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Original Research Article

Assessment of ecological civilization construction from the perspective of environment and health in China

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ABSTRACT

This study innovatively evaluated ecological civilization in China from the perspective of environment and health. A Composite Environmental Health Index (CEHI) was constructed based on the Driving force-Pressure-State-Impact-Response (DPSIR) and Coupling Coordination Degree (CCD) models. Results showed that significant and sustained improvements were observed in the ecological environment after ecological civilization, while economic development continued to progress at a steady pace. However, the advancement in population health (impact subsystem), exhibited comparatively modest progress, potentially linked to issues such as demographic aging and the enduring consequences of past exposure to environmental pollutants. At the provincial level, the regional development was uneven. The CEHI performance was highest in the eastern regions, followed by the central regions, with the western regions showing the least progress. Beijing, Guangdong, Jiangsu, Shanghai, and Zhejiang emerged as top performers with higher CEHI scores, which can be attributed to their favorable geographical positioning and the response subsystem. Conversely, northeastern regions (Heilongjiang, Jilin, and Liaoning) and northwestern regions (Shanxi, Gansu, Ningxia, and Qinghai) experienced limited advancements in post-ecological civilization implementation. For these underperforming regions, there is a pressing need to intensify efforts aimed at enhancing their response subsystems. In summary, China's pursuit of ecological civilization has yielded significant successes, potentially offering valuable insights for other nations striving for sustainable development. The ecological civilization model's integration of ecological environmental protection into economic, political, cultural, and social constructs may serve as a meaningful reference for the sustainable development of other countries.

1. Introduction

Ecological civilization emerged as a pivotal national strategy in China, aimed at addressing pressing environmental challenges. The development of ecological civilization in China unfolded over an extended period (Fig. 1). China's early environmental consciousness was significantly shaped by Western and international ideologies. The inception of the first and second national environmental protection working conferences can be attributed to the assimilation of Western environmental protection concepts [1]. Subsequently, China adopted the principles of “Sustainable Development” and introduced the “Scientific Outlook on Development”, emphasizing the imperative to conserve resources and protect the environment while advancing the economy [2]. The term “Ecological Civilization” made its initial appearance in official documents in 2007, though no substantial measures or actions followed at that time. However, a significant turning point occurred in 2012 during the 18th National Congress of the Communist Party of China, where ecological civilization was formally designated as a guiding political framework and a national governance strategy [3]. The policy provisions pertaining to ecological restoration and pollution control have experienced a gradual augmentation. However, the overall management landscape is characterized by chaos, a lack of inter-departmental coordination within administrative bodies, and suboptimal efficiency in certain policies [4,5]. In an effort to enhance the operationalization of ecological civilization, two pivotal guidelines were promulgated in 2015: the “Proposal on Accelerating the Construction of Ecological Civilization” and the “Overall Plan of Ecological Civilization System Reform”, which furnish tangible implementation measures. The two documents serve as a comprehensive foundation for the execution of ecological civilization in China [6,7]. Subsequent to these developments, China's

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ecological civilization construction has shown a positive trajectory. By 2020, several pilot trials reached their conclusion, and commencing in 2022, the nation's ecological civilization construction underwent a transformative shift, disseminating mature experiences nationwide [8]. Until now, a noteworthy progression is the integration of climate change considerations into the framework of ecological civilization construction. Pollution prevention and control strategies have pivoted towards addressing longstanding issues such as urban water pollution, elevated pollutant and carbon emissions, and the treatment of fine particulate matter. The principal objective of China's current economic development now centers on green and high-quality development [9]. Unlike antecedent environmental protection strategies, ecological civilization necessitates the seamless integration of environmental preservation into the economic, social, cultural, and political fabric of China, encapsulated in the concept of "the Five-Sphere Integrated Plan" (meaning comprehensive development of economic, political, cultural, social, and ecological civilization). Furthermore, it underscores the imperative of establishing a long-term environmental protection mechanism with active engagement from diverse stakeholders, including the public, businesses, and government officials [10]. Besides, grounded in China's distinctive political context, the nation has progressively erected its ecological environment protection system. This encompassing system comprises a comprehensive ecological environment planning policy framework, a well-structured ecological environment governance system, and a fully-fledged ecological environment protection legal framework. In contrast to other sustainable development strategies, ecological civilization represents a unique and profoundly meaningful exploration and implementation of sustainable practices.

Since the inception of the ecological civilization strategy in China, there has been a gradual increase in scholarly investigations aimed at assessing its effectiveness and progress. The majority of these studies focus on evaluating the economic and environmental developments that have occurred in the wake of ecological civilization implementation. Notably, these assessments rely heavily on two government-issued index systems, namely the "Green Development Index" and the "Evaluation Index System of Ecological Civilization Assessment", mainly including the aspects of economic development, environmental improvement, pollutant discharge, and resource utilization [11–14], resulting in the heterogeneous construction of ecological civilization in different regions [15–20]. Furthermore, some researchers have conducted specific evaluations in distinct environmental domains within particular regions. For instance, Zhang et al. developed an index system to gauge urban resources and environmental carrying capacity to evaluate Tianjin's ecological civilization construction [21]. Some studies have evaluated Jiangsu and Chengdu-Chongqing, and have found that the performance of ecological civilization construction in Jiangsu Province has improved [22], while the coordination degree of ecological civilization construction in Chengdu-Chongqing has declined [23]. Additionally, other studies have constructed index systems to appraise ecological civilization development from a single visual angle, such as resource carrying capacity, marine ecological civilization, and ecological services [24–26]. However, it is important to note that few studies have delved into the dimension of human health within the context of ecological civilization, and those that paid more attention to the psychological imbalance were mainly conducted at the national level [24, 27]. In summary, current research has predominantly focused on the intersection of economic development and environmental quality or pollution within the framework of China's ecological civilization. The research on the intricate interplay among economic and social development, the environment, and human health has been limited, particularly at the provincial or regional level. Recognizing that the establishment of ecological civilization is rooted in achieving harmony between humanity and nature, and that population health is a pivotal objective in the construction of ecological civilization, there is a compelling need for a comprehensive assessment from the perspective of environment and human health. Such an evaluation not only aligns with the fundamental principles of ecological civilization but also provides novel insights conducive to advancing the construction of ecological civilization in China.

When examining the underlying causes, it becomes evident that the substantial threats posed to public health by environmental issues stand as a central impetus for sustainable development strategies. Consequently, it is of paramount importance to reevaluate China's ecological civilization with a specific emphasis on the environmental and health

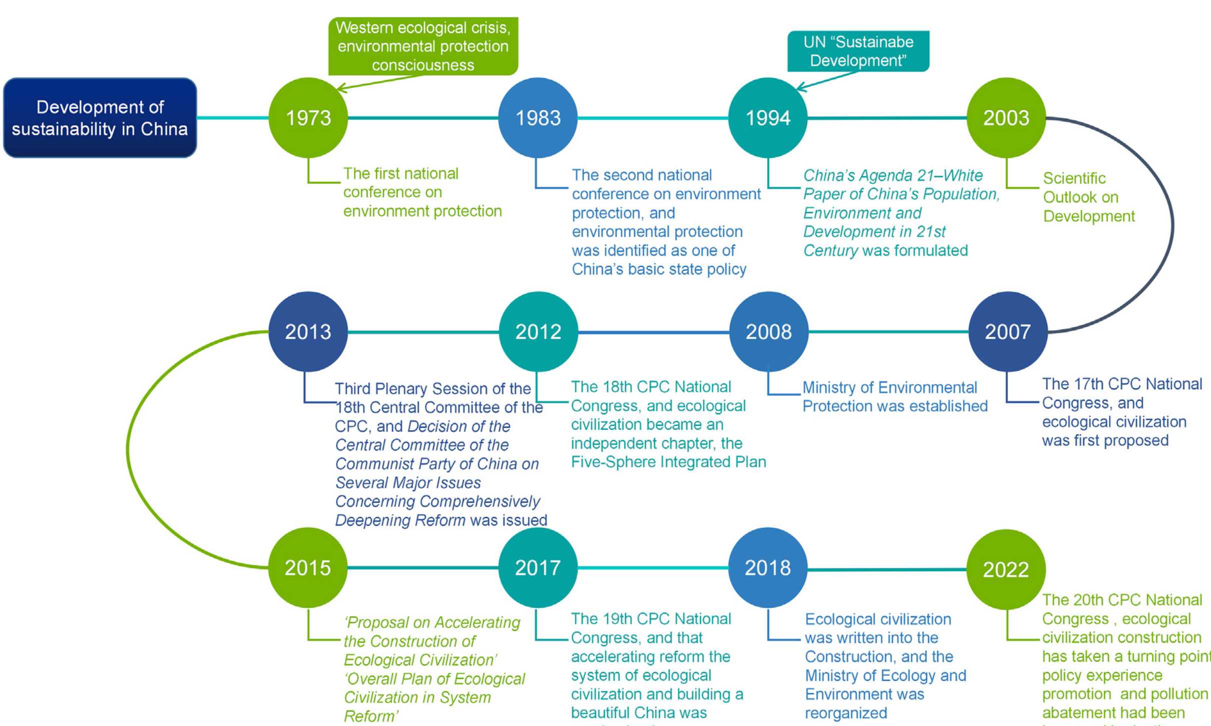

Fig. 1. History of China's Ecological Civilization development.

dimensions. The primary objective of this research is to conduct a comprehensive, long-term evaluation of ecological civilization performance at both national and provincial levels in China. To achieve this, a Composite Environmental Health Index (CEHI) has been developed by drawing from the Driving Force-Pressure-State-Impact-Response (DPSIR) framework and the Coupling Coordination Degree (CCD) models. The findings of this study hold the potential to enhance our comprehension of ecological civilization construction and offer profound insights into sustainable development practices applicable to other countries.

2. Methods and data

2.1. Methods

To evaluate ecological civilization construction in China from the environmental and health perspective, this study constructed a CEHI. The CEHI was calculated in a three-step manner (Fig. S1). The indicators framework was established based on the DPSIR framework, and then the entropy method was used to assign weights to each index after standardization. The Environmental Health Index (EHI) was calculated by weight, the CCD of the EHI's subsystem was calculated by the CCD model, and the CEHI was constructed by combining EHI and CCD.

2.1.1. Evaluation indicators of the DPSIR model

The DPSIR model, as an indicator framework for environmental sustainability, effectively portrays the intricate relationship between human actions and the natural environment, and has been widely used [28–30]. The DPSIR framework consists of driver, pressure, state, impact, and response, which have causal chains (Fig. S2). Drivers are the potential cause of environmental change, mainly socioeconomic perspectives, like GDP per capita, natural population growth rates, living standards, and urbanization rates. Pressure refers to the impact of human activities on the environment, serving as the direct pressure factor of environmental pollution, such as pollutant discharge like waste gas and wastewater, solid waste, fertilizers, and pesticides. The state means the performance of the environment under the above pressure. Impact is the impact of the state of environment on human health in turn. Response indicates the countermeasures that human beings take in the process of promoting sustainable development, such as improving resource utilization efficiency, reducing pollution, and increasing investment. Based on the aforementioned discussion, DPSIR effectively captures the interplay between human activities and the natural environment. Simultaneously, the establishment of ecological civilization could be seen as a response to human-induced environmental issues [2,3], and its interactions are also manifested within this framework. Therefore, the framework of DPSIR was used to construct the indicators in this study.

Based on the common indicators and considering the scientific, accurate, accessible, and quantifiable principles, the final evaluation indicators of the DPSIR model for environment and health are shown in Table 1.

2.1.2. Data normalization

The collected data must be normalized because of the different measurements and units between each indicator in the DPSIR framework. In this study, the raw data were standardized using the extreme value processing method (Eqs. 1–3). In this method, the sign (positive, negative, and neutral/moderate) of each indicator was determined first. Then, Eq. 1 was used for the positive indicator (the higher data value of the indicator, the better the performance), Eq. 2 for the negative indicator (the lower data value of the indicator, the better the performance), and Eq. 3 for the moderate indicator (the closer the data value is to a moderate value, the better the performance), respectively.

$$Y_{ijk} = \frac{X_{ijk} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{1}$$

$$Y_{ijk} = \frac{\max(X_i) - X_{ijk}}{\max(X_i) - \min(X_i)} \tag{2}$$

$$Y_{ijk} = \begin{cases} 1 - \dfrac{X_q - X_{ijk}}{\max\left[X_q - \min(X_i),\ \max(X_i) - X_q\right]} & X_{ijk} < X_q \\ 1 - \dfrac{X_{ijk} - X_q}{\max\left[X_q - \min(X_i),\ \max(X_i) - X_q\right]} & X_{ijk} > X_q \\ 1 & X_{ijk} = X_q \end{cases} \tag{3}$$

where Y_{ijk} is the normalized value of the kth year of the ith indicator in province j; X_{ijk} is the actual value of the kth year of the ith indicator in province j; max() and min() are the maximum and minimum values, and X_q represents the moderate value for a moderate indicator. The ideal value of each moderate indicator is generally referenced from the literature or relevant national documents. In this study, the ideal value of the natural population growth rate was based on the national population growth rate planning target of 6%, and the ideal value of the average urbanization rate was based on the urbanization rate of 75% in developed countries.

2.1.3. Index weighting methods

Weighting the indicator is an important process in a comprehensive evaluation. Commonly used weighting methods include principal component analysis, the entropy method, data envelopment analysis, weighting based on experts or public opinion surveys, and assigning the same weight. When assuming the same weight of indicators, evaluation analysis only focuses on the value of the indicators rather than the weight of indicators. Here, the entropy method was used to avoid deviations caused by subjective factors [31,32].

In this study, the EHI consisted of five parts (DPSIR), and each of the five subsystems was assigned the same weight. The entropy method was

Table 1
Evaluation index system.

Goal	Subsystem layer	Indicators		Weight coefficient
Environmental and health index	Drivers	D1	Urbanization rate	0.0821
		D2	Natural growth rate of population	0.0294
		D3	GDP	0.3693
		D4	Per capita urban disposable income	0.2527
		D5	Per capita rural disposable income	0.2665
	Pressure	P1	Total sulfur dioxide (SO_2) emission	0.1711
		P2	Consumption of chemical fertilizer	0.2287
		P3	Consumption of pesticide	0.1071
		P4	Effluent volume	0.0887
		P5	General industrial solid waste production	0.0737
		P6	Per capita CO_2 emissions (tons)	0.0633
		P7	Energy consumption structure (coal share)	0.2673
	State	S1	Annual average concentration of $PM_{2.5}$	0.2601
		S2	Proportion of excellent water quality	0.4058
		S3	Normalized difference vegetation index (NDVI)	0.2993
		S4	Number of environmental emergencies	0.0347
	Impact	I1	Mortality	0.5918
		I2	Maternal mortality rate	0.1343
		I3	Perinatal mortality rate	0.1817
		I4	Prevalence of low weight in children under 5 years old	0.0922
	Response	R1	Per capita urban green space	0.1304
		R2	Number of patent applications (Domestic)	0.3540
		R3	Comprehensive utilization rate of solid waste	0.0428
		R4	Treatment rate of domestic sewage	0.0185
		R5	Intensity of environmental regulation[a]	0.1132
		R6	Research and Experimental Development (R&D) expenditure	0.2838
		R7	Proportion of Tertiary sector of GDP	0.0573

[a] Intensity of environmental regulation was calculated as industrial governance investment divided by the second industry value.

used five times to weight the evaluation indices of the five subsystems instead of using the entropy method to weight all the indices simultaneously. See Eqs. 4–7 for the calculations:

$$s_{ijk} = \frac{y_{ijk}}{\sum_{j=1}^{n} y_{ijk}} \tag{4}$$

$$e_i = -\frac{\sum_{j=1}^{n} s_{ijk} \ln s_{ijk}}{\ln n} \tag{5}$$

$$g_i = 1 - e_i \tag{6}$$

$$w_i = \frac{g_i}{\sum_{i=1}^{m} g_i} \tag{7}$$

where y_{ijk} is the kth year normalized value of the original data for indicator i in province j; s_{ijk} is the proportion of y_{ijk} in indicator i; n is the number of indicator i; e_i is the entropy value of indicator i; g_i is the information utility value of the indicator i; w_i is the weight of indicator i; m is the number of the subsystem (D, P, S, I, and R).

2.1.4. CEHI calculations

The CEHI was constructed by combining the EHI and CCD sub-indexes in a three-step manner:

First, the EHI index was calculated using Eqs. 8–13:

$$D_{jk} = \sum_{i=1}^{5} w_i y_{ijk} \tag{8}$$

$$P_{jk} = \sum_{i=1}^{5} w_i y_{ijk} \tag{9}$$

$$S_{jk} = \sum_{i=1}^{5} w_i y_{ijk} \tag{10}$$

$$I_{jk} = \sum_{i=1}^{4} w_i y_{ijk} \tag{11}$$

$$R_{jk} = \sum_{i=1}^{5} w_i y_{ijk} \tag{12}$$

$$EHI_{jk} = 0.2 \times \left(D_{ijk} + P_{ijk} + S_{ijk} + I_{ijk} + R_{ijk}\right) \tag{13}$$

where D_{jk}, P_{jk}, S_{jk}, I_{jk}, and R_{jk} are the scores for the subsystem of the DPSIR model, and EHI_{jk} is the index score of region j in k_{th}-year.

Second, coupling coordination, originating from physics, reflects the level of harmony in the interaction of two or more subsystems in a region during the development progress [32,33]. The five subsystems (D, P, S, I, and R) of EHI affect and restrict each other, and the coordinated development between them is also important. If the development between the five subsystems is not coordinated, the sustainability of the implementation of ecological civilization will be hindered. Therefore, we used the CCD model [33,34] to calculate the CCD scores of EHI. The calculations are Eqs. 14–16:

$$CD_{jk} = 5 \times \left[\frac{D_{jk} \times P_{jk} \times S_{jk} \times I_{jk} \times R_{jk}}{\left(D_{jk} + P_{jk} + S_{jk} + I_{jk} + R_{jk}\right)^5}\right]^{1/5} \tag{14}$$

$$T_{jk} = \alpha D_{jk} + \beta P_{jk} + \gamma S_{jk} + \delta I_{jk} + \varepsilon R_{jk} \tag{15}$$

$$CCD_{jk} = \sqrt{CD_{jk} \times T_{jk}} \tag{16}$$

where CD is the coupling degree between five dimensions (D_{jk}, P_{jk}, S_{jk}, I_{jk}, and R_{jk}) of EHI; T is the comprehensive target correlation degree of subsystems, and α, β, γ, δ, and ε represent the weight of five DPSIR subsystems [as described above, each of subsystem has the same weight (0.2)], respectively; CCD is the coupling coordination degree of the EHI. CCD's score is in the range of [0,1]; the closer CCD is to 1, the better the system coordination.

Third, the *CEHI* was calculated using Eq. 17 [33,35], and its score (0–1) was used to finally assess the comprehensive performance of ecological civilization in China.

$$CEHI = \sqrt{EHI \times CCD} \tag{17}$$

2.2. Data sources

The corresponding representative indicators were selected according to the DPSIR model, the data are shown in Table 1. Except for $PM_{2.5}$ and normalized difference vegetation index (NDVI), the other data in this study come from the China Statistical Yearbook (2004–2020), China Environment Bulletin (2003–2020), Research and Experimental Development (R&D) Expenditure Census Bulletin (2003–2019), Urban Construction Statistics Yearbook (2004–2020), China Health Statistics Yearbook (2007–2020), China Water Resources Bulletin (2003–2019), and Annual Report on Ecological Environment Statistics. Since $PM_{2.5}$ was not officially included in China's air quality standards until 2012, the long-term data of $PM_{2.5}$ were obtained from the interpretation products of the V4.CH.03 product (China Regional Estimates) developed by the Washington University Atmospheric Composition Analysis Group. This data showed high consistency ($R^2 = 0.81$) with globally distributed ground monitors and met the application requirements [36,37]. In addition, China's forest coverage rate is not updated every year, and the data in the bulletin are generally from the once-a-decade forest census data. The NDVI is another important index for measuring and testing environmental changes in the ecosystem. Therefore, the annual NDVI data used in this study is from the Scientific Data Center (https://www.resdc.cn/). The indicators and their weights are listed in Table 1.

3. Results

According to the important node of ecological civilization (in the years 2007, 2012, and 2015 in Fig. 1), the entire period is divided into four stages for better comparison, namely the "pre-ecological civilization proposal" period from 2003 to 2007 as Phase I, and the "pre-ecological civilization construction" from 2007 to 2012 as Phase II, the "post-ecological civilization construction" from 2013 to 2015 as Phase III, and the "ecological civilization system reform" as Phase IV.

3.1. The change trend of the indicators

The change of indicators is shown in Fig. 2. The indicators of the D subsystem (drivers) were obviously improved. It is indicated that economic development and increasing the social status of local residents are still two of the key focuses of China, and relevant policies such as China's poverty alleviation have indeed achieved certain results. The SO_2 emissions and energy consumption under the pressure system have greatly improved, but the industrial parts, such as wastewater discharge and solid waste discharge, are still a serious problem for the environment. In addition, although CO_2 emissions slowed down, overall emissions increased on a per capita basis, which is related to the increase in power consumption brought about by the increase in per capita income [38]. The air quality and surface water quality have been greatly improved after ecological civilization, which is also related to the continuous environmental prevention and control policies under the construction of ecological civilization, such as *the system of central inspection on eco-environmental protection*, *Air Pollution Prevention and Control Action Plan*, and *Action Plan for Prevention and Control of Water Pollution.*

In the I subsystem (impact), the total mortality increased in Phases III and IV, while the mortality of pregnant women and perinatal infants and

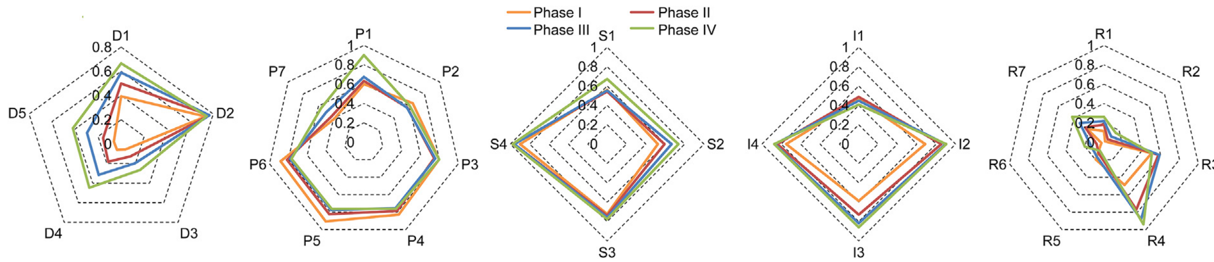

Fig. 2. Changes of individual index in different stages.

malnutrition rates of children under 5 years old all improved, but they were similar in Phases III and IV. For the R subsystem (response), R1, R2, R4, R6, and R7 were significantly improved in Phases III and IV. R3 (the decline of the comprehensive utilization rate of solid waste) in Phase IV decreased due to the influence of population and recycling intensity, leaving much room for improvement [39,40]. In addition, the intensity of environmental regulations weakened slightly, which may be one of the reasons for the increase in the discharge of pressure system wastewater and industrial solid waste.

3.2. The interaction changes of EHI's subsystems

Changes in the five subsystems of the DPSIR framework are shown in Fig. 3. Among all subsystems, the rise of the D subsystem is the fastest (from 0.081 to 0.446). The rapid socio-economic development has caused great pressure on the environment, which has increased rapidly since 2012. The change of the S subsystem (state) fluctuated in Phases I and II. In the two stages, due to the frequent occurrence of environmental pollution events such as children's blood lead exceeding the standard, cadmium pollution incident (Liuyang, Hunan Province), arsenic pollution (Yangzonghai, Yunnan Province), dead fish incidents (Baiyangdian, Hebei Province), Taihu Lake pollution incident, and so on, people's attention of environmental protection has been aroused, but the uncertainty of relevant policies and the lack of government supervision has led to the tortuous change in the S subsystem. Thanks to the strong and effective environmental pollution control policies after ecological civilization construction [3,41], the S subsystem improved slowly in Phase III and more apparently in Phase IV. The I subsystem was improved in Phases I and II, mainly because the health benefits brought by the improvement of medical conditions outweighed the short-term effects brought by environmental pollution. Whereas in Phases III and IV, the I subsystem decreased. This may be linked to the higher weight of mortality and the long-term cumulative effects of environmental exposure in Phases I and II. The growth rate of the R subsystem (response) in Phases III and IV was faster than that in Phases I and II, indicating that the construction of ecological civilization has indeed increased people's response to environmental protection.

3.3. The temporal characteristics of EHI, CCD, and CEHI

At the national level, the scores of EHI, CCD, and CEHI increased from 0.385, 0.499, and 0.438 in 2003 to 0.552, 0.697, and 0.620 in 2019, respectively (Fig. 3). For EHI, the growth rate was higher in Phases III and IV than in Phases I and II, indicating that the construction of the ecological civilization had a positive effect on taking solutions to deal with the environmental issues. The CCD score can characterize the degree of benign coupling in the coupling-interaction relationships of the subsystems of the DPSIR model, which can reflect the quality of coordination. The score of CCD was lower after ecological civilization construction (Phases III and IV) due to the decline of the I subsystem, while the growth of CCD in Phases I and II depends on the rapid economic development. The growth rate of CHEI in Phases III and IV was slightly higher than in Phases I and II. Compared with the previous ecological civilization indices, CEHI synthesized EHI and CCD, which is more precise in evaluating the ecological civilization construction from an environmental and health perspective.

3.4. The spatial characteristics of EHI, CCD, and CEHI

At the provincial level, the scores ranged from 0 to 1, with higher scores representing better overall performance in the regions. On the whole, the regional development was uneven (Fig. 4). Besides, based on the clustering trend analysis of different indices and the exploration of the reasons for its development, we divided all 30 regions into four groups to amplify. The first group is Guangdong, Zhejiang, Beijing, Shanghai, and Jiangsu; the second group is Hebei, Henan, Guizhou, Gansu, Shanxi, Ningxia, and Qinghai; the third group is Heilongjiang,

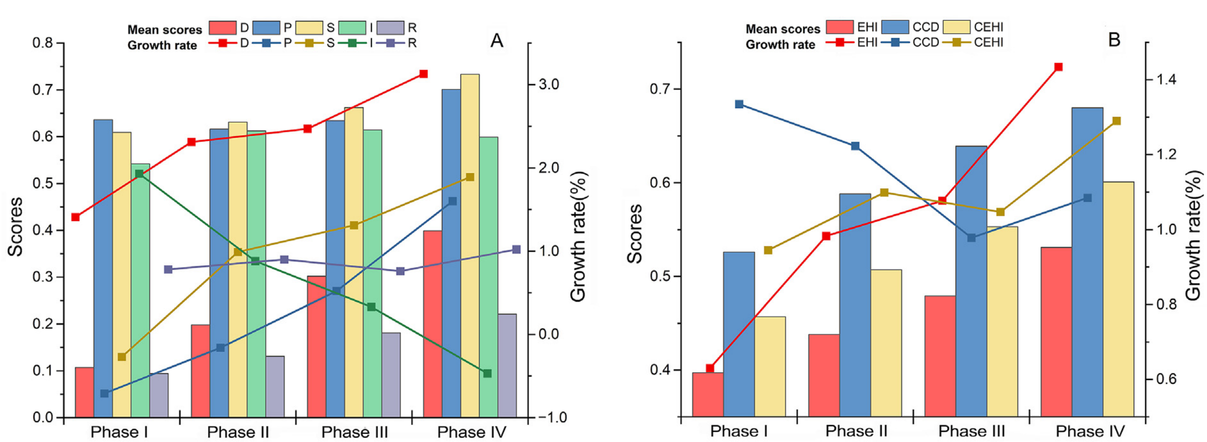

Fig. 3. Changes in DPSIR subsystem and indices (EHI, CCD, and CEHI).

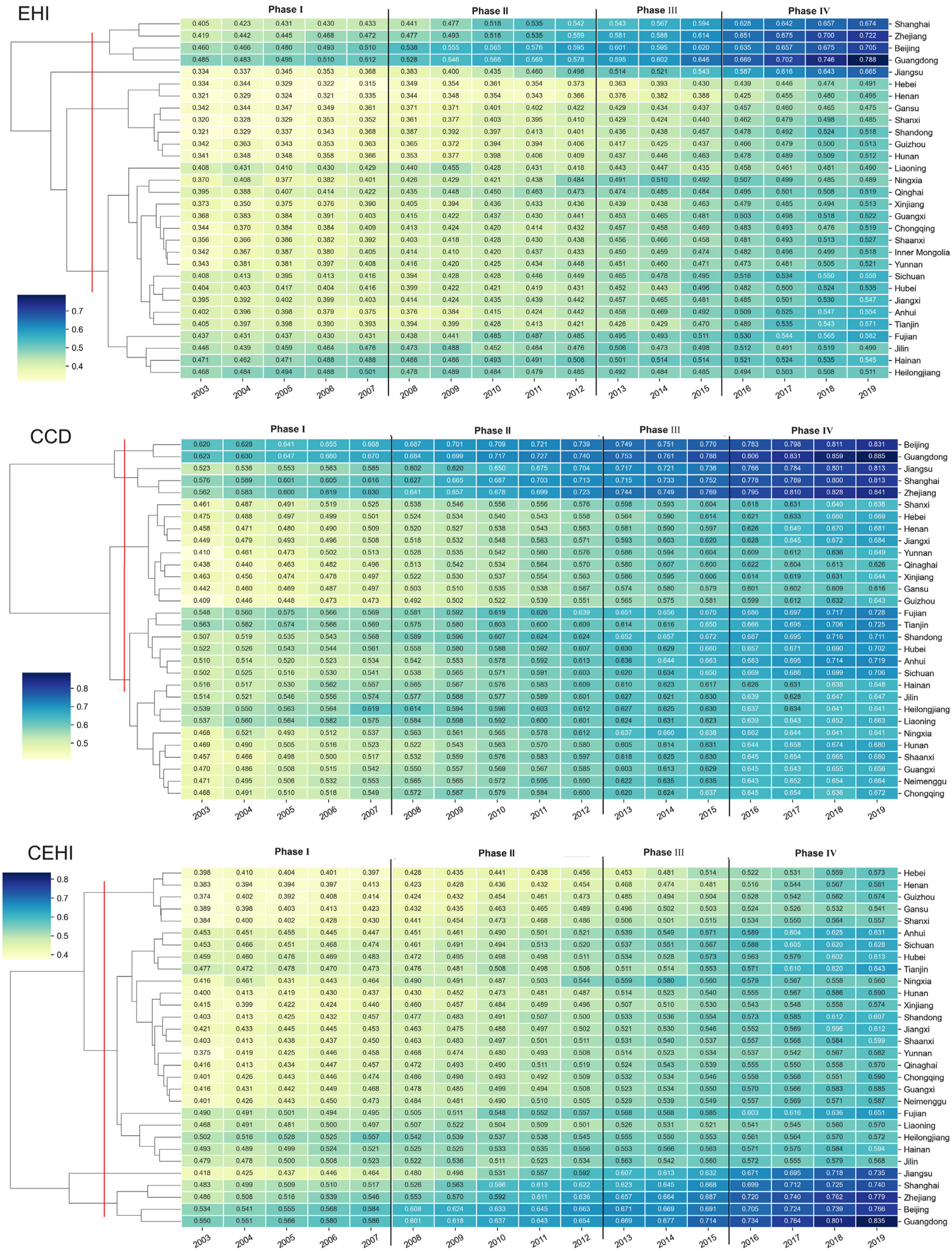

Fig. 4. The heat maps of EHI, CCD, and CEHI indices in 30 regions during 2003–2019.

Jilin, and Liaoning; and the rest is the fourth group.

By 2019, the first group was the five fastest-growing regions in terms of all the EHI, CCD, and CEHI. The heat maps show that the development trends of EHI and CEHI are consistent. The growth rate of Jiangsu was slower in Phase II than in Phases III and IV, while the growth rates of the other four regions were slightly faster. For the CCD's development, Jiangsu, Zhejiang, and Shanghai were the same, while Beijing and Guangdong were similar. The growth rates of the former slowed down after the construction of ecological civilization (in Phases III and IV), while the latter two accelerated. For the second group, the scores of EHI, CCD, and CEHI were the lowest in 2019. For Henan, Hebei, and Guizhou, the EHI scores grew faster in Phases III and IV than in Phases I and II. This indicated that the construction of ecological civilization has a positive impact on the environment-human health system in these three regions, although their lower baseline value (year 2003) resulted in lower final scores. However, the EHI scores of Gansu, Shanxi, Ningxia, and Qinghai decreased in Phases III and IV.

Similar to the second group, the third group regions, located in the northeast China, had the lowest scores. Their index score growth rates were not obvious or even negative in Phases III and IV. For the rest of the regions (the fourth group), their development of the indices was in-between. It should be noted that although Jiangxi, Fujian, Guizhou, and Hainan are ecological civilization demonstration areas, their development is not particularly prominent or tends to be consistent due to the different strategic positioning of different demonstration areas.

4. Discussion

4.1. Ecological civilization was conducive to a sustainable improvement of the ecological environment

The period of 2003–2019 in this study has been divided into four distinct Phases. Phases I and II serve as the control group for evaluating ecological civilization construction. Our findings align with earlier research [13,19,20] by confirming an overall enhancement in the ecological environment following the implementation of ecological civilization. Notably, the ecological civilization strategy stands apart from preceding sustainable development approaches, characterized by its heightened stringency and comprehensive scope. It not only mandates the preservation of resources and environmental safeguards within the industrial sector but extends this obligation to agriculture, daily life, and other human activities [42]. In a concerted effort to bolster environmental consciousness among the population, annual "National Energy Efficiency Promotion Week" have been instituted, complemented by extensive media coverage through news broadcasts, television, and the internet [43]. Recognizing the historical shortcomings of insufficient oversight and governance centered on economic development within local governments, the ecological civilization has introduced a system of inspectors focusing on energy conservation [44] and environmental protection [45], while the previous performance evaluation model based solely on economic development has been canceled. Furthermore, the ecological civilization has taken progressive steps to balance space development and preservation. These measures include the establishment of national parks and the delineation of ecological protection red lines designed to safeguard ecologically delicate regions and specific ecological functional areas. Collectively, these measures ensure that China can address the persistent degradation of its ecological environment at its foundational roots, eschewing the ephemeral and erratic improvements seen under prior policies, as exemplified by the outcomes observed in Phases I and II.

4.2. The population health improvement was comparatively modest

In the changes in EHI's subsystems, it is noteworthy that only Subsystem I did not exhibit conspicuous improvements. Further examination revealed that, in Phases III and IV, there was no discernible reduction in any of the human health indicators. This observation can likely be attributed to two primary factors. Firstly, it may be largely influenced by the early-stage advancements in medical and healthcare conditions within China. These improvements encompass the proliferation of midwifery technicians and knowledge dissemination, coupled with enhancements in transportation and living conditions [46,47]. Additionally, the reforms and developments in the Chinese medical system since 2000 have significantly bolstered the national basic medical security framework. This could also elucidate the observed improvements in overall mortality during Phases I and II. However, the elevated mortality rates witnessed in Phases III and IV may be linked to the effects of aging and the delayed impact of environmental pollution on public health. Since 2011, the population structure of China has undergone a significant change, mainly manifested in rapid population aging and declining fertility rates [48,49]. The proportion aged 65 and above grew from 7.0% in 2000 to 13.5% in 2020, according to the census data, and the mortality rate of those aged 60 and above accounted for 82.1% of the total death population from 2019 to 2020, according to the 7th census data [50]. Besides, air and water pollution predominantly manifest as chronic diseases with enduring implications for human health [31,51–53]. Secondly, the cumulative exposure effect of environmental pollution may contribute to the outcomes observed. This effect, in conjunction with improved medical and health conditions, could help explain the intricate dynamics [54].

4.3. The development of ecological civilization was uneven at the provincial level

With the passage of time, the scores of EHI, CCD, and CEHI gradually increased at the national level, but there was an imbalance at the provincial level. Basically, the development of the eastern China was better than that of the central China, and the development of the central China was better than that of the western China. In this way, from the perspective of environmental and health development, it was more consistent with the previous conclusions of ecological civilization construction [16,18–20,55]. To specifically explore the situation, it was elaborated in detail according to the four groups divided in *Section 3.4*. For the first group, the D and R subsystems increased the most, particularly after ecological civilization construction. Owing to a lot of manpower, material, and financial resources in the R subsystem, the pressure did not increase during the implementation of ecological civilization, and the environmental state was maintained [56]. In addition, the superior geographical location may also bring some convenience to its development. Due to the convenient features of ports [57], coastal areas like Guangdong, Jiangsu, Zhejiang, and Shanghai have developed more rapidly.

For the second group, though CEHI's score increased after ecological civilization, the overall level was still lower than in other groups. There may be two reasons. First, the four regions were located in the western China, which was relatively barren and had slow economic development in the early stages. After ecological civilization construction, to ensure the ecological environment and maintain the ecological service function (like Sanjiangyuan water source and Qinghai wild bird habitat protection areas), no suitable development path has been found, and the development was relatively backward. Besides, due to poor climatic conditions [58,59], most of the northwest region was an ecologically fragile area, and human activities, such as urbanization, could destroy the ecological environment relatively quickly, making recovery rather difficult.

The third group was mainly in the northeast, with most items showing negative growth except for the D subsystem. Northeast China had not found a suitable green development path either, but different from the northwest, the original rapid economic development mostly relied on the coal industry in the northeast before ecological civilization construction. When ecological civilization construction began, the R subsystem was deficient, and the Northeast experienced a significant intellectual migration [60]. All these factors have further exacerbated the risk to local population health and are detrimental to ecological civilization construction. As for the fourth group, though some other studies have found that these regions are in a leading position in green development [12,13], it is not obvious from the perspective of environment and health in this study. In addition, because these regions have relatively good ecological environment before ecological civilization construction, the exposure risk to population health may not be obvious, which may also be one of the reasons why the change of CEHI is not particularly prominent.

4.4. Limitations

This study is subject to several limitations. First, the unavailability of long-term provincial data restricted the inclusion of certain indicators and introduced potential biases. For instance, within the status system, the assessment of air quality relied solely on $PM_{2.5}$ measurements. A more comprehensive and accurate evaluation could consider other pollutants such as SO_2, O_3, and NO_2, or the index reflecting the proportion of good air quality days in a given year, particularly since 2007 when this data became available. However, the lack of continuous historical data, especially prior to 2007, limited our ability to incorporate these factors. Second, there are notable disparities between urban and rural development at the provincial level. A more in-depth analysis is warranted to explore the similarities and differences in their developmental trajectories under ecological civilization strategy. This analysis should encompass the impact of ecological civilization on rural ecological environments and the evolution of agricultural development models, particularly in light of China's Rural Revitalization Strategy introduced in 2017. Finally, while the selected health indicators within the impact section of our study provide insights into the population's health, the inclusion of more specific metrics, such as mortality rates related to chronic diseases (e.g., respiratory diseases and cancer), which have strong associations with environmental pollution, could offer a more effective pathway of gauging the health benefits resulting from ecological civilization construction. Additionally, we recommend a heightened focus on investigating the long-term health consequences of environmental pollution.

5. Conclusion and implication

CEHI synthesized EHI and CCD, offering a more refined assessment of ecological civilization construction from an environmental and health perspective. Ecological civilization represents a holistic and sustainable development strategy imbued with distinctive Chinese characteristics, presenting a fundamental solution to China's innate environmental challenges. The findings suggest that the ecological civilization strategy has successfully addressed the issue of environmental pollution in China. At the national scale, the construction of ecological civilization serves as a mechanism to sustain economic growth while concurrently providing enduring solutions to ecological harm. However, improvements in population health within the impact subsystem appeared to be less prominent after the implementation of ecological civilization. This could be attributed to the persistent effects of past exposure to environmental pollution. Additionally, the aging population may counteract the short-term health benefits resulting from environmental improvements. At the provincial level, regional development displayed significant disparities. The eastern regions exhibited the most robust development, while the western regions fared less favorably. Regions such as Beijing, Guangdong, Jiangsu, Shanghai, and Zhejiang achieved higher CEHI scores, attributed to their advantageous geographic locations and effective response subsystems. In contrast, northeastern regions (Heilongjiang, Jilin, and Liaoning) and northwestern regions (Shanxi, Gansu, Ningxia, and Qinghai) have experienced more limited progress following ecological civilization construction. In the context of China's existing technical conditions, coupled with an increased emphasis on ecological and environmental protection, the economic development of certain regions appeared to be constrained. The formulation of an appropriate and sustainable development model for these areas may consequently require an extended duration.

The adoption of the ecological civilization strategy opens up new avenues for green and sustainable development in China. In seizing this opportunity, it becomes imperative to bolster the regulatory framework for mitigating environmental pollution emissions in both industrial and agricultural sectors, thereby alleviating the mounting environmental pressures. Additionally, China can benefit from the wealth of knowledge and expertise on green management and technology available in more developed foreign nations. Despite commendable progress, China's resource management and marine protection efforts still fall short of international benchmarks [61]. Furthermore, given China's vast national expanse, regional development exhibits significant disparities. Notably, both the northeastern and northwestern regions must intensify their efforts to enhance their response subsystems. This includes augmenting local investments in scientific research and safeguarding intellectual talent. These regions should actively seek novel development models that align with the principles of ecological civilization. Moreover, the ecological civilization construction model, characterized by the integration of ecological environmental preservation into economic, political, cultural, and social development, holds the potential to serve as a valuable reference for other countries striving for sustainable development.

Credit authorship contribution statement

Y.N. G.: data curation, methodology, software, writing–original draft, preparation, modification. L.S. Y.: conceptualization, supervision, writing–review & editing. L. W.: methodology, software, writing–preparation, modification. H.R. L.: data curation, writing–original draft, preparation, modification. Q.S. G.: methodology, writing–modification.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eehl.2024.02.008.

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