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Original Research

Spatiotemporal Measurement of the Coupling Coordination in a Region's Economy-Technological Innovation-Ecological Environment System: A Case Study of Anhui Province, China

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Abstract

High-quality development has become an inevitable requirement for China's economic and social development in the new era. The coordinated development of the economy, technology innovation, and ecological environment is the key to achieving high-quality development. This study used entropy weight and a degree of coupling coordination model to construct the economy, technological innovation, and ecological environment system (ETES) to analyze the coupling coordination relationship among the three subsystems in Anhui Province from 2010-2019. The results show that (1) from the temporal perspective, the degree of coupling coordination in ETES shows a significant improvement, with a change from imminent imbalance to quality coordination. (2) From the spatial perspective, there are differences among cities, and the number of regions with a low degree of coupling coordination is greater than that with a high degree of coupling coordination. Additionally, the degree of coupling coordination in southern Anhui is significantly better than that in northern Anhui. The results suggest that governments at all levels should develop and deploy differentiated strategies according to the characteristics and positioning of their own regions to achieve balanced and high-quality regional development.

Keywords: ETES, coupling coordination, kernel density estimation, Ward clustering, spatiotemporal characteristics

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Introduction

High-quality development is a major strategy for China's modernization drive in the new era. The report of the 19th National Congress of the Communist Party of China pointed out that Chinese socialism has entered a new era and that the economy should shift from high-speed growth to high-quality growth. High-quality development refers to development that is efficient, innovative, green, and sustainable and that aims to meet the growing needs of the people to ensure a better life [1-3]. Among them, the capacity for technological innovation is an important support for innovative development. The quality of the ecological environment is a major way to measure green development. In addition, ETES is organically unified and mutually reinforcing. The ecological environment is the material basis of the economy. Technological innovation is the power source of the economy. Economic development also provides guarantees for technology innovation, while economic development can destroy the ecological environment. Consequently, what is crucial to promote regional high-quality development is to balance the relationship between ETES and achieve the coordinated development of ETES.

The Yangtze River Delta is one of the regions with the most dynamic economy, the highest degree of openness and the strongest innovation capability in China, and it is also an important meeting point of the "One Belt One Road" and the Yangtze River Economic Belt. As an important part of the Yangtze River Delta, Anhui Province's development quality will affect the integrated development of the Yangtze River Delta. Since the integrated development of the Yangtze River Delta region became a national strategy in 2018 [4], the integrated development of the Yangtze River Delta has pressed the "fast forward" button. Anhui Province has achieved good results in ETES. In 2020, Anhui Province's GDP was RMB 38.680.6 trillion, which is much smaller than that of top-ranked Jiangsu Province, which had a GDP of RMB 102.719 trillion [5]. Regional innovation capability has been in the first echelon of the country for nine consecutive years. However, there is still a certain gap with other regions in the Yangtze River Delta. Moreover, Anhui Province is a resource endowment region. An unsatisfactory industrial structure and its previous rough economic model have resulted in the excessive consumption of resources and severe damage to the ecological environment. This damage has placed great pressure on the ecological environment. According to relevant data, the direct economic losses from pollution in Anhui Province reached RMB 6.957 million in 2020, or approximately 2‱ of GDP [6]. Obviously, the economy is still low quality and inefficient, and there is still much room to improve the capacity for technological innovation and much to do in terms of ecological protection in Anhui Province. It is of great significance to explore the coupling coordinated development of ETES, analyze its problems and propose corresponding countermeasures and suggestions to achieve high-quality development in Anhui Province.

Technological innovation and the economy are complementary. The study on the relationship between them mainly focused on three aspects. First, technological innovation provides impetus and new kinetic energy for the economy [7-11]. Second, the quality of the economy is an important guarantee for technological innovation [12]. Third, there is spatial agglomeration in the coordinated development of technological innovation and the economy [13-15].

The ecological environment and economy are organically unified. The ecological environment is the material basis of the economy [16-18]. At the same time, the economy has also brought pollution and damage to the ecological environment [19, 20]. Therefore, scholars have conducted an in-depth analysis of the correlation between the two, especially in terms of coupling and coordinated development. [21-28].

There is a certain optimization relationship between technological innovation and the ecological environment [29-31]. Technological innovation can alleviate the ecological environment pollution caused by economic development [32-36]. Furthermore, environmental factors have a significant impact on the innovation activities of strategic emerging industries [37-41].

In summary, the ecological environment is a prerequisite for the regional economy and technological innovation, while technological innovation is the main driving force for the economy. ETES is complementary to each other, and the absence of one is essential. It was found that the study on the relationship between ETES is relatively mature, but there are still some deficiencies. In terms of study depth, most previous studies have focused on the coordination in the development of or interactions between any two of these subsystems, and there are few studies on the coupling coordinated development of the three subsystems. Additionally, in terms of study area, most of them are the whole country, key areas, urban agglomerations and river basins, etc., and there are few studies on the coupling and coordinated development of the ternary system under the characteristics of provinces and specific cities. Moreover, from the perspective of the study method, the degree of coupling coordination model, projection pursuit method, EKC, gravity model, DEA and regression model, were mainly used to analyze the relationship between the systems, which cannot analyze the dynamic evolution characteristics of the study object exactly. Thus, this study introduces the kernel density estimation method to explore the dynamic evolution characteristics of the degree of coupling coordination. To further clarify the coupling coordination in ETES, this study analyses the status of each subsystem in depth with panel data on Anhui Province from 2010-2019. Then, the temporal characteristics of the coupling coordination are analyzed by kernel density estimation. Finally, Ward clustering, visualization and other methods are employed to analyze the characteristics of the spatial distribution of ETES. Then, appropriate management recommendations are proposed to facilitate high-quality development in Anhui Province.

Material and Methods

Data and Materials

Indicators

According to relevant studies, we use the criteria of data availability, index representativeness, and the quality of the measurements to set up a conceptual index system for analyzing the coupling coordination among the three subsystems: economy, technological innovation and ecological environment (Table 1). We select twenty indicators that fall under nine dimensions: the scale of the economic development, the structure of the economic development, the benefits of the economic development, technological innovation inputs, technological innovation output, technological innovation environment, ecological environment foundation, pressure on ecological environment and ecological environment protection. Among them, industrial wastewater discharge, industrial solid waste generation, and energy consumption per RMB 10,000 of GDP are negative indicators.

Data Sources

This study considers the quality of the economy, capacity for technological innovation, and the quality of ecological environment in Anhui Province from 2010-2019. The original data used come mainly from China Statistical Yearbooks (2011-2020) [42], China Environmental Statistical Yearbook (2011-2020) [43], China Science and Technology Statistical

Table 1. The indicators for the three subsystems and their weights.

Subsystem	First level indicators	Basic level indicators	Unit	Nature of Index	Weight
Economy	Economic development scale	GDP	Yuan	Positive	0.150
		Total retail sales of social consumer goods	Yuan	Positive	0.197
	Economic development structure	Value added of the secondary sector as a proportion of GDP	%	Positive	0.101
		Value added of tertiary industry as a proportion of GDP	%	Positive	0.263
	Economic development benefit	GDP per capita	Yuan/capita	Positive	0.144
		Urbanization rate	%	Positive	0.145
Technological innovation	Technological innovation input	R&D personnel full time equivalent	Person-year	Positive	0.158
		R&D expenditure	Yuan	Positive	0.219
	Technological innovation output	Number of scientific and technical papers published	#	Positive	0.149
		Number of patents granted	#	Positive	0.144
	Technological innovation environment	Number of higher education institutions	#	Positive	0.121
		Number of scientific research institutions	#	Positive	0.210
Ecological environment	Ecological environment foundation	Parkland area per capita	m^2/ capita	Positive	0.105
		Total water resources	m^3	Positive	0.142
		Greenery coverage in built-up areas	%	Positive	0.091
	Ecological environment pressure	Industrial wastewater discharge	ton	Negative	0.196
		Industrial solid waste generation	ton	Negative	0.062
		Energy consumption per RMB10,000 of GDP	Tonnes of standard coal / RMB 10,000	Negative	0.146
	Ecological environment protection	Comprehensive utilization rate of industrial solid waste	%	Positive	0.094
		Investment in environmental pollution control	Yuan	Positive	0.165

Yearbook (2011-2020) [44], Anhui Statistical Yearbook (2011-2020) [45] and the 2010-2019 Statistical Bulletin on the National Economic and Social Development of Cities. As is standard, interpolation was used to estimate any missing data.

Methodology

Entropy Method

The entropy weight method is an objective weighting method that circumvents the subjectivity problems inherent in subjective weighting methods such as the Delphi method and the analytical hierarchy process (AHP). And it is more objective and scientific. The calculation process is as follows.

The first step is data standardization. Differences in orders of magnitude, dimensionality, and the nature of the indicator data will affect the quality of the analysis results. Therefore, it is necessary to transform the indicator data to be dimensionless [46].

Positive indicators: $X_{ij}^{'} = \frac{x_{ij} - \min\{x_j\}}{\max\{x_j\} - \min\{x_j\}} * 0.9 + 0.1$

Negative indicators: $X_{ij}^{'} = \frac{\max\{x_j\} - x_{ij}}{\max\{x_j\} - \min\{x_j\}} * 0.9 + 0.1$

(1)

In formula (1), $X_{ji}^{'}$ is the normalized value of indicator j in a given year, and x_{ji} is the actual value of indicator j in the same year.

The second step is to determine the weight of indicators.

First, the share of indicator $x_{ji}^{'}$ attributable to region i is calculated.

$$R_{ij} = x_{ij}^{'} \Big/ \sum_{i=1}^{m} x_{ij}^{'} \quad (2)$$

Second, the entropy value of each indicator is calculated.

$$e_j = -(\ln m)^{-1} \sum_{i=1}^{m} R_{ij} \ln R_{ij} \quad (3)$$

In formula (3) j∈ = [1, 2, ..., m].

Third, the coefficient of variation is calculated for each indicator.

$$g_j = 1 - e_j \quad (4)$$

Fourth, the weight of each indicator is calculated.

$$w_j = g_j \Big/ \sum_{j=1}^{m} g_j \quad (5)$$

Fifth, we obtain a comprehensive index of the status of the economy, technological innovation, and the ecological environment.

$$V_j = \sum_{j=1}^{m} w_{ij} X_{ij}^{'} \text{ (i = 1, 2, 3, …, n; j = 1, 2, 3)} \quad (6)$$

Degree of Coupling Coordination Model

Usually, the degree of coupling measures the strength of the association between two or more systems. By combining coupling coordination theory and related studies [47, 48], the degree of coupling coordination model is used to analyze the coupling coordination relationship among the three subsystems, and the formulas are as follows.

$$C = \left\{ \frac{V_1 V_2 V_3}{(V_1 + V_2 + V_3)^3} \right\}^{\frac{1}{3}} \quad (7)$$

In formula (7), V_1, V_2, and V_3 denote the comprehensive index for the economy, technological innovation, and the ecological environment, respectively. C denotes the degree of coupling.

$$D = \sqrt{C\,T}, \text{ where } T = \alpha V_1 + \beta V_2 + \delta V_3 \quad (8)$$

In formula (8), D represents the degree of coupling coordination, and T is the comprehensive index for ETES. α, β and δ are the unknown coefficients, which reflect the relative importance of the three subsystems. In this study, it is assumed that $\alpha = \beta = \delta = 1/3$. The criteria for classifying the level of coupling coordination are determined according to the distribution function [49] and are given in Table 2.

Table 2. Criteria for evaluating the degree of coupling coordination.

D		Grade
Dissonance Decline	0.0-0.09	Extreme imbalance
	0.10-0.19	Serious imbalance
	0.20-0.29	Moderate imbalance
	0.30-0.39	Mild imbalance
Over conciliation	0.40-0.49	Imminent imbalance
	0.50-0.59	Barely coordination
Coordination development	0.60-0.69	Primary coordination
	0.70-0.79	Intermediate coordination
	0.80-0.89	Good coordination
	0.90-1.00	Quality coordination

Kernel Density Estimation Method

The kernel density estimation method is a nonparametric estimation method that uses an intuitive, continuous and dynamic density curve to describe the trends in the dynamic changes in random variables. Therefore, we use kernel density estimation to illustrate the dynamic changes in the degree of coupling coordination in ETES in Anhui Province.

$$F(x)=\frac{1}{nh}\sum_{i=1}^{n}K(\frac{X_i-X'}{h}) \tag{9}$$

where n is the number of observations. X_i is a set of independent and identically distributed observations. X' denotes the mean. h is the bandwidth, which determines the accuracy of the kernel density estimation and the smoothness of the kernel density curve. Following Sun et al. [50], it is assumed that $h = 0.9S*n^{(-0.8)}$, where S is the sample standard deviation. In this study, we use the Gaussian kernel function and the formula is as follows.

$$K(x)=\frac{1}{\sqrt{2\pi}}\exp(-\frac{x^2}{2}) \tag{10}$$

Results and Discussion

Analysis of Weights

Table 1 shows that within each of the three subsystems, the contribution of each indicator to the overall index is relatively uniform. This indicates that each indicator is an important factor influencing the development of the subsystem to which it belongs.

In the subsystem of the economy, compared with economic development benefit, the scale and the structure of economic development can better reflect the quality of economic development. Because the value added of tertiary industry as a proportion of GDP makes the largest contribution, the total retail sales of social consumer goods have the second largest effect on the magnitude of the index. The impact of GDP per capita and urbanization rate is relatively small, and they are both indicators of economic development benefit.

For the technological innovation system, compared with the number of higher education institutions, R&D expenditure and the number of scientific research institutions provide better representations of capacity for technological innovation. The ranking of the various indicators in terms of the contribution of each indicator is as follows: (1) R&D expenditure, (2) the number of scientific research institutions, (3) R&D personnel full time equivalent, (4) the number of scientific and technical papers published, (5) the number of patents granted, and (6) the number of higher education institutions.

From the perspective of the ecological environment system, industrial wastewater discharge is a better indicator of the quality of the ecological environment than industrial solid waste generation. Both are negative indicators, and the lower the value of the indicator is, the better the quality of ecological environment. The contributions of the different indicators in the ecological environment system ranged from 0.091 to 0.196. Among them, industrial wastewater discharge has the largest contribution, followed by investment in environmental pollution control, while the contribution of industrial solid waste generation was relatively small.

Temporal Characteristics of ETES

Comprehensive Index

Fig. 1 shows the comprehensive indexes for the three subsystems and ETES overall:

(1) The quality of the economy and of the ecological environment have improved significantly, and these improvements have occurred more slowly than the improvement in capacity for technological innovation. The comprehensive indexes for the three subsystems basically fluctuate but improve from 2010-2019. The comprehensive index for the economy increased from 0.192 to 0.874, that for technological innovation increased from 0.122 to 0.99, and that for the ecological environment increased from 0.269 to 0.715. The average annual increases were 21.45%, 30.04% and 13.02%, respectively. During the study period, the comprehensive index for technological innovation exhibited the greatest variation, followed by that for the economy and then for the ecological environment. This is mainly due to Anhui Province's policies, which include the active promotion of a supply-side structural reform, the transformation and upgrading of the industrial structure, integration into the Yangtze River Delta, and industrial transfers, which have led to further improvements in the quality of the economy. In addition, Anhui Province has actively implemented green development, resulting in further improvements to the ecological environment. Moreover, Anhui Province has vigorously and successfully promoted the implementation of its technological innovation-driven strategy for economic growth. During the study period, investments in technological innovation and the technological innovation environment improved substantially in Anhui Province. In particular, R&D personnel full time equivalent nearly doubled. R&D expenditure and the number of scientific research institutions quadrupled. This has led to increasingly fruitful technological innovations, with the number of patents granted quadrupling from 2010.

(2) The quality of ETES improved continually. The comprehensive index for ETES trended upward year by year from 2010-2019. Its value increased from 0.194 to 0.874, with an average annual increase of

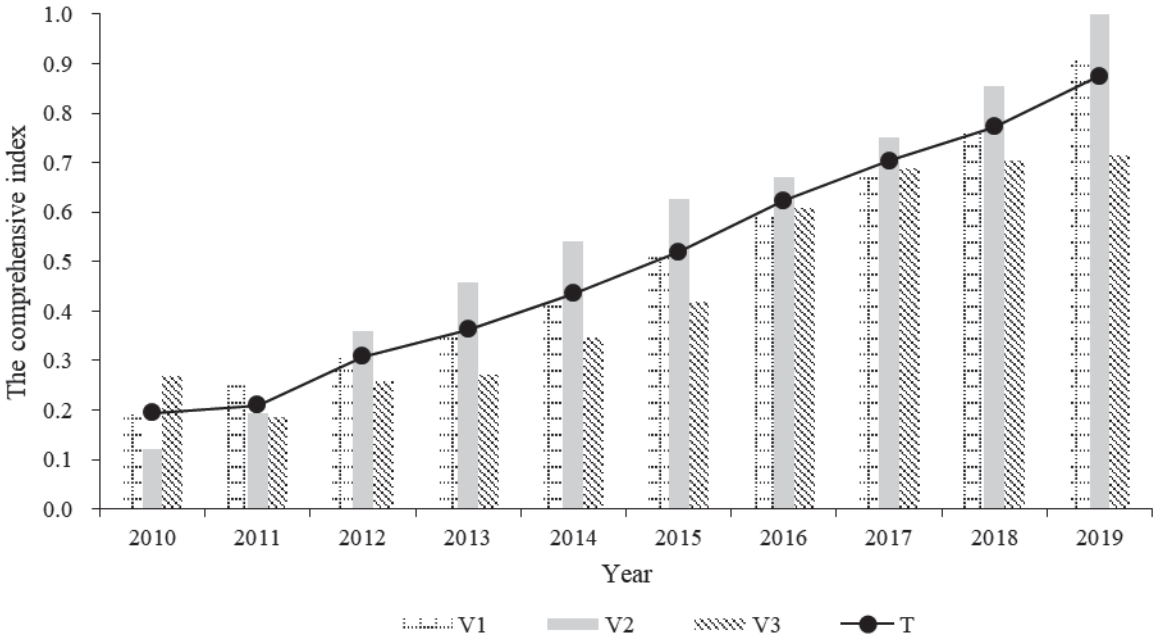

Fig. 1. The comprehensive indexes for ETES and the three subsystems in Anhui Province.

20.69%. The growth in the comprehensive index for ETES can be divided into two phases according to the rate of growth. 1) Phase one occurred in 2010-2011, during which time the comprehensive index for ETES grew slowly. During this period, the comprehensive index for economy and technological innovation both improved to varying degrees, but the index for the ecological environment decreased slightly. This is mainly due to an increase in the production of industrial solid waste generation but a decline in its overall utilization rate. Other indicators improved modestly, but the changes were small, resulting in the deterioration of the ecological environment. 2) The second phase encompassed 2012-2019, during which time the comprehensive index for ETES grew rapidly. The comprehensive index for technological innovation grew the fastest, followed by that for the economy and then that for the ecological environment. Moreover, the comprehensive index for technological innovation has always been higher than that for the economy and the ecological environment since 2012. This is mainly because Anhui Province, after entering the "Twelfth Five-Year Plan" period, began to seriously implement its innovation-driven development strategy and has always placed innovation at the core of its overall development. This focus has greatly improved Anhui Province's capacity for technological innovation and promoted the steady growth of the regional economy. Anhui Province has continuously increased the greenness of and reduced the carbon emissions from its production and lifestyle activities and promoted work to protect the ecological environment. These

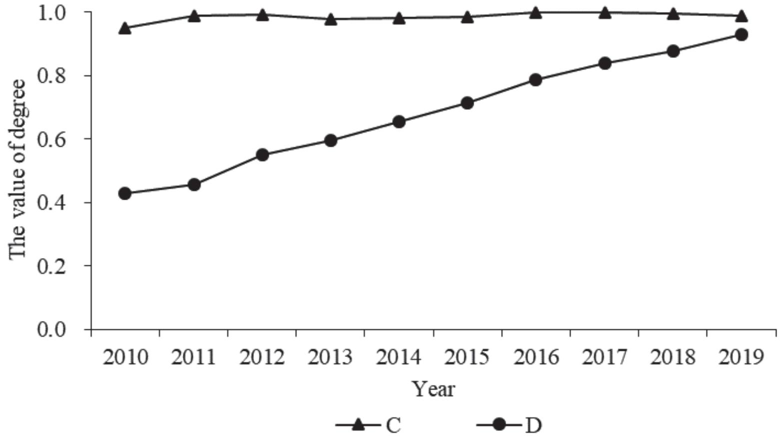

Fig. 2. The degree of coupling and of coupling coordination in the Anhui Province ETES.

actions have significantly improved the ecological environment. However, due to the influence of past extensive development, there is still much room for its ecological environment to improve.

Degree of Coupling and of Coupling Coordination

The changes in the degree of coupling and of coupling coordination in Anhui Province from 2010-2019 are shown in Fig. 2. They both exhibit a steady upward trend, while the variation in the degree of coupling is relatively small, while fluctuations in the degree of coupling coordination are more pronounced.

The development level is comparable across the quality of the economy, the capacity for technological innovation, and the quality of the ecological environment. The degree of coupling exhibited a fluctuating upward trend. Its value rose from 0.951 to 0.99, always approaching 1.0. These results indicate that the system has a generally high level of coupling, which indicates a high level of interconnectedness and dependence and strong internal coordination.

The level of coupling coordination improved substantially during the study period. The degree of coupling coordination maintained an upward trend. Its value increased from 0.430 to 0.931, with a large average annual increase. Moreover, the type of coupling coordination shifted from an imminent imbalance to quality coordination, indicating a gradual increase in the orderliness of ETES. The development of coupling coordination can be divided into 6 stages according to the type of coupling coordination. The first stage was 2010-2011 (0.430, 0.457), which exhibited an imminent imbalance. The second stage was 2012-2013 (0.552, 0.595), during which ETES was barely at the coordination level. The third stage was 2014 (0.655), with the coupling coordination at the primary coordination. The fourth stage was 2015-2016 (0.716, 0.789), with intermediate coordination, and the fifth stage was 2017-2018 (0.839, 0.877), with good coordination. During the sixth stage, it was 2019 (0.931), with the coupling coordination at the quality coordination level.

Temporal Evolution of the Coupling Coordination

To further understand the temporal evolution of the coupling coordination in the Anhui Province ETES from 2010-2019, we use a kernel density estimation curve (Fig. 3) to evaluate the changes the patterns, peaks, locations and tails of the distribution of the comprehensive index, the degree of coupling in, and the degree of coupling coordination in ETES.

The trends in the evolution of the comprehensive index, the degree of coupling, and the degree of coupling coordination in ETES are depicted in Fig. 3. There is a general upward trend in the coupling coordination in ETES, with a gradual increase in regional differences.

Fig. 3a) shows that the development level of ETES has a gradual improvement and a trend toward convergence, owing to the distribution of the comprehensive index for ETES having a single peak in each year and the density distribution curve shifting to the right. Compared with 2010, the peak in the density

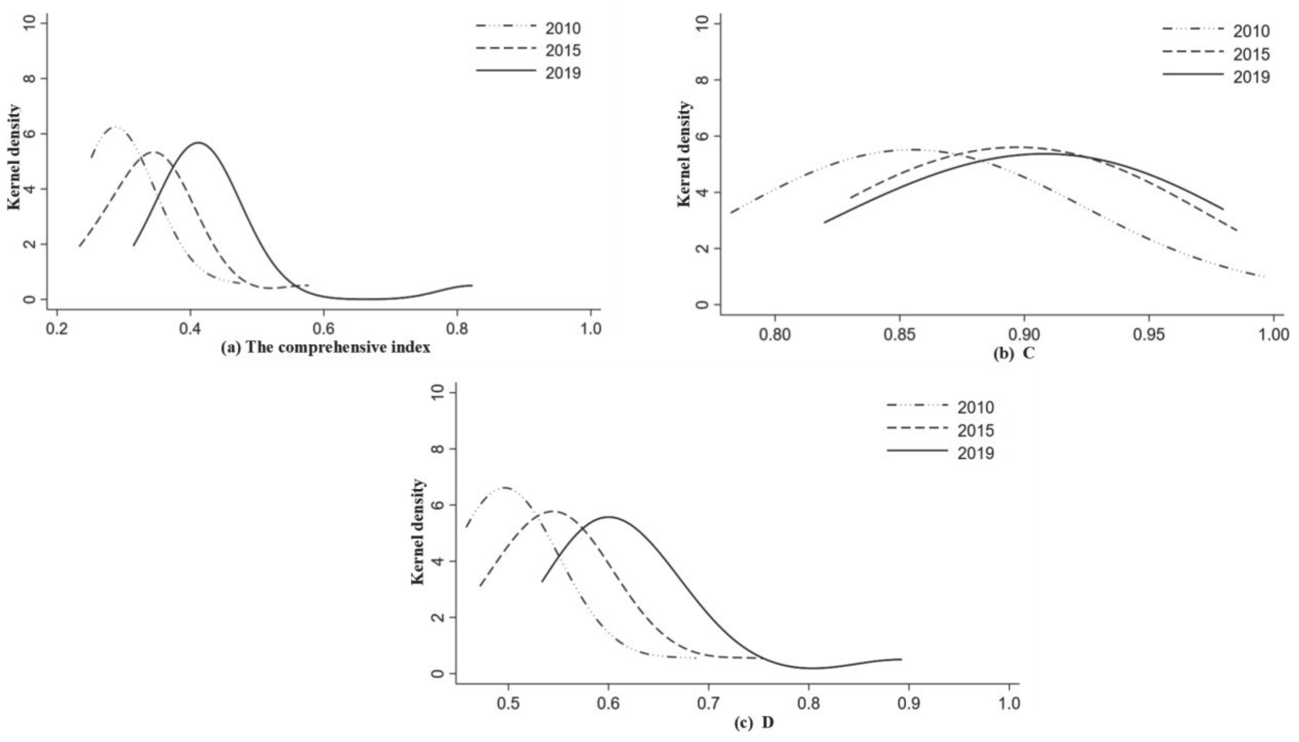

Fig. 3. Kernel density estimation curve.

function in 2015 was substantially smaller, indicating that the variation in the comprehensive index for ETES between regions decreased. Compared with 2015, the peak in the density function in 2019 increased slightly, while the right tail lengthened, indicating an increase in the variation in the comprehensive index for ETES between regions and an increase in polarization.

As shown in Fig. 3b), the degree of coupling in ETES increased, and the coordination in the development of the three subsystems gradually increased. The overall shape of the distribution of the degree of coupling in ETES is single-peaked and flat. In addition, the density distribution curve shifts to the right. Compared with 2010, the density distribution curve shifted to the right, while the peak remained almost the same, and the right tail became shorter. This indicates that the variation in the degree of coupling between regions has changed little over time and the overall level of coupling has tended to improve. Compared with 2015, the density distribution curve for 2019 shifted slightly to the right, with a slight decrease in the peak and a longer left tail. This indicates the degree of coupling has increased in the polarization between regions.

As shown in Fig. 3c), there is variation in the degree of coupling coordination between regions. The density distribution for the degree of coupling coordination in ETES is basically unchanged over time, with the distribution exhibiting skewness due to a long right tail, and the distribution is essentially single-peaked. Compared with 2010, the single peak was shorter and leans more to the right, while the kurtosis was smoother in 2015, which indicates that the degree of coupling coordination increased and the share of regions with barely any coupling coordination increased. The left and right tail sections became longer, indicating an increase in the polarization of coupling coordination. Compared with 2015, the peak was unchanged, and the density distribution shifted to the right, while the right tail lengthened in 2019. This indicates that there was a slight increase in the overall degree of coupling coordination in 2019, while the share of regions at primary coordination increased and the number of areas with a low degree of coupling coordination was greater than that with a high degree of coupling coordination.

Spatial Characteristics

Regional Differences in the Degree of Coupling Coordination

To describe the general characteristics of the coupling coordination in ETES in the different regions of Anhui Province, we analyze the regional differences in the distribution by Ward clustering (Fig. 4) and regional rankings (Fig. 5). The distribution of the degree of coupling coordination in ETES is uneven. The 16 regions can be divided into five categories according to the level of coupling coordination.

(1) Hefei and Wuhu perform exceptionally well and belong to the first and second categories, respectively. According to Fig. 5, these two regions consistently rank 1st and 2nd during the study period. This is mainly

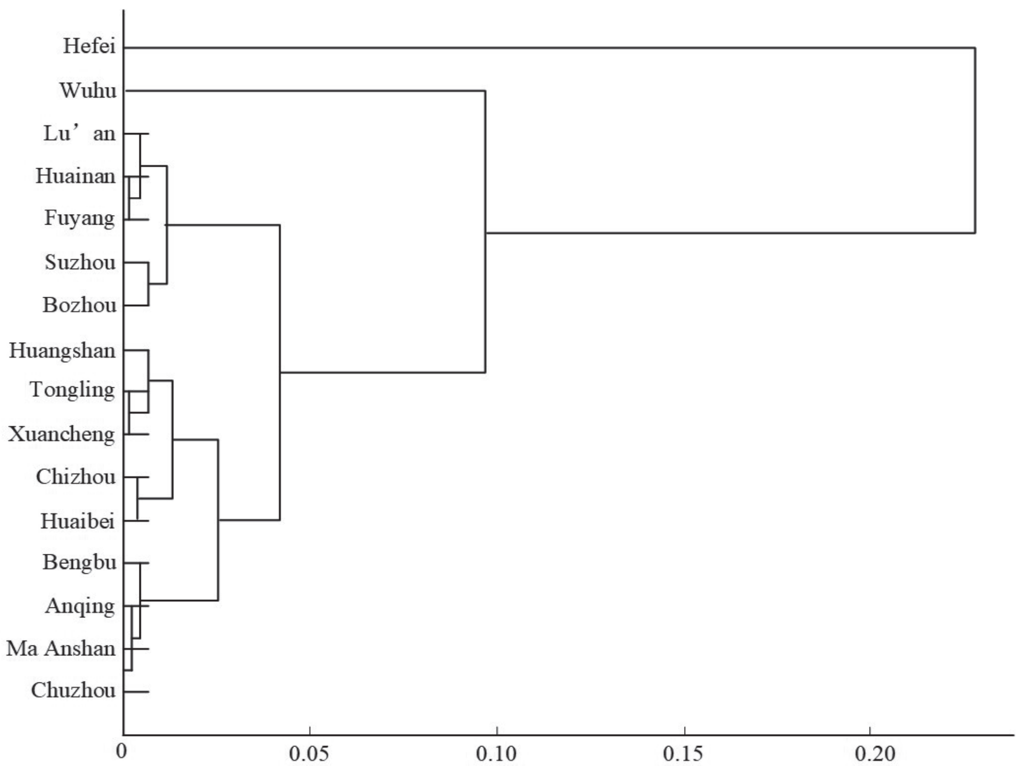

Fig. 4. Clustering tree for the degree of coupling coordination in the Anhui Province ETES.

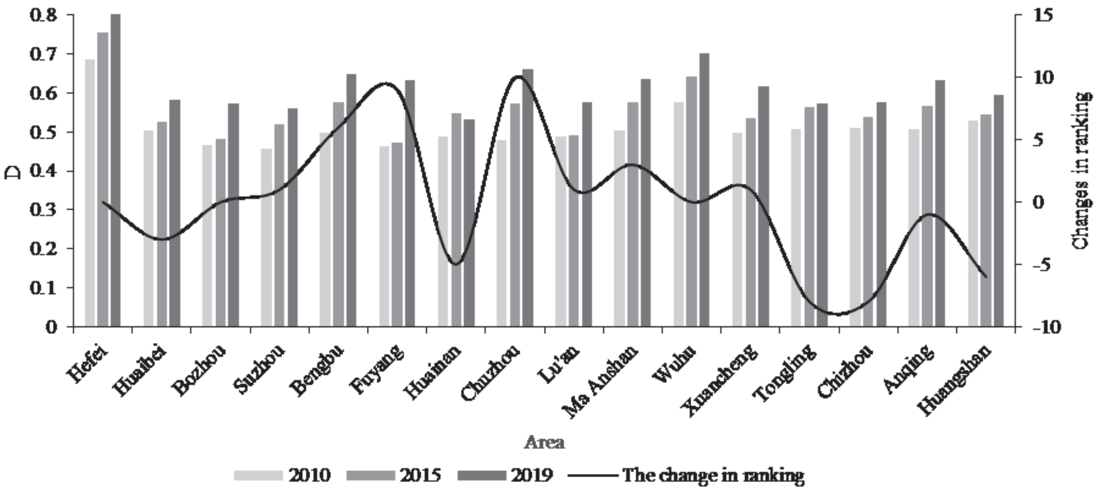

Fig. 5. Trend in the city-level changes in the degree of coupling coordination in the Anhui Province ETES.

because Hefei and Wuhu are the two core cities in Anhui Province and their GDP is always the highest in the province.

Hefei is the capital city of Anhui Province, its economic center and the center of science and innovation. In terms of the economy, the economic structure of Hefei is excellent, with the value added of tertiary industry as a proportion of GDP accounting for more than 60%. The economic development benefit is obvious, with an urbanization rate of 76.33%. In terms of technological innovation, Hefei has a high-quality technological innovation environment, with nearly one-half of higher education institutions in the province and more than 1,400 scientific research institutions. The share of investment in technological innovation is large; one-third of all R&D personnel full time equivalent are in Hefei, and R&D expenditure is more than double that of Wuhu, which ranks second. Hefei is fruitful in terms of technological innovation output, accounting for about one-half of that of the province. In terms of ecological environment, Hefei focuses on green development, and it makes large investments in environmental management. In summary, Hefei is at the forefront of the development in the province.

As an important regional center city and transportation hub in East China as well as within the Yangtze River Delta city cluster, Wuhu has obvious locational advantages. It is actively practicing the five development concepts and continuously improving its economic development in gold content, technology content, green content and per capita amount. Consequently, it has extensive advantages in economic development, technological innovation and the ecological environment.

(2) The third category includes Chuzhou, Ma Anshan, Anqing and Bengbu, whose degrees of coupling coordination are between 0.5 and 0.575. Chuzhou exhibits the greatest improvement, increasing its rank by 10 places, while Anqing dropped 1 place. The capacity for technological innovation is rapidly improving in Chuzhou, Bengbu, and Ma Anshan. Because of their outstanding performance in technological innovation investment and output, R&D personnel full time equivalent and R&D expenditures in these regions are high compared with those in other regions. In addition, the quality of their economic development falls in the middle-top of the provincial ranking. Meanwhile, in terms of green development, these regions have increased their efforts to protect the ecological environment. However, the value added of the secondary sector as a proportion of GDP in regional economic growth is still large, resulting in high pressure on the ecological environment. Moreover, given its natural locational advantage, Anqing's ecological environmental conditions have been in the province's leading level. However, its economic development benefit is relatively low, and its GDP per capita and urbanization rate are among the lowest in the province, which limits the degree of coupling coordination in the region.

(4) The fourth type includes Huaibei, Chizhou, Xuancheng, Tongling and Huangshan, which have degrees of coupling coordination between 0.538 and 0.556. Of these, Huaibei fell 3 places in the ranking, Chizhou dropped 8 places, Xuancheng rose 1 place, Tongling dropped 8 places, and Huangshan dropped 6. The GDP of Huaibei, Chizhou, Xuancheng, Tongling and Huangshan is in the middle and lower reaches of the province. Moreover, the quality of economic development is relatively low. In addition, the environment and investment in technological innovation are general, resulting in an unexceptional capacity for technological innovation. Compared with other regions, these regions have hindered the improvement in their regional coupling coordination.

(5) The fifth category includes Bozhou, Suzhou, Fuyang, Huainan, and Lu'an, which have degrees of coupling coordination ranging from 0.507 to 0.524. Of these regions, Bozhou's ranking does not change, Suzhou's ranking increases by 1 place, Fuyang's

ranking rises by 9 places, Huainan's ranking drops by 5 places, and Lu'an's ranking rises by 1 place. These regions have very low-quality economic development, low capacity for technological innovation, and poor ecological environment, resulting in a lower level of coupling coordination. The reasons are that in these regions, the primary industry accounts for more than 10% of the economic growth and the industrial structure is relatively backward. In addition, due to the limitation of economic structure and level, the technological innovation environment, such as the scientific research institutions and higher education institutions, is relatively poor, which has led to a low level of technological innovation inputs and outputs. Moreover, the ecological environment has a weak foundation, and investment in environmental pollution control is insufficient, which has led to relatively poor ecological environmental conditions. All these have greatly hindered the development of the region to a higher level of coupling coordination.

Spatial Distribution of Coupling Coordination

To further study the spatial distribution of coupling coordination levels in Anhui Province, three years of regional data were selected and Arc GIS10.2 software was used to plot the spatial distribution of the degree of coupling coordination (Fig. 6).

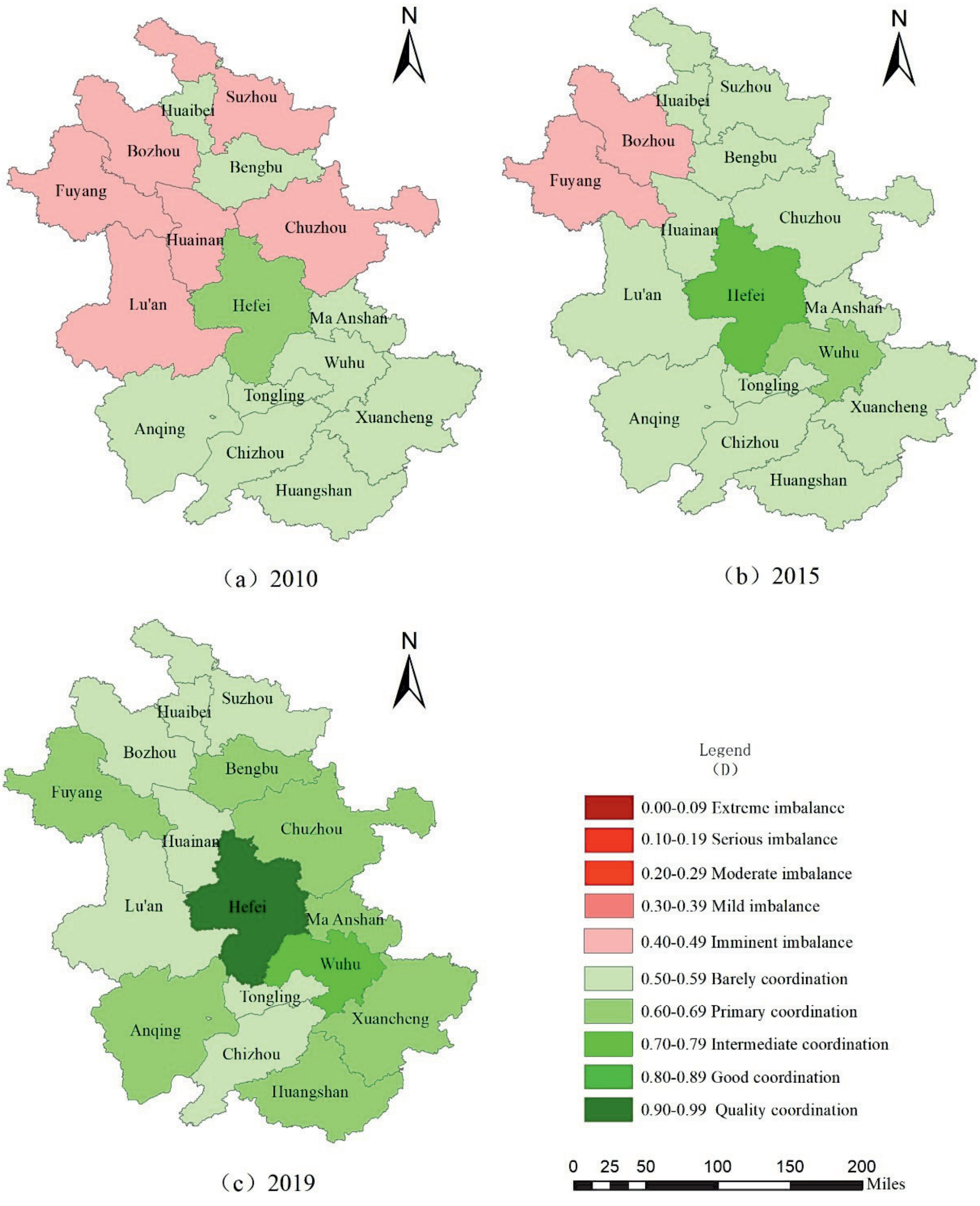

Fig. 6. Spatial distribution of the degree of coupling coordination in the Anhui Province ETES.

In general, the 16 cities exhibit positive trends in their degree of coupling coordination, but there are regional differences. In particular, the degree of coupling coordination in southern Anhui is significantly better than that in northern Anhui, and Hefei always has the highest degree of coupling coordination in the province.

In 2010, most cities were over conciliation, owing to the degree of coupling coordination ranging from 0.4 to 0.59. The cities with an imminent imbalance are located mainly in northern Anhui, while those at barely coordination are in southern Anhui. Particularly, the regions with a low level of coupling coordination are Suzhou, Bozhou, Fuyang, Lu'an, Huainan and Chuzhou.

In 2015, most cities were barely coordination, while Fuyang and Bozhou were still imminent imbalance. Hence the spatial distribution of coupling coordination was relatively uniform. In addition, the degree of coupling coordination in Suzhou, Huainan, Lu'an and Chuzhou improved significantly.

In 2019, the spatial distribution was uneven. The city with the best coupling coordination level was Hefei (0.892), which had good coordination. Hefei is followed by Wuhu (0.702), which has intermediate coordination. Additionally, Huainan (0.534) was barely coordination and had the worst degree of coupling coordination in the province. This indicates that there are differences in the degree of coupling coordination across cities. Except for Hefei and Wuhu, no city had a degree of coupling coordination higher than 0.7, and most cities were barely coordination or had only primary coordination. Moreover, the degree of coupling coordination in southern Anhui was significantly better than that in northern Anhui. The reason is not only the technological innovation environment and input in northern Anhui are significantly lower than those in southern Anhui, resulting in a distinct gap in technological innovation output but also the tertiary industry contributes more to economic growth in southern Anhui, where the leading industries are mainly the military, the service industry and the tourism industry. In addition, environmental pollution emissions are relatively low, and investments in environmental pollution control are increasing each year. Therefore, the coupling coordination level in southern Anhui is obviously good. However, Anhui Province has still not achieved high-quality regional development as a whole.

Conclusions

This study analyzes the characteristics of the temporal and spatial distribution of the degree of coupling coordination in ETES with panel data on 16 cities in Anhui Province from 2010-2019. The main conclusions are as follows.

(1) The comprehensive index for ETES exhibited a fluctuating upward trend. The increase in the comprehensive index for technological innovation was higher than that for the economy and the ecological environment.

(2) From the temporal perspective, the degree of coupling in ETES exhibited a fluctuating upward trend with small changes, while the level of coupling remained high, which indicates a high level of internal coordination. In addition, the degree of coupling coordination in ETES maintained a steady upward trend, while the degree of coupling coordination changed from an imminent imbalance to quality coordination.

(3) From the spatial perspective, the 16 cities can be divided into five categories according to the degree of coupling coordination. Meanwhile, the coupling coordination level of the 16 cities increased overall, but there were regional differences. The number of regions with a low level of coupling coordination was greater than that with a high level of coupling coordination. And the coupling coordination in southern Anhui was significantly better than that in northern Anhui, while the coupling coordination level in Hefei was always the highest in the province.

The above findings provide useful insights for understanding the characteristics of the spatial and temporal distribution of the degree of coupling coordination in the Anhui Province ETES. Therefore, the government should carry out differentiated strategies in connection with the actual conditions. In terms of the research results, this study provides the following implications.

(1) For Bozhou, Suzhou, Huainan and other cities with a low degree of coupling coordination, the government can give moderate policy incentives for investment in scientific research, technology research and development, the introduction of talent, etc. In addition, the industrial structure can be reasonably planned to encourage and support the development of strategic emerging industries and high-tech industries and to strengthen the utilization of scientific and technological achievements.

(2) It is vital to actively utilize their own advantages for cities with high levels of coupling coordination. The synergistic development of the region should be emphasized, especially in terms of economic development and technological innovation. Through bilateral or multilateral governmental cooperation, neighboring cities with low levels of coupling coordination can be driven to narrow the gap between them.

(3) Moreover, high-quality development involves the coordination of three subsystems. It is necessary to continuously strengthen awareness of ecological environmental protection and to increase investments in ecological environmental protection and governance. We must always adhere to the tenets of green and sustainable development to achieve balanced and sustainable regional development.

The research and analysis of this topic in this article are not comprehensive and perfect. In the future we would like to improve the construction of the indicators of the three subsystems, and select more comprehensive and representative indicators. Meanwhile, from the perspective of the study method, we would like to select other development indexes that can measure the relationship between the three subsystems and compare the degree of coupling coordination. By analyzing the relationship and development trend, the article is more convincing.

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Conflict of Interest

The authors declare no conflicts of interest.

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