DOI: 10.2478/eces-2025-0010 ECOL CHEM ENG S. 2025;32(2):189-212

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GREEN DEVELOPMENT SYNERGIES AND REGIONAL DISPARITIES IN THE YANGTZE RIVER DELTA URBAN AGGLOMERATION

Abstract: The comprehensive green transition of China necessitates synergistic development among carbon reduction (CR), pollution reduction (PR), green expansion (GE), and economic growth (EG). This study evaluates the spatiotemporal dynamics of this synergy in the Yangtze River Delta urban agglomeration from 2005 to 2021 through a multidimensional assessment framework. Employing coupling coordination degree analysis, spatial econometrics, and geographically weighted regression models, we investigate the spatiotemporal patterns and driving factors of coordinated development in the region. Our findings reveal steady annual improvements in the comprehensive evaluation of these four dimensions, indicating positive progress in green development. The coupling coordination degree demonstrates distinct spatial heterogeneity, characterised by strengthening southeast-northwest variations and clear migration patterns. Spatial correlation analysis shows fluctuating synergistic relationships during the study period. Innovation level and educational investment emerge as significant factors influencing coupling coordination. We recommend enhanced investment in technological innovation and education, alongside strengthened cross-regional cooperation and resource sharing, to accelerate green transformation and achieve sustainable development goals.

Keywords: carbon reduction, pollution reduction, green expansion, economic growth, coupling coordination degree, spatial heterogeneity, geographically weighted regression model

Introduction

Currently, global issues such as climate change, environmental pollution, and ecological degradation are becoming increasingly severe, posing significant challenges to the sustainable development of society and the economy [1]. To address these challenges, the United Nations adopted the "2030 Agenda for Sustainable Development" in 2015, which includes 17 Sustainable Development Goals (SDGs). It specifically urges nations to take decisive steps in addressing climate change and its consequences, while safeguarding, restoring, and fostering the sustainable management of terrestrial ecosystems [2]. In this context, reducing carbon emissions, lowering pollution, expanding ecological land, and promoting green economic development have become key goals for governments worldwide in achieving sustainable development [3].

As a major developing country, China bears significant responsibility in achieving the United Nations' SDGs. The Chinese government places high importance on ecological civilisation, establishing the goal to reach peak carbon dioxide emissions prior to 2030 and attain carbon neutrality by 2060 [4]. However, due to differences in natural endowments,

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development stages, and other factors, there is evident regional heterogeneity in economic development and carbon emissions across the country [5]. For instance, the Yangtze River Delta urban agglomeration is not only one of China's most economically advanced areas but also a key center for manufacturing and energy consumption, confronting significant challenges in cutting carbon emissions. At the same time, the region's ecological environment is under significant stress, with some areas suffering from severe ecosystem degradation. This conflict between economic development and ecology highlights the substantial challenges in achieving the coordinated development of carbon reduction (CR), pollution reduction (PR), green expansion (GE), and economic growth (EG) within the region and in relation to other regions. Thus, using the Yangtze River Delta urban agglomeration as a case study to assess the coordinated development of CE, PR, GE, and EG across cities, identify key driving factors, and propose strategies to enhance regional synergy is crucial for guiding the achievement of the UN's SDGs in both the Yangtze River Delta and nationwide in China.

In recent years, with the increasing recognition of sustainable development principles, the coordinated development of CR, PR, GE, and EG has become a critical objective for regional development across various countries. The academic community has extensively explored related fields, including the construction of evaluation frameworks, identification of influencing factors, and investigation of coordinated development mechanisms. In terms of evaluation frameworks, prior studies have constructed comprehensive indicator systems incorporating dimensions such as carbon emissions, environmental pollution, and ecological pressure [6, 7]. Regarding influencing factors, scholars identified key drivers of regional disparities in sustainable development, including economic development level, industrial structure, and technological innovation [8, 9]. Furthermore, research on coordinated development mechanisms has examined effective pathways for promoting inter-regional cooperation, focusing on institutional frameworks, policy interventions, and interest alignment [10, 11]. These studies have yielded valuable insights for policy formulation and implementation.

However, several gaps remain in the existing literature. First, the synergy among CR, PR, GE, and EG has yet to be systematically assessed from the perspective of spatiotemporal heterogeneity. Second, a systematic understanding of the diverse factors shaping regional coordination and their underlying mechanisms remains insufficient.

Building on this, this study focuses on the Yangtze River Delta urban agglomeration in China. First, an evaluation index system is constructed to assess the coordination level of CR, PR, GE, and EG across cities. Next, the dynamic evolution trends of coordinated development is analysed. In order to explore the inter-city variability from both time and space levels. Finally, the key factors driving the coordinated progress of CR, PR, GE, and EG are identified from a dynamic perspective. This study addresses the gap in assessing the synergies among CR, PR, GE, and EG by considering spatial and temporal heterogeneity, particularly in understanding the factors and mechanisms influencing regional coordinated development.

It is expected that the findings of the study will contribute to the achievement of the United Nations' SDGs in China and globally, and promote a more equitable and sustainable path for global development.

Literature review

The carbon reduction effect and its impact on economic development

Numerous scholars have found that the "dual carbon" goals not only facilitate CR through various mechanisms but also have a significant impact on economic development. Studies have shown that the "dual carbon" goals can achieve CR effects through various mechanisms, including improving energy ecological efficiency [12], carbon trading policies [13], and low-carbon city pilot policies [14]. Additionally, carbon trading policies [15], low-carbon cities, and renewable energy technology innovation [16] also play a significant role in influencing economic development. Moreover, low-carbon cities and renewable energy technology innovation are important drivers of economic growth [17]. Therefore, it is evident that the "dual carbon" goals play a dual role between carbon reduction and economic development through technological innovation, policy incentives, and institutional design.

However, existing research also highlights the complex economic impact of carbon peaking. Studies indicate that the earlier carbon emissions peak, the greater the short-term economic shock [18], particularly in scenarios where government revenues and savings may experience significant declines. Moreover, this economic impact varies considerably across industries. For instance, the construction sector is relatively less affected by carbon peaking, whereas other industries exhibit slight output growth [19].

Despite these findings, current research lacks a comprehensive analysis of regional and industrial differences, particularly regarding how carbon trading policies and low-carbon technologies play differentiated roles across various regions. Further exploration is needed to understand these disparities and their implications for sustainable economic transitions.

Synergistic effects of the multiple goals of green development

Numerous studies have shown that CR policies have pollution reduction effects. For example, the CO_2 emission reduction policy in the U.S. power sector has improved air quality [20], and moderate carbon tax policies in China have also been effective in controlling air pollution [21]. PR policies have CR effects, such as the use of low-sulphur fuels and environmental regulations that promote the coordinated reduction of pollutants and greenhouse gases by enterprises [22]. The impact of these factors is shaped by the energy structure and consumption patterns of the enterprises [23]. The CR effect of green expansion primarily strengthens carbon sequestration through increasing vegetation coverage [24]. The carbon accumulation in areas with dense vegetation distribution, such as forest and grassland areas, is significantly higher than in other functional land areas [25], which contributes to advancing the carbon neutrality process. However, the pollution reduction effect of green expansion is weaker. Existing studies have found that, compared to factors such as annual wind speed, average annual temperature, topographical variation, secondary industry proportion, and energy consumption, vegetation coverage has a relatively weak effect on air pollution control [26]. GE has some pollution reduction and CR effects to a certain extent. While environmental protection may incur economic costs, local government competition for growth under environmental regulations encourages clean technology innovation, helping to mitigate the negative impact on economic growth [27]. Clean energy and green technological innovation are effective pathways for promoting both ecological environmental protection and economic growth [28]. In the short term, green technologies carry higher risks, requiring sustained investment, which may lead to the crowding-out effect of capital, thus restraining economic growth and being difficult to gain recognition from the capital markets [29]. However, in the long term, they are beneficial for green transformation and high-quality economic growth [30].

Institutional mechanisms for CR, PR, GE, and EG

Research on the institutional mechanisms for coordinating CR, PR, GE, and EG under the "dual carbon" goals has gained increasing attention. A substantial body of work has explored the coupling of multiple green development objectives, including CR, pollution mitigation, green expansion, and economic growth, across various regions. Several studies have explored sustainable development strategies under the "dual carbon" framework in regions such as the Yellow River Basin, China’s border areas, the Jin-Shaan-Mongolian region, and the western regions, offering valuable insights into regional implementation [31]. Most scholars agree that the coordinated development and mutual promotion of the three-dimensional system - comprising carbon emissions, economic growth, and the ecological environment - create favourable conditions for economic development by leveraging resource endowments and ecological environmental carrying capacity. Furthermore, the heterogeneity in environmental regulation policy design can lead to differentiated impacts on the coordinated advancement of the ecological environment and economic growth [32].

For instance, optimising the environmental protection tax rate design helps achieve the coordinated goals of the economy, environment, and innovation. Increasing the intensity of environmental protection tax implementation strengthens the synergy of economy, environment, and innovation; however, excessively strengthening the implementation intensity of the environmental protection tax has the opposite effect [33]. Factors such as local government competition under environmental regulations [34], resource allocation [35], and the transformation of fixed asset investment [36] have also been explored by scholars as important institutional mechanisms. Additionally, some scholars have studied the synergy and co-benefits of green consumption, supply-side structural reforms, the comprehensive savings strategy, new technological and industrial revolutions, population and economic concentration in central cities and urban agglomerations, as well as the coordination of CR, pollution reduction, and ecological protection [37]. In the study of institutional mechanisms under the ‘dual-carbon’ objective, it is worthwhile to strengthen the reference to international experience, especially the practices of the European Union and the United States in green policies. For example, the EU’s Green New Deal provides important insights into the synergy between carbon emission reduction and economic growth by strengthening the interaction between environmental policies, technological innovation and market mechanisms [38]. The policies of the United States on clean energy investment and green technology innovation also provide a reference for countries such as China on green transformation [39].

A comprehensive review of the literature underscores that the integrated progress of CR, PR, GE, and EG represents a critical pathway toward achieving sustainable development. Theoretical frameworks on the coordinated coupling of environmental, economic, and social systems, along with their underlying mechanisms, provide a foundational basis for constructing evaluation indicator systems and analysing the determinants of coordinated development. However, existing research on the synergy among these four dimensions remains relatively limited, with an even greater scarcity of studies examining the spatiotemporal dynamics of their coordinated progression.

The main issues are as follows: first, the definition of green development goals and their connotations is not clear, and the mechanisms for their coordinated promotion are even more difficult to determine, which restricts the effective design and implementation of institutional arrangements and various initiatives.

Second, there is no research that comprehensively considers the regional differences in ecological and environmental protection policy heterogeneity, resource endowments, climate, population, social, and institutional environments, and forms a unified framework.

Third, studies focusing on CR, PR, GE, and EG are often confined to individual sectors and lack a comprehensive approach. Additionally, research on regional cooperation mechanisms is still weak.

This study develops an evaluation framework for the coordinated development of CR, PR, GE, and EG. It examines the spatial distribution patterns and evolutionary trends of their coupling coordination in the Yangtze River Delta urban agglomeration in China, while also identifying the key factors that influence these dynamics.

Research framework

Based on insights from existing research, this study proposes a research design framework for CR, PR, GE, and EG, which includes overall analysis, research models, and data sources, as shown in Figure 1.

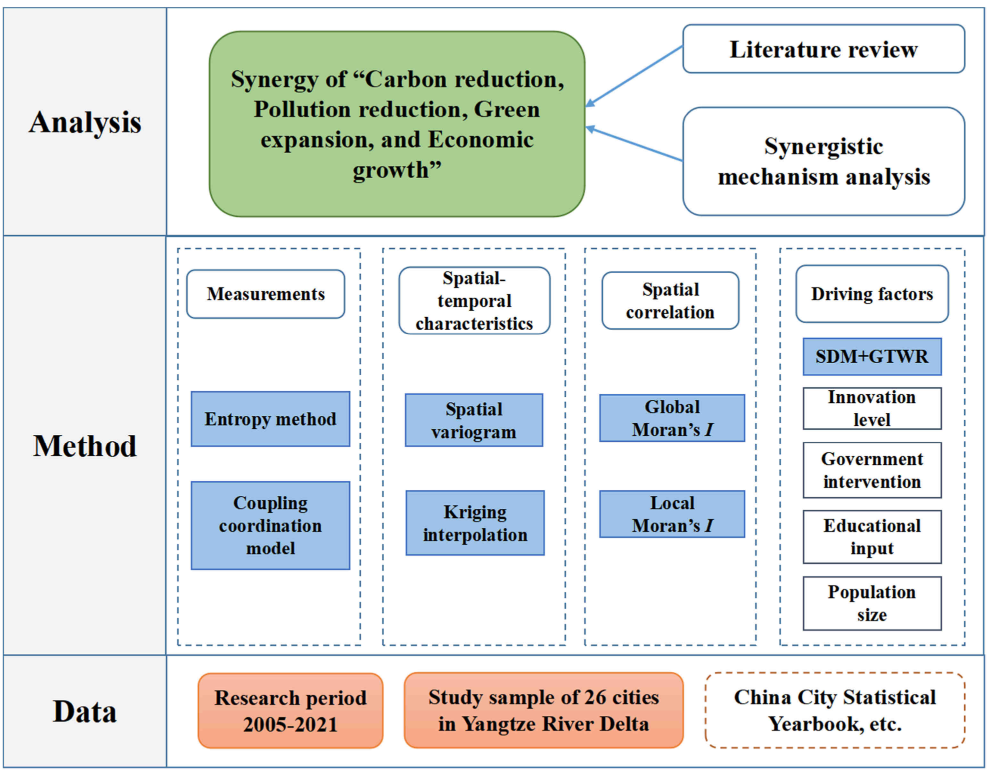

Fig. 1. Research framework

Evaluation system

Building on existing studies and adhering to the principles of objectivity, rationality, and data availability [40], this study constructs an evaluation indicator system to assess CR, PR, GE, and EG (Table 1). This comprehensive indicator system provides a structured approach for analysing the coordinated development of environmental sustainability and economic progress, offering a robust framework for further research and policy evaluation.

Specifically, CR is measured using indicators such as total CO_2 emissions, annual electricity consumption, total gas supply, and liquefied petroleum gas supply [41, 42]. Pollution reduction is assessed through indicators including SO_2 concentration, industrial SO_2 emissions, industrial wastewater discharge, industrial dust emissions, and the harmless treatment rate of household waste [43]. Green expansion is evaluated based on forest coverage and green space area [44, 45]. Lastly, economic growth is represented by indicators such as GDP per capita, labour force and employment numbers, and GDP per capita growth rate [46, 47].

Table 1

CR, PR, GE, and EG: a synergistic development evaluation system

Variant	Indicator	Connotation of indicators	Unit	Causality
CR	Total CO_2 emissions	Total CO_2 emissions	t*	-
	Annual electricity consumption	Annual electricity consumption	GWh	-
	Total gas supply (coal gas, natural gas)	Annual gas supply (coal gas, natural gas)	t	-
	Liquefied petroleum gas supply	Annual liquefied petroleum gas supply	t	-
PR	SO_2 concentration	The content of SO_2 in each cubic meter of air	$\mu g/m^3$	-
	Industrial SO_2 emissions	Total industrial SO_2 emissions	t	-
	Industrial wastewater discharge	Total industrial wastewater discharge	t	-
	Industrial smoke emissions	Total industrial smoke emissions	t	-
	Non-hazardous domestic waste disposal rate	Proportion of waste disposed of safely	%	+
GE	Rate of forest cover	Forest cover as a percentage of zoned area	%	+
	Green area	Total area of all parks, meadows, woodlands and other green spaces	ha**	+
EG	GDP per capita		Yuan RMB	+
	Labor force and employment		10,000 persons	+
	GDP per capita growth rate	GDP per capita increase over previous year	%	+

* t = tonne = 10^3 kg = 10^6 g = Mg, ** ha = hectare = 10^4 m^2

Data source

This study focuses on 26 cities in the Yangtze River Delta region of China. The main data sources include the China Statistical Yearbook (2005-2021), the China Population and Employment Statistical Yearbook, as well as official websites of the National Bureau of Statistics (http://www.stats.gov.cn/) and the Ministry of Natural Resources of the People's Republic of China (http://gi.mnr.gov.cn/), as well as statistical yearbooks from various provinces. To address missing data for certain indicators, linear interpolation was applied for estimation and calculation.

Research methods

Entropy method

The entropy method assigns weights to each indicator by assessing their degree of variation (dispersion), where the level of dispersion indicates the weight of each indicator [48]. In this study's synergy evaluation framework, the entropy method was employed to compute the objective weights for 14 secondary indicators, and the weights for the four primary indicators were aggregated. This approach provides essential data for the rigorous analysis of the synergistic effects between CR, PR, GE, and EG. The calculation procedure is as follows:

(1) Data normalisation

To eliminate dimensional differences, each indicator is normalised.

For positive indicators (the higher, the better), the following range normalisation method is applied:

$$Z'_{ab} = \frac{Z_{ab} - \min(Z_{1b}, Z_{2b}, \dots, Z_{mb})}{\max(Z_{1b}, Z_{2b}, \dots, Z_{mb}) - \min(Z_{1b}, Z_{2b}, \dots, Z_{mb})} \quad (1)$$

For negative indicators (the lower, the better), the following range normalisation method is applied:

$$Z'_{ab} = \frac{\max(Z_{1b}, Z_{2b}, \dots, Z_{mb}) - Z_{ab}}{\max(Z_{1b}, Z_{2b}, \dots, Z_{mb}) - \min(Z_{1b}, Z_{2b}, \dots, Z_{mb})} \quad (1)$$

$$(a = 1, 2, \dots, m; b = 1, 2, \dots, n)$$

(2) Calculation of proportion of indicator *a* under *b*:

$$P_{ab} = \frac{Z_{ab}}{\sum_{a=1}^{m} X_{ab}} \quad (3)$$

(3) Summing and calculating the entropy value of indicator *b*:

$$H_b = -k \sum_{a=1}^{m} P_{ab} \ln(P_{ab}) \quad (4)$$

where, $k = 1/\ln(m)$, and $H_b \geq 0$.

(4) Calculating the Coefficient of variation of indicator *b*:

$$G_b = 1 - H_b \quad (5)$$

The larger G_b, the more important the indicator.

(5) Calculating the Weight of Indicator *b*:

$$W_b = \frac{G_b}{\sum_{b=1}^{n} G_b} (b = 1, 2, \dots, n) \quad (6)$$

(6) Calculating the Comprehensive score of each plan:

$$S_a = \sum_{b=1}^{n} W_b \cdot Z_{ab} (b = 1, 2, \dots, n) \quad (7)$$

Coupling coordination degree model

To assess the level of coupling coordination among subsystems, the coupling coordination degree model is applied. The coupling degree is determined using the following formula:

$$C = \left\{\frac{V_{CR} \cdot V_{PC} \cdot V_{GE} \cdot V_{EG}}{[V_{CR} \cdot V_{PC} \cdot V_{GE} \cdot V_{EG}]^4}\right\}^{\frac{1}{4}} \tag{8}$$

where *C* represents the coupling degree between the four subsystems of CR, PR, GE, and EG, and $V_{CR} \cdot V_{PC} \cdot V_{GE} \cdot V_{EG}$ represent the comprehensive scores of the CR, PR, GE, and EG, respectively.

The coupling coordination degree model is established to study the coordinated development level among the four subsystems, with the following calculation formulas:

$$T(V_{CR}, V_{PC}, V_{GE}, V_{EG}) = \beta_1 V_{CR} + \beta_2 V_{PC} + \beta_3 V_{GE} + \beta_4 V_{EG} \tag{9}$$

$$D(V_{CR}, V_{PC}, V_{GE}, V_{EG}) = \sqrt{C(V_{CR}, V_{PC}, V_{GE}, V_{EG}) \cdot T(V_{CR}, V_{PC}, V_{GE}, V_{EG})} \tag{10}$$

where T represents the comprehensive contribution index of the CR, pollution reduction, green expansion, and economic growth systems; D - the coupling coordination degree; and β is an undetermined coefficient, representing the weight of each subsystem in the composite system. Related studies suggest that CR, PR, GE, and EG are of equal importance, so the weight coefficients are all set to 1/4.

Spatial variogram

This study uses the spatial variogram to measure the spatial pattern variability of each geographic unit to describe the variation in attribute values between different spatial locations as a function of distance [49]. The calculation formula is:

$$\gamma(h) = \frac{1}{zN(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{11}$$

where $Z(x_i)$ and $Z(x_i + h)$ represent the spatial attribute values of Z(*x*) at positions x_i and $(x_i + h)$, respectively; $N(h)$ - the sample size at distance *h*; and the key parameters of the spatial variogram include nugget, structural variance, sill, nugget coefficient, range, and fractal dimension.

$$2\gamma(h) = h^{4-2E} \tag{12}$$

where *E* is the fractal dimension. The closer *E* is to 2, the more the spatial structure approaches a smooth, flat surface, reflecting strong regularity in the spatial structure; the smaller the fractal dimension, the more complex and irregular the structure becomes.

Spatial autocorrelation test

Spatial autocorrelation refers to the similarity of values between neighbouring or close locations in spatial data. The coupled coordination degrees of CR, PR, GE, and EG systems of cities in the study area may be correlated, for which spatial correlation analysis is required. This includes global spatial autocorrelation and local spatial autocorrelation, which is usually evaluated using the Moran index. The global Moran index is used to assess the degree of spatial autocorrelation of variables in the whole study area, i.e., the spatial aggregation or disaggregation pattern of variables. The formula is given below:

$$\text{Moran's } I = \frac{N}{W} \cdot \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{13}$$

$$W = \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} \tag{14}$$

The local Moran's index is used to detect the degree of spatial autocorrelation in a specific region, revealing the local spatial aggregation mode. The formula is as follows:

$$I_i = \frac{(x_i - \bar{x}) \sum_{j=1}^{N} w_{ij}(x_j - \bar{x})}{\sum_{j=1}^{N}(x_j - \bar{x})^2} \tag{15}$$

where N is the number of data points (i.e., the number of spatial units); both i and j denote regions; x_i and x_j denote the attribute values of region i and region j, respectively; $\bar{x}$ is the average of the attribute values of the sample points, $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$; w_{ij} is an element of the spatial weighting matrix, which denotes the degree of interactions between region i and region j; and W is the total of all weights.

Spatial econometrics models

Spatial econometric models, such as the spatial lag model, spatial error model, and spatial Durbin model, are derived by adjusting the parameters within a generalised spatial framework [50]. The expression is as follows:

$$Z_{it} = \rho Q_{it} Z_{it} + \sum_{j=1}^{n} \beta_j X_{j,it} + E_{Xit}\theta + u_i + \gamma_t + \varepsilon_{ti} \tag{16}$$

$$\varepsilon_{it} = \lambda m_i' \varepsilon_t + v_{it} \tag{17}$$

where Z_{it} is the dependent variable; $\rho Q_{it} Z_{it}$ is the spatial lag of the dependent variable; ρ is the spatial lag coefficient; Q_{it} is the spatial weight matrix, with a spatial adjacency matrix selected for regression in this study; $X_{j,it}$are the explanatory variables; $E_{Xit}\theta$ represents the spatial lag effect of the explanatory variables; γ_t is the time effect; u_i represents the individual effect; ε_{ti} is the random disturbance term. When $\lambda = 0$ and $\theta = 0$, the model is a SAR (Spatial Autoregressive) model; when $\rho = 0$ and $\theta = 0$, the model is a SEM (Spatial error model); when $\lambda = 0$, the model is a SDM (Spatial Durbin Model).

Spatiotemporal geographically weighted regression model

To comprehensively investigate the determinants of CR, PR, GE, and EG, this study selects key indicators based on existing literature, ensuring rigorous testing and analysis while mitigating multicollinearity among influencing factors [51]. The selected factors include:

(1) Innovation level (IL): The innovation level represents the technological innovation and scientific development capabilities of a region. High levels of technological innovation help achieve sustainable development goals by improving productivity and reducing resource consumption, thereby facilitating the coordinated development of the

economy and environment [52]. This is measured by the logarithm of the total number of innovation patent authorisations.

(2) Government intervention (GI): Government policies and their implementation directly influence the balance between environmental protection and economic development. Government intervention can promote environmental awareness and the application of green technologies through fiscal support, policy regulations, and public awareness campaigns [53]. This is measured by the ratio of local general public budget expenditure to GDP.

(3) Educational investment (EI): Educational investment not only improves the quality and skill levels of the labor force but also enhances public environmental awareness and social responsibility. High levels of education help cultivate environmental protection talents, promote technological innovation, and support the development of green industries [54]. This is measured by the proportion of local general public budget expenditure allocated to education.

(4) Population size (PS): Population size directly affects resource consumption and environmental pressure. The population plays a dual role in resource utilisation and environmental impact. Proper population planning and management help alleviate environmental pressure while promoting economic development [55]. This is measured by the logarithm of the total permanent population.

After selecting the factors that needed to be influenced, the analysis was carried out using geographically weighted regression (GTWR). The GTWR model, by integrating both time and spatial dimensions in regression analysis, can effectively address the issue of spatiotemporal nonstationarity, revealing the dynamic variation patterns of the driving factors [56].

$$W_i = \beta_0(e_i, o_i, t_i) + \sum_{k=1}^{n} \beta_k(e_i, o_i, t_i)x_{ik} + \varepsilon_i \tag{18}$$

where W_i is the synergy degree of carbon emissions and pollution in province i; β_0 is the constant term; (e_i, o_i, t_i) represents the spatiotemporal geographic coordinates of province i; β_k is the regression coefficient of the k-th driving factor of the CR and PR synergy effect in province i; n is the number of spatial locations; x_{ik} is the k-th driving factor of the CR and PR synergy effect in province i; ε_i is the random error term for province i.

Results

Comprehensive evaluation analysis

The development indices of CR, PR, GE and EG were calculated according to Equations (1)-(7), respectively. The results (Fig. 2) show significant differences in the level of coordinated development between cities. Overall, cities in the southeastern direction perform relatively well in CR, PR, and GE, while cities in the northwest direction are relatively lagging behind in economic growth and green expansion. These differences mainly stem from varying levels of economic development, industrial structure, policy implementation, and technological innovation capabilities across cities. Cities in the southeastern direction have advantages in technological innovation and policy implementation, thus progressing faster in their green transformation.

From Figure 2a, it can be seen that the carbon emissions of most cities gradually decreased during the study period. However, there are considerable variations in the CR outcomes across different cities. Some cities, such as Shanghai and Hangzhou, showed noticeable CR effects at an early stage (2005-2010), while others, such as Nanjing and Suzhou, only began to show significant CR effects in the later period (2015-2021), with uneven spatial and temporal distribution. The cities in the east and southeast have made relatively faster progress in CR.

From Figure 2b, it can be seen that the pollution emission intensity has decreased in most cities of the Yangtze River Delta, but the pollution reduction effects of some cities fluctuate greatly in certain years. Some cities, such as Nanjing and Suzhou, achieved significant pollution reduction effects after 2010, while other cities only began to see noticeable results after 2015. The spatiotemporal distribution of pollution reduction effects shows clear differences, with more significant progress in the southern and coastal cities.

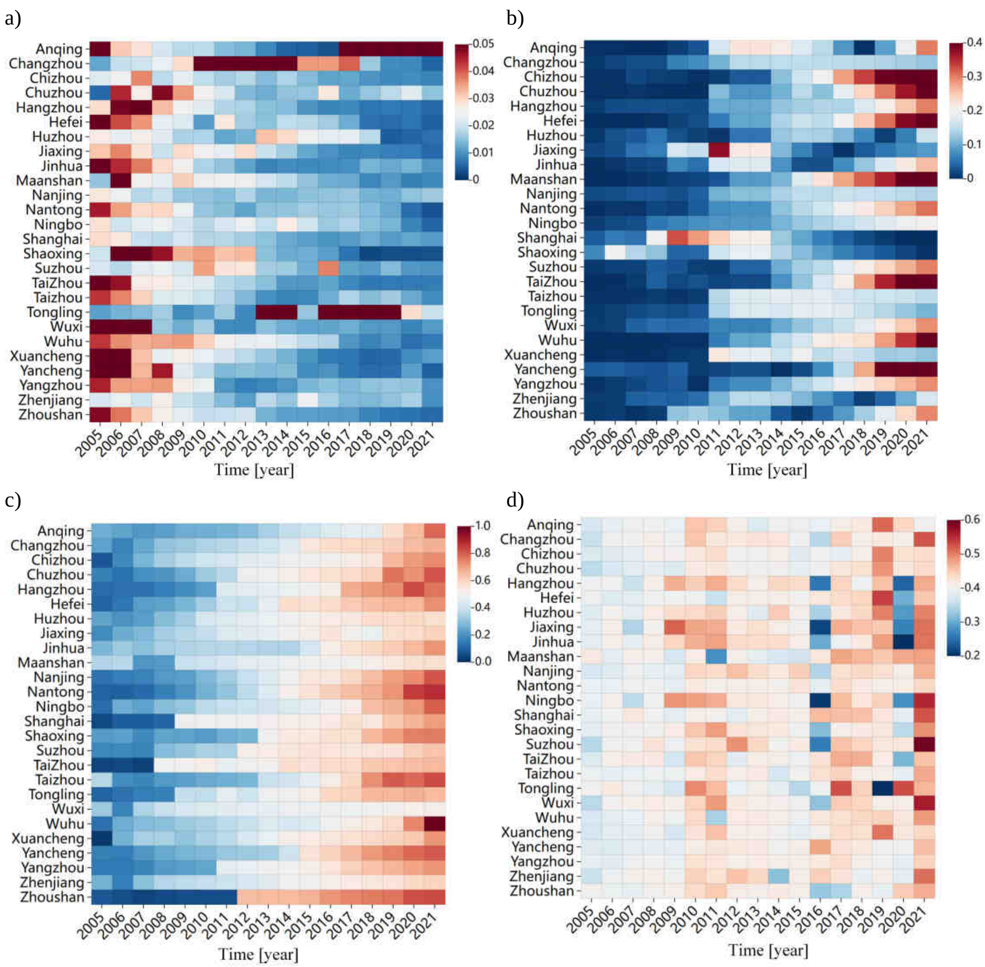

Fig. 2. Spatiotemporal evolution characteristics of: a) CR, b) PR, c) GE, and d) EG

From Figure 2c, it can be seen that green expansion in the Yangtze River Delta region generally shows an upward trend. However, there are differences in the speed and effectiveness of green expansion across cities. Some cities, such as Hangzhou and Nanjing, made significant progress in green expansion, especially after 2010, with a substantial increase in green coverage. The spatiotemporal distribution of green expansion shows considerable differences. Cities in the east and south expanded their greenery more rapidly, while some inland cities, such as Hefei, made slower progress.

From Figure 2d, it can be seen that most cities in the Yangtze River Delta experienced continuous economic growth, but the growth rate and magnitude vary. Cities such as Shanghai, Hangzhou, and Suzhou exhibited outstanding economic growth, while some cities, such as Anqing and Chuzhou, had relatively slow economic growth. The spatiotemporal distribution of economic growth shows significant differences, with coastal cities experiencing faster economic growth, while inland cities had relatively slower growth.

Spatial heterogeneity characteristics

This study assigns the synergy levels of CR, PR, GE, and EG to the geometric centroids of each city. Using GIS+ software, data from 2005, 2010, 2015, and 2021 were calculated, and the model with the best fit was selected to fit the variogram. Among these, the optimal model for 2005 and 2010 is the Gaussian model, the optimal model for 2015 is the Spherical model, and the optimal model for 2021 is the Exponential model. As shown in Table 2, the R^2 of the fitting models continually increases, indicating a good model fit. The coefficient of coupling coordination shows good spatial self-organisation. The nugget and sill values are both less than 0.1, indicating that the spatial variation primarily occurs at a local micro-scale. Both values show an increasing trend, suggesting that the spatial variation degree of the synergy level has increased. The nugget coefficient decreased from 0.979 in 2005 to 0.775 in 2015, indicating that the changes in synergy levels exhibit strong spatial correlation.

Table 2

Parameters of the variance function fit

Year	Nugget value E_o	Abutment value E_o+E	Nugget coefficient $E_o/(E_o+E)$	Fit model	Fitting coefficient	Residual *RSS*
2005	0.0019	0.0898	0.979	Gaussian	0.144	$8.82{\cdot}10^{-4}$
2010	$1.00{\cdot}10^{-5}$	$5.53{\cdot}10^{-3}$	0.998	Gaussian	0.076	$3.12{\cdot}10^{-6}$
2015	0.0111	0.0494	0.775	Spherical	0.965	$1.47{\cdot}10^{-5}$
2021	0.0007	0.0452	0.985	Exponential	0.102	$1.54{\cdot}10^{-4}$

E_0 is nugget value, E is abutment value, *RSS* is residual sum of squares

Intercepting the data for 2005, 2010, 2015 and 2021, the coupled coordination of CR, PR, GE, and EG was calculated using equations (8)-(12), see Figure 3. From 2005 to 2021, the coupling coordination degree between CR, PR, GE, and EG in the 26 cities of the Yangtze River Delta shows significant spatial variation. The variability from southeast to northwest has continuously strengthened, with clear migration characteristics.

As shown in Figure 3a, in 2005, regions with higher coupling coordination were concentrated in the southeastern direction, while the northwest regions were relatively low. As shown in Figure 3b, in 2010, the coupling coordination in the northwest improved, but imbalances between regions still existed. As shown in Figure 3c, by 2015, the coupling coordination in the northwest significantly increased, forming a high-coupling zone centered around major cities, while the southeast remained relatively low. As shown in Figure 3d, by 2021, the overall coupling coordination had generally improved, but significant spatial heterogeneity still existed. The northwest maintained a high level, while some cities in the southeast saw slower improvements.

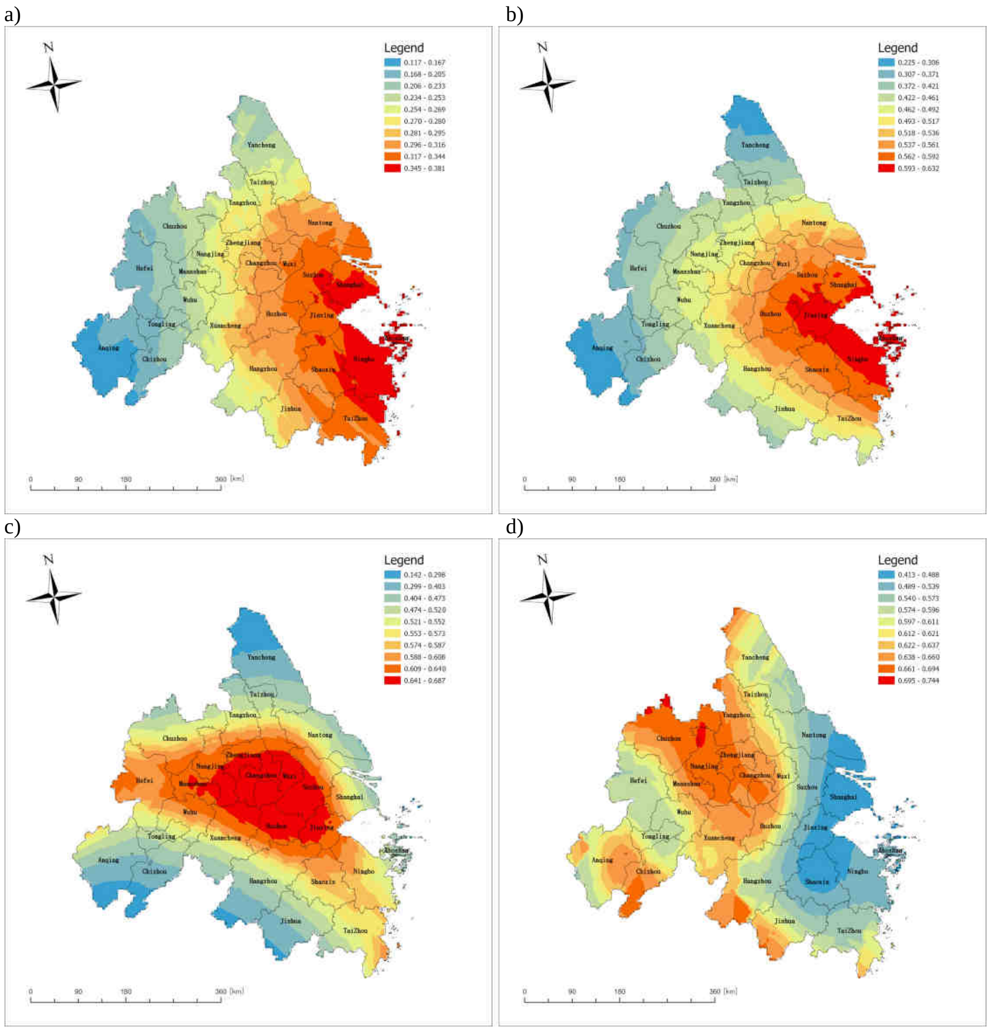

Fig. 3. Spatial-temporal evolution of synergy level in: a) 2005, b) 2010, c) 2015, d) 2021

The main reason for this is the unbalanced regional development. Cities in the southeastern direction exhibited relatively low coupling coordination at multiple stages, facing challenges in CR, PR, GE, and EG. In contrast, the northwest has made faster progress in green transformation and sustainable development. Therefore, to address the regional development imbalance, it is necessary to implement differentiated policies, promote technological innovation, and foster regional cooperation to enhance the overall level of green transformation and sustainable development.

Analysis of the influencing factors

Spatial correlation results

Before constructing the spatial econometrics model for CR, PR, GE, and EG synergy, a spatial correlation test of the variables should first be conducted. The global Moran's index was calculated according to equations (13)-(15). The results (Table 3 and Fig. 4) show that from 2006 to 2021, the Moran's *I* of the CR, PR, GE, and EG synergy in the 26 cities of the Yangtze River Delta is positive.

Table 3

Global Moran's *I*

Years	2006	2008	2010	2012	2014	2016	2018	2020	2021
Moran's *I*	0.401***	0.240**	0.302***	0.093	0.132	0.166*	0.258*	0.126	0.147*
Z	3.926	2.486	3.012	1.161	1.537	1.791	1.908	1.448	1.69

$^{*}P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$

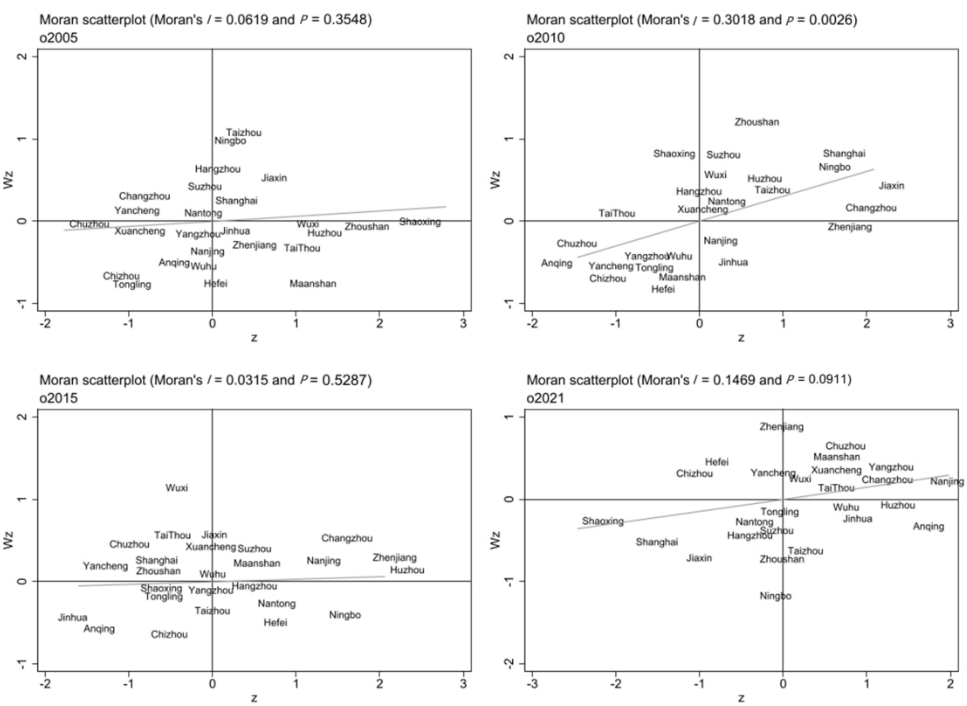

Fig. 4. Local Moran's *I*

In 2006, 2008, and 2010, the Moran's index *I* had high significance ($P < 0.05$). During this period, the Chinese government began to strengthen its policy enforcement on environmental protection, along with rapid economic growth, resulting in significant spatial clustering of CR, PR, GE, and EG in these years. However, from 2012 to 2021, the significance fluctuated, with most years' *P*-values being below 0.1, suggesting that while spatial clustering effects exist, their significance is not as pronounced.

Despite the progress in technological innovation in the Yangtze River Delta region, there are regional differences in the pace of innovation and the scope of application. Cities such as Shanghai, Suzhou and Ningbo have promoted the application of green technologies earlier, while other cities may be constrained by the lag in technology introduction, limitations in industrial structure and difficulties in technology diffusion, which have affected the progress of their green transitions, and hence the significance of the spatial agglomeration effect.

Model test

This study uses the Spatial Durbin Model (SDM) to verify whether the influencing factors have spatial effects and to test the robustness of the GTWR model estimation results. According to the model analysis, the LM test results indicate that both spatial lag effects and spatial error effects are significant, suggesting that the target variable is not only influenced by its own historical values but also by neighbouring regions. This finding emphasises the importance of spatial interdependence in the analysis. The Wald test further confirms the significance of the spatial lag and spatial error effects, supporting the use of the Spatial Durbin Model and Spatial Error Model to explain the relationships between variables.

Table 4

Spatial Durbin Model regression coefficients

Variable	Main effect	Spillover effect	Direct effect	Indirect effect	Total effect
Innovation level IL	–0.061** (0.025)	0.130*** (0.049)	–0.018 (0.042)	0.228** (0.093)	0.2093** (0.093)
Government intervention GI	–0.244 (0.301)	2.069*** (0.441)	–0.890*** (0.259)	–0.870 (0.931)	–1.800* (1.048)
Educational investment EI	0.049*** (0.018)	–0.029 (0.025)	0.047** (0.022)	0.037 (0.048)	0.085* (0.045)
Population size PS	0.0173 (0.032)	0.118 (0.074)	–0.008 (0.028)	–0.013 (0.065)	–0.021 (0.084)
ρ	0.481159*** (0.05015)				
σ^2	0.009908*** (0.000679)				
R^2	0.3802				
Log_L	380.4661				
N	442				

*** $P < 0.01$, ** $P < 0.05$, * $P < 0.1$; values in parentheses represent standard errors; σ^2 is the variance of the error term; SDM model test results are LM-spatial-lag = 208.517***, Robust-LM-spatial-lag = 75.479***, LM-spatial error = 196.441***, Robust-LM-spatial error = 63.403***, Wald-spatial-lag = 47.12***, Wald-spatial-error = 51.32***

From the regression results and effect decomposition of the SDM model (fit $R^2 = 0.3802$) (Table 4), it can be observed that the three factors - innovation level, government intervention, and educational investment - have significant spatial effects on the synergy levels among CR, PR, GE, and EG in the 26 cities of the Yangtze River Delta. Among the total effects, the innovation level and education investment show positive effects, while government intervention shows negative effects. Additionally there is no significant spatial effect of population size on the degree of coupled coordination.

The result suggests that technological innovation and industrial upgrading help optimise resource allocation, enabling environmental protection and economic growth to reinforce each other, thus improving coupling coordination. Education enhances the quality and innovation capacity of the labour force, driving green technology development and raising awareness of sustainable development, which in turn reduces carbon emissions and pollution. However, excessive government intervention can hinder these efforts, as it may lead to inefficient resource allocation and market distortion, negatively affecting inter-regional coordination. Regarding population size, while it influences resource consumption, labour markets, and demand, its impact on regional coupling coordination is more indirect.

Analysis of factors influencing tendencies in temporal evolution

This study plots box plots of the regression coefficients for each influencing factor (innovation level, government intervention, educational investment, and population size) from 2005 to 2021 using the GTWR model to reveal their temporal evolution trends (Fig. 5). Additionally, the spatial distribution of each influencing factor's effect intensity is depicted based on the mean values (Fig. 5).

(1) The effect intensity of innovation level on the synergy of CR, PR, GE, and EG in the 26 cities of the Yangtze River Delta shows a temporal evolution trend of "decrease-increase-decrease" (Fig. 5a). From 2005 to 2006, the number of cities with negative effects decreased as the national focus on energy conservation and emission reduction became clearer. Cities like Shanghai and Hangzhou promoted green industries by strengthening innovation. From 2006 to 2012, positive effects grew, with the 12th Five-Year Plan advancing green development and cities like Shanghai, Nanjing, and Hangzhou introducing green policies, particularly through green finance in Shanghai. After 2012, the effects stabilised, but most cities showed negative impacts, partly due to slow industrial transformation and varied implementation of the 13th Five-Year Plan's green innovation goals.

From the perspective of spatial distribution, the promotion effect of innovation level on synergistic effect is mainly concentrated in Hangzhou, Ningbo, Nantong and other cities with strong economic foundation and high scientific and technological innovation capacity. While Zhenjiang, Chuzhou, Anqing and other cities have more obvious short-term negative effects of innovation on synergistic effect due to factors such as industrial structure and technology diffusion. Therefore, when improving the level of urban innovation, factors such as policy support, economic foundation and differences in industrial structure should be taken into account to reduce regional development imbalance.

(2) From 2005 to 2021, the negative effect of government intervention showed a temporal evolution trend of "increase-decrease-stabilisation" (Fig. 5b). Initially, from 2005 to 2006, the negative effect increases due to insufficient intervention or lagging policy effects. From 2006 to 2009, the negative effect diminished as policies improved and began

to have a positive impact. After 2009, the impact stabilised and the positive and negative impacts equalised. Especially in the 12th Five-Year Plan and 13th Five-Year Plan, green development has become a mainstream goal, and the government has introduced more policies to promote green transformation, such as green financial policies and environmental protection taxes.

Spatially (Fig. 5b), government intervention positively affects synergies in cities such as Yancheng, Suzhou and Ningbo, while negative impacts occur in cities such as Zhenjiang, Changzhou and Shanghai. These differences highlight differences in local government capacity, economic environment and policy coordination. To improve green development, targeted policies and improved local government capacity are essential for effective policy implementation.

(3) The effect intensity of educational investment on the synergy of CR, PR, GE, and EG in the 26 cities of the Yangtze River Delta shows a temporal evolution trend of "decrease-increase-stabilisation" (Fig. 5c). From 2005 to 2009, the short-term benefits of education investment did not significantly contribute to green development due to the lag in policy implementation. However, from 2009 to 2015, the number of cities with positive effects gradually increased, as education investment focused more on technological innovation, environmental education, and green talent cultivation during the Twelfth Five-Year Plan. After 2015, the impact stabilised, with more cities showing positive contributions to green transformation.

Spatially (Fig. 5c), cities like Nantong, Ningbo, Hangzhou, Anqing, and Tongling benefitted most from educational investment, while cities such as Chuzhou, Nanjing, Zhenjiang, Jiaxing, Shaoxing, and Taizhou saw negative effects. This can be attributed to the better alignment of educational resources and industrial ties in certain cities, which helped drive green development. In contrast, cities with uneven educational distribution and limited industrial diversity faced challenges in leveraging educational investment for green growth. Therefore, when formulating and implementing educational investment policies, it is important to fully consider the temporal and spatial differences, ensuring the reasonable allocation and effective utilisation of educational resources to maximise their contribution to promoting green development.

(4) From a temporal perspective (Fig. 5d), population size initially had a negative, suppressive effect on the synergy of CR, PR, GE, and EG in the Yangtze River Delta, but shifted to a positive impact in some cities after 2018. Spatially (Fig. 5d), cities like Zhenjiang, Ningbo, and Shanghai, with higher population densities and industrial structures focused on high-energy, high-pollution sectors, showed stronger negative impacts due to greater resource consumption and environmental pressure. In contrast, cities such as Zhoushan, Jinhua, and Hangzhou exhibited positive effects, largely due to effective policies promoting green technologies, stricter environmental standards, and strong support from environmental professionals. These findings suggest that addressing population-related environmental pressures requires a holistic approach, incorporating policies, technology, industry, and education to achieve green development synergy.

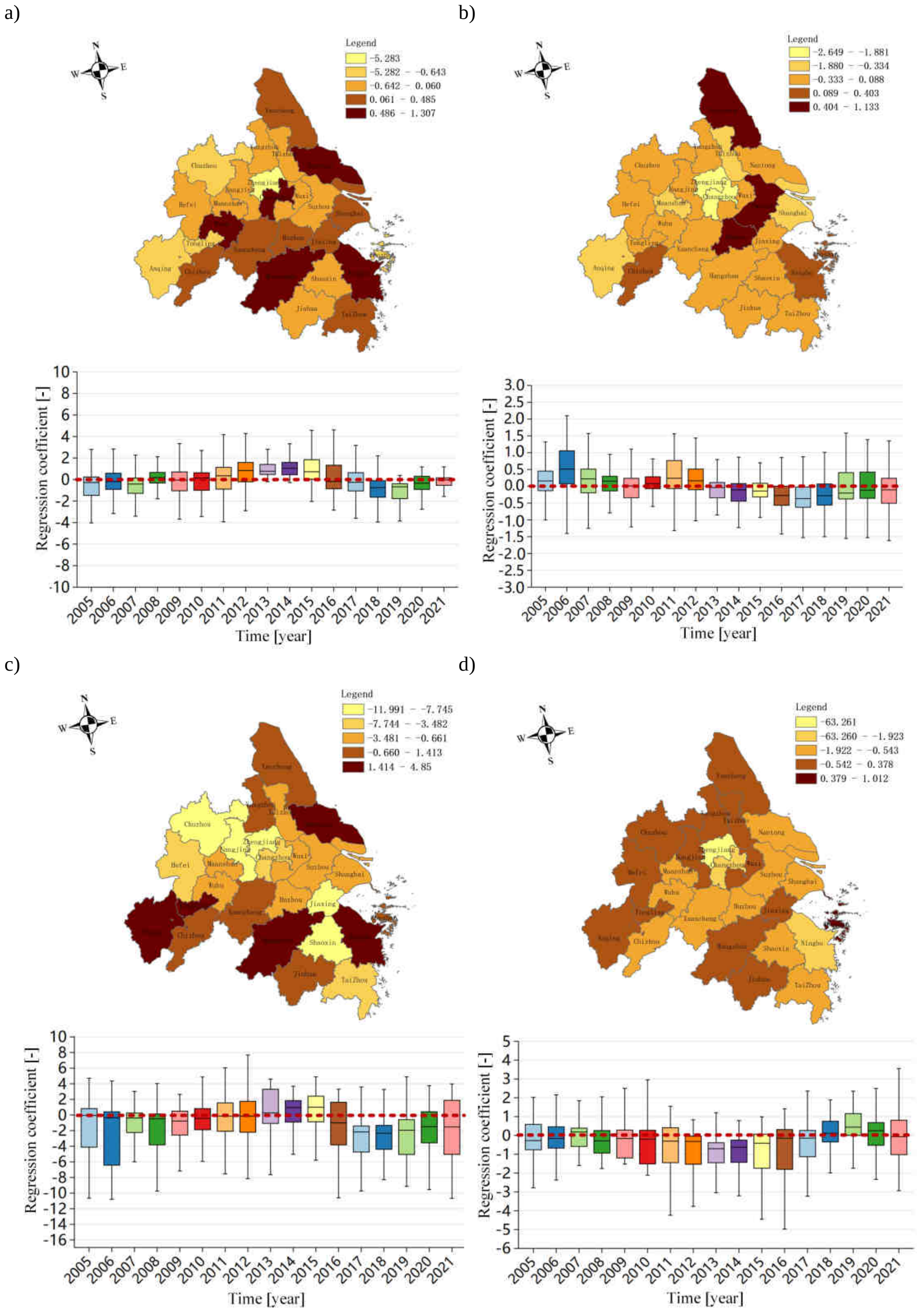

Fig. 5. Spatial and temporal trends in influencing factors, a) IL, b) GI, c) EI, d) PS

Discussion

Green transformation and development is a key challenge for contemporary society and economic development. This study employs the entropy method, spatial variogram, coupling coordination degree model, and spatiotemporal geographically weighted regression to analyse spatial heterogeneity, synergy distribution, and the dynamic evolution of geographic relationships. It also identifies key factors influencing coupling coordination. The findings offer insights for policy and regional development.

(1) Promoting green transformation and development is an inevitable choice. It is essential to drive economic growth while also focusing on environmental protection and ecological construction. Existing studies have shown that the coordination between economic growth and environmental protection is a crucial strategy for global responses to climate change [57]. From 2005 to 2021, the Yangtze River Delta made significant progress in CR, PR, GE, and EG. However, development remains uneven, with significant differences in green development between the southeastern and northwestern regions, which aligns with previous findings on China's regional green development disparities [58]. As a key driver of green transformation [59], technological innovation varies across cities. For instance, Hangzhou, as an innovation hub, has achieved remarkable advancements in green technological innovation, while Zhenjiang's reliance on high-energy-consuming and high-polluting industries has hindered industrial restructuring, leading to slower progress in green transformation.

As a manufacturing-intensive region, the Yangtze River Delta industrial restructuring to drive green and coordinated development. Shifting from heavy industries to high-tech and service sectors reduces emissions and pollution while promoting regional sustainability through innovation and green finance. In this regard, the Yangtze River Delta region needs to enhance interregional cooperation in technological innovation and resource sharing, strengthen policy coordination and alignment, and facilitate industrial structuring towards a more sustainable and synergistic development trajectory.

(2) Strengthening technological innovation and educational investment is crucial for green development. Research shows that technological innovation not only improve production efficiency but also reduce environmental pollution, driving the green transformation of regional economies [60]. Although spatial heterogeneity among the 26 cities in the Yangtze River Delta declined from 2005 to 2021, differences remains in government intervention, innovation level, educational investment, and population size. Underdeveloped areas, in particular, face challenges due to weak innovation capacity and limited educational resources.

To address these disparities, promoting regional platforms for technological innovation and educational resource sharing is essential. The Yangtze River Delta Innovation Cooperation Alliance, established by Shanghai, Jiangsu, Zhejiang and Anhui, has facilitated the sharing of scientific resources and technology transfer, demonstrating the effectiveness of cross-regional cooperation in reducing development gaps [61]. For underdeveloped areas, establishing special education funds and improving educational facilities can enhance education levels and employability in the green economy. Additionally, long-term stable green development policies and incentives are key to sustaining green investment and social participation. By fostering regional collaboration in innovation and education, the Yangtze River Delta can achieve more efficient and sustainable green development.

(3) Enhancing the synergy of CR, PR, GE, and EG, along with capacity building and policy support, is essential for green transformation. Research indicated that technological innovation plays a crucial role in promoting green development [62]. It improves resource efficiency, reduces pollution, and accelerates the adoption of energy-efficient technologies and equipment. Furthermore, interregional technological cooperation enhances overall innovation capacity [63].

To bridge regional disparities, coordinated efforts across eastern, western, southern, and northern regions are necessary. Sharing technologies, resources, and experiences, can facilitate cross-regional green development projects and reduce development gaps. Significant policy disparities among Yangtze River Delta cities reflect broader imbalances in China's green development [64]. Addressing these requires differentiated regional strategies, strict policy supervision and evaluation mechanisms, and public engagement in environmental initiatives. Additionally, formulating and implementing long-term stable green development policies, providing policy support and incentives such as tax breaks, subsidies, and low-interest loans, can effectively promote green investment by businesses and society. Through these measures, the green transformation and sustainable development of the Yangtze River Delta and even China as a whole can be advanced, thereby achieving more efficient and sustainable economic growth and environmental protection goals.

Conclusion

This study investigated the synergistic development of CR, PR, GE, and EG across 26 cities in the Yangtze River Delta from 2005 to 2021. Our analysis reveals three key conclusions:

1. First, the region exhibited a gradual improvement in synergistic development, though with notable fluctuations. A clear spatial dichotomy emerged, with southeastern cities demonstrating superior performance in environmental metrics, while northwestern cities showed comparatively slower progress in economic growth and green expansion. This pattern reflects the complex interplay between environmental protection and economic development priorities across the urban agglomeration.
2. Second, spatial analysis revealed increasing local-scale variation in synergistic development levels, with a pronounced southeast-northwest gradient. While southeastern cities maintained their advantage due to early adoption of green technologies and innovative practices, northwestern cities have begun closing this gap through intensified investment in green development initiatives, suggesting an emerging trend toward regional convergence.
3. Third, our investigation of driving factors identified innovation capacity and educational investment as primary positive influences on synergistic development, while the initially negative effects of government intervention and population size have diminished over time. The positive impacts of these factors have gradually extended to northwestern cities, indicating successful policy diffusion across the region.

To promote balanced regional development, we recommend boosting support for technological innovation and education, particularly in northwestern cities. This can be achieved by funding green technologies, clean energy, and environmental protection through special funds and policy incentives. The Ningbo Green Economy Talent Cultivation Programme can serve as a model to enhance talent and technological capabilities in the northwest through school-enterprise collaboration and international exchanges. Additionally, leveraging the Yangtze River Delta Eco-Green Integrated Development Demonstration Zone model will help promote regional green development by sharing resources, technologies, and experiences, and fostering stronger policy coordination across cities to optimise green transformation in the entire region.

This study explores the spatiotemporal evolution and key drivers of CR, PR, GE, and EG synergy in the Yangtze River Delta from 2005 to 2021, aiming to contribute to green transformation and development. However, due to data limitations, the study does not account for the movement of regional factors within the synergy of these four areas. Additionally, key driving factors such as natural conditions, socioeconomic development stages, and policy effects were not fully explored. As a result, the coupling coordination evaluation index system and factor selection may not comprehensively capture the characteristics of these systems. Future research should address regional disparities, policy conditions, and spatial heterogeneity by adopting a system dynamics perspective to analyse the coordinated coupling and spatiotemporal distribution relationships of CR, PR, GE, and EG. Furthermore, as data availability improves, refining the index system with more interactive indicators and adapting factor selection to evolving resource supply and demand will provide a more accurate understanding of the determinants influencing coupling coordination. These efforts will contribute to achieving more efficient green transformation and sustainable development.

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