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Spatial-temporal evolution and trend prediction of ecological civilization construction efficiency from the perspective of audit

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The performance evaluation of ecological civilization construction is an important content of ecological civilization audit. The super-efficiency slacks-based measure model measured inter-provincial ecological civilization construction efficiency based on the panel data of Chinese provinces and cities during 2000–2020. Based on the time series and spatial correlation analyses, the traditional and spatial Markov probability transfer matrixes were constructed to explore the spatial and temporal dynamic evolution characteristics of China's ecological civilization construction efficiency and predict its long-term trend. The study revealed that China's ecological civilization construction efficiency has a "bimodal" distribution with a stable increase in fluctuation. The gap between the peak heights is small; however, the overall ecological civilization construction efficiency is low. We also revealed that from the long-term evolution trend forecast, most provinces and cities gradually shift to higher levels of ecological civilization construction efficiency and gradually evolve into having a gradual increase pattern in the geographical context of low ecological civilization construction efficiency, resulting in the long-term evolution of the stable state performance. In the geographic context of low ecological civilization construction efficiency, the long-term evolution of the stable state is a partial "single-peaked" distribution. Finally, we analyzed the directions for improvement in this study and suggested that inter-regional ecological civilization construction policy connections and the fortification of inter-regional ecological civilization construction cooperation and exchange can effectively improve China's ecological civilization construction efficiency, narrow the gap between provinces and cities, and promote the construction of ecological civilization.

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Introduction

China's ecological progress has entered a new stage where pollution prevention and control, ecological protection, and restoration receive equal emphasis. As an important tool of national governance, national audits should actively adapt to the new needs of ecological governance to promote the construction of ecological civilization and achieve new results. However, the depth and breadth of the role of auditing in the construction of ecological civilization have not been fully demonstrated, thereby necessitating the expansion of the scope of audit responsibilities, acceleration of the transformation of resource and environmental audit, and natural resources and asset audit of leading cadres leaving office to facilitate ecological civilization audit. The performance evaluation of ecological civilization construction is an important aspect of ecological civilization audit. Economy, efficiency and effectiveness are the three dimensions of performance evaluation and are interrelated. Despite being emphasized in performance evaluation, effectiveness must be oriented towards the economy and efficiency. Therefore, how to further evaluate the efficiency of the audited unit, find the unit with low efficiency, and put forward suggestions for improvement is the key issue facing auditors when the audited unit has achieved the established goals and outputs.

In his book, Ecological Democracy, published in 1995, Morrison proposed the concept of ecological civilization (Morrison, 1995), a new form of civilization that differed from industrial civilization, thus introducing research on the construction of ecological civilization. Related scholars study ecological civilization construction mainly from the perspective of the interaction between the economy and environment, using the sustainable development index (Barrera-Roldán and Saldívar-Valdés, 2002), environmental performance index (Bastianoni et al., (2007)), and ecological footprint method to discuss regional sustainable development (Wackernagel, 2009), thereby providing significant theoretical and evaluation methods for the study of ecological civilization construction. In recent years, research on the evaluation of ecological civilization construction has increasingly become intensive. From the evaluation scope, there are three main levels: national (Lai et al., 2013), provincial (Chen et al., 2022; Zhang et al., 2022), and city (Zhang et al., 2022). From the analysis of evaluation priorities, there three main emphases: First, it focuses on resource utilization, thinking that the level of ecological civilization construction in a region is represented by the utilization degree of resources, and ecological footprint and other indicators are often used to measure it (Zuo et al., 2021); Second, it focuses on economic development and evaluates the construction of ecological civilization from the aspects of ecological finance, ecological industry, and economic development speed, among which the weight of economic indicators is relatively large (Yan et al., 2021). Third, it focuses on environmental protection and emphasizes the supervision and governance of the ecological environment. There are numerous ecological environment indicators in the index system constructed (Peng et al., 2021; Zhang et al., 2021). Although these research results have been scientific, systematic, and operable by simplifying the number of indicators and considering the cooperative relations among subsystems such as economy, society, and links, the following problems persist. First, efficiency considerations have been disregarded. At present, most studies only evaluate the status quo of ecological civilization construction in each region, and the evaluation results largely depend on the inherent economic level, industrial base, and ecological endowment of the region. However, the construction of ecological civilization should not only pursue the expansion of quantity but also consider quality improvement. The corresponding evaluation needs to measure the construction efficiency to make full use of limited resources and thus accelerate the construction of ecological civilization. Although certain scholars have begun to attach importance to the efficiency of ecological civilization construction, most of them calculate the ecological efficiency on the basis of GDP, resulting in the large economic provinces being highly correlated with the large ecological provinces (Meng et al., 2021; Du et al., 2021). Second, comprehensive elucidation is lacking. At present, the theoretical framework of ecological civilization construction research is not perfect, resulting in an excessive emphasis on ecological protection and economic development of the evaluation index, thereby complicating the accurate reflection of the connotation of ecological civilization construction. As the main goal of ecological civilization construction, optimizing the pattern of territorial space development has not received enough attention in the existing evaluation index system. Although a few scholars (Cui and Jin, 2021; Zhao et al., 2021) have carried out innovative research, further exploration is needed in terms of the comprehensiveness and operability of the index.

In summary, the non-expected output slacks-based measure (SBM) model overcomes the inherent defects of the traditional Data Envelopment Analysis (DEA) model by introducing relaxation variables of input-output and non-expected output into linear programming expressions; moreover, introducing it into the efficiency evaluation of ecological civilization construction and constructing corresponding evaluation indexes is scientific and reasonable. Its applicability is embodied in the following three aspects. First, the construction of ecological civilization is an activity embodied in the multi-input of funds and resources and the output of the economy, society, environment and other aspects, and there is no similarity between these inputs and outputs. Auditors have difficulty constructing evaluation indicators to measure and evaluate the efficiency level. Instead of the expected output, the SBM model finds the most appropriate weighted set between input and output using a computer and directly realizes the calculation of efficiency value. In this case, auditors only need to construct corresponding input indicators and output indicators according to audit objectives and audit content to carry out efficiency evaluation, and determining the weight between these indicators is unnecessary. Second, the specific conditions of ecological civilization construction in different places vary, thereby complicating the uniformization of the evaluation standards. Furthermore, the inconsistent standards make the audit conclusions different, thus complicating adaptation to the current common special audit organization. Instead of the expected output, the SBM model can effectively overcome this problem through quantitative calculation of the efficiency of ecological civilization construction. Auditors only need to compare the efficiency values to determine the efficiency of different units. Third, the construction of ecological civilization is a systematic project to realize the coordinated development of the economy, society, and environment. This process is inevitably accompanied by the production of environmental pollutants and other undesirable outputs. By constructing the evaluation index of the unexpected output, the efficiency value obtained by this model can better reflect the essential attributes of ecological civilization.

Materials and methods

Super-efficiency SBM model based on non-desired outputs. The non-expected output-based SBM model was first proposed by Tone in 2001 (Tone, 2001). Tone further defined the super-efficiency SBM model based on the SBM model (Tone, 2002). The SBM model combines the super-efficiency DEA and SBM models and their advantages. Compared to the general SBM model, the super-efficiency SBM model can compare and distinguish efficient DMUs in the frontier plane, and the model is expressed as follows:

$$Min\,p = \frac{\frac{1}{m}\sum_{i=1}^{m}(\overline{x}/x_{ik})}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\overline{y^d}/y_{sk}^d + \sum_{q=1}^{r_2}\overline{y^u}/y^u q^k\right)} \quad (1)$$

$$\begin{cases} \overline{x} \geq \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j; \overline{y^d} \leq \sum_{j=1,\neq k}^{n} y_{sj}^d\lambda_j; \overline{y^d} \geq \sum_{j=1,\neq k}^{n} y_{qj}^d\lambda_j; \overline{x} \geq x_k; \overline{y^d} \leq y_k^d; \overline{y^u} \geq y_k^u; \\ \lambda_j \geq 0, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n, j \neq 0; s = 1, 2, \cdots, r_1; q = 1, 2, \cdots, r_2; \end{cases} \quad (2)$$

Where p is the efficiency value of ecological civilization construction; m, r_1, and r_2 respectively represent the number of indicators of input, expected output, and unexpected output; $\bar{X}$, $\overline{y^d}$, and $\overline{y^u}$ represent the relaxation variables of the ith input element, the sth expected output, and the qth unexpected output respectively; X_{ik}, yd_{sk}, and yu_{qk} respectively represent the optimal input quantity of factor i, expected output quantity of factor s, and unexpected output quantity of factor q in the kth decision-making unit improved by relaxation variables; k is the number of decision-making units; X_{ij}, y_{sk}^d, and y_{qk}^u respectively represent the input quantity of factor i, expected output quantity of factor s, and unexpected output quantity of factor q of the jth decision-making unit; λ_j is the weight vector.

Non-parametric Kernel Density Estimation. Density mapping (Yan and Hou, 2015), a process of surface interpolation through discrete sampling points, includes kernel density estimation, a non-parametric estimation method that can describe the distribution pattern of a random variable with a continuous density curve. Supposing the density function of the random variable is *f(x)*, and for the random variable Y, there are n independent and identically distributed observations, y1, y2, …, yn, the Kernel density function estimate is expressed as follows (Ye, 2005):

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{y_i - y}{h}\right) \quad (3)$$

Where n is the number of study regions; h is the window width (bandwidth); *K(-)* is a random kernel, weighting, or smoothing function, including Gaussian (Normal), Epanechnikov, Triangular, Quartic, and other kernel types. In this study, the kernel density function of Gaussian Kernel distribution was used, and the window width was $h = 0.9SeN^{-0.2}$ ($c = 0.9Se$, Se was the standard deviation of the random variable observations). Kernel density estimation was performed using Eviews software.

Spatial correlation analysis. The efficiency of the ecological civilization construction varies owing to differences in resources, economies, and spatial contexts of different regions. Therefore, the geographical location of a region affects its ecological civilization construction efficiency and that of its neighboring regions. In this case, the spatial autocorrelation of regional ecological civilization construction efficiency, including global and local spatial autocorrelation, needs to be measured. In this study, global spatial autocorrelation was used to understand the spatial correlation and differences in regional ecological civilization construction efficiency. Additionally, in spatial statistics, the statistical index commonly used to measure the degree of spatial autocorrelation is Moran's I index, calculated formulas follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \overline{x}\right)\left(x_j - \overline{x}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \overline{x}\right)^2} \quad (4)$$

Where n is the sample size; x_i and x_j are the observations of spatial positions i and j; w_{ij} represents the proximity relationship between spatial positions i and j, when i and j are adjacent, $w_{ij} = 1$; otherwise, it is 0. The value range of the global Moran's I index is $[-1, 1]$; it is a spatial positive correlation when it exceeds 0, a negative correlation when it is below 0, and uncorrelated when equal to 0.

Table 1 Probability transfer matrix of Markov chain ($N = 4$).

t_i/t_{i+1}	1	2	3	4
1	P_{11}	P_{12}	P_{13}	P_{14}
2	P_{21}	P_{22}	P_{23}	P_{24}
3	P_{31}	P_{32}	P_{32}	P_{34}
4	P_{41}	P_{42}	P_{43}	P_{44}

Table 2 Conditional probability transfer matrix of spatial Markov chain ($N = 4$).

Spatial lag	t_i/t_{i+1}	1	2	3	4
1	1	$P_{11/1}$	$P_{12/1}$	$P_{13/1}$	$P_{14/1}$
	2	$P_{21/1}$	$P_{22/1}$	$P_{23/1}$	$P_{24/1}$
	3	$P_{31/1}$	$P_{32/1}$	$P_{32/1}$	$P_{34/1}$
	4	$P_{41/1}$	$P_{42/1}$	$P_{43/1}$	$P_{44/1}$
2	1	$P_{11/2}$	$P_{12/2}$	$P_{13/2}$	$P_{14/2}$
	2	$P_{21/2}$	$P_{22/2}$	$P_{23/2}$	$P_{24/2}$
	3	$P_{31/2}$	$P_{32/2}$	$P_{32/2}$	$P_{34/2}$
	4	$P_{41/2}$	$P_{42/2}$	$P_{43/2}$	$P_{44/2}$
3	1	$P_{11/3}$	$P_{12/3}$	$P_{13/3}$	$P_{14/3}$
	2	$P_{21/3}$	$P_{22/3}$	$P_{23/3}$	$P_{24/3}$
	3	$P_{31/3}$	$P_{32/3}$	$P_{32/3}$	$P_{34/3}$
	4	$P_{41/3}$	$P_{42/3}$	$P_{43/3}$	$P_{44/3}$
4	1	$P_{11/4}$	$P_{12/4}$	$P_{13/4}$	$P_{14/4}$
	2	$P_{21/4}$	$P_{22/4}$	$P_{23/4}$	$P_{24/4}$
	3	$P_{31/4}$	$P_{32/4}$	$P_{32/4}$	$P_{34/4}$
	4	$P_{41/4}$	$P_{42/4}$	$P_{43/4}$	$P_{44/4}$

Spatial Markov chain theoretical basis. Assuming that P_{ij} is the transfer probability of the ecological civilization construction efficiency of a region from state i in year t to state j in year $t+1$. The transfer frequency can be used to approximate the estimation of state transfer probability $P_{ij} = n_{ij}/n_i$, where n_{ij} represents the number of provinces that have transferred from state i in year t to state j in year $t+1$ during the sample investigation period, and n_{ij} represents the number of provinces that belong to state i during the sample investigation period and meet $\sum_j P_{ij} = \sum_j P\{X_{n+1} = j \mid X_n = i\} = 1$ (Fingleton, 1997). Supposing the ecological civilization construction efficiency is divided into N states; an $N \times N$ state transfer probability matrix can be constructed (see Table 1). The direction of transfer is the upward (increase) and downward (decrease) constant changes of ecological civilization construction efficiency types.

The spatial lag type of a region is determined by classifying the spatial lag value of its ecological civilization construction efficiency value in the initial year (See Table 2). The spatial lag value is the spatially weighted average of the ecological civilization construction efficiency values of the neighboring regions of the selected region, estimated using the product of the regional ecological civilization construction efficiency value and the spatial weight matrix $\sum_j W_{ij}Y_j$. Y_j denotes the ecological civilization construction efficiency value of a region. W_{ij} denotes the element of the spatial weight matrix W. In this study, the principle of common boundary is used to determine the spatial weight matrix if the regions are adjacent, $W_{ij} = 1$; otherwise, $W_{ij} = 0$.

Table 3 Evaluation indicator system of ecological civilization construction efficiency.

Type	Indicator name	Unit
Investment	Energy conservation and environmental protection expenditure	RMB100mn
	Total energy consumption	10,000 tons of standard coal
Expected output	Days of good air quality in a year	day
	Total sewage treatment	10,000 tons
	GDP	RMB100mn
	Per capita disposable income of residents	RMB/person
	Ecological restoration area	hectares
Unexpected output	Discharge of main pollutants	10,000 tons

The Markov probability transfer matrix can be used to determine the smooth distribution of this stochastic process, which can predict the dynamic evolution trend of an economic phenomenon (ecological civilization construction efficiency in this study). For instance, in the traditional Markov chain $\{X_n, n = 0, 1, 2, \cdots\}$, state space, p_{ij} is the one-step transfer probability, and $\{\pi_i, i \in S\}$ is the probability distribution of each state. If $\{\pi_i, i \in S\}$ satisfies the equation system $\pi_i = \sum_{j=0}^{\infty} \pi_j p_{ij} (i = 0, 1, 2, \cdots)$, the probability distribution $\{\pi_i, i \in S\}$ of the traditional Markov chain is the smooth distribution. Extending it to spatial Markov chains, the smooth spatial distribution under each spatial lag type is obtained according to the similarity principle. The maximum value of the transfer probability is considered the possible evolution trend of the corresponding state (Hou and Yao, 2018).

Indicator system and data source

Indicator system. Ecological civilization construction is a major strategic task proposed by China based on the severe situation of resource constraints, severe environmental pollution, and ecosystem degradation. The basic path of ecological civilization construction includes resource conservation, environmental protection and management, and ecological protection and restoration. Audit institutions should focus on these three basic approaches when evaluating the effectiveness of ecological governance of governments at all levels. Therefore, in this study, we build upon previous research results (Wang and Chen, 2021), and believe that the evaluation of the efficiency of ecological civilization construction is reflected in three aspects: resource utilization efficiency, environmental pollution control efficiency, and ecological protection and restoration efficiency.

(1) Resource utilization efficiency. The extensive exploitation of resources has caused the destruction of ecological environment. The basis of ecological civilization lies in the economical utilization of resources. To realize ecological civilization, realizing optimal utilization of resources is the top priority of all levels of government, and the evaluation of resource utilization efficiency of audit institutions is an important regulatory means. Resources are not only important materials on which social and economic development depend but also essential material sources for daily production and living. However, environmental pollutants discharged in the process of resource utilization affect environmental quality. Therefore, auditing institutions should include the following elements when evaluating the efficiency of resource utilization: whether governments at all levels and relevant departments use limited resources to maximize economic output and promote the improvement of people's living standards to the greatest extent; whether they reduce environmental damage as much as possible in the process of resource utilization, that is, whether the utilization of resources produces corresponding economic and social benefits; and whether they pay attention to ecological benefits at the same time.

(2) Efficiency of environmental pollution control. Environment is the space on which human beings live, and all human activities are inseparable from it. Good ecological and living environments are related to people's sense of happiness and gain. Effective environmental protection and governance and with the creation of a beautiful habitat with a blue sky, green land, and clean water for future generations is key to the construction of ecological civilization. Therefore, when evaluating the efficiency of government environmental pollution control, audit institutions should pay attention to whether governments at all levels can achieve the maximum effect of air, water, and soil pollution control with limited financial investment.

(3) Efficiency of ecological protection and restoration. Resource abuse has caused extensive land desertification, desertification, natural grassland degradation; in the wake of such a severe ecological reality, ecological protection and restoration are particularly urgent, and governments at all levels need to fortify ecological restoration to achieve ecological civilization construction. As an important regulatory tool in the ecological governance system, audit institutions should supervise and evaluate the ecological restoration results, and at the same time, pay attention to the financial funds invested to evaluate the efficiency of ecological protection and restoration.

Based on the above analysis, the evaluation index of ecological civilization construction efficiency based on the non-expected output SBM model constructed in this paper is shown in Table 3.

(1) Input index. Capital investment is the starting point for the government to realize the three basic tasks of resource-saving, environmental pollution control, and ecological protection and restoration. Therefore, "Expenditure on energy conservation and environmental protection" is one of the investment indicators. At the same time, to evaluate the efficiency of resource utilization, we used "total energy consumption" to measure resource consumption.

(2) Output index. Combined with the content of efficiency evaluation, the output index should be able to reflect the achievements of resource conservation, environmental pollution control, and ecological protection and restoration.

Under the connotation concept of ecological civilization construction, resource utilization should realize the output of the economy, society, and environment, to promote the common development of the economy, society, and environment. On the economic side, "GDP" measures its economic output; On the social side, output in terms of social benefits is measured in terms of "per capita disposable income of residents". On the environmental side, output in terms of ecological benefits is measured in

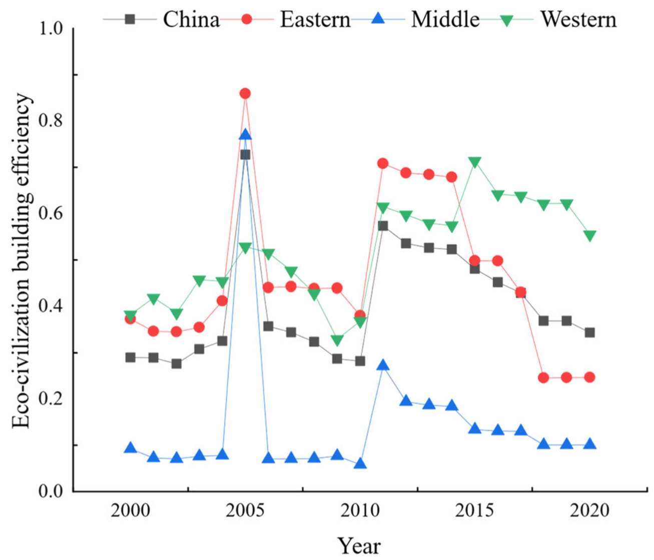

Fig. 1 The evolutionary trend of ecological civilization construction efficiency in China from 2000–2020. Based on DEASOLVER Pro 5.0 software, the non-radial (non-oriented), variable scale payoff (VRS) super-efficient SBM model was used to measure the ecological civilization construction efficiency of 31 provinces and cities in China in 2000–2020, estimate the average yearly value, and adopt the usual 11:8:12 East-West regional division method to conduct a comparative analysis of different regional ecological civilization constructional efficiencies.

terms of "major pollutant emissions". According to the composition of the main pollutants, the discharge is calculated by summing up the chemical oxygen demand, ammonia nitrogen emission, sulfur dioxide emission, and nitrogen oxide emission.

Output indicators for pollution control should be able to reflect the effect of water, air, and soil pollution control. The Water Pollution Control Action Plan calls for the improvement of water quality and an increased proportion of good water quality; however, available water quality data are based on river basins rather than localities, thereby complicating water quality measurements. At the same time, reducing polluted water is a key means to improving water quality. Therefore, "total sewage treatment" was selected as the output index in the present study. In addition, combined with the air control targets in the Air Pollution Control Action Plan, "the number of days in a year with good air quality" is selected as the output index of air pollution control. Considering the lack of data related to soil and the fact that the main sources of soil pollution are closely connected with pollution sources of water and air pollution, no separate output index is set to measure the quality of soil pollution control. The key to measuring the governance results of ecological protection and restoration is the size of the ecological restoration area; therefore, the "ecological restoration area" is selected as the output index. Governments at all levels and relevant departments should focus on increasing the wetland protection rate, thereby improving the grassland coverage rate and promoting desertification land management through grass planting and afforestation measures. Therefore, the "ecological restoration area" herein represents the sum of the area of the constructed wetland, the cumulative grass planting and retention area, and the total afforestation area.

Data sources. In this study, 31 provinces in China from 2000 to 2020 were selected to calculate the efficiency of ecological civilization construction. Expenditure on energy conservation and environmental protection, GDP, and per capita discretionary income were obtained from the China Statistical Yearbook for 2001–2021, total energy consumption was obtained from the China Energy Statistical Yearbook for 2001–2021, and other data are from the China Environmental Statistical Yearbook for 2001–2021.

Results and discussion

Environmental efficiency of ecological civilization construction in China and time series analysis. Based on DEASOLVER Pro 5.0 software, the non-radial (non-oriented), variable scale payoff (VRS) super-efficiency SBM model was used to measure the ecological civilization construction efficiency of 31 provinces and cities in China in 2000–2020, estimate the average yearly value, and adopt the usual 11:8:12 East-West regional division method to conduct a comparative analysis of different regional ecological civilization constructional efficiencies. The mean efficiency values were compared and analyzed (see Fig. 1).

The non-parametric Kernel density function with normal Gaussian distribution (Liao and Zhang, 2021; Liao and Zhang, 2022) was used to continue exploring the clustering differences in the evolution of ecological civilization construction efficiency over time in each province and city. Five years, 2000, 2005, 2010, 2015, and 2020, were the observation time points for kernel density estimation (Munro et al., 2019) to obtain the distribution at different time points (see Fig. 2). The peak heights reflect the degree of agglomeration of ecological civilization construction efficiency in each province. As seen in Fig. 2, China's overall ecological civilization construction efficiency displays a bimodal evolutionary distribution from left to right, with peaks from high to low. This is a steady improvement trend of ecological civilization construction efficiency in China over time, with most provinces and cities gradually moving from low to high-low agglomeration levels.

Analysis of spatial and temporal characteristics of China's ecological civilization construction efficiency. We aimed to scientifically reflect on the spatial divergence characteristics of China's ecological civilization construction efficiency. According to China's ecological civilization construction efficiency in 2000–2020, we borrowed the ArcGIS10.5 software and selected data from 2000, 2005, 2010, 2015, and 2020 to draw the spatial distribution map of China's large ecological civilization construction efficiency (see Fig. 3).

Temporal evolution characteristics of ecological civilization construction efficiency in China. The temporal and Kernel density analyses of ecological civilization construction efficiency portray the temporal trends and evolutionary differences of ecological civilization construction efficiency. However, they cannot comprehensively reflect its inherent spatial and temporal evolutionary laws. First, the traditional Markov chain probability transfer matrix was determined, and 31 provinces and cities were divided into different types of state spaces according to the high and low ecological civilization constructional efficiencies in 2000–2020. Considering that the observations in each province and city were approximately the same, the ecological civilization construction efficiency values were divided into four adjacent but not mutually intersecting completeness intervals. These four states of completeness intervals are denoted by $k = 1$, 2, 3, and 4, respectively. A larger k indicates higher regional ecological civilization construction efficiency. In addition, according to the evolutionary trend of Fig. 1, the entire study period was roughly divided into two phases: 2000–2010 and 2011–2020. The traditional Markov probability transfer matrix was obtained according to the division of state types, respectively (see Table 4). The

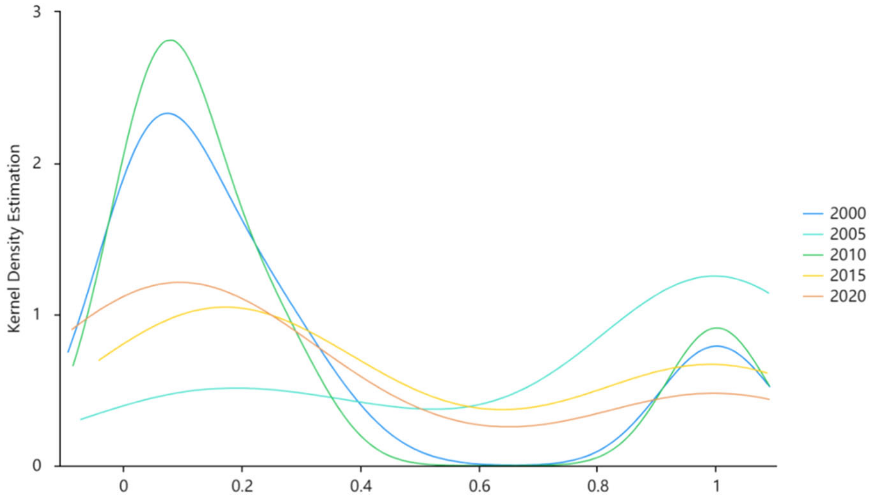

Fig. 2 The Kernel density estimation of ecological civilization construction efficiency in China. The non-parametric Kernel density function with normal Gaussian distribution was used to continue exploring the clustering differences in the evolution of ecological civilization construction efficiency over time in each province and city. Five years, 2000, 2005, 2010, 2015, and 2020, were the observation time points for kernel density estimation to obtain the distribution at different time points.

elements on the diagonal of Table 4 indicate the probability that the state types of regional ecological civilization construction efficiency remained unchanged. This reflects the stability of the region's evolution of ecological civilization construction efficiency.

Furthermore, ecological civilization construction efficiency exhibits a significant trend of shifting toward high levels. From the perspective of the frequency of shifting in both phases, the number of types 1 and 2 in 2010–2020 is significantly less than that in 2000–2010. In contrast, the number of types 3 and 4 is more than that in 2000–2010. Nonetheless, differences were observed in the transfer within different stages. Moreover, the difference between the probability of types 2 and 3 transferring upward or downward was relatively small during 2000–2010. The difference between P22 and P33 was also relatively small, indicating that the change in ecological civilization construction efficiency is more stable in the provinces and cities at this stage. In contrast, in 2011–2020, $P_{21} = 0.1528 < P_{23} = 0.1806$, $P_{32} = 0.0787 > P_{34} = 0$. Therefore, the probability of continuous improvement in ecological civilization construction efficiency of provinces and cities within this period was relatively high.

Spatial evolution characteristics of ecological civilization construction efficiency in China

Analysis of the spatial distribution pattern of ecological civilization construction efficiency in China. Based on China's estimated ecological civilization construction efficiency in 2000–2020, ArcGIS10.5 software was used to obtain the relevant parameters of the standard deviation ellipse of China's ecological civilization construction efficiency (Zheng et al., 2018). The direction of its center of gravity, distance (east-west and north-south directions), and shape index (the ratio of the short to the long half-axes) were determined to obtain the spatial distribution pattern of China's ecological civilization construction efficiency (see Fig. 4).

The center of gravity of the spatial distribution pattern of the efficiency of China's ecological civilization construction has experienced the changes of "Northwest (2000–2004)–Southeast (2004–2008)–Northeast (2008–2012)–Southeast (2012–2016)–Northeast (2016–2020)", and the overall trend of moving to the northwest. The moving speed of the center of gravity in the east-west and north-south directions during 2000–2008 was 9.16 km/a and 7.87 km/a respectively. The east-west and south-north moving speeds of the center of gravity during 2008–2012 were 5.06 km/a and 3.16 km/a, respectively. During 2012–2020, the east-west moving speed of the center of gravity slowed down, while the south-north moving speed increased slightly. During 2012–2020, the moving speed of the center of gravity in the east-west direction and the south-north direction decreased to 4.13 km/a and 3.09 km/a, respectively.

The rotation angle during the study period was θ. The variation range of temperature was 87.54–104.85°. Specifically, the rotation angle decreased from 104.85 ° in 2000 to 101.69° in 2004. At this time, the spatial distribution pattern of the efficiency of China's ecological civilization construction presented a northeast –southwest trend, but this stage only focused on the speed and scale of economic development, disregarding the ecological environmental benefits. Therefore, the rotation angle decreased to 102.25° in 2008, and the spatial distribution pattern of the efficiency of ecological civilization construction almost presented a due north - due south pattern. From the "11th Five-Year Plan" to the early stage of the "12th Five-Year Plan", and following the appearance of the marginal effect of environmental protection investment in the western region in the early stage, the rotation angle decreased from 96.35° in 2012 to 97.38° in 2016. At this time, the spatial distribution pattern of the efficiency of ecological civilization construction presented a north-south pattern; In the later stage of the 12th Five-Year Plan, although the rotation angle gradually declined, the decline was small, and the spatial distribution pattern of the efficiency of ecological civilization construction remained basically stable.

Spatial distribution pattern of ecological civilization construction efficiency type transfer in China. With the increasing improvement in China's economy and the expansion of inter-regional openness, the spatial mobility of production factors is increasing in frequency. In addition, the spatial connections between economies are growing (Cuccia et al., 2017), and the location effects of ecological civilization construction efficiency between neighboring provinces and cities will increase in significance. To gain insight into the spatial and temporal evolution differences of ecological civilization construction efficiency in different provinces and cities, a spatial Markov chain probability transfer matrix was constructed to compare the corresponding elements in both matrices and explore the relationship between the transfer

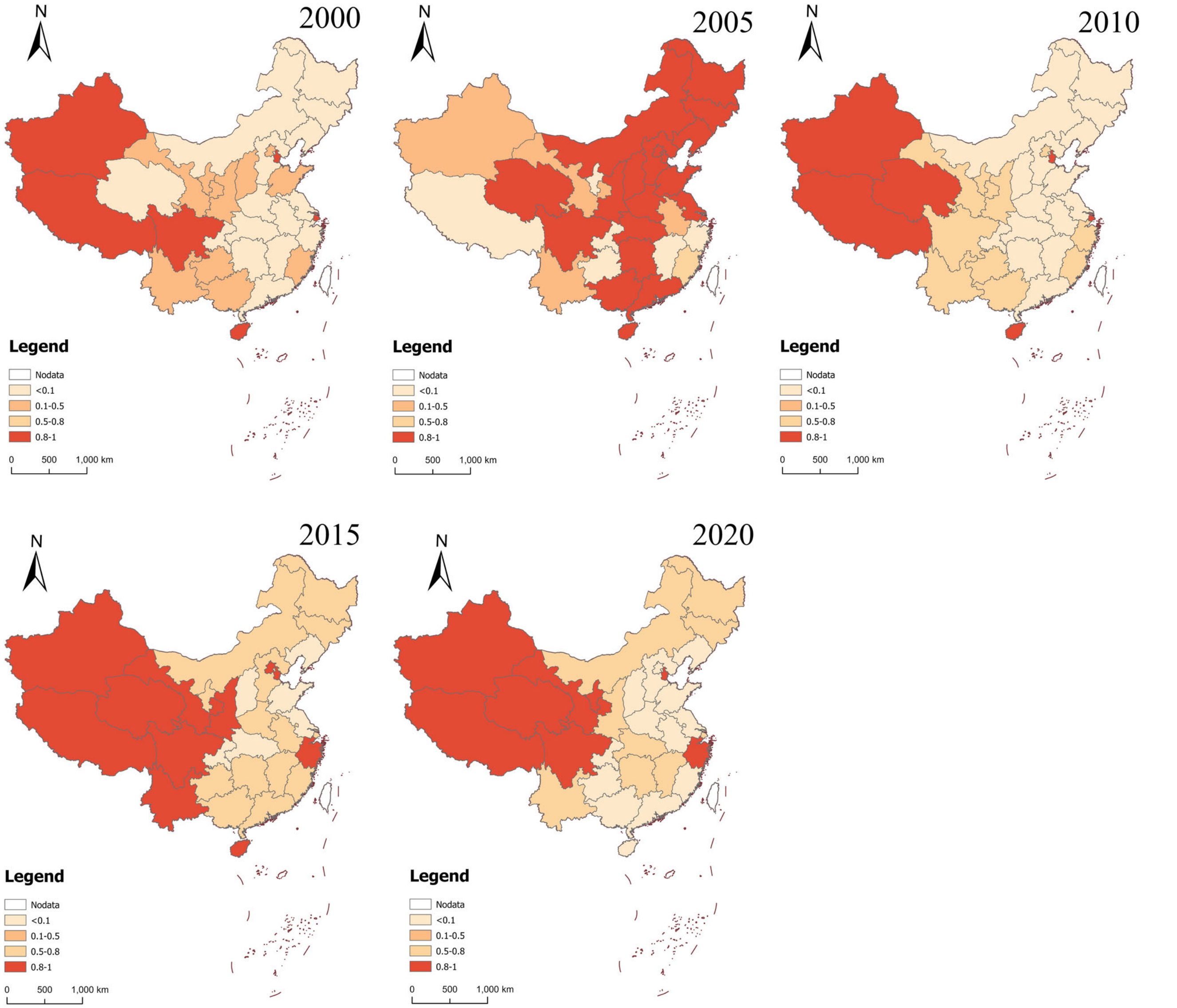

Fig. 3 The spatial distribution of ecological civilization construction efficiency in China. According to China's ecological civilization construction efficiency in 2000–2020, we borrowed the ArcGIS10.5 software and selected 2000, 2005, 2010, 2015, and 2020 data to draw the spatial distribution map of China's large ecological civilization construction efficiency.

Table 4 Traditional Markov probability transfer matrix of ecological civilization construction efficiency in China from 2000 to 2020.

$t/t+1$	2000–2010					2011–2020				
	n	**1**	**2**	**3**	**4**	***n***	**1**	**2**	**3**	**4**
1	72	0.7083	0.1944	0.0972	0	72	0.7639	0.1944	0.0417	0
2	87	0.1494	0.7356	0.1149	0	72	0.1528	0.6667	0.1806	0
3	64	0.0781	0.0625	0.6719	0.1875	127	0.0472	0.0787	0.8740	0
4	56	0.0536	0.0893	0.0714	0.7857	8	0.265683	0.2657	0.4686	0

probability of ecological civilization construction efficiency types in a province and city and the neighboring provinces and cities with or without the influence of spatial context. Based on the ArcGIS 10.5 platform, the spatial distribution of ecological civilization construction efficiency transfer in two periods—2000–2010 and 2011–2020—was plotted (see Fig. 5).

The traditional Markov probability transfer matrix does not consider the influence of the surrounding neighborhood transfer. The upward or downward transfer of ecological civilization construction efficiency is not isolated in space. However, it is paved with the surrounding neighborhood and is effectively related. Based on the traditional Markov probability transfer matrix, the geographic spatial context factor is introduced to construct the spatial Markov probability transfer matrix conditional on the spatial lag type of each province and city in the initial year. The spatial Markov probability transfer matrix was

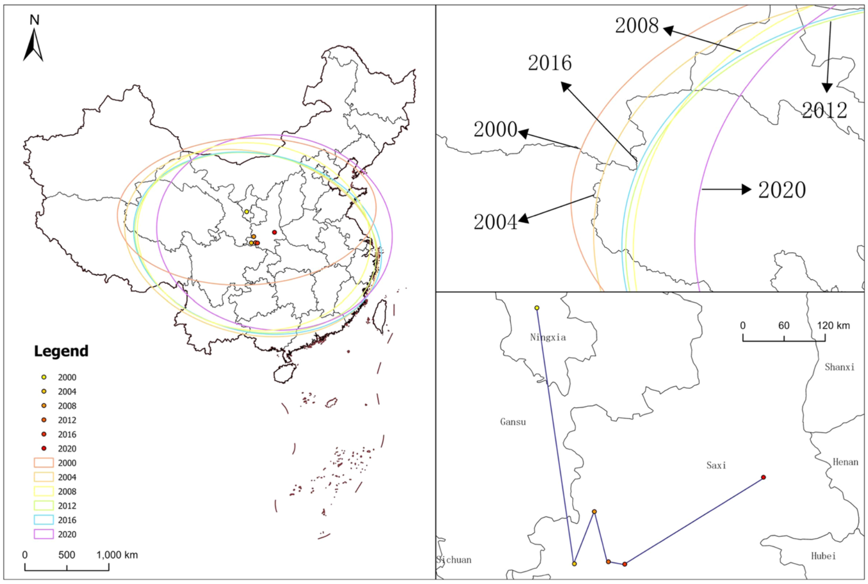

Fig. 4 The standard deviational ellipse of ecological civilization construction efficiency and trajectories of gravity in China from 2000–2020. Based on China's estimated ecological civilization construction efficiency in 2000–2020, ArcGIS10.5 software was used to obtain the relevant parameters of the standard deviation ellipse of China's ecological civilization construction efficiency.

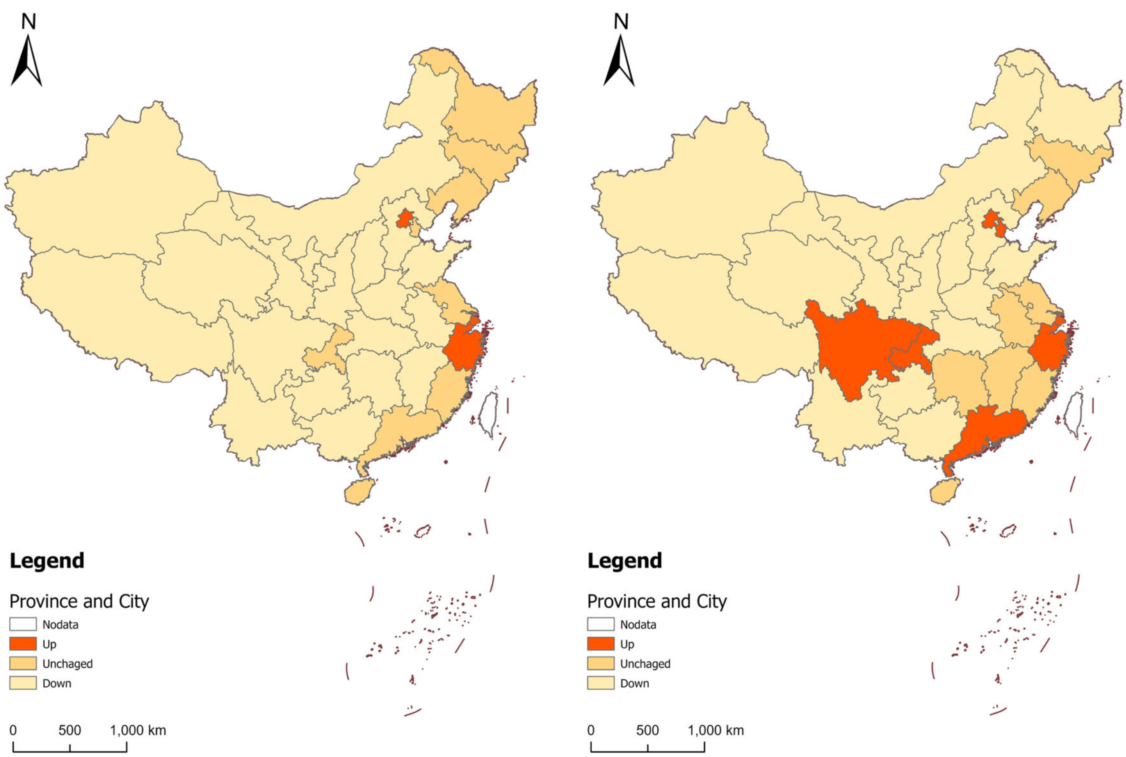

Fig. 5 Spatial distribution of ecological civilization construction efficiency type transfer in China in different stages. Based on the ArcGIS 10.5 platform, the spatial distribution of ecological civilization construction efficiency transfer in two periods—2000–2010 and 2011–2020—is plotted.

obtained based on the spatial lag types of different regions in the initial years. The division of both study periods reveals that the type transfer of ecological civilization construction efficiency is unstable with time. Similarly, the spatial Markov probability transfer matrices are established for 2000–2010 and 2011–2020 (see Table 5). The spatial pattern distribution (see Fig. 6) was determined to examine the influence of the surrounding neighborhoods on different provinces and cities on the efficiency of the ecological civilization construction.

The above comparative analysis between matrices reveals that the spatial context pattern greatly impacts the spatio-temporal evolution of ecological civilization construction efficiency in China. The provinces and cities with higher ecological civilization construction efficiency have a positive spillover effect by increasing the possibility of an upward shift in the surrounding provinces and cities. Conversely, the provinces and cities with lower ecological civilization construction efficiency inhibit the upward shift possibility of the surrounding provinces and cities and continue to maintain the low

Table 5 Spatial Markov probability transfer matrix of ecological civilization construction efficiency in China from 2000 to 2020.

t/*t* + 1		2000–2010					2011–2020				
		n	1	2	3	4	*n*	1	2	3	4
1	1	51	0.797	0.141	0.062	0	9	0.725	0.157	0.078	0.039
	2	11	0.151	0.671	0.151	0.027	51	0.161	0.661	0.125	0.054
	3	4	0.053	0.093	0.68	0.173	4	0.085	0.136	0.678	0.051
	4	2	0.03	0.045	0.104	0.821	0	0.015	0.015	0.088	0.75
2	1	9	0.714	0.19	0.095	0	11	0.583	0.333	0.083	0
	2	49	0.1	0.7	0.2	0	49	0.133	0.533	0.2	0.133
	3	7	0.056	0.111	0.667	0.167	11	0.1	0.2	0.6	0.1
	4	3	0	0	0.333	0.667	2	0	0	0	0.846
3	1	4	0.778	0.167	0.056	0	4	0.7	0.1	0.1	0.1
	2	11	0.211	0.737	0.053	0	7	0.143	0.786	0.071	0
	3	51	0	0.176	0.706	0.118	51	0	0.444	0.556	0
	4	7	0	0.133	0	0.867	13	0	0	0.125	0.812
4	1	0	0.8	0.1	0.1	0	2	0.333	0.333	0.333	0
	2	2	0.167	0.667	0.083	0.083	3	0.05	0.05	0.1	0.7
	3	13	0.045	0	0.682	0.273	7	0.125	0.688	0.125	0.062
	4	55	0.071	0.036	0.071	0.821	55	0	0	0.2	0.4

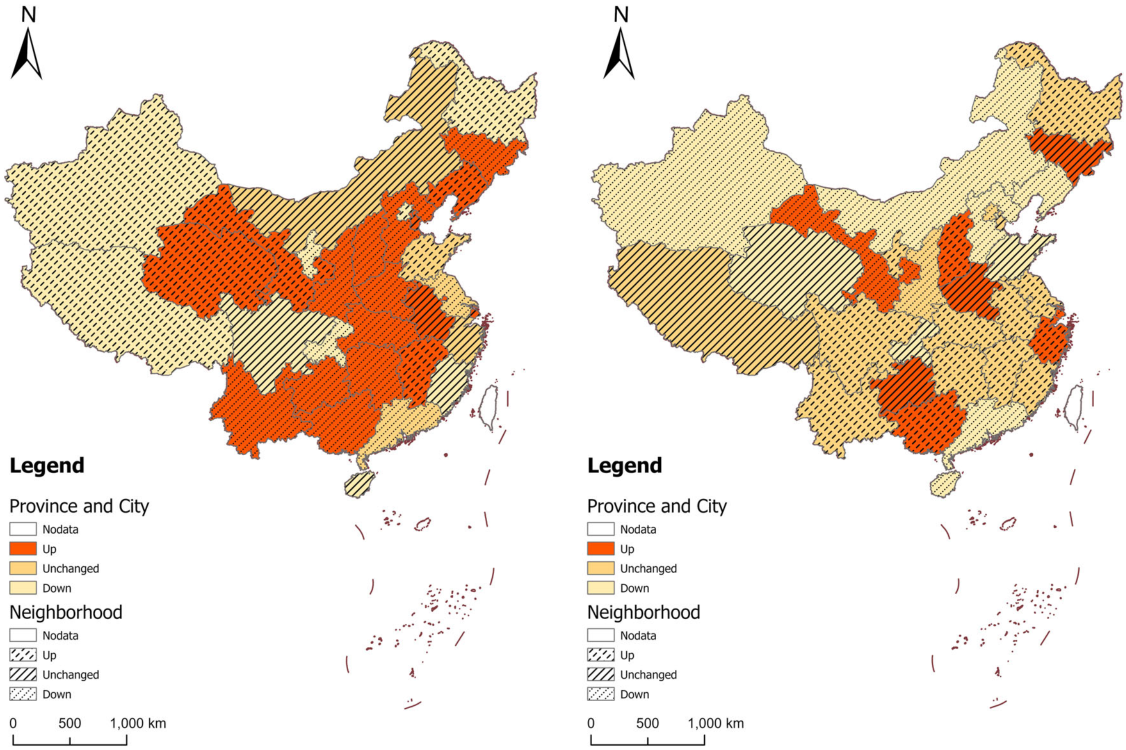

Fig. 6 Spatial distribution of ecological civilization construction efficiency type transfer and adjacent in China in different stages. The spatial pattern distribution was determined to examine the influence of the surrounding neighborhoods on different provinces and cities on the efficiency of the ecological civilization construction.

ecological civilization construction efficiency. With the negative spillover effect, the spatial pattern gradually formed the high-high agglomeration, low-low agglomeration, high radiation low, low inhibition high, and club convergence phenomenon. Therefore, the Spatial Markov chain provides a spatial explanation for "club convergence" (Ramona et al., 2017; Pearce, 2011; Nina, 2020; Purnomo et al., 2020).

Trend prediction of the spatial and temporal evolution of ecological civilization construction efficiency in China

Trend prediction of the spatial distribution pattern of ecological civilization construction efficiency in China. The GM (1,1) in the gray dynamic model is used to construct a time series model for each parameter of the standard deviation ellipse of the efficiency of China's ecological civilization construction, and the prediction results are tested by the posterior difference test method. According to the predicted elliptic parameters of the standard deviation of the efficiency of ecological civilization construction in 2025 and 2030, it is visualized with the help of ArcGIS 10.5 software (see Fig. 7).

The prediction results show that the efficiency center of ecological civilization construction will shift 1031.43 km from the north to the south of Hubei Province in 2020–2030, moving to the southeast as a whole, and moving 1004.67 km and 675.43 km

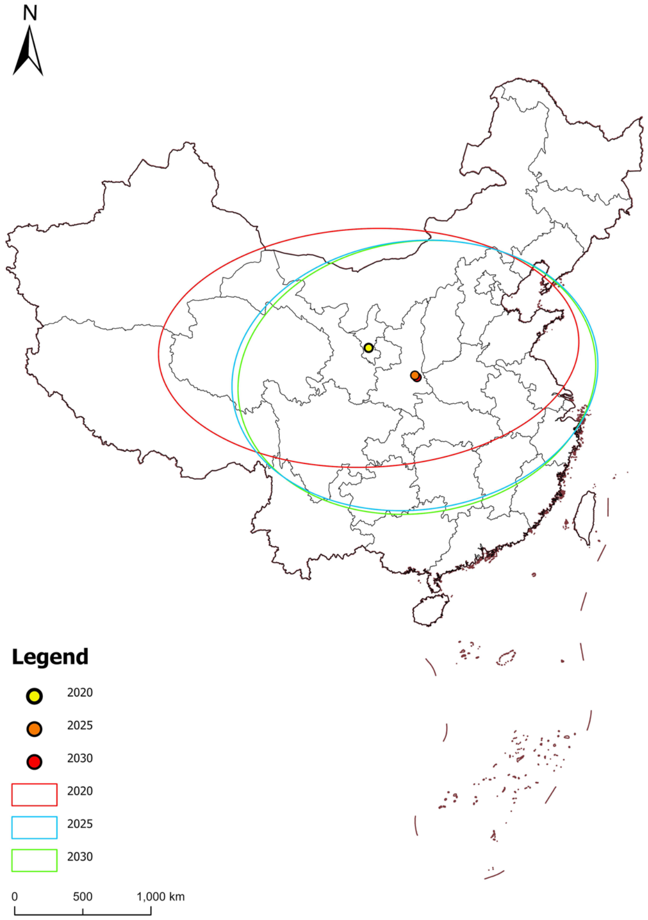

Fig. 7 The forecast of spatial pattern trend for ecological civilization construction efficiency in China. According to the predicted elliptic parameters of the standard deviation of the efficiency of ecological civilization construction in 2025 and 2030, it is visualized with the help of ArcGIS 10.5 software, as shown in Figure 7.

in the east-west and north-south directions, respectively, indicating that the Bohai Rim and the middle and lower reaches of the Yangtze River will affect the overall spatial distribution of the efficiency of China's ecological civilization construction in the future. The rotation angle decreased from 97.59°in 2020 to 89.53° in 2035, indicating that the spatial distribution of China's ecological civilization construction efficiency will gradually change to the "Northeast Southwest" pattern in the future.

Prediction of the evolutionary trend of ecological civilization construction efficiency type transfer in China. The spatial Markov probability transfer matrix reveals that China's ecological civilization construction efficiency evolution will gradually form a "club convergence." However, whether it will maintain the convergence characteristics in the long-term evolution process is of concern. The type of ecological civilization construction efficiency transfer in Chinese provinces and cities can maintain the original state; therefore, the transfer process has not yet achieved a steady state, and the mutual transfer process of state types will continue. The limitation of Markov probability transfer distribution is when each type of transfer attains equilibrium. Therefore, for the n-step probability transfer matrix of ecological civilization construction efficiency state types, when $n \to \infty$, the limit distribution of the probability transfer of the state can be obtained. The spatial Markov probability transfer matrix with spatial lag is added. The respective limit distribution can be obtained according to each spatial lag type, facilitating the determination of the development trend of the long-term evolution of ecological civilization construction efficiency in China. The previous study divided 2000–2020 into two phases to facilitate the solution of the overall limiting distribution. This study re-measured the conventional and spatial Markov probability transfer matrices for the entire study period. The limit distributions for both background conditions were measured using these two matrices (see Table 6) and compared with the probability distribution of the initial state.

Table 6 Evolutionary trend prediction of ecological civilization construction efficiency type transfer in China.

	Spatial lag	1	2	3	4
Initial state		0.571	0.286	0	0.143
Limit distribution without considering space lag		0.333	0.167	0.333	0.167
Limit distribution considering spatial lag	1	0.797	0.141	0.062	0
	2	0.151	0.671	0.151	0.027
	3	0.053	0.093	0.680	0.173
	4	0.030	0.045	0.104	0.821

Comparing the solved limiting distributions with the initial state without considering the spatial lag revealed that the number of provinces and cities in types 1 and 2 decreased, while that of provinces and cities in types 3 and 4 significantly increased. This indicates the significance of ecological civilization construction efficiency improvement in Chinese provinces and cities over time, with most provinces and cities shifting upward to higher levels and only a few shifting downward or remaining at lower levels. From the limiting distribution shape, the transfer of ecological civilization construction efficiency in China is not a situation of "high and low clustering." However, it reveals an evolutionary pattern of gradual increase from low to high (Liao et al., 2022). Therefore, in the long-term evolution process, China's ecological civilization construction efficiency gradually develops to a high level. The "bimodal" characteristic of "club convergence" summarized by the traditional Markov probability transfer matrix will evolve into a partial "unimodal" distribution in the long-term evolution. The provinces and cities with relatively low ecological civilization construction efficiency short term will evolve into a "unimodal" distribution with the development of ecological and environmental protection. In the short term, the provinces and cities with relatively low ecological civilization construction efficiency will gradually shift upward to higher levels under enhanced awareness of ecological and environmental protection. The shifting process is stable and continuous.

Nonetheless, a few provinces continue to improve slowly (Fang et al., 2018). Considering spatial lags, there are significant differences in the probability of transfer of ecological civilization construction efficiency in China in the long-term evolution of different geospatial patterns. When neighboring provinces and cities have lower levels (types 1 and 2) of ecological civilization construction efficiency, the steady state of their long-term evolution of ecological civilization construction efficiency also reveals a pattern of gradual increase. The "single-peak" distribution is more obvious, revealing that in this geographical context, China has great potential for long-term improvement of ecological civilization construction efficiency; when the provinces and cities with higher levels (type 3 and 4) of ecological civilization construction efficiency are neighbors, their long-term evolution gradually forms a "double-peak" distribution with high levels of agglomeration (type 3 and 4). For instance, the number of provinces and cities in type 3 is higher than that in the other types, when the provinces and cities in type 3 are adjacent.

Overall, the long-term evolution trend of ecological civilization construction efficiency in China is more considerably influenced by the geospatial pattern.

Conclusion

In this study, the panel data of Chinese provinces and cities between 2000 and 2020 were used as the research unit. The inter-provincial ecological civilization construction efficiency was measured using the super-efficiency SBM model. The traditional and spatial Markov probability transfer matrices were constructed according to the temporal analysis based on Kernel density estimation and the spatial correlation analysis of the global Moran's I index. The comparison of the matrices was used to analyze the ecological civilization construction efficiency. The spatial and temporal dynamic evolution characteristics of ecological civilization construction efficiency were analyzed by comparing matrices. In addition, the trend of its long-term evolution was predicted to explore the influence of geospatial patterns in the spatial and temporal evolution of ecological civilization construction efficiency (Jusup et al., 2022; Perc, 2019). The following main conclusions were obtained.

(1) From the temporal evolution differences, China's ecological civilization construction efficiency based on the line graph and Kernel density estimation revealed a stable upward trend in fluctuation. Volatility was primarily concentrated in 2000–2010 and 2011–2020, when the eastern region improved more significantly than the central and western regions. However, the overall ecological civilization construction efficiency remained low, with room for improvement. The Kernel density estimation map revealed that China's wave of ecological civilization construction efficiency has a "bimodal" distribution that evolves from high to low. The gap of wave height is narrowing, gradually forming a "low-low agglomeration, high-high agglomeration"—the "club convergence" pattern.

(2) From the spatial evolution pattern, the global Moran's I index revealed that China's ecological civilization construction efficiency is significantly positively correlated with spatial distribution. Moreover, inter-provincial environmental efficiency is spatially interdependent. The traditional Markov probability transfer matrix revealed that the overall trend of ecological civilization construction efficiency shifts significantly upwards. The evolution of ecological civilization construction efficiency maintains the original state. Achieving leapfrogging transfer is challenging, and the probability of maintaining the same type at both ends of the matrix is the largest. The possibility of "low-low agglomeration and high-high agglomeration" Is observed. Furthermore, comparing the spatial and the traditional transfer matrixes revealed that the geospatial pattern is essential in the spatial and temporal evolution of ecological civilization construction efficiency in addition to their shared characteristics. The spatial spillover effect increased, and its downward transfer probability increased with the ecological civilization construction efficiency of the adjacent lower provinces and cities. Therefore, the ecological civilization construction efficiency of the higher provinces and cities has a positive spillover effect. In comparison, the ecological civilization construction efficiency of the lower provinces and cities has a negative spillover effect. Therefore, the spatial pattern gradually formed the "high-high agglomeration, low-low agglomeration, high radiation low, low inhibit high." The "club convergence" can correspond to temporal evolution characteristics.

(3) From the long-term evolution trend, most provinces and cities gradually shift to higher ecological civilization construction efficiency levels. Its evolution characteristics gradually evolved from "club convergence" to a gradual increase pattern, which was stable and continuous. In different geospatial patterns, when the provinces and cities with lower ecological civilization construction efficiency are neighbors, the stable state of its long-term evolution also reveals a gradual increase from low to high. The distribution of "single peak" is more obvious. Therefore, in this context, ecological civilization construction efficiency has great potential for improvement. In comparison, when the provinces and cities with higher ecological civilization construction efficiency are adjacent, the long-term evolution gradually evolves from the "club convergence" of high and low respective agglomeration to the partial "bimodal" distribution of higher level (types 3 and 4) agglomeration.

Based on the super-efficiency SBM model and the spatial Markov probability transfer matrix, the spatial and temporal evolution characteristics and trend prediction of China's ecological civilization construction efficiency are summarized as follows.

The super-efficiency SBM model based on non-expected output can fully consider the influence of the resource environment on ecological civilization construction efficiency and compare DMU with an efficiency of 1. However, various socio-economic factors that led to the loss of ecological civilization construction efficiency were not considered in this study. Moreover, since the loss of ecological civilization construction efficiency results from the joint influence of various factors, future studies can consider structural changes, policy changes, technological changes, urbanization, foreign direct investment, and other factors to explore the factors influencing ecological civilization construction efficiency loss in depth. The eastern provinces have significant advantages in terms of economy, technology, and policies, but their high population and economic density play a limiting role in further improving the efficiency of ecological civilization construction. Therefore, continuing to explore high-quality development paths is a key issue that these provinces need to clarify. The economic development level of the central region is average, and certain regions are highly dependent on resources. Its development should focus on the three major urban agglomerations as the growth core, continue to increase talent introduction, vigorously develop high-tech industries, effectively transform green mountains and clear waters into golden mountains and silver mountains, and effectively improve the efficiency of ecological civilization construction. The ecological environment in the western region has relatively low carrying pressure and weak ecological and economic levels. Therefore, continuously reinforcing exchanges and cooperation with the eastern region, seizing the opportunities of national support for the development of the central and western regions, developing and utilizing advantageous resources in protection, and sustainable development are still necessary.

The spatial Markov probability transfer matrix is an effective method for studying the spatial and temporal evolution characteristics of different economic phenomena (ecological civilization construction efficiency) and forecasting the long-term evolution trend. It emphasizes the close correlation between the years before and after the research object. It also emphasizes the influence of geospatial patterns on the evolution process of ecological civilization construction efficiency, incorporating spatial lag conditions into the influencing factors of ecological civilization construction efficiency loss. Therefore, constructing a spatial panel econometric model is crucial for future in-depth research.

The efficiency evaluation index of ecological civilization construction based on the non-expected output SBM model is constructed to solve the efficiency evaluation problem under the condition of high quality. The auditors then combine the economic and effective conclusions obtained through such methods as inquiry and review methods to ensure the performance evaluation results of ecological civilization construction are more accurate and the audit suggestions more constructive, which is relatively conducive to the audit governance function.

In recent years, China has made significant progress in the theory and practice of ecological civilization but still faces challenges such as theoretical research lagging behind management needs, the latest practical achievements needing theoretical sublimation, and the need to enhance international influence. Drawing on interdisciplinary theories and methods such as ecology, ecosystem management, and economics, fortifying research on the theory and methods of ecological civilization construction, promoting the standardization, internationalization, and standardization of ecological civilization construction, and making ecological civilization an important support for China to participate in and lead global governance are urgent needs. China's ecological civilization construction has deepened the theory and practice of global sustainable development, provided a model for developing countries to pursue a new path of modernization, and provided value guidance for global society to respond to ecological crises. The achievements of China's ecological civilization construction are attributed to its own institutional advantages, political advantages, ideological advantages, cultural advantages, and value position advantages. In global ecological environment governance, China will play a role in regional cooperation, international discourse dissemination, experience exchange and cooperation, and global responsibility.

Data availability

The original contributions presented in the study are included in the article/(Supporting Materials S1. Dataset), further inquiries can be directed to the corresponding author/s.

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Author contributions

Conceptualization: ZL data curation: HZ formal analysis: ZL and HZ writing—original draft: ZL and HZ software: HZ writing—review and editing: ZL and HZ. All authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
This article does not contain any studies with human participants performed by any of the authors.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

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