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Research on Regional Collaborative Carbon Emission Reduction Pathways Based on Coupled Model of Carbon Emission Reduction Effect Index and Spatial System Dynamics: A Case Study of China's Yangtze River Economic Belt

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ABSTRACT

Against the backdrop of accelerating global climate governance and China's "dual carbon" goals, the Yangtze River Economic Belt (YREB), a major source of carbon emissions, exhibits substantial internal disparities in resource endowments and stages of economic development, thereby creating an urgent need for collaborative regional carbon abatement. Existing research has predominantly focused on carbon mitigation within individual regions, largely overlooking multi-regional collaborative frameworks. Addressing this gap, this paper investigates 108 cities within the YREB, categorized into upper, middle, and lower reaches. Following a logical framework of "capacity measurement—effect quantification—factor analysis—path regulation," we construct a methodological system for regional collaborative carbon emission reduction by integrating the super-efficiency SBM model, gravity model, coordination degree model, QAP model, and multi-regional system dynamics model. The results indicate that from 2007 to 2023, the spatial correlation of collaborative carbon abatement in the YREB has deepened continuously, with intra-basin collaborative effects proving stronger than inter-basin ones. The upper reaches demonstrate the fastest growth rate in collaboration, whereas the lower reaches maintain the

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highest absolute level of collaboration. Through scenario combination analysis, we identify the optimal scenario for each basin. Furthermore, by integrating these optimal basin-specific scenarios, we project the overall development trajectory of the YREB. This approach balances emission reduction efficiency with practical viability, offering an actionable implementation strategy for regional collaborative carbon mitigation.

Keywords： Yangtze River Economic Belt; Carbon Emission Reduction Capacity; Collaborative Carbon Emission Reduction Effect; Scenario Analysis

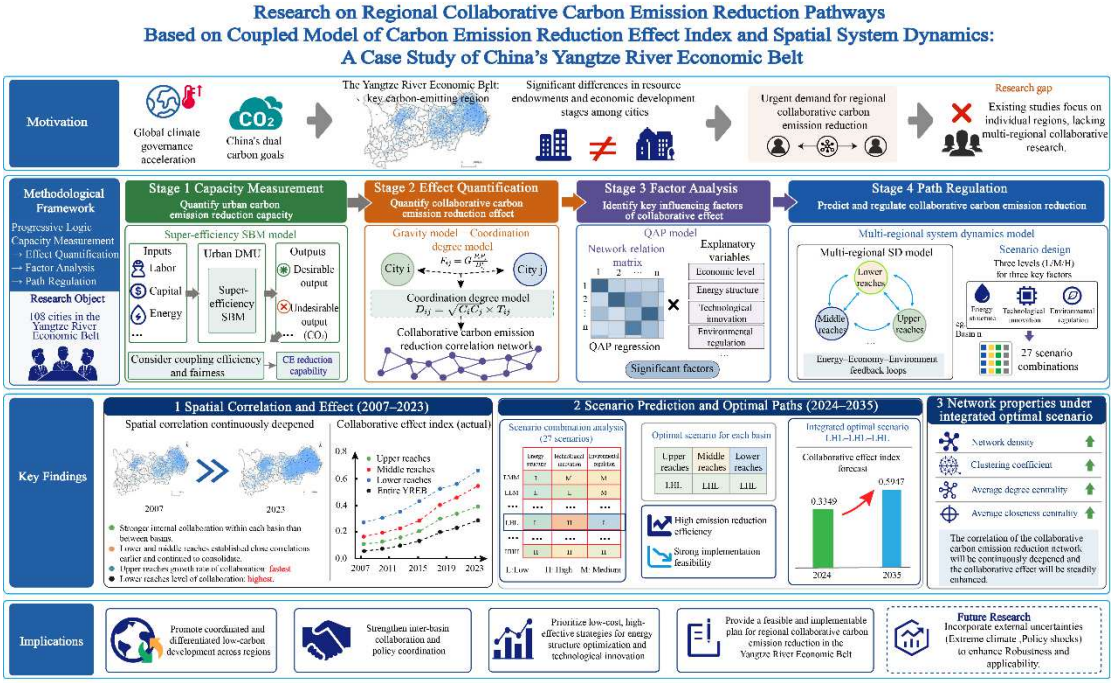


Fig. 1 Graphical Abstract

1.Introduction

Amidst the acceleration of global climate governance, China has heavily prioritized climate change mitigation, emerging as a vital participant, contributor, and leader in this international arena. However, independent, single-region approaches to carbon reduction face inherent limitations. Regional collaborative mitigation strategies can integrate diverse low-carbon technologies and industrial strengths across areas through unified planning, standard harmonization, and resource complementarity. This collaborative paradigm not only lowers overall abatement costs but also circumvents the inefficiencies of fragmented initiatives, thereby fostering robust synergies in emission reduction.

Among China's regional development strategies, the Yangtze River Economic Belt (YREB) occupies a pivotal position as a core axis of the nation's territorial spatial development. Encompassing approximately 2.05 million square kilometers—or 21.4% of China's total landmass—the YREB is responsible for over 35.3% of the nation's total carbon emissions, making it a critical region for realizing the country's "dual carbon" goals. However, as a primary engine for both economic growth and carbon mitigation, the YREB exhibits pronounced internal heterogeneities in resource endowments, energy structures, and stages of economic development. Consequently, there is an imperative need to establish a rigorous methodological framework to scientifically guide its carbon reduction efforts.

Research on pathways to achieve regional carbon mitigation has emerged as a focal point in current scholarship. Existing literature predominantly formulates these mitigation strategies through two primary approaches: identifying the underlying drivers of carbon emissions, and employing scenario simulations to determine optimal regional reduction pathways.

In formulating mitigation pathways based on driver identification, scholars have employed diverse methodologies to investigate the underlying mechanisms of factors such as economic growth, industrial structure, technological progress, energy structure, and environmental regulation. Firstly, panel regression models, such as fixed-effect models, threshold regression models, and spatial Durbin models, are often used to analyze the degree of influence of various factors on carbon emission reduction (Ding and Liu, 2024; Sun et al., 2024; Zhang et al., 2024). For example, Ge et al. (2025) used panel data of 107 cities in the Yangtze River Economic Belt from 2003 to 2021, and applied the spatial Durbin model and mediating effect model to study the impact of green transformation of urban land use on urban carbon emissions. They found that green transformation can reduce local carbon emissions but has a positive spatial spillover effect on neighboring cities, and environmental regulation plays a mediating role. Zhang et al. (2025) used panel data of 54 countries from 2000 to 2021, and adopted fixed-effect, PVAR, and threshold regression models to analyze the relationship between renewable energy technology innovation, climate risk, and

carbon emissions. They concluded that the former can reduce carbon emissions, and climate risk has a double-threshold regulating effect on the relationship between the two. Secondly, the Environmental Kuznets Curve (EKC) hypothesis is often used to test the non-linear relationship between economic growth and carbon emissions. Most studies have confirmed that there is an inverted "U" -shaped or "N" -shaped relationship between them, and some scholars have proposed regional carbon emission reduction paths by studying the EKC curve(Rahman et al., 2022; Sun and Qamruzzaman, 2025; Zhang et al., 2023). For example, Wu et al. (2025) used data from the Pearl River Delta urban agglomeration from 2000 to 2020 to explore the correlation between EKC and carbon emission reduction. They found that per capita GDP and carbon emissions show an "N" -shaped EKC curve, and mid-to-high emission cities have a technology rebound effect, so emission reduction strategies need to be customized according to the urban development stage. Choudhury et al. (2023) combined data from the world's five major high-emission countries from 1990 to 2019 and confirmed the existence of the EKC curve. Among them, energy consumption and GDP promote carbon emissions in the short term but inhibit them in the long term, and industrial production promotes carbon emissions in the short term but has no significant impact in the long term. Thirdly, regarding inter-regional relationship data, due to its characteristics of focusing on inter-regional interactive correlations, it is different from attribute data. Therefore, the Quadratic Assignment Procedure (QAP) model is often used to analyze the influencing factors of inter-regional relationship data (Li et al., 2025; Yang and Zhu, 2025). For example, Zhu et al. (2025) took Jiangsu Province as the research object, constructed a monthly grid-scale carbon emission model combined with nighttime light data, and used social network analysis and the QAP model to analyze the spatial correlation network of county-level carbon emissions and its driving factors. They found that geographical proximity, economic level, and urbanization level positively promote the formation of this network.

In terms of scenario simulation, the System Dynamics (SD) model is often used to simulate the carbon emission trend under different scenarios due to its ability to

handle feedback relationships in complex systems. By constructing a multi-interactive system dynamics model, the effect of carbon emission reduction under different energy policies and industrial policies can be simulated (Du et al., 2024; Huo et al., 2022; Xu et al., 2024). For example, Xiong et al. (2025) took Taiyuan as the research object, integrated the system dynamics and Long-range Energy Alternatives Planning (LEAP) system models, and analyzed three scenarios: industrial transformation, energy efficiency improvement, and extensive development. They found that the combination of energy efficiency improvement and industrial transformation is more conducive to low-carbon transformation, and policy support and technological breakthroughs need to be strengthened. Xu et al. (2025) used the STIRPAT model and system dynamics model to study the impact of factors such as population on carbon emissions from residential buildings in Chongqing. They found that household size has the greatest impact on carbon emissions, and energy-saving technologies need to be vigorously promoted to reduce carbon emissions. In addition, the Computable General Equilibrium (CGE) model is a macro-model based on microeconomic theory, which is mostly used to analyze the impact of different policy scenarios, such as carbon tax policies and carbon emission trading policies, on regional carbon emission reduction (Du et al., 2025; Zheng et al., 2025). For example, Shi et al. (2025) used a CGE model with a learning effect module and took Zhejiang as the research region. They found that strict carbon policies will increase the dependence on external electricity and restrict the development of local renewable energy. Su et al. (2024) constructed a dynamic computable general equilibrium model to study the impact of Carbon Capture, Utilization, and Storage (CCUS) on China's carbon emission reduction and energy structure. They found that CCUS can better help achieve carbon peaking and optimize the energy structure to promote better and faster economic development.

Drawing upon the aforementioned literature, the System Dynamics (SD) model demonstrates not only robust interactivity and feedback mechanisms but also the capacity to effectively simulate the carbon mitigation outcomes of diverse future scenarios. Furthermore, compared to Computable General Equilibrium (CGE) models,

the SD approach imposes lower data requirements and benefits from superior data accessibility. However, existing applications of the SD model have predominantly focused on single-region studies, largely neglecting multi-regional collaborative analyses. Additionally, the limited number of scenarios typically formulated in prior research fails to capture a broad range of potential contingencies, thereby constraining the comprehensiveness and generalizability of the conclusions. To address these gaps, this paper innovatively quantifies the effects of regional collaborative carbon abatement, integrating multiple regions into a unified SD framework. By employing combinatorial scenario analysis, this study systematically evaluates these collaborative mitigation effects across a wide spectrum of conditions to identify the most optimal pathways for regional carbon reduction.

2. Methodology

This paper follows a progressive logical framework of "capacity measurement - effect quantification - factor analysis - path regulation" to carry out the research. Firstly, drawing on the relevant research results of other scholars and considering the availability of data, 108 cities in the Yangtze River Economic Belt are selected as the detailed research objects, and they are divided into three major basins: the upper, middle, and lower reaches of the Yangtze River. Through the measurement and analysis of the carbon emission reduction capacity of these 108 cities, the spatio-temporal distribution change trends and causes of the three basins are explored. Secondly, the spatial autocorrelation of the carbon emission reduction capacity of the Yangtze River Economic Belt is tested, and then a collaborative carbon emission reduction correlation network of the Yangtze River Economic Belt is constructed from the dual perspectives of "gravity-coordination". The node and overall network characteristics are decomposed by combining social network analysis, and the collaborative carbon emission reduction effect is quantified. Thirdly, the QAP model is used to identify the key influencing factors of the comprehensive index of the collaborative carbon emission reduction effect. Finally, a multi-regional carbon emission reduction SD model is constructed, and combined with the collaborative carbon emission reduction effect of each scenario combination and the difficulty of

implementation, a suitable path for collaborative carbon emission reduction in each segment of the Yangtze River Economic Belt is proposed. Subsequent research contents are all based on previous research results, achieving in-depth progress in the depth of research content and interlocking logic.

2.1. Quantification of carbon emission reduction capacity

2.1.1. Quantification of carbon emission efficiency

This paper uses the super-efficiency SBM model to measure the carbon emission efficiency of each urban region. The super-efficiency SBM model can effectively solve the problem that the traditional SBM model cannot distinguish multiple decision-making units with an efficiency value of 1, making the evaluation results more objective and accurate. The specific form of the model is shown in Eq. (1).

$$
\begin{aligned}
&\min \gamma = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x}}{x_{ik}}}{\frac{1}{w_1+w_2}\left(\sum_{s=1}^{w_1}\frac{\overline{y^u}}{y^u_{sk}}+\sum_{q=1}^{w_2}\frac{\overline{y^v}}{y^v_{qk}}\right)} \\
&\overline{x} \ldots \sum_{j=1,j\neq k}^{n} x_{ij}\theta_j, i=1,\cdots,m \\
&\overline{y^u},, \sum_{j=1,j\neq k}^{n} y^u_{sj}\theta_j, s=1,\cdots,w_1 \\
&\overline{y^v} \ldots \sum_{j=1,j\neq k}^{n} y^v_{qj}\theta_j, q=1,\cdots,w_2 \\
&\theta_j .. 0, j=1,\cdots,n, j\neq 0 \\
&\overline{x} .. x_k, \overline{y^u},, y^u_k, \overline{y^v} .. y^v_k
\end{aligned}
\tag{1}
$$

Where, γ represents the efficiency index of the decision-making unit, n represents the number of decision-making units, m represents the number of input indicators, w_1 and w_2 represent the number of expected outputs and unexpected outputs respectively, x represents the input indicators (the indicators included are shown in Table 1), y^u and y^v represent the expected and unexpected outputs respectively, $\overline{x}$ 、 $\overline{y^u}$ 、 $\overline{y^v}$ are slack variables.

Table 1 Construction of carbon emission efficiency index system

Nature	Element	Indicator	Unit
Input	Energy	Total Energy Consumption	10,000 tons of standard coal
	Capital	Capital Stock	10,000 yuan

Output	Labor	Number of Employees	10,000 people
	Expected Output	Gross Regional Product (GRP)	100 million yuan
	Unexpected Output	Carbon Emissions	1 million tons

2.1.2. Quantification of low-carbon development level

The regional carbon emission reduction equity index is comprehensively quantified from three aspects: carbon emission level, environmental development level, and economic development level. The constructed index system is shown in Table 2.

Table 2 Construction of carbon emission reduction equity index system

Element Level	Indicator	Unit	Direction
Low-Carbon	Per Capita Carbon Emissions	100 tons/person	Negative
	Carbon Emissions per 100 Million Yuan of GDP	1 million tons	Negative
Environment	Industrial Wastewater Generation per 100 Million Yuan of GDP	10,000 tons	Negative
	Smoke and Dust Generation per 100 Million Yuan of GDP	Ton	Negative
Economy	Per Capita GDP	Yuan/person	Positive
	Per Capita Fiscal Revenue	Yuan/person	Positive

2.1.3. Quantification of carbon emission reduction capacity

Due to the different magnitudes of the original data, they cannot be directly used to construct comprehensive indicators. Therefore, according to the panel matrix formed by the original data, the data are standardized. The indicators include the carbon emission efficiency and the six indicators in the low-carbon development level. For positive indicators, standardization is carried out according to Eq. (2), and for negative indicators, standardization is carried out according to Eq. (3).

$$Z_{ij} = \frac{x_{i,j} - x_{imin,j}}{x_{imax,j} - x_{imin,j}} \tag{2}$$

$$Z_{ij} = \frac{x_{imax,j} - x_{i,j}}{x_{imax,j} - x_{imin,j}} \tag{3}$$

Where, Z_{ij} represents the standardized value of the j-th indicator in the i-th year, To ensure the comparability of data among different cities and different years, $x_{imax,j}$

represents the maximum value of the j-th indicator among all cities in all years during the research period. Similarly, $x_{imin,j}$ represents the minimum value of the j-th indicator.

Based on the standardized values of each indicator, the weighted sum of each indicator is calculated to obtain the regional carbon emission reduction capacity, as shown in Eq. (4).

$$CRC_{it} = \sum_{\mathrm{j}} \omega_{\mathrm{j}} \times E\mathrm{RT}_{\mathrm{itj}} \tag{4}$$

Where, ω_{j} represents the weight of the j-th carbon emission reduction indicator. The weights of carbon emission efficiency, per capita carbon emissions, carbon emissions per 100 million yuan of GDP, industrial wastewater generation per 100 million yuan of GDP, smoke and dust generation per 100 million yuan of GDP, per capita GDP, and per capita fiscal revenue are calculated by the combined weighting method (Wang et al., 2020) as 0.333, 0.105, 0.101, 0.103, 0.078, 0.152, and 0.127 respectively. $E\mathrm{RT}_{\mathrm{itj}}$ represents the j-th indicator of the i-th city in the t-th year.

2.2. Construction of collaborative carbon emission reduction correlation network

The carbon emission reduction correlation network is constructed through the gravity model and the coordination degree model respectively, and then the collaborative carbon emission reduction correlation network is constructed by means of coupling.

The carbon emission reduction gravity correlation is based on the theory of the regional economic gravity model, and based on the differences in emission reduction capacity between cities, it realizes the gravity-driven carbon emission reduction between cities through the radiation and output of low-carbon technologies, green funds, advantageous industries, and advanced policies. The carbon emission reduction coordination correlation is to avoid the regional emission reduction imbalance that may be caused by the gravity correlation. It constructs the interactive relationship of carbon emission reduction between cities by establishing a cross-regional benefit compensation mechanism and optimizing the balanced allocation of resources, so as to ensure the balance and sustainability of emission reduction. The carbon emission reduction gravity focuses on efficiency improvement, and the carbon emission

reduction coordination focuses on fairness guarantee, forming a closely complementary collaborative closed loop.

2.2.1. Gravity model

On the basis of quantifying the carbon emission reduction capacity of each city, the gravity model is used to measure the carbon emission reduction gravity correlation between each pair of cities, as shown in Eqs. (5) and (6).

$$y_{ij} = k_{ij} \frac{CRC_i \times CRC_{\mathrm{j}}}{D_{ij}^2} \tag{5}$$

$$k_{ij} = \frac{CRC_i}{CRC_i + CRC_j} \tag{6}$$

Where, i、j are prefecture-level cities, CRC_i is the carbon emission reduction capacities of city i, D_{ij} is the geographical distance between city i and city j.

2.2.2. Coordination degree model

Based on the measurement results of carbon emission reduction capacity, the coordination degree between cities is quantified. The coordination degree model is shown in Eq. (7).

$$y_{ij} = \sum_j \left[\frac{\sqrt{CRCS_{kj} \times CRCS_{mj}}}{(CRCS_{kj} \times CRCS_{mj}) / 2} (CRCS_{kj} \times CRCS_{mj}) \right]^{\frac{1}{2}} \tag{7}$$

Where, k、m represent different cities, $CRCS_{kj}$ represents the j-th indicator of the k-th city.， including carbon emission reduction efficiency, carbon emission level, environmental development level, and economic development level, all of which are standardized values.

2.2.3. Collaborative carbon emission reduction correlation network

The correlation matrix at the gravity level can be established through Eqs. (5) and (6), and each element in the matrix represents a pair of correlation relationships. Each element in the matrix is divided by the sum of all years in the research period to standardize the matrix. Similarly, the correlation matrix at the coordination degree level can be established through Eq. (7). The collaborative carbon emission reduction matrix is obtained by adding the two correlation matrices and dividing by two. The average value of the collaborative carbon emission reduction matrices in all years of

the research period (excluding diagonal elements) is taken as the critical value. When an element in the collaborative carbon emission reduction matrix is greater than the critical value, it is recorded as "1"; otherwise, it is recorded as "0", forming a 0-1 collaborative carbon emission reduction matrix. Then, the 0-1 matrix can be converted into a collaborative correlation network between cities through graphical visualization

$$G = \begin{bmatrix} X_{1,1} & \cdots & X_{1,n} \\ \vdots & \ddots & \vdots \\ X_{n,1} & \cdots & X_{n,n} \end{bmatrix} \tag{8}$$

2.3. Social network model

Based on the constructed collaborative carbon emission reduction network between cities, the social network analysis method is used to decompose the collaborative carbon emission reduction correlation network from the node and overall levels.

2.3.1. Node network characteristics

(1)Degree Centrality

Degree centrality reflects the number of connections between a node and other nodes. Nodes with higher degree centrality occupy a more critical position in the network. The calculation method is shown in Eq. (9). The average degree centrality represents the average value of the degree centrality of nodes in the entire network, as shown in Eq. (10).

$$C_{RD}(i) = \frac{(Ind_i + Out_i)}{2N - 2} \tag{9}$$

$$C_{RD} = \frac{1}{N}\sum_i C_{RD}(i) \tag{10}$$

Where, $C_{RD}(i)$ represents the degree centrality of node i, Ind_i represents the in-degree of node i, Out_i represents the out-degree of node i, N represents the number of nodes in the network, C_{RD} represents the average degree centrality of the network.

(2)Closeness Centrality

Closeness centrality represents the degree to which a node is close to other nodes. Nodes with higher closeness centrality have better information transmission in the network. The calculation method is shown in Eq. (11). The average closeness

centrality represents the average value of the closeness centrality of nodes in the entire network, as shown in Eq. (12).

$$C_{RP}(i) = \frac{\sum_{j=1}^{N} d_{ij}}{2N-2} \tag{11}$$

$$C_{RP} = \frac{1}{N}\sum_{i} C_{RP}(i) \tag{12}$$

Where, $C_{RP}(i)$ represents the closeness centrality of node i, d_{ij} represents the shortest path distance between node i and node j, N represents the number of nodes in the network, and C_{RP} represents the average degree centrality of the network.

2.3.2. Overall network characteristics

(1) Network density

Network density represents the degree of closeness of the connection relationships between nodes in the network. The greater the network density, the higher the degree of connection between nodes. The calculation method is shown in Eq. (13).

$$N_{DE} = \frac{M}{N(N-1)} \tag{13}$$

Where, N_{DE} represents the network density, M represents the actual number of relationships existing in the network.

(2) Clustering coefficient

The clustering coefficient represents the degree of aggregation of nodes in the network. The larger the clustering coefficient, the closer the connection between a node and its neighboring nodes, and the stronger the overall cohesion of the network. The calculation formulas are shown in (14) and (15).

$$N_{CL}(i) = \frac{2V_i}{C_{RD}(i)\left[C_{RD}(i)-1\right]} \tag{14}$$

$$N_{CL} = \frac{1}{N}\sum N_{CL}(i) \tag{15}$$

$N_{CL}(i)$ represents the local clustering coefficient, N_{CL} represents the global clustering coefficient, and V_i represents the actual number of relationships between node i and its neighbors.

2.4. Collaborative Carbon Emission Reduction Effect Index

Based on the quantification of various indicators at different levels of the collaborative carbon emission reduction correlation network, the collaborative carbon emission reduction effect index is constructed, as shown in Eq. (16).

$$CRE = \omega_1 C'_{RD} + \omega_2 C'_{RP} + \omega_3 N'_{DE} + \omega_4 N'_{CL} \tag{16}$$

Where, CRE represents the collaborative carbon emission reduction effect index, C'_{RD}、C'_{RP}、N'_{DE}、N'_{CL} represent the standardized values of the average degree centrality of the network, The standardization method refers to Eqs. (2) and (3), and the maximum or minimum values of the indicators are based on the maximum or minimum values of the indicators in the entire Yangtze River Economic Belt and its upper, middle, and lower reaches. ω_1、ω_2、ω_3、ω_4 represent the weights of each indicator respectively. According to the combined weighting method (Wang et al., 2020), the weights are obtained as 0.265, 0.193, 0.324, and 0.218 respectively.

2.5. QAP Model

QAP, or Quadratic Assignment Procedure regression method, can obtain the correlation coefficient of the explanatory variable on the explained variable by analyzing the differences between matrices. The model requires that both the explanatory variable and the explained variable data are in matrix form. The detailed process is shown in Appendix A.

2.6. Multi-regional system dynamics model

① Construction of SD Model for a Single City。Firstly, the urban carbon emission reduction system in each basin of the Yangtze River Economic Belt is divided into multiple subsystems such as economic development and energy consumption. Secondly, the logical relationships between variables within each subsystem are clarified to draw the causal loop diagram of each subsystem. On this basis, the logical relationships between variables are quantified through regression analysis and other methods. The various causal relationships and feedback loops are combined to draw the system flow diagram of the urban system. The construction of the SD model for a single city is detailed in Appendix B.

② Construction of Multi-Regional SD Model. Different from the previous modeling ideas of the system dynamics model, first, on the basis of the construction of the SD model for a single city, cities are taken as the basic simulation units, and a collaborative carbon emission reduction correlation network is constructed for each

basin respectively. Cities serve as the nodes of the collaborative carbon emission reduction correlation network, and the connections between cities serve as the edges of the collaborative carbon emission reduction correlation network. By integrating the indicator characteristics at the node level and the network level, and according to the quantification method of the collaborative carbon emission reduction effect, the collaborative carbon emission reduction effect index is obtained. So far, the research model not only predicts and regulates the carbon emission reduction development of each city but also takes into account the comprehensive consideration of the overall collaborative carbon emission reduction effect of the network.

2.7. Data Sources

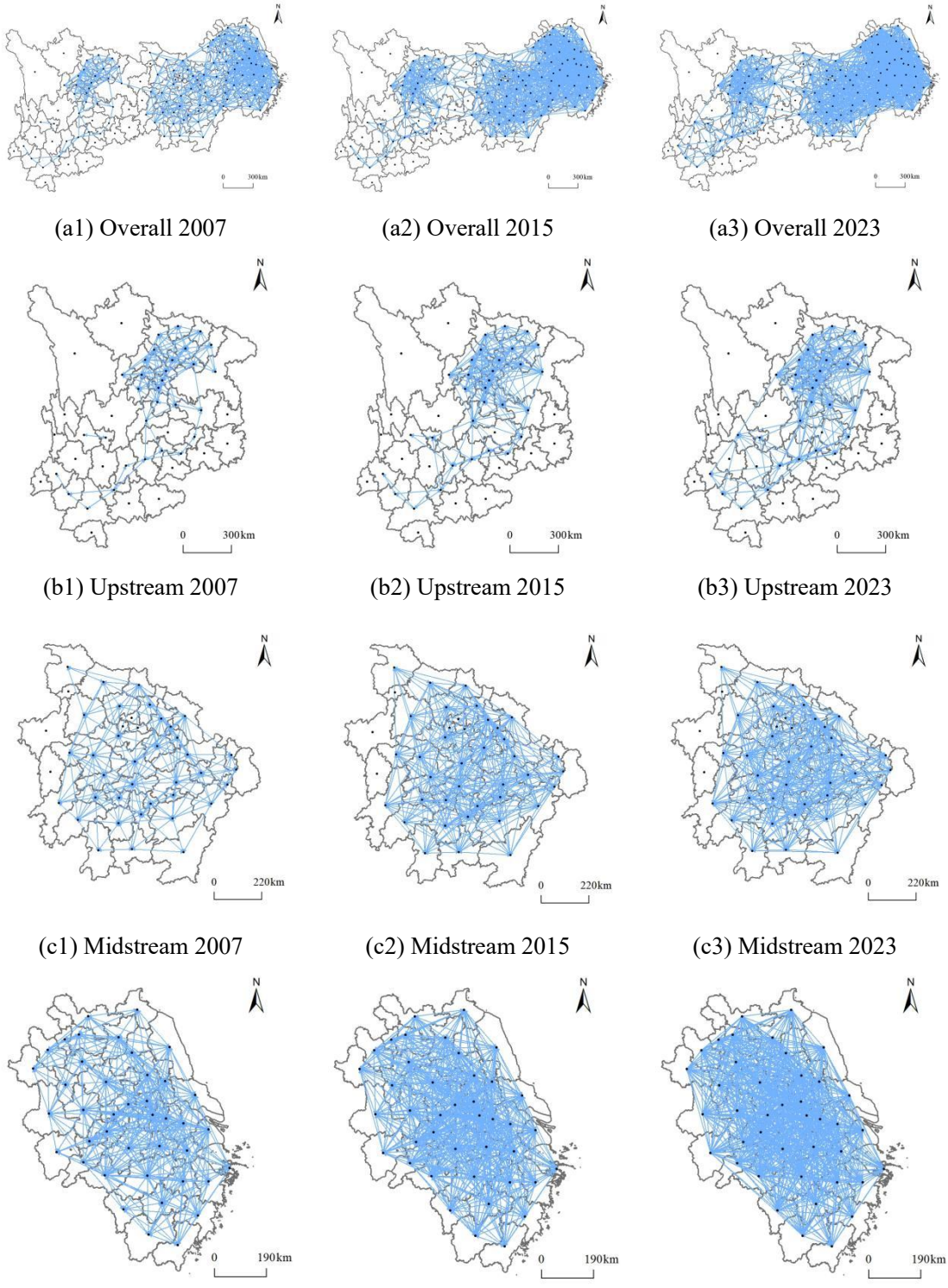
At present, there are 110 prefecture-level and above cities in the Yangtze River Economic Belt. Except for Bijie City and Tongren City, where data are missing and difficult to obtain, the other 108 cities can basically represent the development status of the Yangtze River Economic Belt. Therefore, conducting research with 108 cities in the Yangtze River Economic Belt as cases has good typicality and representativeness. The data of various indicators from 2007 to 2023 required in this paper are obtained from the "China City Statistical Yearbook", "China Statistical Yearbook", "China Environmental Statistical Yearbook", and statistical yearbooks of various provinces. In addition, they also include the China Carbon Accounting Database, China Economic and Social Big Data Research Platform, etc. For missing data, methods such as interpolation, trend extrapolation, and nighttime light data fitting are used to fill them. The perpetual inventory method is used to calculate the capital stock. To eliminate the impact of price fluctuations on data analysis, data such as GDP and fiscal revenue are deflated with 2007 as the base year.

3. Results and discussion

3.1. Analysis of spatial correlation and collaborative effect of carbon emission reduction in the yangtze river economic belt

According to the collaborative correlation calculation method, the collaborative carbon emission reduction correlation between cities in the Yangtze River Economic Belt is first calculated, and then the spatial correlation network diagram of

collaborative carbon emission reduction in the Yangtze River Economic Belt is drawn with the help of ArcGIS, as shown in Fig. 2.



(a1) Overall 2007 (a2) Overall 2015 (a3) Overall 2023

(b1) Upstream 2007 (b2) Upstream 2015 (b3) Upstream 2023

(c1) Midstream 2007 (c2) Midstream 2015 (c3) Midstream 2023

(d1) Downstream 2007 (d2) Downstream 2015 (d3) Downstream 2023

Fig. 2 Spatial correlation network diagram of collaborative carbon emission reduction in the Yangtze River Economic Belt

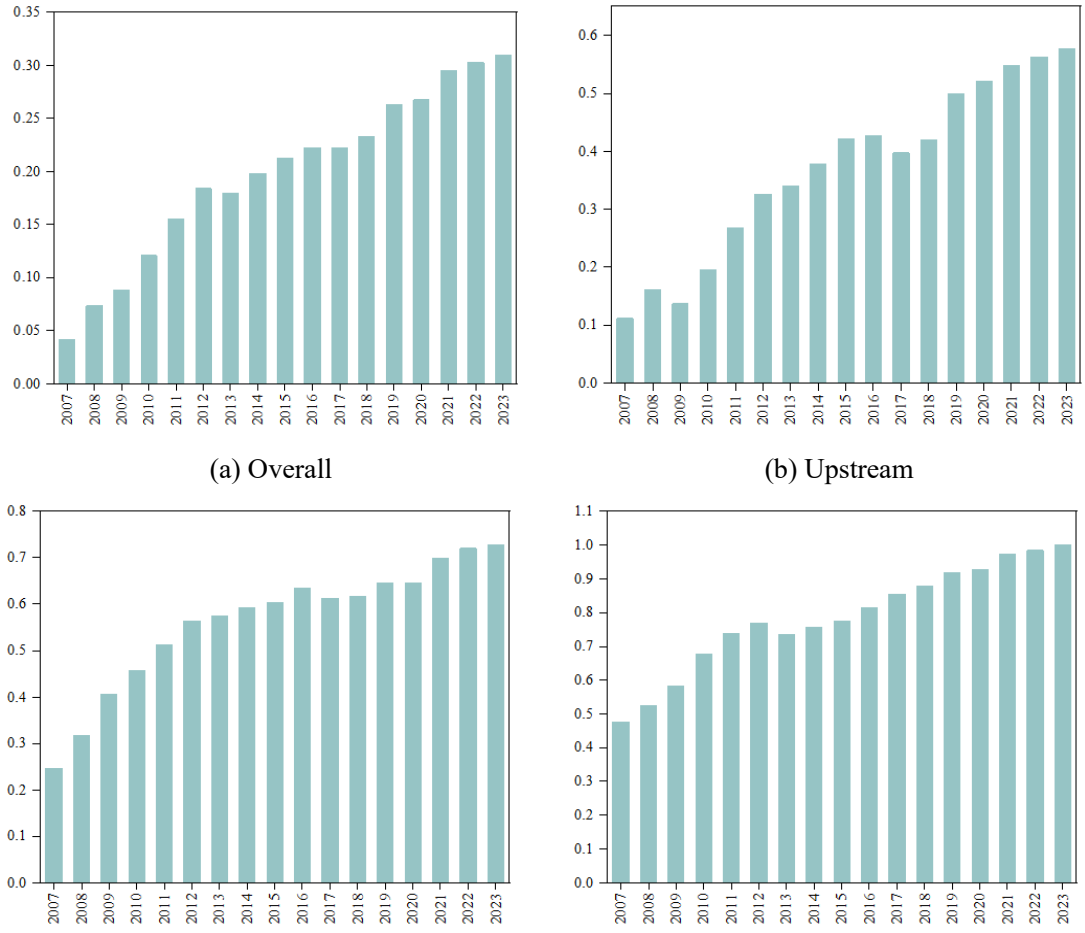
Overall, between 2007 and 2023, the spatial correlation of collaborative carbon

mitigation within the Yangtze River Economic Belt exhibited a continuously deepening trend. Notably, spatial linkages between the lower and middle reaches had already emerged as early as 2007. By 2015, a robust collaborative relationship had been established between these two regions; by 2023, these ties were further consolidated, resulting in highly significant collaborative synergies. In contrast, collaborative connections linking the upper reaches with the middle and lower reaches remained comparatively weak. Although these interactions demonstrated a steadily strengthening trajectory over time, their overall level of integration remains insufficient. Moving forward, it is imperative to further enhance the collaborative mechanisms connecting the upper reaches to the rest of the basin.

From the perspective of river basins, different basins show different evolution trends. In 2007, the upper reaches had a weak spatial correlation of collaborative carbon emission reduction. After years of development, by 2023, the spatial correlation of collaborative carbon emission reduction had been significantly improved. However, this improvement was more concentrated within the Chengdu-Chongqing urban agglomeration, and the spatial correlation of collaborative carbon emission reduction in regions such as Guizhou and Yunnan still needed to be strengthened. In 2007, the middle reaches initially had a relatively simple-structured spatial correlation network of collaborative carbon emission reduction. With the deepening of regional cooperation, by 2015 and 2023, a dense and star-distributed spatial correlation network structure of collaborative carbon emission reduction had been formed, showing the rapid improvement of the collaborative carbon emission reduction level in the middle reaches and a good trend of regional collaborative development. Since 2007, the lower reaches had already formed a relatively close spatial correlation network of collaborative carbon emission reduction. By 2023, the collaborative spatial correlation network had become increasingly dense. Among them, the collaborative carbon emission reduction correlation in the regional scope of Hefei, Nanjing, Suzhou, Changzhou, etc. was particularly prominent, becoming an important region driving collaborative emission reduction in the lower reaches.

On the basis of constructing the collaborative carbon emission reduction

correlation network of the Yangtze River Economic Belt, the collaborative carbon emission reduction effect indexes of the entire Yangtze River Economic Belt and each basin are obtained according to Eq. (16), as shown in Fig. 3 in detail.



(a) Overall (b) Upstream

(c) Midstream (d) Downstream

Fig. 3 Collaborative carbon emission reduction effect index of the Yangtze River Economic Belt from 2007 to 2023

From 2007 to 2023, the collaborative carbon emission reduction effect index of the Yangtze River Economic Belt increased from 0.041 in 2007 to 0.310 in 2023, with an average annual growth rate of 13.39%, showing a relatively rapid growth trend. This indicates that the regional development strategy of the Yangtze River Economic Belt is gradually playing a role, promoting the improvement of the overall collaborative carbon emission reduction effect. From 2007 to 2023, the collaborative carbon emission reduction effects of the upper, middle, and lower reaches of the Yangtze River Economic Belt all showed an increasing development trend, with the average annual growth rates of the effect indexes being 10.82%, 7.00%, and 4.76%

respectively. The upper reaches had the fastest growth rate of the collaborative carbon emission reduction effect, increasing from 0.111 in 2007 to 0.577 in 2023. The lower reaches had the slowest growth rate, but the overall level of collaborative carbon emission reduction in the lower reaches was relatively high. At the same time, it can be found that the collaborative carbon emission reduction index of each basin was higher than that of the entire Yangtze River Economic Belt in the same period. This is because the collaborative carbon emission reduction effect between different basins was significantly weaker than that within the basins.

3.2. Validity test of the SD model

To validate the research findings, the simulated outputs of the SD model were compared against historical empirical data to calculate the relative error. Designating the collaborative carbon mitigation effect as the core variable, we analyzed a ten-year dataset spanning from 2014 to 2023 (Table 3). The validation results for the multi-regional SD model of the YREB reveal an average relative error of 3.57% for this variable, with only marginal deviations observed in a few specific years. The overall error rate remains stable and well within acceptable thresholds. This demonstrates that the model reliably captures the real-world dynamics of multi-regional collaborative carbon reduction within the YREB, thereby confirming its robust empirical validity.

Table 3 Validity test results and errors of the SD model of the Yangtze River Economic Belt in the past ten years

	Simulated Value of Collaborative Carbon Emission Reduction Effect	Error(%)
2014	0.213	7.75
2015	0.215	1.28
2016	0.22	1.01
2017	0.217	2.29
2018	0.226	3.14
2019	0.248	5.49
2020	0.247	7.78
2021	0.282	4.57
2022	0.301	0.35
2023	0.316	2.01

3.3. Sensitivity analysis

Sensitivity refers to the degree of impact on the dependent variable when an independent variable in the model changes. The higher the sensitivity of a variable, the more significant its effect on the dependent variable. In this paper, the input values of each auxiliary variable are adjusted by ±5%, and the sensitivity value corresponding to each auxiliary variable is obtained based on its impact on the collaborative carbon emission reduction effect.

Table 4 Sensitivity analysis results of each basin in the Yangtze River Economic Belt

Variables	Upper Reaches	Middle Reaches	Lower Reaches
Primary Industry Added Value	1.43	0.65	0.45
Secondary Industry Added Value	3.71	2.23	1.92
Tertiary Industry Added Value	3.11	1.89	1.62
LPG Consumption	0.00	0.09	0.01
Natural Gas and Artificial Gas Consumption	0.17	0.14	0.05
Total Electricity Consumption	0.02	0.79	0.29
Permanent Population	3.51	2.82	1.92
Urbanization Rate	0.20	0.31	0.48
Education Expenditure	0.65	0.27	0.39
Science and Technology Expenditure	0.20	0.09	0.05
Environmental Protection Expenditure	0.50	0.23	0.10
Digital Economy Level	0.00	0.00	0.00
Green Space Area	0.03	0.07	0.11

The results of the sensitivity analysis are shown in Table 4. In the upper reaches, the secondary industry added value, permanent population, tertiary industry added value, and primary industry added value have relatively high sensitivity coefficients; education expenditure, urbanization rate, environmental protection expenditure, and science and technology expenditure also show a certain degree of sensitivity. In the middle reaches, the permanent population, secondary industry added value, tertiary industry added value, and total electricity consumption have relatively high sensitivity; the primary industry added value, urbanization rate, education expenditure, and environmental protection expenditure also show a certain degree of sensitivity. In the lower reaches, the secondary industry added value, permanent population, tertiary industry added value, and urbanization rate have relatively high sensitivity coefficients; the primary industry added value, education expenditure, total electricity

consumption, and green space area also show a certain degree of sensitivity.

3.4. Scenario combination prediction and regulation path of collaborative carbon emission reduction in the yangtze river economic belt

On the basis of the sensitivity analysis, combined with the results of the QAP influencing factor analysis, the regulatory factors are screened, and then the scenario combination design of the regulatory factors is carried out. The detailed process is shown in Appendix C and Appendix D. Based on the multi-regional system dynamics model, the collaborative carbon emission reduction effect of different scenario combinations in the upper reaches of the Yangtze River Economic Belt in the future planning years is obtained. At the same time, taking the collaborative carbon emission reduction effect of the region in 2035 and the difficulty of implementation of each scenario combination as the evaluation indicators, the TOPSIS calculation method is used to comprehensively score each scenario combination. The relevant results are shown in Table 5.

Table 5 Comprehensive evaluation of each scenario combination in the lower reaches of the Yangtze River Economic Belt

		Upper Reaches			Middle Reaches			Lower Reaches		
Scenario Preference	A	B1	B2	B3	B1	B2	B3	B1	B2	B3
Reference Scenario	MMM	0.9294	0.5001	0.4372	1.0942	0.5718	0.4622	1.2189	0.8403	0.4923
	HHH	0.9699	0.6252	0.5937	1.1327	0.7147	0.5531	1.2412	1.0503	0.5859
	LLL	0.902	0.3751	0.4063	1.0603	0.4288	0.4249	1.1967	0.6302	0.4091
Factor I	HLL	0.9146	0.4689	0.356	1.0691	0.5414	0.3414	1.2022	0.7877	0.3288
	HLM	0.9146	0.5044	0.3037	1.0683	0.5769	0.2915	1.2022	0.8474	0.2724
	HML	0.9342	0.5115	0.469	1.1071	0.5925	0.5312	1.2228	0.8593	0.5352
	HMM	0.9342	0.547	0.4269	1.0989	0.628	0.4376	1.2218	0.919	0.4763
	MLL	0.9118	0.422	0.4003	1.0652	0.4851	0.3897	1.1995	0.709	0.3738
Factor II	LML	0.927	0.4177	0.5129	1.0916	0.48	0.5356	1.2161	0.7018	0.5503
	LHL	0.9598	0.4604	0.7709	1.144	0.5311	0.8129	1.2366	0.7734	0.7879
	LHM	0.9598	0.4959	0.7142	1.1341	0.5666	0.7238	1.2366	0.8331	0.7267
	MHL	0.9699	0.5073	0.7437	1.1486	0.5874	0.7408	1.2412	0.8522	0.7381
	MHM	0.9699	0.5428	0.6907	1.1363	0.6229	0.6599	1.2412	0.9119	0.6841
Factor III	LLH	0.9004	0.4462	0.3196	1.0505	0.4999	0.3278	1.1967	0.7495	0.3272
	LMH	0.9257	0.4888	0.4172	1.0836	0.551	0.4125	1.2161	0.8212	0.4659
	MLH	0.9118	0.493	0.3022	1.0588	0.5561	0.2802	1.1995	0.8283	0.2717
	MMH	0.9294	0.5357	0.3932	1.0918	0.6073	0.4077	1.2189	0.8999	0.4471
	LLM	0.902	0.4106	0.3689	1.0584	0.4643	0.3865	1.1967	0.6899	0.3715

Factor I - Factor III	HLH	0.9146	0.5399	0.2495	1.0644	0.6124	0.2229	1.2022	0.9071 0.2111
	HMH	0.9342	0.5826	0.3905	1.1001	0.6636	0.4149	1.2218	0.9787 0.4372
	MLM	0.9118	0.4575	0.3544	1.0641	0.5206	0.3452	1.1995	0.7686 0.3264
Factor II-Factor III	LMM	0.927	0.4533	0.4736	1.0875	0.5155	0.4754	1.2161	0.7615 0.5108
	LHH	0.9598	0.5314	0.6605	1.1263	0.6022	0.6394	1.2366	0.8928 0.6704
	MHH	0.9699	0.5783	0.6445	1.1288	0.6584	0.5886	1.2412	0.9715 0.6372
Factor I - Factor II	MML	0.9294	0.4646	0.4814	1.1008	0.5362	0.5455	1.2189	0.7806 0.5376
	HHL	0.9715	0.5541	0.6804	1.1486	0.6437	0.6722	1.2422	0.931 0.6728
	HHM	0.9699	0.5897	0.6311	1.1486	0.6792	0.6354	1.2412	0.9906 0.6236

Note: In the table, “A” represents the scenario combination, “B1” represents the collaborative carbon emission reduction effect in 2035, “B2” represents the implementation difficulty of the scenario combination, and “B3” represents the comprehensive score of the scenario combination calculated by the TOPSIS method. “Factor I” denotes the added value of the secondary industry in the upper, middle and lower reaches of the Yangtze River Economic Belt. “Factor II” denotes the added value of the tertiary industry in the upper, middle and lower reaches of the Yangtze River Economic Belt. “Factor III” denotes the urbanization rate in the upper and lower reaches of the Yangtze River Economic Belt, and represents the education input in the middle reaches.

Among the six optimal schemes for various scenario combination preferences in the upper reaches of the Yangtze River Economic Belt, the LHL scheme has the highest comprehensive score. The collaborative carbon emission reduction effect index of this scheme ranks second among the six schemes, with an average annual growth rate of 3.75%, but the difficulty of implementation is the lowest among the six schemes. Therefore, the optimal scheme for the upper reaches of the Yangtze River is to adopt the low scenario for the secondary industry, the high scenario for the tertiary industry, and the low scenario for the urbanization rate. The low scenario does not mean reducing the scale of development, but focusing on improving quality. The secondary industry should promote upgrading towards high value-added directions such as green manufacturing and clean energy. Areas such as Yunnan are rich in hydropower resources, which can help the industrial transformation and upgrading, reducing pollution while avoiding excessive reliance on resource consumption. At the same time, the tertiary industry in the upper reaches has great development potential and should be vigorously developed. For example, vigorously developing the big data industry in Yunnan and Guizhou can not only serve the secondary industry but also help achieve low-carbon development. In terms of urbanization, attention should be paid to the quality of urbanization development. In view of the fragile ecology in

some areas of the upper reaches, the service capacity of cities should be improved while reducing carbon emissions through compact urban planning, optimization of public transportation, and promotion of green buildings. In all scenarios in the middle reaches, the LHL scenario combination is the optimal one. The average annual growth rate of the collaborative carbon emission reduction effect in the future planning years is 3.60%, the difficulty of implementation is 0.4604, and the comprehensive score is 0.7709. The combination mode of adopting the low scenario for the secondary industry added value, the high scenario for the tertiary industry added value, and the low scenario for education expenditure can produce the optimal comprehensive effect, which can better help the collaborative carbon emission reduction and sustainable economic development in the middle reaches of the Yangtze River Economic Belt. After comprehensive consideration in the lower reaches, the LHL scenario has the highest comprehensive score and is the optimal scenario combination among all scenario combinations. The average annual growth rate of the collaborative carbon emission reduction effect in this scenario in the future planning years is 1.84%. Although the growth rate is relatively slower than that in the upper and middle reaches, the collaborative carbon emission reduction effect is better than that in the upper and middle reaches scenarios.

Based on the previous analysis conclusions, the optimal scenario combination for the upper, middle, and lower reaches of the Yangtze River Economic Belt is LHL. When integrating the LHL scenarios of each basin, due to the systematic and interrelated nature of the overall collaborative carbon emission reduction network of the Yangtze River Economic Belt, its effect is not a simple superposition of the scenarios of the upper, middle, and lower reaches of the basins. Therefore, it is necessary to re-calculate and integrate based on the basic prediction data of each basin under the LHL scenario, and finally obtain the overall collaborative carbon emission reduction effect and various sub-indicators of the Yangtze River Economic Belt. The specific calculation results are shown in Table 6.

Table 6 Collaborative carbon emission reduction effect index and sub-indicators of the Yangtze River Economic Belt in the future planning years

	Network Density	Clustering Coefficient	Average Degree Centrality	Average Closeness Centrality	Collaborative Carbon Emission Reduction Effect Index
2024	0.2677	0.7569	0.5355	0.4204	0.3349
2025	0.2775	0.7605	0.5550	0.4295	0.3486
2026	0.2903	0.7659	0.5807	0.4443	0.3681
2027	0.3058	0.7699	0.6116	0.4626	0.3901
2028	0.3179	0.7734	0.6359	0.4759	0.4071
2029	0.3363	0.7755	0.6726	0.4944	0.4303
2030	0.3503	0.7817	0.7006	0.5054	0.4501
2031	0.3695	0.7890	0.7390	0.5206	0.4766
2032	0.3903	0.7956	0.7805	0.5378	0.5044
2033	0.4096	0.8008	0.8191	0.5546	0.5300
2034	0.4286	0.8077	0.8572	0.5759	0.5579
2035	0.4564	0.8143	0.9128	0.6018	0.5947

The network density of the Yangtze River Economic Belt shows an increasing trend in the future planning years, increasing from 0.2677 in 2024 to 0.4564 in 2035. Network density is an important indicator to measure the density of interconnections between nodes in the network. The continuous growth of network density means that the carbon emission reduction connections between various entities in the Yangtze River Economic Belt are becoming increasingly close. In the process of collaborative carbon emission reduction in the Yangtze River Economic Belt in the future planning years, the cooperation and exchanges between various regions and departments will be continuously strengthened, promoting the flow of information, technology, resources, etc. between regions, and providing a solid foundation for the collaborative carbon emission reduction of the Yangtze River Economic Belt.

The clustering coefficient of the Yangtze River Economic Belt shows a fluctuating upward trend from 2024 to 2035, increasing from 0.7569 in 2024 to 0.8143 in 2035. The clustering coefficient is mainly used to describe the degree of aggregation of nodes in the carbon emission reduction correlation network. A higher clustering coefficient means that the neighbors of a node are more closely connected to each other. This means that in the future planning years, various entities in the Yangtze River Economic Belt will form closely connected small groups. Within these small groups, close cooperation and exchanges will be carried out in carbon emission

reduction work, which can effectively share the experience and achievements of carbon emission reduction and jointly promote the collaborative carbon emission reduction work of the Yangtze River Economic Belt.

The average degree centrality of the Yangtze River Economic Belt shows an upward trend in the future planning years, increasing from 0.5355 in 2024 to 0.9128 in 2035. The average degree centrality reflects the average degree of direct connections between a node and other nodes. A higher average degree centrality means that the average importance of nodes in the network is higher. It reflects that each node in the carbon emission reduction network of the Yangtze River Economic Belt is playing an increasingly important role, which can effectively transmit information, coordinate resources, and promote the collaborative carbon emission reduction of the Yangtze River Economic Belt.

The average closeness centrality of the Yangtze River Economic Belt continues to increase in the future planning years, increasing from 0.4204 in 2024 to 0.6018 in 2035. The average closeness centrality measures the average degree of closeness between a node and other nodes in the network, reflecting the efficiency of the node in information dissemination and resource allocation. It indicates that in the future planning years, the information communication and resource transmission between various entities in the Yangtze River Economic Belt will be more efficient, reducing the time and cost of information transmission, which is conducive to quickly responding to various problems and needs in the carbon emission reduction work and further improving the effect of collaborative carbon emission reduction.

The collaborative carbon emission reduction effect index of the Yangtze River Economic Belt shows an upward trend in the future planning years, increasing continuously from 0.3349 in 2024 to 0.5947 in 2035, with an average annual growth rate of 5.36%. The collaborative carbon emission reduction effect index is a comprehensive reflection of the collaborative effect of carbon emission reduction in the Yangtze River Economic Belt. The upward trend indicates that under the joint action of the sub-indicators of the collaborative carbon emission reduction effect index, the collaborative carbon emission reduction effect of the Yangtze River

Economic Belt is continuously enhanced. The increase in network density, the rise in the clustering coefficient, and the improvement of the average degree centrality and average closeness centrality jointly promote the optimal allocation of carbon emission reduction resources in the region, strongly driving the development of collaborative carbon emission reduction in the Yangtze River Economic Belt and promoting the Yangtze River Economic Belt to achieve better results in carbon emission reduction work.

4. Conclusions and recommendations

4.1. Conclusions

Focusing on regional collaborative carbon mitigation within the Yangtze River Economic Belt (YREB), this paper adopts a systematic analytical framework. First, we quantify urban carbon abatement capacity through the lens of balancing efficiency and equity. Second, by integrating the gravity model with the coordination degree model, we construct a spatial correlation network for collaborative mitigation and explicitly quantify the resulting synergistic effects. Finally, we develop a multi-regional system dynamics (SD) model encompassing 27 combinatorial scenarios to forecast and optimize these collaborative abatement efforts. A key innovation of this study lies in its robust quantification of collaborative mitigation effects and the integration of multiple regions into a unified SD framework. By employing extensive scenario analyses, this research comprehensively evaluates mitigation outcomes, thereby providing a highly rigorous methodological paradigm for future studies on regional collaborative carbon reduction.

Regarding the spatial correlation and effects of collaborative carbon mitigation, the spatial network within the YREB deepened continuously from 2007 to 2023. The middle and lower reaches established and consistently consolidated strong spatial linkages early on, whereas connections between the upper reaches and the rest of the basin—though historically weaker—exhibited a clear upward trend. In terms of scenario forecasting and pathway optimization, the LHL configuration emerged as the optimal scenario across all three basins. Integrating these basin-specific optimal scenarios for a holistic assessment of the YREB reveals that, under this unified

framework, the collaborative carbon mitigation effect index is projected to rise from 0.3349 to 0.5947 between 2024 and 2035. Concurrently, key network structural metrics—including density, clustering coefficient, average degree centrality, and average closeness centrality—are expected to undergo significant growth. These projections indicate that the interconnectivity of the collaborative mitigation network across the YREB will continue to deepen, yielding steadily enhanced synergistic abatement effects throughout the future planning horizon..

The study does not fully consider the impact of external uncertain factors such as extreme climates and sudden policy changes on collaborative carbon emission reduction. In the future, the research dimension can be further expanded to enhance the anti-interference ability and applicability of the conclusions.

4.2. Policy recommendations

(1) Strengthening coordinated regional development is imperative for bridging the inter-basin gap in carbon mitigation capacity. As this study demonstrates, substantial disparities exist in carbon abatement capabilities across the sub-basins of the YREB, particularly between the upper reaches and the middle and lower reaches. To address these imbalances, policymakers should leverage national macro-strategies, such as the "Rise of Central China" and the "Western Development" initiatives. Specifically, support for low-carbon R&D must be augmented in pivotal central and western hubs, including Wuhan, Kunming, and Guiyang, enabling these cities to catalyze the green transformation of surrounding areas through technological spillovers and industrial diffusion. Furthermore, an East-West collaborative support mechanism for carbon mitigation should be established. This framework would incentivize the developed eastern regions in the lower reaches to facilitate the low-carbon transition of traditional, energy-intensive industries in the middle and upper reaches via technology transfer and talent exchange, ultimately narrowing the broader regional development divide.

(2) Establish intra- and inter-basin collaborative mechanisms and consolidate the top-level design of an "integrated strategic framework." Our findings indicate that while the collaborative carbon mitigation effect within the YREB exhibits a positive

growth trajectory, substantial untapped potential for further abatement remains. To strengthen intra-basin integration, policymakers must tailor strategies to the distinct developmental profiles of individual cities, thereby facilitating the seamless flow of production factors and enhancing collaborative spatial linkages. In the upper reaches, for instance, efforts should prioritize strengthening synergies between the Chengdu-Chongqing urban agglomeration and the Yunnan-Guizhou region. By fostering exchange channels for green and low-carbon industries and promoting the sharing of clean energy and green building technologies, stakeholders can systematically elevate collaborative mitigation ties across the upper basin, guided by the overarching paradigm of an integrated policy framework.

(3) Target key influencing factors within each basin and implement differentiated regulatory policies. Policymakers must formulate targeted, region-specific strategies based on the primary drivers of carbon mitigation in each area, ensuring that synergistic emission reductions are tailored to local contexts. For instance, in the lower reaches, investment in green and low-carbon R&D should be intensified in pivotal cities such as Nanjing, Shanghai, and Hefei. Concurrently, establishing a Yangtze River Delta green technology sharing platform will facilitate the transfer and commercialization of low-carbon technologies to central and northern Jiangsu, thereby amplifying the overall regional collaborative mitigation effect.

(4) Enhance low-carbon infrastructure and establish a "wind-solar-hydro-storage" multi-energy complementary belt. Our findings reveal that geographical distance acts as a ubiquitous constraint on collaborative carbon mitigation effects across all basins. For regions exhibiting strong collaborative potential yet hindered by significant spatial friction, upgrading infrastructure is essential to bridge these geographical divides. Given that the YREB is abundantly endowed with renewable energy resources, particularly hydropower, it is crucial to fully leverage these regional assets. Specifically, the upper reaches should capitalize on their hydroelectric advantages by accelerating the smart transformation of energy infrastructure, deploying large-scale auxiliary energy storage facilities, and ultimately forging a "western clean energy corridor." Furthermore, policymakers must prioritize

the comprehensive deployment of cross-regional low-carbon infrastructure throughout the YREB. By focusing on the construction of trans-regional power transmission corridors, natural gas pipelines, and charging networks for new energy vehicles, regions can significantly strengthen infrastructural interconnectivity. This, in turn, will mitigate the impediments of geographical distance on factor mobility, thereby driving the effective implementation of inter-regional collaborative carbon abatement.

Declaration of competing interest

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

Data Availability

Data will be made available on request.

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