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Provincial Green Transformation in China: Spatio-temporal Pattern and Evolutionary Characteristics

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Abstract: China's development has embarked on the path of ecological priority, green and low-carbon development, and driving green transformation through environmental protection, industrial restructuring and technological innovation has become an important path. This paper constructs an indicator evaluation system on the basis of existing research, uses the entropy value method to more accurately measure the efficiency of green transformation in 29 Chinese provinces from 2003 to 2020. Through the use of ArcGIS, a spatial layout map of green transformation is drawn to analyze the spatiotemporal pattern and evolution characteristics of green transformation. The results indicate: (1) Overall, during the period of 2003-2020, the green transformation of each province has shown a stable and rising development trend. (2) There are significant regional differences in green transformation. The southeastern region has maintained a relatively good momentum in green transformation. (3) The effectiveness of China's green transformation has shifted from mainly cold spot regions in the past, with a few hot spot areas, to more intermediate and hot spot areas, mainly showing the characteristics of a stronger south and weaker north, and a stronger east and weaker west.

1. Introduction

China has entered a crucial stage of transforming its development mode, optimizing its economic structure, and transforming growth drivers. Promoting reforms in the quality, efficiency, and dynamics of economic development, the exploration of a new path for high-quality development has become the strategic direction of China’s socio-economic development. To address the contradiction between economic growth and environmental protection and achieve high-quality development, green transformation has become an inevitable choice for China. With vast territory, there are differences in green transformation efficiency among provinces, and in the medium to long term, China still faces significant pressure for green transformation. Therefore, promoting green transformation play a vital role in the high-quality development of the China's economy.

The concept of green transformation is evolved from the "green economy" in Pierce's "Blueprint for a Green Economy" (Zheng et al., 2015)[1]. The green economy integrates economics and the environment, placing equal importance on both during development and emphasizing sustainability. The International Union for Conservation of Nature has put forward the concept of sustainable development, which has been continuously expanded and transformed from an abstract idea to tangible topics such as sustainable communities, sustainable energy, and sustainable cities. Green transformation involves multiple fields, aiming to achieve harmonious development among people, nature, and society. It promotes the transition from traditional development models to scientific development models and achieves regional sustainable development (Zhuang, Duan, 2024)[2].

Scholars have rich research results on the calculation and discussion of China's green transformation (Liu, 2018; Zeng, 2018; Wu et al., 2023)[3]-[5]. They have used methods such as the entropy method, Logarithmic Mean Divisia Index (LMDI) model, Tapio decoupling model, Super-SBM model and the Dagum Gini coefficient to calculate the green transformation efficiency of manufacturing, industrial, and other heavily polluting industries, as well as resource-based and resource-depleted city groups from economic and environmental perspectives. However, few studies comprehensively consider the effects of green transformation from various aspects such as regional economy, environment, and society. Most existing research focus on numerical comparisons of measurement results (Fan et al., 2021; Hao, Zhu, 2019)[6][7], lacking intuitive analysis of spatial characteristics of green transformation. Therefore, based on sustainable development theory, this article uses the entropy method to more accurately calculate the green transformation efficiency of 29 provinces in China from 2003 to 2020. Additionally, an ArcGIS map is created to analyze the spatiotemporal pattern and evolution characteristics of green transformation.

2. Research Design

2.1. Research method

2.1.1. Entropy methods

"Entropy method" is an objective weighting method, which takes the difference between the index values of each evaluation index as the starting point to determine the weight coefficient (Zhu, Wei , 2015)[8]. Referring to the practice of Zhang et al. (2016)[9], firstly, before using the entropy method to calculate the weights, in order to eliminate the influence of units of different indicators on the calculation results, the data was first processed by means of deviation standardization, and the data was recorded as Xij. The calculation formula of deviation standardization was as follows: $X_{ij}=\frac{A_{ij}-\max(A_{ij})}{\max(A_{ij})-\min(A_{ij})}$; Second, calculate the proportion of item i of the JTH province (n represents the number of provinces) :$P_{ij}=\frac{X_{ij}}{\sum_{j=1}^{n}X_{ij}}$; Third, calculate the information entropy of the index: $E_i=-k\times\sum_{j=1}^{n}P_{ij}\times \ln p_{ij}$,where $k=\frac{1}{\ln n}$; Fourth, calculate the redundancy of information entropy: $d_i=1-E_i$; Fifth, calculate the index weight: $W_i=\frac{d_i}{\sum_{i=1}^{m}d_i}$;Finally, the green transformation scores of each province are calculated: $S_j=\sum_{i=1}^{m}W_i\times X_{ij}$.

In the above formula, A_{ij} represents the original value of item i of the j province, X_{ij} represents the value after the standardization of item i of the j province, and P_{ij} represents the proportion of item i of the j province. E_i represents the information entropy of item i; K stands for Boltzmann constant; d_i indicates the information entropy redundancy of item i. W_i indicates the weight of item i, and S_j indicates the green transformation score of each province.

2.1.2. Analysis of cold hot spots

Cold hot spot analysis is a spatial clustering method, which can show the spatial aggregation distribution law of high and low values of indicators, and can also make up for the shortcomings of spatial feature analysis such as equal breakpoint classification. In this paper, the hot and cold spot analysis method is used to identify the high and low value regions in different spatial locations, that is, to explore the spatial distribution characteristics of the hot and cold spot regions of green transformation. The formula is as follows:

$$G_i^* = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}X_iX_j}{\sum_{i=1}^{n}\sum_{j=1}^{n} X_iX_j}$$

In order to facilitate the elaboration, it is standardized:

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{Var(G_i^*)}}$$

In the above formula: is the spatial weight matrix, respectively the observed value of region $W_{ij}X_iX_j$ i and j, and the mathematical expectation and coefficient of variation respectively. $E(G_i^*)Var(G_i^*)G_i^*$If the value is significantly positive, it means that the value around this region is high and belongs to the hot spot region; Otherwise, it belongs to the cold spot region.

2.2. Evaluation system construction

In this paper, referring to the studies of Cui (2022)[10], Zhao (2019)[11], Wang et al. (2012)[12], combined with the Assessment Target System of Ecological Civilization Construction and the Green Development Indicator System to select indicators, and the green transformation indicator system is constructed in Table 1.

Table 1: Green transformation index system

A Resources and Environ-ment	A1 Resource Utilization	A11	Energy consumption per unit of GDP (tons of standard coal / 10,000 yuan)
		A12	Daily domestic water consumption per capita (liters)
		A13	General Industrial solid waste Composite utilization rate (%)
		A14	Carbon emissions per unit of GDP (tons/billion yuan)
	A2 pollution emissions	A21	Industrial smoke (powder) dust emissions (tons)
		A22	Industrial sulfur dioxide emissions (tons)
		A23	Wastewater discharge (tons)
	A3 Environmental treatment	A31	Harmless disposal rate of household waste (%)
		A32	Centralized treatment rate of sewage treatment plant (%)
B Industrial transform-ation	B1 Industrial benefits	B11	Total profits of industrial enterprises above designated size (100 million yuan)
		B12	Secondary industry comparative labor productivity (%)
		B13	Comparative labor productivity in the tertiary industry (%)
	B2 Industrial structure	B21	Tourism revenue as a share of GDP
		B22	Total output value of agriculture, forestry, animal husbandry and fisheries as a percentage of GDP (%)
		B23	Tertiary sector as a share of GDP (%)
C Power support	C1 Science and Technology Innovation	C11	R&D intensity
		C12	Number of authorized patent applications (pieces)
		C13	Technology market turnover (billion yuan)
	C2 Urban construction	C21	Per capita park green space (square meters)
		C22	Green coverage rate of built-up area (%)

2.3. Data sources

The data of 29 provinces in China from 2003 to 2020 are used in this paper. The data come from China Environmental Statistical Yearbook, China Industrial Statistical Yearbook, provincial statistical Yearbook, Energy Yearbook and City Yearbook.

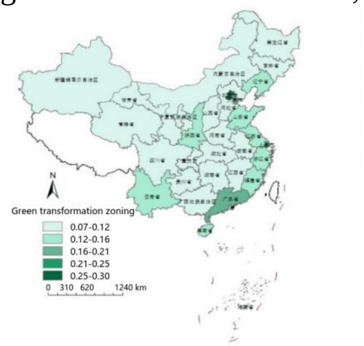
3. Analysis of the measurement results and temporal and spatial characteristics of green transformation

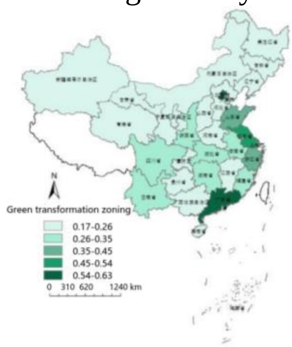
3.1. Temporal and Spatial characteristics

In order to more intuitively reflect the characteristics of green transformation in various provinces of China, ArcGIS is used to create spatial distribution maps of green transformation in 2003 and 2020 for spatial analysis, as shown in Appendix 1, Figure 1, and Figure 2.

Overall, from 2003 to 2020, the green transformation in various provinces showed a stable but increasing trend. In 2003, the green transformation effect in most provinces of China was within the range of [0.07, 0.12], with the highest reaching only 0.30. The effect of green transformation was not ideal. By 2020, about half of the provinces in China had achieved a green transformation efficiency of over 0.26, with ten achieving a green transformation efficiency of 0.3, with the highest being 0.63. This indicates that China's overall green transformation has been effective in resource environment, industrial transformation, and power support over the past 18 years.

The regional differences in green transformation are significant. From Figures 1 and 2, it can be seen that the green transformation in the southeast region has maintained a good momentum, while the green transformation in the northwest region has been relatively slow. The overall green transformation effect in Beijing is the best, with an average green transformation efficiency of 0.42 between 2003 and 2020. The average values in Guangdong Province, Shanghai City, and Jiangsu Province are also above 0.30, indicating a good effect of green transformation. The green transformation effect in Qinghai Province is the worst, with a green transformation efficiency ranging from 0.10 to 0.17 in 2003, with an average of only 0.13.





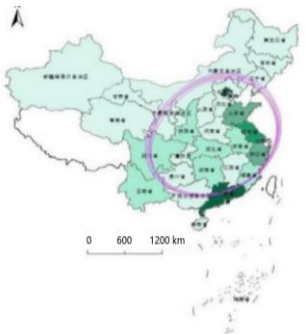


Figure 1: Spatial layout of green transformation in 2003 (Left)

Figure 2: Spatial layout of green transformation in 2020 (Medium)

Figure 3: Spatial distribution of standard deviation Ellipse of green transformation from 2003 to 2020 (Right)

From the perspective of time scale, the effect of green transformation in all provinces has changed significantly from 2003 to 2020. In 2003, Beijing had the best effect of green transformation, with a green transformation efficiency of 0.30, Shanghai, Tianjin and Guangdong Province also had a good effect of green transformation. In 2008, the region with the best effect of green transformation was still Beijing, while Gansu Province had the worst effect of green transformation. In 2013, Beijing was the region with the best effect of green transformation, which separated from Guangdong Province and Jiangsu Province with the second and third green transformation efficiency of 0.34. The green transformation efficiency of Qinghai Province was only 0.13. By 2020, the green transformation efficiency of Guangdong Province will be 0.63, surpassing Beijing to become the region with the best green transformation effect. The green transformation efficiency of Beijing, Jiangsu, Zhejiang and Shanghai are also in the forefront of the country. The green transformation efficiency of Qinghai Province is the worst.

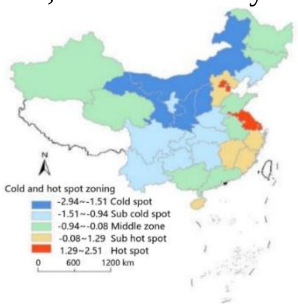
There are obvious regional differences in the effect of green transformation, which is caused by regional differences in industrial structure, resource and environment utilization and residents' green awareness. Economically developed areas such as Beijing, Guangdong Province and Shanghai have better development of green industries with low energy consumption and high efficiency, better regional green planning, and more attention to green transformation, while economically backward areas such as Qinghai Province and Gansu Province have the opposite effect. After the outbreak of the financial crisis in 2008, Guangdong Province took the lead in recognizing the existing structural problems, actively promoted the green transformation, vigorously promoted the two major strategies of "industrial transfer" and "labor transfer", and promoted the integration of environmental protection in the Pearl River Delta region. It has invested nearly 750 billion yuan to control water pollution and air pollution, introduced ecological protection policies to encourage and support social capital to participate in ecological restoration, and achieved good results in green transformation. Since 2000, when Beijing successfully won the right to host the 2008 Summer Olympic Games, it began to vigorously promote green transformation, relocated Shougang, increased forest coverage, and adjusted Beijing's energy structure from coal to natural gas.

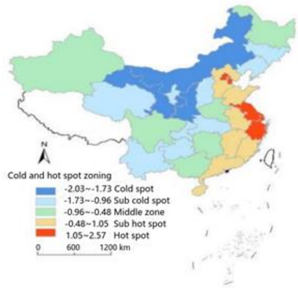
The green transformation effects of each province in China from 2003 to 2020 had spatial characteristics. Standard Deviation Ellipse (SDE) was adopted as an identification tool to reflect the spatial distribution characteristics of the green transformation effects. As shown in Figure 3, the standard deviation ellipse shifted to the northeast, reflecting that the center of gravity of the green transformation moved to the northeast region. The long and short axis of the standard deviation ellipse reflects the direction in which the spatial distribution of green transformation deviates from the center of gravity. The short axis is southeast and the long axis is northeast, and there is a significant difference between the short and short axes, indicating that the green transformation has strong direcality. The area of the ellipse covering the eastern provinces is the largest, indicating that the green transformation speed of the provinces inside the ellipse is faster than that of the provinces outside the ellipse, and the effect of green transformation is weak in the northwestern remote areas.

3.2. Cold Hot spot analysis

In order to further reveal the spatial agglomeration characteristics and evolution law of green transformation, ArcGIS was used to draw the cold and hot spots maps of Chinese provinces in 2003, 2008, 2013, 2018 and 2020, as shown in Fig. 4-8.

Overall, the effectiveness of China's green transformation has shifted from being mainly focused on cold spots in the past, with individual hot spots, to more intermediate and hot spots. The characteristics of green transformation have produced significant effects in various provinces after promoting resource and environmental protection, industrial transformation, and supporting technological innovation. The green transformation effect mainly presents the characteristics of strong in the south and weak in the north, and strong in the east and weak in the west. The hot spots are mainly distributed in Beijing and the eastern coastal areas, forming obvious cold spot accumulation areas around Inner Mongolia Autonomous Region and Gansu Province. With the rapid increase in population in Inner Mongolia and Gansu, people's excessive exploitation of resources has led to significant changes in the ecological environment. Inner Mongolia Autonomous Region and Gansu Province face prominent problems in economic development and environmental coordination, such as water scarcity, deterioration of natural environment, and tense human land relations, which seriously affect the green transformation of the two regions.





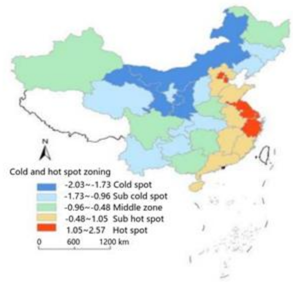
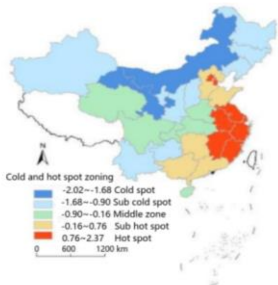


Figure 4: Analysis of cold hot spots in green transition in 2003 (Left)

Figure 5: Analysis of cold hot spots in green transition in 2008 (Medium)

Figure 6: Analysis of hot and cold spots in green transformation in 2013 (Right)



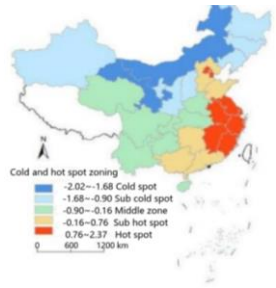


Figure 7: Analysis of cold and hot spots in Green transformation in 2018 (Left)

Figure 8: Analysis of cold and hot spots in Green transformation in 2020 (Right)

4. Conclusions and policy implications

This paper utilizes the entropy method to calculate the green transformation efficiency of 29 provinces in China and conducts spatiotemporal feature analysis through mapping the green transformation spatial layout using ArcGIS. The results indicate: (1) On the whole, from 2003 to 2020, the green transformation of all provinces basically presents a stable but rising development trend. (2) There are significant regional differences in green transformation. (3) The effectiveness of green transformation in China has shifted from being mainly cold spot regions in the past, with a few hot spot areas, towards more intermediate and hot spot areas.

The research conclusions of this paper can provide some policy implications.

First, enhance innovation level and accumulate green transformation increments. The government should enhance policy support for green technology innovation activities, increase tax relief for green production and energy-saving enterprises, and encourage green transformation.

Second, progress gradually and focus on green transformation quality. Green transformation requires high standards for technological innovation, environmental protection, talent recruitment, and various aspects, necessitating gradual progress to identify specific reasons, and to utilize legal and economic tools comprehensively to jointly promote targeted measures.

Third, adapt to local conditions and plan green transformation paths. Gansu Province and other typical cold spot areas. Local governments should introduce appropriate strategies like returning farmland to forests and grasslands, establish a sound environmental protection system suitable for local conditions, vitalize the tertiary industry especially tourism, and drive industrial upgrades.

Fourth, regional cooperation should form synergy for green transformation.Local governments at various levels should actively explore mutual trust mechanisms, build a green information sharing network, jointly plan rational resource utilization plans.

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Appendix

Attached Table 1 is the results of green transformation measurement

district	2003	2004	2005	2006	2007	2008	2009	2010	2011
beijing	0.30	0.33	0.33	0.34	0.34	0.34	0.36	0.37	0.39
tianjin	0.18	0.19	0.19	0.19	0.21	0.21	0.22	0.23	0.24
hebei	0.09	0.09	0.10	0.11	0.12	0.13	0.15	0.15	0.15
shanxi	0.08	0.08	0.09	0.09	0.11	0.12	0.13	0.14	0.14
neimenggu	0.09	0.09	0.10	0.11	0.13	0.13	0.14	0.15	0.16
liaoning	0.12	0.13	0.13	0.13	0.14	0.15	0.16	0.18	0.18
jilin	0.11	0.11	0.12	0.12	0.13	0.13	0.14	0.15	0.15
heilongjiang	0.11	0.12	0.12	0.13	0.13	0.14	0.14	0.15	0.15
shanghai	0.22	0.23	0.24	0.25	0.27	0.27	0.29	0.30	0.28
jiangsu	0.15	0.16	0.17	0.18	0.20	0.22	0.24	0.28	0.31
zhejiang	0.15	0.16	0.18	0.18	0.20	0.21	0.23	0.25	0.26
anhui	0.11	0.11	0.11	0.12	0.14	0.14	0.16	0.17	0.18

fujian	0.15	0.16	0.16	0.16	0.18	0.18	0.20	0.21	0.21
jiangxi	0.09	0.09	0.09	0.10	0.11	0.12	0.14	0.15	0.16
shandong	0.13	0.14	0.14	0.16	0.18	0.19	0.21	0.23	0.24
henan	0.10	0.10	0.10	0.11	0.12	0.13	0.15	0.16	0.17
hubei	0.12	0.11	0.13	0.13	0.14	0.15	0.16	0.17	0.18
hunan	0.09	0.10	0.11	0.12	0.13	0.13	0.15	0.16	0.16
guangdong	0.18	0.19	0.20	0.21	0.22	0.23	0.25	0.29	0.30
guangxi	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.14	0.15
hainan	0.13	0.14	0.15	0.16	0.17	0.17	0.16	0.17	0.17
chongqing	0.11	0.12	0.13	0.14	0.16	0.17	0.17	0.18	0.20
sichuan	0.10	0.11	0.11	0.12	0.13	0.14	0.15	0.16	0.16
guizhou	0.07	0.08	0.10	0.10	0.11	0.11	0.13	0.14	0.15
yunnan	0.13	0.13	0.14	0.13	0.15	0.15	0.16	0.17	0.17
shanxi	0.12	0.12	0.13	0.14	0.14	0.15	0.16	0.18	0.19
gansu	0.09	0.09	0.10	0.10	0.11	0.11	0.11	0.12	0.12
qinghai	0.10	0.11	0.11	0.11	0.12	0.11	0.12	0.12	0.14
ningxia	0.09	0.09	0.11	0.11	0.12	0.13	0.13	0.15	0.15
district	2012	2013	2014	2015	2016	2017	2018	2019	2020
beijing	0.41	0.43	0.45	0.46	0.49	0.51	0.54	0.57	0.59
tianjin	0.26	0.27	0.27	0.28	0.29	0.29	0.27	0.30	0.32
hebei	0.15	0.16	0.16	0.17	0.19	0.20	0.21	0.22	0.25
shanxi	0.16	0.16	0.15	0.16	0.17	0.17	0.19	0.18	0.19
neimenggu	0.16	0.17	0.17	0.17	0.19	0.19	0.19	0.19	0.20
liaoning	0.19	0.20	0.18	0.18	0.20	0.21	0.22	0.23	0.24
jilin	0.16	0.17	0.17	0.17	0.18	0.18	0.19	0.20	0.21
heilongjiang	0.16	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.19
shanghai	0.30	0.30	0.31	0.32	0.33	0.34	0.37	0.38	0.40
jiangsu	0.34	0.34	0.33	0.36	0.37	0.37	0.40	0.41	0.50
zhejiang	0.28	0.29	0.29	0.31	0.31	0.32	0.35	0.37	0.43
anhui	0.20	0.21	0.21	0.23	0.23	0.24	0.26	0.26	0.29
fujian	0.22	0.23	0.23	0.24	0.25	0.26	0.25	0.26	0.28
jiangxi	0.16	0.17	0.17	0.18	0.18	0.19	0.20	0.21	0.23
shandong	0.26	0.27	0.28	0.29	0.30	0.30	0.31	0.31	0.38
henan	0.17	0.18	0.19	0.20	0.22	0.22	0.23	0.24	0.26
hubei	0.19	0.21	0.22	0.23	0.24	0.26	0.28	0.29	0.31
hunan	0.17	0.18	0.18	0.19	0.20	0.22	0.23	0.25	0.27
guangdong	0.32	0.34	0.34	0.38	0.40	0.43	0.49	0.54	0.63
guangxi	0.16	0.17	0.16	0.17	0.18	0.19	0.19	0.20	0.21
hainan	0.17	0.17	0.17	0.17	0.18	0.18	0.19	0.20	0.21
chongqing	0.20	0.21	0.22	0.22	0.24	0.23	0.24	0.24	0.25
sichuan	0.17	0.18	0.18	0.20	0.21	0.22	0.26	0.27	0.29
guizhou	0.16	0.16	0.16	0.17	0.17	0.18	0.19	0.20	0.21
yunnan	0.17	0.18	0.18	0.19	0.19	0.20	0.21	0.21	0.33
shanxi	0.20	0.22	0.22	0.23	0.26	0.25	0.27	0.28	0.30
gansu	0.13	0.14	0.15	0.15	0.17	0.18	0.18	0.19	0.20
qinghai	0.14	0.13	0.14	0.14	0.15	0.16	0.16	0.16	0.17
ningxia	0.15	0.17	0.17	0.17	0.17	0.17	0.18	0.19	0.19