12] Potentiality and strength present the possibility and reality of ecological industrialization, respectively (Fig. 2). Potentiality refers to the capability of an ecological economic zone to provide eco-friendly commodities and services through socialized, large-scale production and market-oriented management while maintaining the ecosystem balance.[13,22] In this context, potentiality is tightly linked to ecological endowment[9] and industrial endowment.[23] Ecological endowment, which is affected by the total and relative quantities of ecological resources, is the premise of ecological industrialization. Industrial endowment, which depends on production factors such as capital, labor, and transportation, guarantees the transformation from ecological resources to industries from the economic and social aspects. Strength denotes the realistic result of an ecological economic zone's efforts to improve social and material well-being alongside developing "Ecological+" industries based on ecological advantages while maintaining

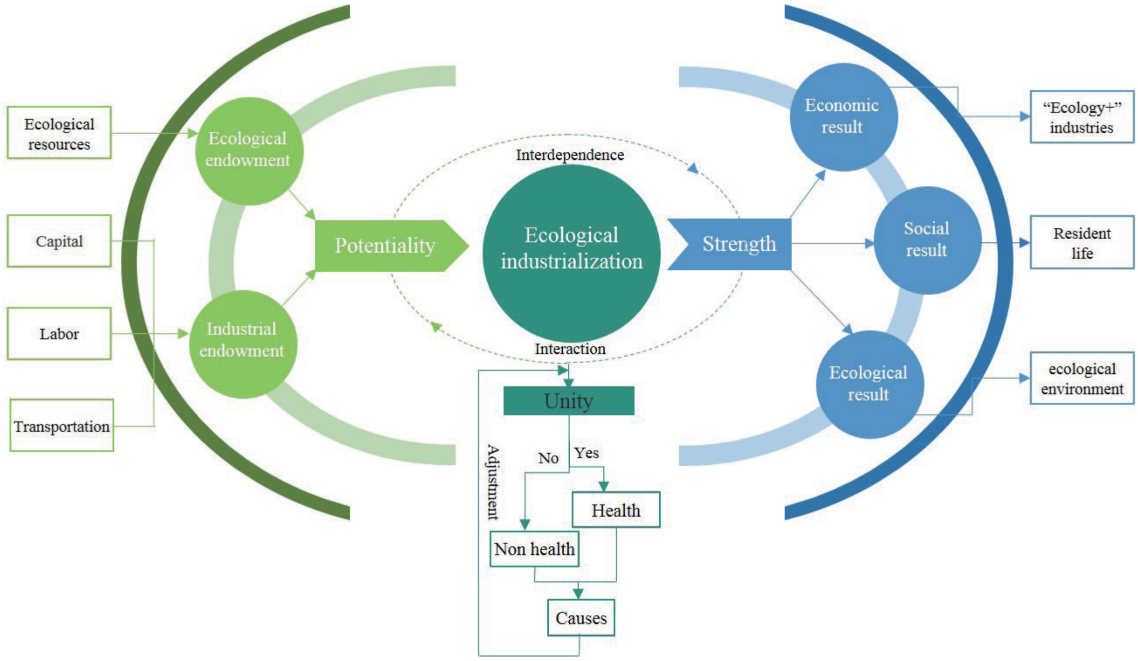

Fig. 2. (Color online) Connotation of unity between ecological industrialization strength and potentiality.

the functions and integrity of the ecosystem.[18,24] Strength in this context is associated with economic, social, and ecological results[11] reflected in the "Ecological+" industry, residents' lives, and ecological environment.

In brief, ecological industrialization strength and potentiality are interdependent and interact with each other. Potentiality is the premise and foundation for the realization of strength. More and greater ecological and industrial resources can produce more economic, social, and ecological results and realize greater strength. Strength, in turn, promotes potentiality; only when strength is increased can the ecological resource environment be optimized and the industrial production capacity be improved to ensure that potentiality continues to rise. The relationship between strength and potentiality directly affects the healthy development of ecological industrialization; specifically, if strength is greater than potentiality, the stamina for ecological industrialization becomes insufficient, limiting the sustainable development progression of ecological industrialization. Conversely, if the level of strength is lower than that of potentiality, the transformation from the advantages of the ecological resource environment to the advantages of "Ecological+" industries is insufficient, which decelerates ecological industrialization. The health development of ecological industrialization can be promoted only when strength and potentiality are in unified development.

2.1.2 Evaluation indicators of unity between ecological industrialization strength and potentiality

The connotation of unity between ecological industrialization strength and potentiality implies that strength and potentiality have an interactive relationship and are affected by multiple complex factors. We referred to results in the literature(6,13) and followed the principles of scientific nature, systematic nature, purpose, comparability, and operability to establish an indicator system for evaluating the unity between ecological industrialization strength and potentiality (Table 1).

(1) Ecological industrialization potentiality. (a) Ecological endowment. Ecological resources are necessary for ecological industrialization, and ecological land is the space supporter of ecological resources. Therefore, the total area of ecological land, the area of ecological land per capita, and the proportion of ecological land are selected to represent the quantity and quality of ecological resources. (b) Industrial endowment. Capital, labor, and transportation are the basic production guarantees of ecological industrialization, which are characterized by investment in fixed assets, employed population, and highway mileage. All these indicators are positive.

(2) Ecological industrialization strength. (a) Economic result. "Ecological+" industries are the aggregation of all produced products in ecological industrialization. The economic result is represented by the total output value of "Ecological+" industries, the output value of

Table 1
Indicator system for evaluating the unity between ecological industrialization strength and potentiality.

Target layer	Criterion layer	Indicator layer	Indicator property	Weight
Ecological industrialization potentiality	Ecological endowment	Total area of ecological land X_1 (km^2)	Positive	0.1642
		Area of ecological land per capita X_2 (m^2/people)	Positive	0.0927
		Proportion of ecological land X_3 (%)	Positive	0.0021
	Industrial endowment	Investment in fixed assets X_4 (¥100 million)	Positive	0.4274
		Employed population X_5 (10000 people)	Positive	0.1163
		Highway mileage X_6 (km)	Positive	0.1973
Ecological industrialization strength	Economic result	Total output value of "Ecological+" industries X_7 (¥100 million)	Positive	0.2218
		Output value of "Ecological+" industries per capita X_8 (¥/people)	Positive	0.1926
		Output value of "Ecological+" industries per square kilometer X_9 (¥100 million/km^2)	Positive	0.2270
		Proportion of "Ecological+" industries output value in GDP X_{10} (%)	Positive	0.0134
		Growth rate of "Ecological+" industries output value X_{11} (%)	Positive	0.0541
	Social result	Per-capita disposable income X_{12} (¥)	Positive	0.1334
		Engel's coefficient X_{13} (%)	Negative	0.0409
		Per-capita disposable income gap between urban and rural residents X_{14} (¥)	Negative	0.0232
	Ecological result	Good air quality days X_{15} (day)	Positive	0.0153
		Sulfur dioxide emissions X_{16} (10000t)	Negative	0.0265
		Chemical oxygen demand emissions X_{17} (10000t)	Negative	0.0250
		Ammoniacal nitrogen emissions X_{18} (10000t)	Negative	0.0268

"Ecological+" industries per capita, the output value of "Ecological+" industries per square kilometer, the proportion of "Ecological+" industries output value in general domestic product (GDP), and the growth rate of "Ecological+" industries output value. (b) Social result. Improving social life is the goal of human struggle. Per-capita disposable income, Engel coefficient, and the per-capita disposable income gap between urban and rural residents can reflect the social result from the perspectives of material, spiritual, and equity, respectively. (c) Ecological result. A beautiful and clean ecological environment is the sustainable development goal of ecological industrialization, characterized by good air quality days, sulfur dioxide emissions, chemical oxygen demand emissions, and ammoniacal nitrogen emissions. Among the indicators, Engel coefficient, the per-capita disposable income gap between urban and rural residents, sulfur dioxide emissions, chemical oxygen demand emissions, and ammoniacal nitrogen emissions were negative indicators; the remaining indicators were positive.

2.1.3 Evaluation model of unity between ecological industrialization strength and potentiality

(1) Entropy weight method. We applied the entropy weight method[25] to estimate the ecological industrialization strength and potentiality of CHREEB. The equations are expressed as follows:

$$Y = \sum_{j=1}^{n} \omega_j X_j, \tag{1}$$

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{n} \left(1 - e_j\right)}, \tag{2}$$

$$e_j = -k \sum_{i=1}^{m} A_{ij} \ln A_{ij}, \tag{3}$$

where Y is the comprehensive evaluation score of ecological industrialization potentiality or strength, ω_j is the indicator's weight, n is the indicator number, X_j is the indicator's standardized value, e_j is the indicator's information entropy, $k = 1/\ln m$, m is the sample size, and A_{ij} is the indicator's normalized value in the sample.

(2) Unity degree model. We constructed a unity degree model to evaluate the unity of ecological industrialization strength and potentiality based on a coupling coordination model.[26,27] It can not only measure the level of unity between ecological industrialization strength and potentiality but also reflect their degree of interdependence and mutual restriction. The formula is as follows:[28]

$$D = \sqrt{C \times T}, \tag{4}$$

$$C = \sqrt{\frac{Y_a \times Y_b}{\left[\frac{Y_a + Y_b}{2}\right]^2}}, \tag{5}$$

$$T = \beta_1 Y_a + \beta_2 Y_b, \tag{6}$$

where D is the unity degree between ecological industrialization strength and potentiality, C is the coupling degree between strength and potentiality, T is the coordination degree between strength and potentiality, Y_a is the ecological industrialization potentiality, Y_b is the ecological industrialization strength, and β_1 and β_2 are the weights of ecological industrialization strength and potentiality, respectively. Let $\beta_1 = \beta_2 = 0.5$ (potentiality was the premise and strength was the result; both were equally essential); when D is greater, the unity degree is higher; conversely, when D is lower, the unity degree is lower.

(3) Division of unity types between ecological industrialization strength and potentiality. On the basis of prior research results,[28] we established unity types between ecological industrialization strength and potentiality according to D and the relationship between Y_a and Y_b. Theoretically, nine types should exist, as shown in Table 2. In the classification process, both Y_a and Y_b should be standardized, and the calculation formulas used are as follows:

$$Z_a = \left(Y_a - \overline{Y}_a\right) / S_a, \tag{7}$$

$$Z_b = \left(Y_b - \overline{Y}_b\right) / S_b, \tag{8}$$

Table 2
Types of unity between ecological industrialization strength and potentiality.

Unity degree	Unity grade	Relationship between Z_a and Z_b	Unity type
$0 < D \leq 0.5$	Low unity (I)	Strength lagged behind potentiality (A): $Z_a > Z_b$ and $\lvert Z_a - Z_b \rvert > 0.2$	Low unity with strength lagged behind potentiality (IA)
		Strength synchronized with potentiality (B): $0 \leq \lvert Z_a - Z_b \rvert \leq 0.2$	Low unity with strength synchronized with potentiality (IB)
		Strength ahead of potentiality (C): $Z_a < Z_b$ and $\lvert Z_a - Z_b \rvert > 0.2$	Low unity with strength ahead of potentiality (IC)
$0.5 < D \leq 0.7$	Moderate unity (II)	Strength lagged behind potentiality (A): $Z_a > Z_b$ and $\lvert Z_a - Z_b \rvert > 0.2$	Moderate unity with strength lagged behind potentiality (IIA)
		Strength synchronized with potentiality (B): $0 \leq \lvert Z_a - Z_b \rvert \leq 0.2$	Moderate unity with strength synchronized with potentiality (IIB)
		Strength ahead of potentiality (C): $Z_a < Z_b$ and $\lvert Z_a - Z_b \rvert > 0.2$	Moderate unity with strength ahead of potentiality (IIC)
$0.7 < D \leq 1$	High unity (III)	Strength lagged behind potentiality (A): $Z_a > Z_b$ and $\lvert Z_a - Z_b \rvert > 0.2$	High unity with strength lagged behind potentiality (IIIA)
		Strength synchronized with potentiality (B): $0 \leq \lvert Z_a - Z_b \rvert \leq 0.2$	High unity with strength synchronized with potentiality (IIIB)
		Strength ahead of potentiality (C): $Z_a < Z_b$ and $\lvert Z_a\text{-}Z_b \rvert > 0.2$	High unity with strength ahead of potentiality (IIIC)

where Z_a and Z_b are the standardized values of ecological industrialization strength and potentiality, $\overline{Y}_a$ and $\overline{Y}_b$ are the average values of ecological industrialization strength and potentiality, and S_a and S_b are the standard deviations of ecological industrialization strength and potentiality, respectively.

2.1.4 Development model of unity between ecological industrialization strength and potentiality

(1) Overall development model. We constructed an overall development model to analyze the factors and their roles in unified development between ecological industrialization strength and potentiality from an overall perspective based on a multiple linear regression model.(29–32) The constructed model is

$$D = \beta_0 + \sum_{k=1}^{p} \beta_k X_k + \varepsilon, \tag{9}$$

where D is the unity degree between ecological industrialization strength and potentiality, β_0 is a constant, X_k is the total area of ecological land, the investment in fixed assets, the highway mileage, and the expenditure for research and experimental development (R&D expenditure), which respectively represent ecological, economic, social, and technological factors, β_k is the correlation coefficient, p is the count of factors, and ε is a stochastic error.

(2) Local development model. We constructed a local development model to analyze the factors and their roles in unified development between ecological industrialization strength and potentiality from a local perspective based on a geographically weighted regression model.(33–37) The constructed model is

$$D = \beta_0 + \sum_{k=1}^{p} \beta_k (u, v) X_k + \varepsilon, \tag{10}$$

$$\omega = \begin{cases} \exp\left(-\frac{1}{2}\left(\frac{d}{b}\right)^2\right), & d < b \\ 0, & d \geq b \end{cases} \tag{11}$$

where (u, v) are the geographic coordinates of the spatial unit, ω is the spatial weight calculated using the Gaussian function, d is the Euclidean distance in space, and b is the bandwidth determined using the Akaike information criterion (AIC) in the case of small samples, and the meanings of the other parameters in the formula are the same as those in Eq. (9).

2.2 Research region

CHREEB is designed to cover the main stem of the Huai River, its first-order tributaries, and the area of the Yishui River system (Fig. 3). The total area is 243000 square kilometers. The research region encompassed the 25 prefecture-level cities of CHREEB, belonging to four provinces: Jiangsu, Anhui, Shandong, and Henan.

2.3 Data source

The ecological land data in this study were retrieved from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/).[38] These data were counted using the remote sensing monitoring data of land use in multiple periods with a resolution of 30 m as the main information source. According to the Chinese Academy of Sciences Land Use Cover classification system,[39] the areas of arable land, forest, grassland, water, and unused land that mainly provide ecological products and services were added up to the total area of ecological land, and the population and total land area were combined with it to obtain the area of ecological land per capita and the proportion of ecological land.

Other data came from the statistical yearbooks or communiques of various cities. In particular, the total output value of "Ecological+" industries was calculated on the basis of the ecological industry system constructed by Xu *et al.*, which focused on ecological agriculture, ecological industry, and ecological service industry.[18] Then, combined with the population, the area, GDP, and the previous period's "Ecological+" industry output value, the output value of "Ecological+" industries per capita, the output value of "Ecological+" industries per square

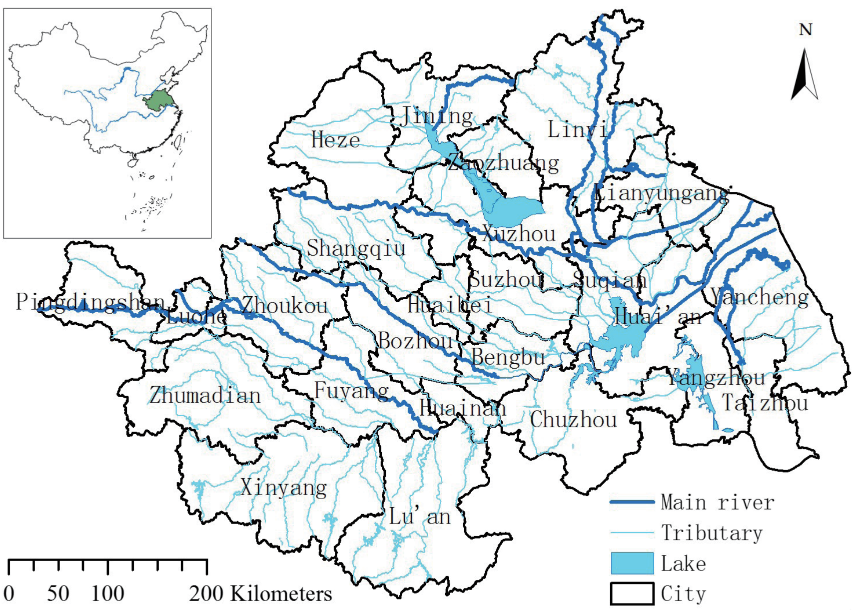

Fig. 3. (Color online) Location and range of CHREEB.

kilometer, the proportion of "Ecological+" industries output value in GDP, and the growth rate of "Ecological+" industries output value were further obtained.

3. Results

3.1 Unity between ecological industrialization strength and potentiality

3.1.1 Time variation characteristics

On the basis of the collected and processed evaluation indicator data, the ecological industrialization strength, potentiality, and their unity of the 25 cities of CHREEB in 2005, 2010, 2015, and 2020 were calculated using Eqs. (1)–(8). Moreover, the unity between ecological industrialization strength and potentiality in this belt was classified according to the method in Table 2, as shown in Table 3.

From a holistic perspective, the unity between ecological industrialization strength and potentiality in CHREEB continued to rise from 2005 to 2020, but there were few cities where the potentiality developed simultaneously with strength (Table 3). Of the 100 samples, only 16

Table 3
Types of unity between ecological industrialization strength and potentiality in CHREEB.

Province	City	2005	2010	2015	2020
Jiangsu	Huai'an	I A	II B	II C	III C
	Yancheng	I A	II A	II A	III C
	Suqian	I B	II B	II C	II C
	Xuzhou	I A	II A	III B	III C
	Lianyungang	I B	II B	II C	II C
	Yangzhou	I B	II C	II C	III C
	Taizhou	I B	II C	II C	III C
Shandong	Zaozhuang	I C	I C	II C	II C
	Jining	I A	II A	II A	III B
	Linyi	I A	II A	III A	III A
	Heze	I A	II A	II A	II B
Anhui	Bengbu	I B	I C	II C	II C
	Huainan	I C	I C	I C	II C
	Fuyang	I A	I A	II A	III C
	Lu'an	I A	II A	II A	II A
	Bozhou	I B	I A	II B	II C
	Suzhou	I A	I A	II C	II B
	Huaibei	I C	I C	I C	II C
	Chuzhou	I A	II A	II A	II A
Henan	Xinyang	I A	II A	II A	III A
	Zumadian	I A	II A	II A	II A
	Zhoukou	I A	II A	II A	II A
	Luohe	I C	I C	I C	II C
	Shangqiu	I A	II A	II A	II B
	Pingdingshan	I A	I A	II B	II C

Note: I, II, and III were low unity, moderate unity, and high unity, respectively. A, B, and C were strength lagged behind potentiality, strength synchronized with potentiality, and strength ahead of potentiality, respectively.

were synchronous development, while the rest were asynchronous, that is, most cities were either strength lagged behind potentiality or strength ahead of potentiality. This meant that the ecological industrialization development in CHREEB was in an unhealthy upward state.

From the perspective of type evolution, the unity between ecological industrialization strength and potentiality in CHREEB transformed from low to high, and from strength lagged behind potentiality to strength ahead of potentiality (Table 3). In 2005, all cities were in low unity; in addition, 60% of the cities showed strength lagged behind potentiality, while 16% of the cities showed strength ahead of potentiality. By 2020, all the cities were in moderate and high unity; furthermore, 60% of the cities showed strength ahead of potentiality, while 24% of the cities showed strength lagged behind potentiality. Accordingly, CHREEB no longer overall exhibited strength lagged behind potentiality, but rather exhibited strength ahead of potentiality. The ecological industrialization potentiality had transformed from redundancy to relative deficiency, that is, the ecological industrialization potentiality in CHREEB was slightly lower at its new starting point.

3.1.2 Spatial distribution pattern

The typed data of all cities' unity between ecological industrialization strength and potentiality in CHREEB in 2020 were imported into ArcGIS 10.5 (GeoScene Information Technology Co., Ltd., Beijing, China) to visualize it, as shown in Fig. 4.

The unity between ecological industrialization strength and potentiality in CHREEB exhibited an evident spatial differentiation pattern, with that in the downstream area being

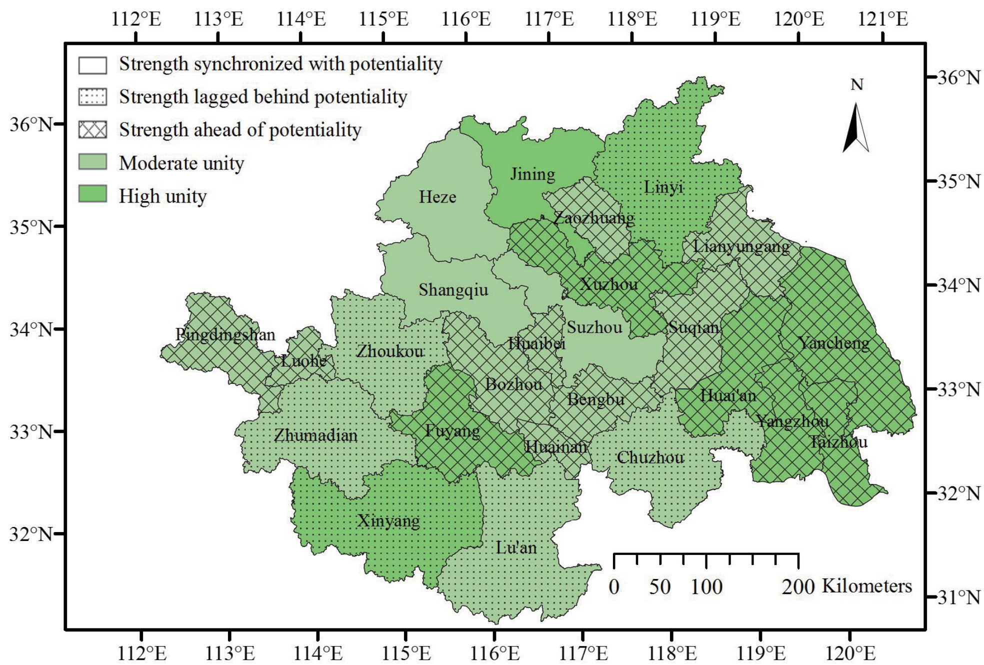

Fig. 4. (Color online) Spatial distribution of unity between ecological industrialization strength and potentiality in CHREEB in 2020.

higher than those in the midstream and upstream areas, and the strength ahead of potentiality being mainly in the trunk stream area while the strength lagged behind potentiality being mainly in the tributary area (Fig. 4). In 2020, nearly 80% of cities with a high unity between ecological industrialization potential and strength were located in the downstream area of CHREEB, while only about 20% of them were located in the midstream and upstream areas. At the same time, 15 cities with ecological industrialization strength ahead of potentiality were mainly located in the trunk stream area, whereas six cities with strength lagged behind potentiality were mainly located in the tributary area. Cities downstream were members of China's Eastern Coastal Economic Belt, which had the highest strength for comprehensive development. These cities had advantages over production experience, marketing, and technological innovation in the process of ecological industrialization and could effectively transform ecological resource advantages into industrial advantages to develop high unity or ecological industrialization strength ahead of potentiality. By contrast, cities upstream and midstream were all inland cities, which had relatively low efficiency for exploiting ecological resources. In addition, the variety and quality of the eco-friendly commodities they provided were deemed unsatisfactory, which explained why they became the moderate unity clusters with ecological industrialization strength lagged behind potentiality.

3.2 Factors and their roles in the unified development of ecological industrialization strength and potentiality

3.2.1 Analysis from an overall perspective

On the basis of the collected and processed development index data, the unified development statuses between ecological industrialization strength and potentiality in 25 cities of CHREEB from 2005 to 2020 were simulated using Eq. (9), as shown in Table 4. We found that the models fitted well and the factors explained the results well. The R^2 values of all the models were above 0.92, and the *F*-values of the test statistic in all the models passed the significance test. 81.25% of the factors explained the results through a passing significance test, and the remaining factors' confidence level of the explanatory results also reached around 60%.

Table 4
Estimation and testing results of overall development models.

Variable	2005			2010			2015			2020		
	Non-standard coefficient	Sig.	Standard coefficient	Non-standard coefficient	Sig.	Standard coefficient	Non-standard coefficient	Sig.	Standard coefficient	Non-standard coefficient	Sig.	Standard coefficient
Ecological factor	5.5×10^{-12}	0.00^{***}	0.22	4.2×10^{-12}	0.01^{***}	0.17	1.8×10^{-12}	0.41	0.07	2.3×10^{-12}	0.31	0.09
Economic factor	8.0×10^{-5}	0.00^{***}	0.88	5.8×10^{-5}	0.00^{***}	0.64	4.1×10^{-5}	0.00^{***}	0.45	4.0×10^{-5}	0.00^{***}	0.44
Social factor	6.0×10^{-6}	0.00^{***}	0.40	3.3×10^{-6}	0.00^{***}	0.22	3.5×10^{-6}	0.03^{**}	0.24	3.0×10^{-6}	0.04^{**}	0.20
Technological factor	0.0×10^{-3}	0.40	0.11	1.0×10^{-3}	0.07^{*}	0.23	1.0×10^{-3}	0.10^{*}	0.15	1.0×10^{-3}	0.01^{***}	0.18
R^2	0.95			0.94			0.93			0.92		
F	88.42	0.00^{***}		84.85	0.00^{***}		66.72	0.00^{***}		58.15	0.00^{***}	

Note: *, **, and *** indicate that the model or variable has passed the significance test with confidence levels of 90, 95, and 99%, respectively. The marks in Table 5 are the same as these.

The unified development between ecological industrialization strength and potentiality in CHREEB was mainly determined by ecological, economic, social, and technological factors. Furthermore, the roles of economic and social factors were far greater than those of ecological and technological factors. However, the roles of ecological, economic, and social factors had a decreasing trend, while those of technological factors had an increasing trend (Fig. 5). In 2005, the standard coefficients of ecological, economic, social, and technological factors were 0.22, 0.88, 0.40, and 0.11, respectively. This was because ecological industrialization was just beginning at that time and there was a long lag from technology research to practical output, while capital investment and transport improvement could rapidly produce results. Afterward, the standard coefficients of the former three decreased, while those of the latter increased gradually. As of 2020, the standard coefficients of these four factors were 0.09, 0.44, 0.20, and 0.18, respectively. Compared with those of 2005, the coefficients of the former three decreased to about half of the initial value, while that of the latter increased to nearly twice the initial value. Therefore, the effects of technological factors were growing rapidly and becoming increasingly significant, while those of economic and social factors were still significant although decreasing.

3.2.2 Analysis from a local perspective

To analyze the roles of factors in local areas, the unified development statuses between ecological industrialization strength and potentiality in CHREEB were further simulated using Eqs. (10) and (11), as shown in Table 5. The R^2 values of all the models were above 0.92, and the

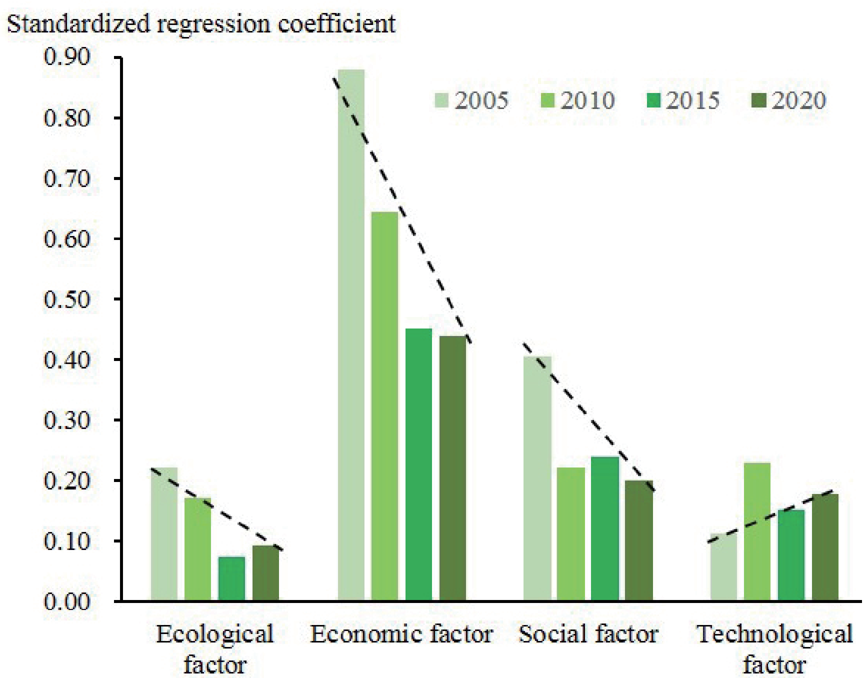

Fig. 5. (Color online) Standard coefficients of factors in the unified development between ecological industrialization strength and potentiality in CHREEB from an overall perspective.

Table 5
Estimation and testing results of local development models.

Year	*AIC*	R^2	R^2_{adj}	sig.	Residual squares
2005	−137.56	0.95	0.94	0.01***	0.00
2010	−119.25	0.94	0.93	0.02**	0.01
2015	−105.59	0.93	0.92	0.02**	0.01
2020	−97.13	0.92	0.91	0.03**	0.02

F-values passed the significance test. That is, the fitting results could well explain the factors and their roles in the unified development of ecological industrialization strength and potentiality in the local area of CHREEB.

The role of the same factor in the unified development between ecological industrialization strength and potentiality differed in different cities in CHREEB (Fig. 6). Cities with higher standard coefficients of ecological factor first appeared in the downstream area, and thereafter, returned to here from the midstream and upstream areas from 2005 to 2020. This was because downstream cities earlier carried out ecological industrialization relying on the superior ecological condition to first achieve better returns, followed by midstream and upstream cities that promoted ecological industrialization construction by the improvement of the local ecological condition, and later downstream cities further optimized the ecological condition to advance the highly efficient development of the ecological industrialization again. Cities with higher standard coefficients of economic and social factors were always concentrated in the midstream and upstream areas during the research period, while cities with higher standard coefficients of technological factors were concentrated in the downstream area. It might be explained that weak technology in cities upstream and midstream resulted in a lower input-to-output ratio of technology, which made them pay more attention to increasing capital investment and improving transportation to promote the ecological industrialization development, while cities downstream with strong technology paid more attention to promoting the ecological industrialization development by technology. It could be seen that each city should formulate appropriate strategies for ecological industrialization development on the basis of the needs of the times and local advantages.

4. Discussion

4.1 New situations: insufficient potentiality for ecological industrialization and spatial differentiation of the unified development

We analyzed the spatiotemporal evolution characteristics of the unified development between ecological industrialization strength and potentiality, and discovered that new situations emerged in CHREEB (Fig. 7). Such unity in CHREEB consistently increased and gradually shifted from the strength lagged behind potentiality to the strength ahead of potentiality, especially in 2020, when the insufficient potentiality of ecological industrialization became evident. This indicated that although ecological industrialization strength and potentiality both increased, the degree and speed of potentiality growth were insufficient to support the steady

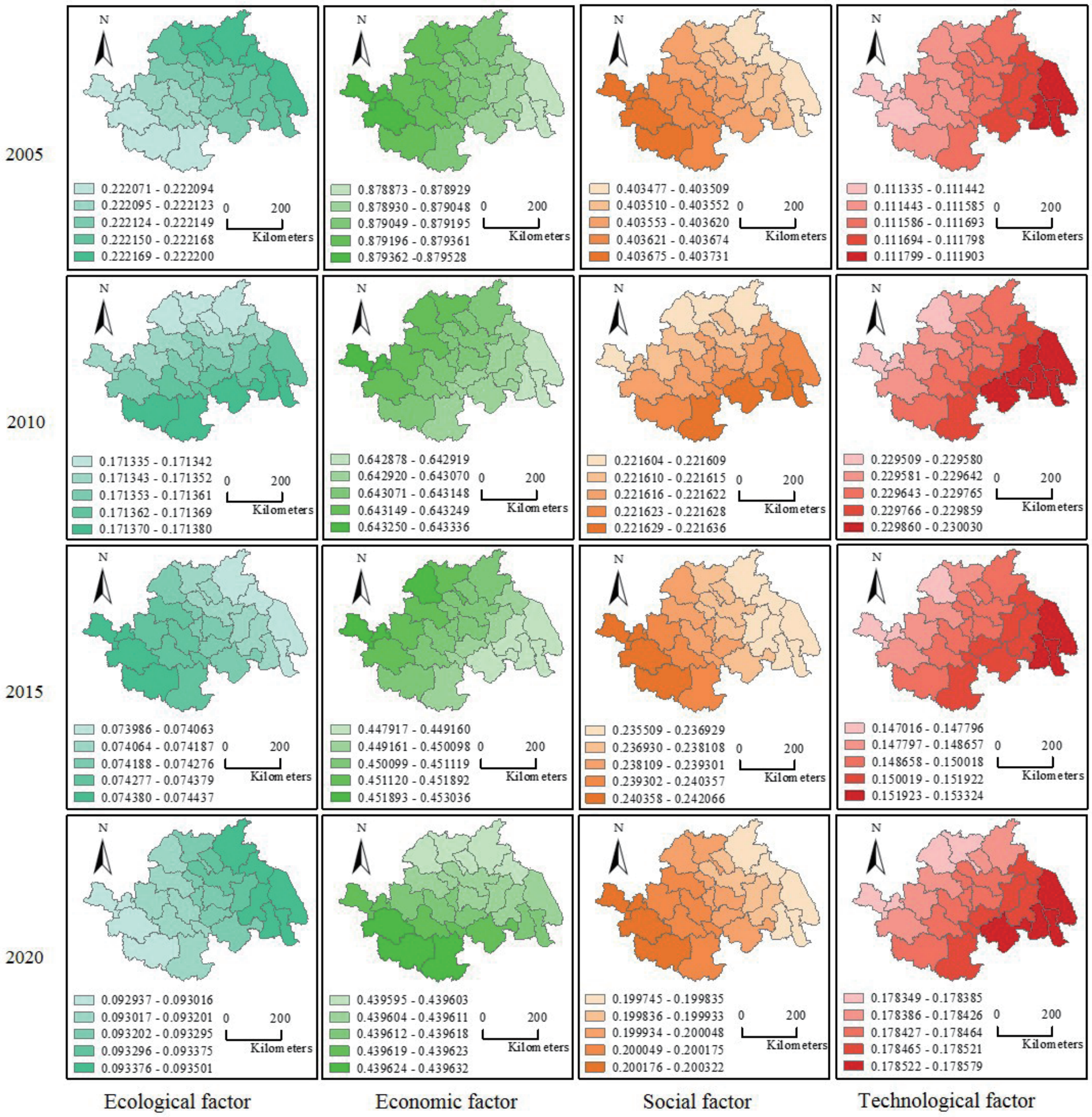

Fig. 6. (Color online) Standard coefficients of factors in the unified development between ecological industrialization strength and potentiality in CHREEB from a local perspective.

improvement of strength. If the difference between the two were excessively high, ecological industrialization strength would stagnate or even be hindered. Moreover, in this study, we detected that the unified development gradually shifted from a balanced spatial distribution to an agglomeration distribution of the same type. In 2020, the high unity was clustered in the downstream area of CHREEB, whereas the moderate unity was clustered in the midstream and upstream areas, and the strength ahead of potentiality was clustered in the trunk stream area,

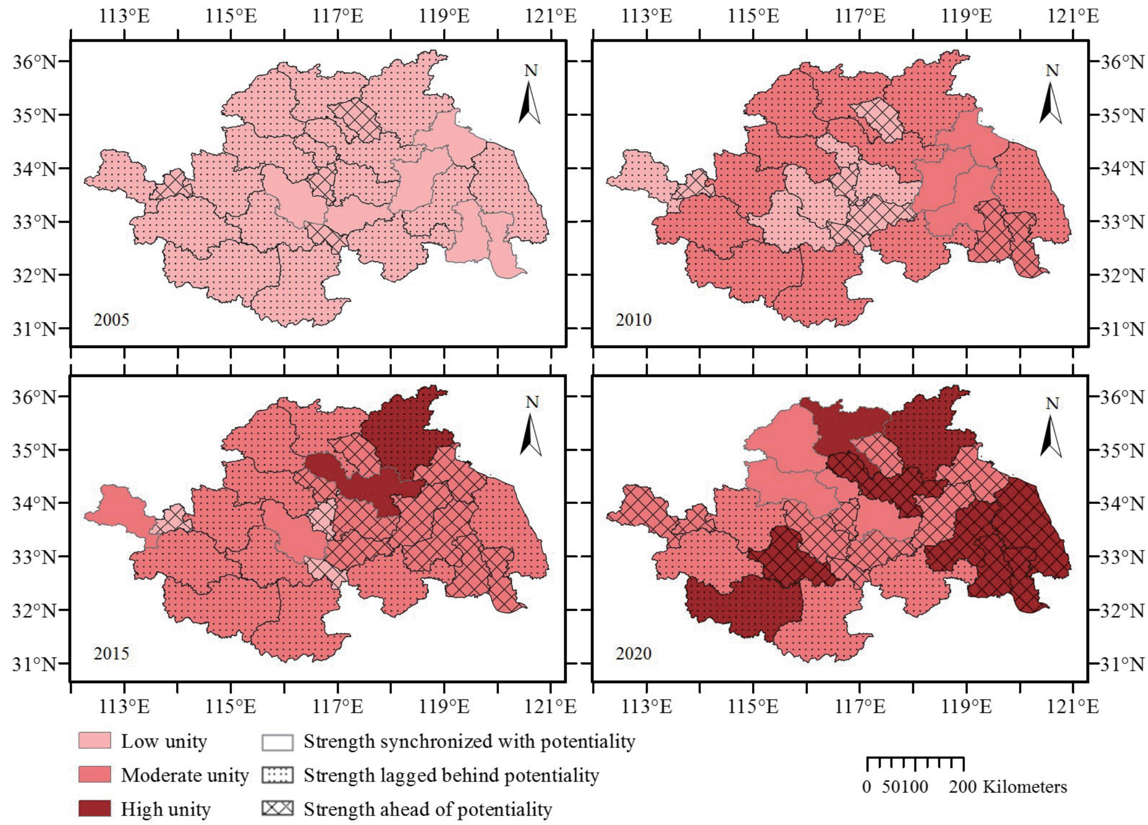

Fig. 7. (Color online) Time-spatial evolution of the unity between ecological industrialization strength and potentiality in CHREEB.

whereas the strength lagged behind potentiality was clustered in the tributary area. If the difference in unity among areas were excessively high, the contradictions of areas would be exacerbated and the effective allocation of resources would not be conducive, thereby hindering the healthy development of ecological industrialization. The harm of excessive areal differentiation has been confirmed by numerous scholars' research.(40)

4.2 Causes: decreased ecological resources, insufficient technologies, and different factor combinations of each area

We analyzed the main factors and their roles in the unified development between ecological industrialization strength and potentiality in CHREEB from an overall perspective, and found that the role of ecological factors gradually decreased while that of technological factors increased significantly but was still far behind that of economic factors. We further analyzed the time changes of ecological, technological, and economic factors in CHREEB, and found that the ecological land areas had been decreasing while the R&D expenditures had been increasing. However, compared with the investments in fixed assets, the R&D expenditures were only eighteen-tenths of ten million at most [Fig. 8(a)]. If the ecological land area should continue to

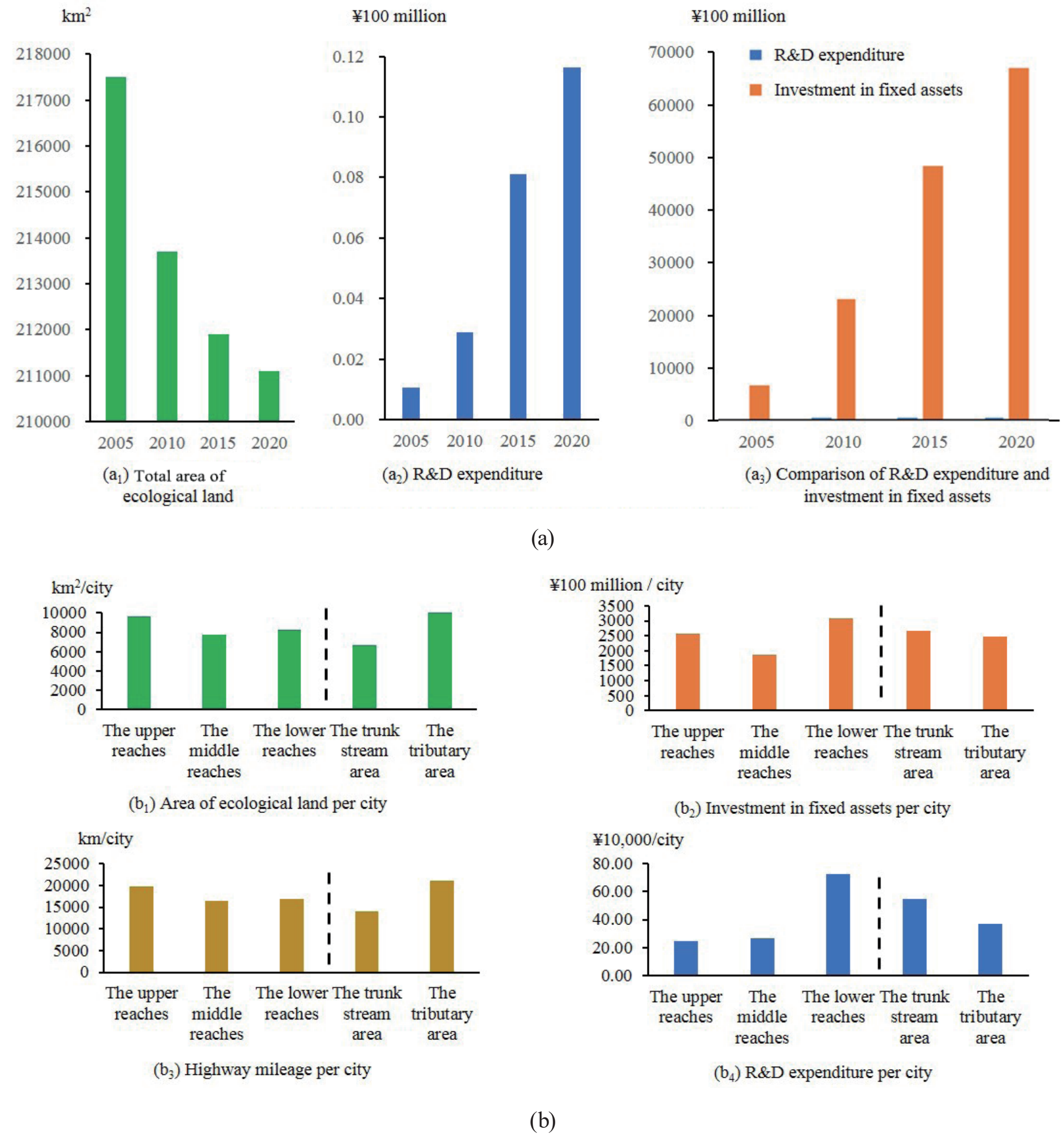

Fig. 8. (Color online) Time-spatial configuration of factors in the unified development between ecological industrialization strength and potentiality in CHREEB. (a) Time variation of some influencing factors in the overall region. (b) Differences in local influencing factors in 2020.

decrease, ecological industrialization might lose its root of development. If the technology investment should not be strengthened, ecological industrialization would be difficult to achieve good-quality development. Protecting ecological resources and vigorously developing technology are important paths to achieve the sustainable good-quality development of ecological industrialization in CHREEB, as well as promoting the harmonious coexistence between humans and nature.[41]

We also analyzed the factors and their roles from a local perspective, and found that different roles of the factors in different areas had led to spatial differentiation in the unified development. We further analyzed combinations of the factors in the upstream, midstream, and downstream areas, and found that the highest investment in fixed assets and R&D expenditure were in the downstream area, the most ecological land area and highway mileage were in the upper reaches, and all factors except for the R&D expenditure were the lowest in the midstream area [Fig. 8(b)]. Moreover, we also analyzed combinations of the factors in the trunk stream and tributary areas, and found that the investment in fixed assets and R&D expenditure were better in the trunk stream area than in the tributary area, while the other two factors were worse than those in the tributary area [Fig. 8(b)]. Various factors do not act independently but rather through mutual connection and interdependence,(41) which means that even if some elements are prominent, it is difficult to achieve good results if other elements are not properly configured. Therefore, optimizing the allocation of factors in various areas(42) can promote the sound construction of ecological industrialization in CHREEB.

4.3 Accurate regulation: regular monitoring, differentiated strategies, and integrated development system

First, the periodic evaluation of unity between ecological industrialization strength and potentiality in CHREEB is required. Many factors affect the unity between ecological industrialization strength and potentiality, and changes in these factors may yield major uncertainty. Conducting the dynamic monitoring of these factors(43) can enable managers and builders to grasp information and accurately formulate response measures.

Second, the ecological industrialization construction of CHREEB should be motivated by a differentiation strategy. Specifically, cities in the downstream and trunk stream areas should not only continue to promote technological innovation but also strictly implement ecological protection. At the same time, cities in the midstream, upstream, and tributary areas should create more economic, social, and ecological values by establishing a comprehensive and effective "Ecological+" industrial chain while maintaining a balanced ecosystem. Differentiated strategies(44) can better adapt to the local situation and promote its development.

Third, integrated development in CHREEB should be strengthened. With the competitive advantages of the upstream, midstream, and downstream areas, the Huai River Waterway could play a role in facilitating infrastructural connections, establishing cooperation platforms, and sharing basic public services,(45) which promote CHREEB as a sustainable, open ecological economic zone of good quality.

5. Conclusions

The rapidly developing GIS has been widely applied in areas such as resource management, regional planning, and land monitoring, and has achieved significant social and economic benefits. In this study, we aimed to develop a monitoring system for the ecological industrialization development based on GIS and to analyze the spatiotemporal evolution process and causes on the basis of evaluating the unity between ecological industrialization strength and potentiality in CHREEB, in order to better assist the government in formulating targeted policies to promote the healthy development of ecological industrialization. The contributions of this study are as follows. First, a GIS-based system structure for monitoring the unity between ecological industrialization strength and potentiality was constructed. Second, much information on the unity between ecological industrialization strength and potentiality was provided to understand the development status, trends, and factors affecting ecological industrialization. Finally, suggestions were put forward for the precise regulation of the healthy development of ecological industrialization.

A rigorous study of the unity between ecological industrialization strength and potentiality in CHREEB was undertaken. Below are the empirical findings.

First, there appeared phenomena such as insufficient potentiality and spatial differentiation in the unified development between ecological industrialization strength and potentiality in CHREEB at present. The insufficient potentiality and excessive spatial differentiation would both limit the sustainable development process of ecological industrialization. Therefore, the insufficient potentiality and spatial differentiation should be highly valued.

Second, the reduced ecological resources, insufficient technology, and different regional factor combinations were the main reasons for the unfavorable results of the unified development between ecological industrialization strength and potentiality in CHREEB at present. The gradual reduction of ecological resources would weaken the foundation of ecological industrialization development, insufficient technological investment would reduce its development pace, and inappropriate regional factor combinations would hinder its development efficiency in some regions. We should address these shortcomings to advance the sustained high-quality ecological industrialization development.

Third, regular monitoring, differentiated strategies, and an integrated development system are effective in promoting the unified development between ecological industrialization strength and potentiality in CHREEB. Regular monitoring would timely master the information of ecological industrialization development, targeted regulatory strategies would better facilitate each area's construction, and an integrated development system would maximize the overall development result in CHREEB. These ways would considerably promote the process of ecological industrialization.

According to the results, the time-spatial evolution characteristics and causes of the unity between ecological industrialization strength and potentiality have been comprehensively grasped, which facilitates the accurate adoption of countermeasures for the promotion of transformation in ecological economic development. These findings could help in the ecological industrialization construction of CHREEB and other similar ecological economic zones worldwide.

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References

1 Y. Liu, P. Gao, D. Liu, M. Xu, Y. Wang, and R. Chen: Sens. Mater. **35** (2023) 135. https://doi.org/10.18494/sam4283
2 I. Mockevičienė, G. Šiaudinis, D. Karčauskienė, R. Repšienė, K. Barčauskaitė, and O. Anne: Land **12** (2023) 866. https://doi.org/10.3390/land12040866
3 P. Sobhani, H. Esmaeilzadeh, I. D. Wolf, A. Deljouei, M. V. Marcu, and S. M. M. Sadeghi: Ecol. Indic. **155** (2023) 110957. https://doi.org/10.1016/j.ecolind.2023.110957
4 E. Cervelli and S. Pindozzi: Appl. Sci. **12** (2022) 2442. https://doi.org/10.3390/app12052442
5 H. Yan, W. Li, H. Yang, X. Guo, X. Liu, and W. Jia: Land **10** (2021) 1383. https://doi.org/10.3390/land10121383
6 L. Li, Y. Zeng, Y. He, Q. Qin, J. Wang, and C. Fu: Int. J. Environ. Res. Public Health **19** (2022) 7580. https://doi.org/10.3390/ijerph19137580
7 Z. Zhuang, C. Li, W.-L. Hsu, S. Gu, X. Hou, and C. Zhang: Water **14** (2022) 2559. https://doi.org/10.3390/w14162559
8 K. Schacht and R. Voss: Ambio **52** (2023) 155. https://doi.org/10.1007/s13280-022-01768-2
9 X. Min, Y. Wang, and J. Chen: Sustainability **14** (2022) 16548. https://doi.org/10.3390/su142416548
10 X. Liang, Y. Li, J. a. Shao, and C. Ran: J. Geogr. Sci. **30** (2020) 281. https://doi.org/10.1007/s11442-020-1728-5
11 F. Zhou, D. Si, P. Hai, P. Ma, and S. Pratap: Systems **11** (2023) 109. https://doi.org/10.3390/systems11020109
12 B. Zhang and L.-y. Bai: J. Beijing Union University (Humanities and Social Sciences) **19** (2021) 11. https://doi.org/10.16255/j.cnki.11-5117c.2021.0002
13 C. Sun, Y. Bao, B. Vandansambuu, and Y. Bao: Sustainability **14** (2022) 15707. https://doi.org/10.3390/su142315707
14 G. Li, W. Chen, X. Zhang, Z. Yang, P. Bi, and Z. Wang: Int. J. Environ. Res. Public Health **19** (2022) 3121. https://doi.org/10.3390/ijerph19053121
15 C. Chen: Guizhou Social Sciences **8** (2019) 122. https://doi.org/10.13713/j.cnki.cssci.2019.08.018
16 A. V. Vasilieva, A. D. Volkov, V. V. Karginova-Gubinova, and S. V. Tishkov: J. Risk Financial Manag. **15** (2022) 484. https://doi.org/10.3390/jrfm15100484
17 A. M. Khan, Q. Li, Z. Saqib, N. Khan, T. Habib, N. Khalid, M. Majeed, and A. Tariq: Forests **13** (2022) 715. https://doi.org/10.3390/f13050715
18 A. Xu, Y. An, and D. Wang: J. Tibet University (Social Science Edition) **25** (2010) 28. https://doi.org/10.16249/j.cnki.1005-5738.2010.04.023
19 D. Yihunie: Arabian J. Geosci. **16** (2023) 235. https://doi.org/10.1007/s12517-023-11297-1
20 W.-L. Hsu, Y. Lu, Z. Ouyang, Z. Dong, and H.-L. Liu: Sens. Mater. **35** (2023) 2681. https://doi.org/10.18494/sam4385
21 C. Kilicoglu: Environ. Sci. Pollut. Res. **29** (2022) 35746. https://doi.org/10.1007/s11356-021-17970-w
22 G. C. Daily, S. Polasky, J. Goldstein, P. M. Kareiva, H. A. Mooney, L. Pejchar, T. H. Ricketts, J. Salzman, and R. Shallenberger: Front. Ecol. Environ. **7** (2009) 21. https://doi.org/10.1890/080025
23 Y. Bai, H. Xu, and H. Ling: Environ. Earth Sci. **71** (2014) 3715. https://doi.org/10.1007/s12665-013-2766-4
24 Z. Yuan, J. Bi, Z. Huang, B. Zhang, and X. Wang: Productivity Research **12** (2004) 152. https://doi.org/10.19374/j.cnki.14-1145/f.2004.12.065
25 Y. Xue, H. Liu, C. Bai, M. Su, D. Qiu, B. Zhou, Y. Yu, and X. Jiang: Environ. Earth Sci. **81** (2021) 24. https://doi.org/10.1007/s12665-021-10139-1
26 S. Iwama, T. Yanagisawa, R. Hirose, and J. Ushiba: Commun. Biol. **5** (2022) 1375. https://doi.org/10.1038/s42003-022-04326-4
27 J. F. Cass and S. J. Hogan: Biol. Cybern. **115** (2021) 343. https://doi.org/10.1007/s00422-021-00879-5
28 C. Zhang, X. Zhang, Q. Wu, and H. Li: Sci. Geogr. Sin. **33** (2013) 16. https://doi.org/10.13249/j.cnki.sgs.2013.01.003
29 B. L. Preston and J. Shackelford: Ecotoxicology **11** (2002) 85. https://doi.org/10.1023/A:1014416827593
30 L. Magalhães Filho, P. Roebeling, and C. Coelho: Environments **10** (2023) 24. https://doi.org/10.3390/environments10020024
31 A. A. Abdul kareem, Z. T. Fayed, S. Rady, S. Amin El-Regaily, and B. M. Nema: Systems **11** (2023) 146. https://doi.org/10.3390/systems11030146
32 P. Tao, Y. Lin, X. Wang, J. Li, C. Ma, Z. Wang, X. Dong, P. Yao, and M. Shao: Land **12** (2023) 1218. https://doi.org/10.3390/land12061218
33 H. Vivas Pacheco, D. Rodríguez-Mariaca, C. Jaramillo, A. Fandiño-Losada, and M. I. Gutiérrez-Martínez: Safety **9** (2023) 34. https://doi.org/10.3390/safety9020034
34 J. M. Sánchez-Martín, A. M. Hernández-Carretero, J. I. Rengifo-Gallego, M. J. García-Berzosa, and L. M. Martín-Delgado: Systems **11** (2023) 236. https://doi.org/10.3390/systems11050236

35 E. Fundisi, S. Dlamini, T. Mokhele, G. Weir-Smith, and E. Motolwana: Healthcare **11** (2023) 881. https://doi.org/10.3390/healthcare11060881

36 C. Chwiałkowski, A. Zydroń, and D. Kayzer: Land **12** (2022) 125. https://doi.org/10.3390/land12010125

37 A. Kokayi, S. Shiode, and N. Shiode: Sustainability **15** (2023) 5677. https://doi.org/10.3390/su15075677

38 Resource and Environment Science and Data Center of Chinese Academy of Sciences: https://www.resdc.cn/ (accessed May 2023).

39 X. Xu, J. Liu, S. Zhang, R. Li, C. Yan, and S. Wu: Resource and Environmental Science Data Registration and Publishing System (2018). https://www.resdc.cn/DOI/DOI.aspx?DOIid=54

40 M. Hachaichi and M. Talandier: Ecol. Indic. **155** (2023) 110947. https://doi.org/10.1016/j.ecolind.2023.110947

41 K. O. Onditi, W. Song, X. Li, S. Musila, Z. Chen, Q. Li, J. Mathenge, E. Kioko, and X. Jiang: Ecol. Indic. **154** (2023) 110595. https://doi.org/10.1016/j.ecolind.2023.110595

42 L. Comte, J. D. Olden, S. Lischka, and B. G. Dickson: Ecol. Indic. **138** (2022) 108840. https://doi.org/10.1016/j.ecolind.2022.108840

43 D. L. Santavy, S. K. Jackson, B. Jessup, C. Horstmann, C. Rogers, E. Weil, A. Szmant, D. C. Miranda, B. K. Walker, C. Jeffrey, D. Ballantine, W. S. Fisher, R. Clark, H. R. Torres, B. Todd, and S. Raimondo: Ecol. Indic. **135** (2022) 108576. https://doi.org/10.1016/j.ecolind.2022.108576

44 O. Fadairo, S. Olajuyigbe, O. Adelakun, and T. Osayomi: GeoJournal **88** (2022) 2153. https://doi.org/10.1007/s10708-022-10741-1

45 B. Wang and Y. Ma: GeoJournal **88** (2023) 5463. https://doi.org/10.1007/s10708-023-10928-0