Coordinated Development and Coupling Mechanisms of Capital Flows and Carbon Emissions from the Perspective of Environmental Justice

Ting Zhang[1], Yuanhong Qiu[2], Jianzhong Huang[1]
[1]College of Architecture and Urban Planning, Tongji University, Shanghai, China (Ting Zhang, corresponding author, Jianzhong Huang);
[2]School of Public Policy and Administration, Chongqing University, Chongqing, China (Yuanhong Qiu)
Email: 18089545176@163.com.com (Ting Zhang).

Abstract
This study explores the coordination between capital flows and carbon emissions in China's Yangtze River Delta (YRD) under an environmental justice framework. Using complex network analysis, coordination models, and multiple linear regression, we diagnose spatial disparities in coupling coordination levels across industries. Results reveal low coordination in manufacturing, power, and financial sectors, with most cities exhibiting incoordination, while construction and agriculture show higher synergy. The environmental justice framework highlights regional equity's critical role in aligning economic activities with carbon neutrality goals. Findings emphasize balancing economic growth and environmental sustainability through equitable policies, offering insights for harmonizing industrial decarbonization with development priorities in economically advanced regions.

1. Introduction
During the critical period of global response to climate change, carbon emissions have become a core challenge restricting sustainable development. Meanwhile, capital, as a key element driving economic growth, its cross-regional flow not only reshapes the global economic geography but also profoundly influences the spatial distribution of carbon emissions. The concept of environmental justice emphasizes fairness in the allocation of environmental resources and the assumption of environmental burdens. However, in the process of promoting regional economic development, current capital flows often come with regional imbalances in carbon emissions, and the issue of carbon emission transfer has become increasingly prominent. Core cities with high capital activity transfer carbon emission pressure to peripheral cities through industrial relocation, forming an "agglomeration of capital - diffusion of pollution" environmental injustice trap, which intensifies the contradiction between different regions in terms of environmental rights and development rights. For instance, developed regions transfer energy-intensive industries to less developed regions through capital outflow, which although promotes their own industrial upgrading and low-carbon transformation, imposes more environmental pressure on less developed regions. This phenomenon seriously violates the principle of environmental justice. As the most dynamic growth pole of China's economy, the Yangtze River Delta region achieved a regional GDP of 30,504.5 billion yuan in 2023. All the prefecture-level cities in the Yangtze River Delta have an economic volume of over 100 billion yuan. With less than 4% of the country's land area, it generates nearly a quarter of China's total economic output, and the scale of regional capital flow accounts for a relatively high proportion of the national total. Against this backdrop, in-depth exploration of the coordinated development and coupling mechanism of capital flow and carbon emissions from the perspective of environmental justice not only helps reveal the intrinsic connection between economic development and environmental protection but is also an urgent need for achieving regional fairness and sustainable development. It holds significant theoretical and practical significance for optimizing resource allocation and promoting green and low-carbon transformation.

2. Literature review
Since the emergence of environmental justice theory in the 1980s, it has gradually become a focus of academic attention. Scholars have interpreted environmental justice from various perspectives. Early research mainly focused on the description of environmental inequality phenomena. For instance, an American scholar found through empirical research that minority communities are often more likely to be the sites for hazardous waste treatment facilities, revealing the issue of racial inequality in the distribution of environmental burdens (Bullard R, 2000). With the deepening of research, the connotation of environmental justice has been continuously expanded, covering multiple dimensions such as intra-generational justice, inter-generational justice, and justice among different regions (Schlosberg D, 2007). At the practical level, the environmental justice movement has driven policy changes, and many countries and regions have begun to incorporate the concept of environmental justice into environmental policy-making. However, existing research has relatively insufficient exploration of the manifestation and influence mechanism of environmental justice in economic activities, especially in capital

flows. How to implement the principle of environmental justice in the coordinated development of capital flows and carbon emissions remains to be further studied.

The impact of capital flows on regional economic development has always been an important field of study in economics. Scholars at home and abroad generally believe that capital flows can promote the optimal allocation of capital factors and drive the upgrading of regional industrial structures (Feldstein & Horioka, 1980; Zhang Jun, 2002). Transnational capital flows, through spillover effects of technology and industrial linkage effects, have driven the economic growth of host countries (Pan et al., 2025). Meanwhile, the cross-regional flow of domestic capital is also reshaping the regional economic landscape. For example, the flow of capital from China's eastern regions to the central and western regions has, to a certain extent, promoted the industrialization and urbanization processes in the central and western regions. However, existing research has mostly focused on the quantitative impact of capital flows on economic growth (Zhao & Jiang, 2025), with relatively weak research on the improvement of economic development quality, especially in the aspect of coordinated development with the environment.

There is a considerable amount of research on the relationship between carbon emissions and economic growth. The "Environmental Kuznets Curve" (EKC) theory holds that in the early stage of economic development, carbon emissions will increase with economic growth. When economic development reaches a certain stage, carbon emissions will decrease due to factors such as industrial structure adjustment and technological progress (Grossman & Krueger, 1995). Many scholars have verified and expanded the EKC curve based on data from different countries and regions. Some studies support this theory, while others have found that the relationship between carbon emissions and economic growth varies among different countries and regions (Panayotou, 2003). However, most of these studies have explored the relationship from a macro perspective, with relatively few studies on how capital flows affect the relationship between carbon emissions and economic growth, and a lack of in-depth analysis of the intrinsic mechanism from the perspective of capital flows.

In recent years, the relationship between capital flows and carbon emissions has begun to attract attention. Some studies have pointed out that international capital flows can lead to the "carbon leakage" phenomenon, where developed countries transfer high-carbon emission industries to developing countries through foreign direct investment, thereby reducing their own carbon emissions but increasing the global total (Ahmad & Wyckoff, 2009). At the domestic regional level, the flow of capital from developed regions to less developed regions may also cause similar environmental problems (Niu et al., 2024; Yan et al., 2025; Zhao et al., 2021; Hata et al., 2023). However, existing research mostly focuses on phenomenon description and qualitative analysis, with relatively scarce quantitative research on the coupling and coordination mechanism between capital flows and carbon emissions, especially from the perspective of environmental justice, where the coordinated development path of the two has not been fully explored.

Overall, existing research has achieved certain results in the fields of environmental justice, capital flows, and carbon emissions. However, systematic research on the coordinated development and coupling mechanism of capital flows and carbon emissions from the perspective of environmental justice is still relatively scarce. This study will employ methods such as the capital flow network space model and the coupling coordination degree model to deeply analyze the relationship between capital flow and carbon emissions in different industries within the Yangtze River Delta region, providing theoretical basis and practical guidance for achieving regional environmental justice and sustainable development.

3. Data sources and research methods

3.1. The data sources

The indicators selected for this study include enterprise investment data, carbon emission data, and socio-economic and natural resource statistics in manufacturing, construction, power, transportation, agriculture, and finance. The enterprise investment data for 2022 is sourced from Qixinbao, which covers investment information among enterprises in cities of the Yangtze River Delta region, providing a foundation for constructing the capital flow network. Meanwhile, carbon emission data is obtained from platforms such as the China Greenhouse Gas Working Group to ensure accuracy and authority. Socio-economic and natural resource statistics are all derived from the 2023 Urban Statistical Yearbook.

3.2. Research methodology

3.2.1. Construction of a Spatial Model of Capital Flow Network

The study selected the enterprise investment data from multiple industries in the cities of the Yangtze River Delta region in 2022, including manufacturing, construction, electricity, transportation, agriculture, and finance. The data were cleaned and filtered to remove invalid or abnormal data, ensuring the completeness and accuracy of the data. The cities in the Yangtze River Delta region were regarded as the nodes of the network, and the investment relationships between enterprises were regarded as the edges. Based on the investment flow and investment relationships of enterprises, a capital flow network between cities was constructed. A weighted asymmetric matrix was built based on the investment scale data, and the elements in the matrix represented the investment weight of city i to city j. By calculating the investment flow between each city, the weighted matrix of the capital flow network was obtained, providing basic data for subsequent network analysis.

3.2.2 Network characteristic measurement method

The study selected the degree centrality as the measurement index for the activity level of nodes in the capital flow network. Degree centrality is used to measure the importance of a city in the network, that is, the number and intensity of investment connections between this city and other cities. The calculation formula is the sum of the scale of cross-city outbound investment and inbound investment by enterprises in the city.

$$NW = MaxAbs(I_{st} + I_{tt}) \qquad (1)$$

"I_{st}" represents the scale of cross-city outbound investment by enterprises aggregated by city, and "I_{tt}" represents the scale of cross-city inbound investment received by enterprises aggregated by city.

3.2.3. Coupling coordination model

Coupling degree is an important indicator used to measure the degree of interaction between two or more elements in a research system. Due to the significant differences in the selection of indicators, the data is first standardized before calculating using the coupling degree formula.

$$C = 2\sqrt{\frac{U_1 U_2}{(U_1 + U_2)^2}} \qquad (2)$$

C represents the coupling degree, U_1 and U_2 are the centrality of the capital flow network and the standardized values of carbon emissions, respectively. In certain circumstances, the coupling degree may not accurately reflect the overall degree and synergy of the two factors. Therefore, a further coupling coordination degree model is employed, and the formula is as follows.

$$D = \sqrt{CT} \qquad (3)$$

$$T = xU_1 + yU_2 \qquad (4)$$

Among them, D represents the coupling coordination degree, where D∈ (0, 1); T is the harmonic coefficient of the central degree of the capital flow network and carbon emissions, reflecting the contribution levels of both to the coupling coordination degree, x and y respectively represent the weights of the central degree of the capital flow network and carbon emissions, with x + y = 1. Their values can be calculated using the entropy weight method. According to the classification standard of coupling coordination degree (Table 1), its coupling coordination degree is divided into ten levels, namely extreme imbalance, severe imbalance, moderate imbalance, mild imbalance, on the verge of imbalance, barely coordinated, primary coordination, moderately excellent coordination, good coordination and excellent coordination.

Table 1 Classification standard of coupling coordination degree

D value interval of coupling coordination degree	Coordination level	Degree of coupling coordination
(0.0~0.1)	1	Extreme imbalance
[0.1~0.2)	2	A serious imbalance between
[0.2~0.3)	3	Moderate disorders
[0.3~0.4)	4	Mild disorder
[0.4~0.5)	5	On the verge of disorder
[0.5~0.6)	6	Barely coordination
[0.6~0.7)	7	Primary coordination
[0.7~0.8)	8	Intermediate coordinate
[0.8~0.9)	9	Good coordination
[0.9~1.0)	10	Great coordination

3.2.4 Multivariate Linear Regression Model

Construct a coupling and coordination mechanism model for urban capital flow and carbon emissions in the Yangtze River Delta region. Analyze it using the multiple linear regression model. The formula is as follows.

$$Y_j = a_1 \ln X_1 + a_2 \ln X_2 + a_3 \ln X_3 + a_4 X_4 + a_5 X_5 + a_6 X_6 + a_7 X_7 + c \qquad (5)$$

Y_{ij} represents the coupling coordination degree of capital flow and carbon emission system in industry j of city i. $\ln X_1$, $\ln X_2$, $\ln X_3$, X_4, X_5, X_6 and X_7 are influencing factors, representing GDP, total passenger volume, annual average concentration of fine particulate matter (PM2.5), urbanization rate of permanent residents, total retail sales of consumer goods, local general budgetary revenue, and local general budgetary expenditure. α is the constant term, $α_1$, $α_2$, $α_3$, $α_4$, $α_5$, $α_6$ are the coefficient values of $\ln X_1$, $\ln X_2$, $\ln X_3$, X_4, X_5 and X_6 respectively, and c is the regression constant term.

4. Research on the Regional Characteristics of Capital Flow Linkage Network and Carbon Emissions

4.1 Research on the Multi-industry Capital Flow Linkage Network and Its Structural Characteristics

4.1.1 Research on the Multi-industry Capital Flow Linkage Network in the Yangtze River Delta Region

The capital flow network of manufacturing industry in the Yangtze River Delta presents a "multi-core with multiple sub-centers" structure, with "Shanghai - Suzhou - Hangzhou" as the main core and Yangzhou, Ningbo, Nanjing, Wuxi, and Hefei as the secondary centers. Among them, Shanghai has a relatively strong capital connection with other regions, while Suzhou and Hangzhou have stronger local connections. Other cities also show a network feature where local connections are greater than external connections. As an international hub, Shanghai has a relatively high proportion of external capital connections and outstanding regional resource allocation capabilities; while Suzhou and Hangzhou have strong local capital connections, reflecting the localization tendency of their industrial clusters, such as Suzhou's electronic information and Hangzhou's digital manufacturing. The local connections of other secondary centers are generally higher than those with other regions, indicating that the manufacturing industry presents a "regional decentralization and concentration" feature. The manufacturing industry network relies on the dual drive of external radiation from core cities and local deepening in secondary nodes, and needs to enhance network collaboration efficiency through cross-city industrial chain division.

The capital network of the construction industry forms a multi-center pattern with five centers in Nanjing, Shanghai, Suzhou, Yancheng, and Hefei. The spatial distribution is more scattered than that of manufacturing. Among them, Suzhou and Nanjing have stronger external connections, and Nanjing and Suzhou undertake the functions of regional infrastructure hubs, mainly connecting cross-provincial projects such as high-speed rail and cross-river passages. While Shanghai, Yancheng, Zhenjiang, and Hefei have stronger local connections, Shanghai and Yancheng are closely related to local urban renewal and coastal development projects. The multi-center pattern of the construction industry is strongly related to the government-led infrastructure investment model, and attention should be paid to the risk of duplication, and a regional major project joint approval mechanism should be established.

The capital network of the power industry presents a "one main with multiple sub-centers" structure, with Ningbo as the strongest local connection and its core position derived from its port location advantage. In 2022, the coal and nuclear power installed capacity in Ningbo accounted for 23% of the total in the Yangtze River Delta. Shanghai has the strongest external connections, mainly transporting electricity to the north of Jiangsu and the Yangtze River Delta. The power network is highly dependent on geographical endowments and needs to strengthen the complementarity between Ningbo and other sub-centers through the construction of special high-voltage transmission channels to avoid the risk of a single energy center.

The capital network of the transportation industry presents a single center in Shanghai and five cities including Suzhou, Hangzhou, Nanjing, Hefei, and Ningbo as sub-centers. Among them, Shanghai has the strongest external connections, mainly undertaking international shipping and transshipment functions in the Yangtze River Delta. Hangzhou has become the only sub-center with balanced local and external capital connections, matching its position as an e-commerce logistics hub. Shanghai's single-pole hub function is temporarily irreplaceable, but it needs to build regional logistics nodes in cities such as Hangzhou and Nanjing to alleviate the pressure of trunk transportation.

The capital flow network of agriculture forms a center structure of Ningbo-Hangzhou-Suzhou, with the intensity of capital connections showing a "core prominent - periphery balanced" feature. Regions with strong connections in Shanghai, Hangzhou, and Hefei all have local connections greater than external connections. It is strongly related to the localized production models such as urban agriculture in Shanghai, tea industry in Hangzhou, and seed industry in Hefei. The agricultural network highly relies on geographical resource endowments and needs to enhance cross-regional capital flow efficiency through technological empowerment , such as research and development in Hefei seed industry - application and transformation in Shanghai.

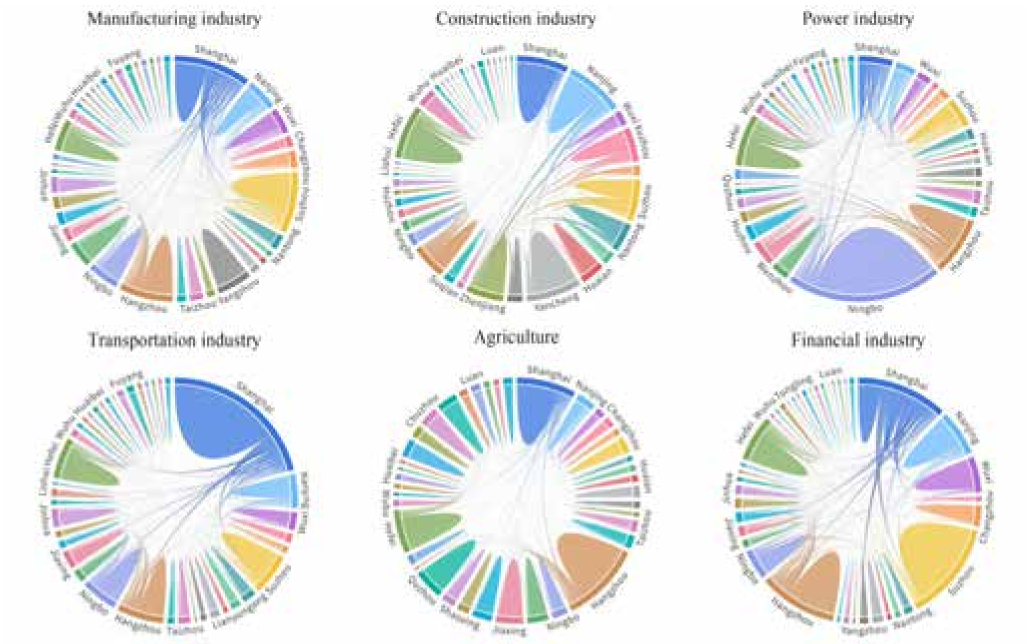

Figure 1 The network connection of capital flow in various industries in the Yangtze River Delta region

4.1.2 Research on the Structural Characteristics of Capital Flow Network in the Yangtze River Delta Region

The centrality of the urban capital flow network in the Yangtze River Delta region was analyzed (Figures 2 and 3). The centralities of cities such as Shanghai, Suzhou, Hangzhou, Hefei, and Nanjing were relatively high. Additionally, the centralities of regions like Ningbo, Zhenjiang, and Yancheng were also high. From the perspective of various industries, compared to other industries, the centralities of manufacturing and construction industries were higher, mainly concentrated in the value ranges of 431-1871 and 274-2352. Among them, the degree values of cities such as Suzhou, Shanghai, and Hangzhou were the highest in the manufacturing industry, while those of cities like Yancheng, Nanjing, and Zhenjiang were the highest in the construction industry. The centrality of the transportation industry was relatively low, mainly concentrated in the value range of 70-235. Shanghai had the highest centrality value. The centrality of the power industry was only concentrated in the value range of 92-270, with Ningbo having the highest centrality, and Hangzhou and Hefei having relatively high centrality. The centrality of agriculture was mainly concentrated in the value range of 92-262, with Hangzhou having the highest centrality, while Shanghai and Hefei had relatively high centrality. The centrality of the financial industry was mainly concentrated in the value range of 81-331, with Hangzhou having the highest centrality, and Suzhou, Shanghai, Nanjing, and Hefei having relatively high centrality as provincial capital cities.

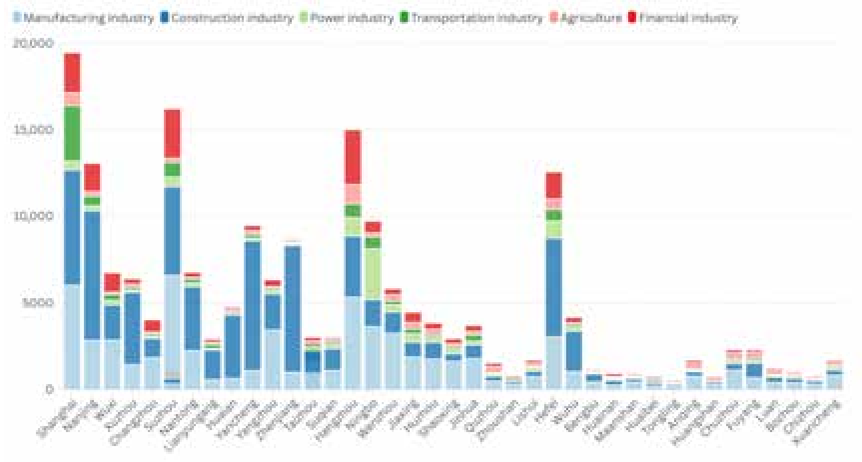

Figure 2 The centrality and cumulative value of capital flow networks in various industries of cities in the Yangtze River Delta region

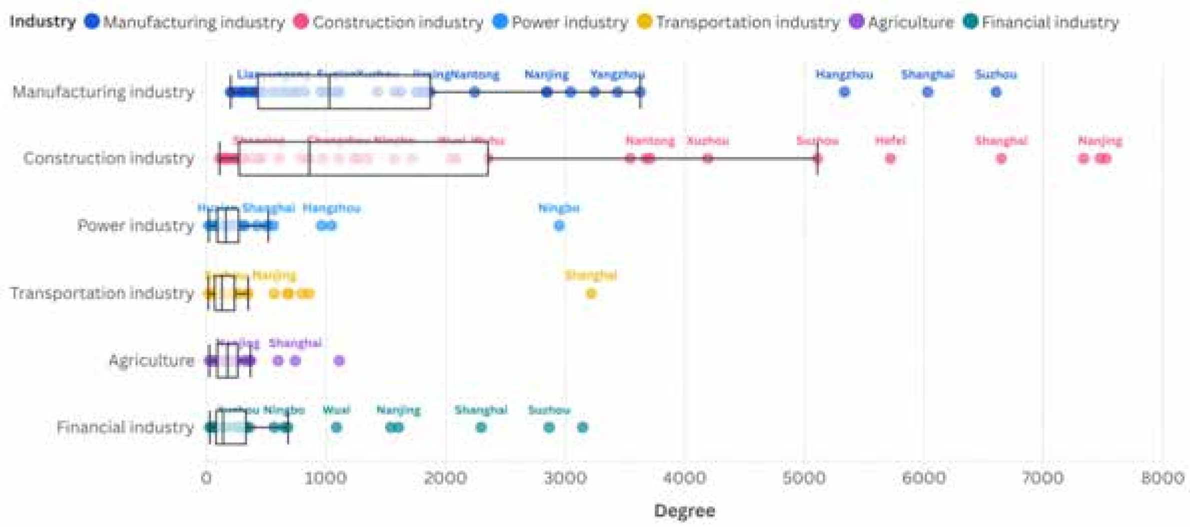

Figure 3 The distribution of centrality values of capital flow networks in various industries of cities in the Yangtze River Delta region

4.2 Spatial Characteristics Analysis of Carbon Emissions in the Yangtze River Delta Region

The spatial distribution characteristics of carbon emissions in the cities of the Yangtze River Delta region were analyzed (Figures 4 and 5). The total carbon emissions of Suzhou and Xuzhou were the highest. The carbon emissions from manufacturing and the power industry were higher than those from other industries. The carbon emissions from finance and agriculture were relatively lower. From the perspective of the spatial distribution of carbon emissions in each industry, the high-value areas of carbon emissions from manufacturing were mainly concentrated in the "Shanghai-Suzhou-Wuxi-Quanzhou-Nanjing-Ma'anshan-Hefei" urban axis. In addition, the carbon emission values in regions such as Xuzhou, Yancheng, Lianyungang, Hangzhou, Quzhou, Jinhua, etc. were relatively high. The high-value area of carbon emissions from the construction industry was relatively wide, with the highest value area concentrated in Shanghai, while the carbon emission values in cities such as Suzhou, Nantong, Yancheng, Hangzhou, Wenzhou, Ningbo, Xuzhou, Nanjing, Hefei, Fuyang, etc. were relatively high. The high-value area of carbon emissions from the power industry was mainly concentrated in cities such as Suzhou, Zhenjiang, Huainan, etc. The carbon emission values in cities such as Xuzhou, Huaihua, Taizhou, Wuxi, Ningbo, Wenzhou, etc. were relatively high. The high-value area of carbon emissions from agriculture was concentrated in cities such as Yancheng, Xuzhou, Suizhou, Bozhou, and Fuyang, while the highest value area was located in regions such as Lianyungang, Suqian, Huai'an, Chuzhou, Hefei, Suzhou, and Nantong. The high-value area of carbon emissions from the transportation industry was concentrated in Shanghai, with the highest value area located in cities such as Suzhou, Wuxi, Nanjing, Hangzhou, etc. The high-value area of carbon emissions from finance was concentrated in Shanghai and Huainan, while the highest value area was located in cities such as Ma'anshan, Wuhu, Wenzhou, etc.

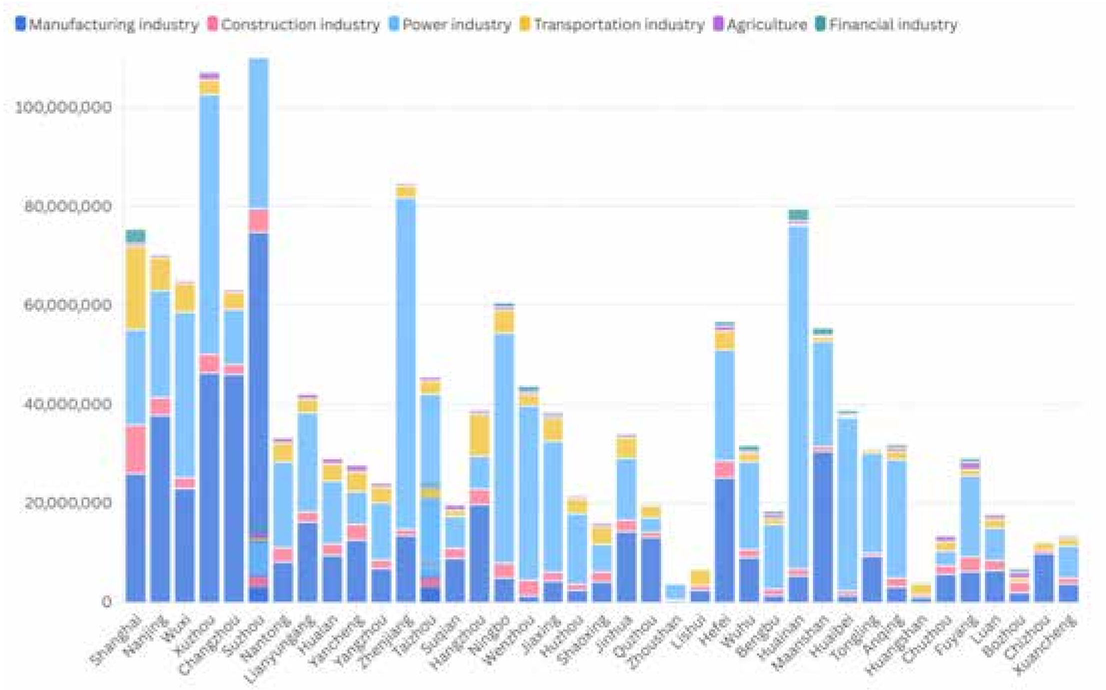

Figure 4 The total carbon emissions of multiple industries in cities in the Yangtze River Delta region

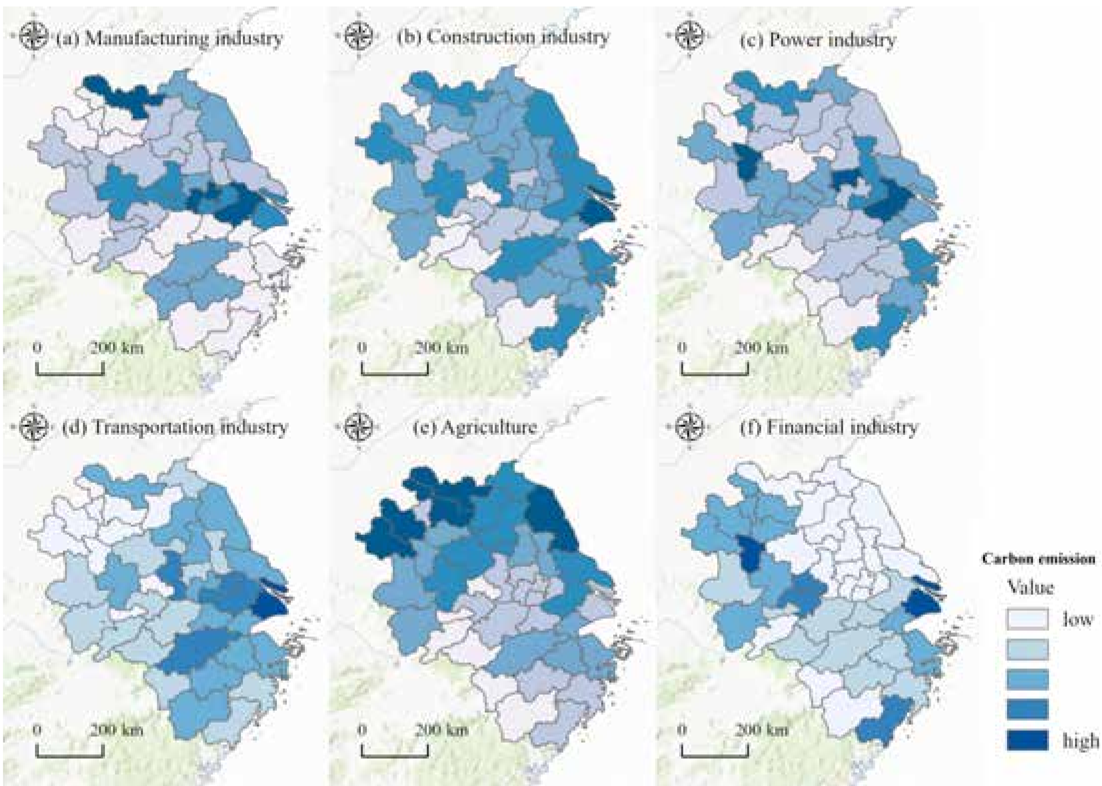

Figure 5 The spatial distribution of carbon emissions in various industries in cities of the Yangtze River Delta region

5. Research on the Coupling and Coordination Mechanism of Capital Flows and Carbon Emission System

5.1 Analysis of the Coupling and Coordination between Capital Flows and Carbon Emissions

Combining the centrality of the capital flow network and the total carbon emissions, an analysis of the current situation of the capital flow and carbon emission system in the cities of the Yangtze River Delta region is conducted (Figure 6). In the manufacturing sector, most cities are in the "low carbon emission - low capital flow" state, while only Suzhou is in the "high carbon emission - high capital flow" state. In addition, Xuzhou and Ma'anshan are in the "high carbon emission - low capital flow" state, while Shanghai and Hangzhou are in the "low carbon emission - high capital flow" state. In the construction industry, all cities are in the "low carbon emission" state, while cities such as Nanjing, Zhenjiang, Yancheng, Shanghai, Hefei, and Suzhou are in the "low carbon emission - high capital flow" state. In the power industry, all cities are in the "low capital flow" state, while cities such as Suzhou, Zhenjiang, and Xuzhou are in the "high carbon emission - low capital flow" state, and Ningbo is relatively balanced. In the transportation industry, most cities are in the "low carbon emission - low capital flow" state, while only Shanghai is in the "low carbon emission - high capital flow" state. In agriculture, all cities are in the "low carbon emission - low capital flow" state. In the financial industry, most cities are in the "low carbon emission - low capital flow" state, while cities such as Hangzhou, Suzhou, and Shanghai are in the "low carbon emission - high capital flow" state.

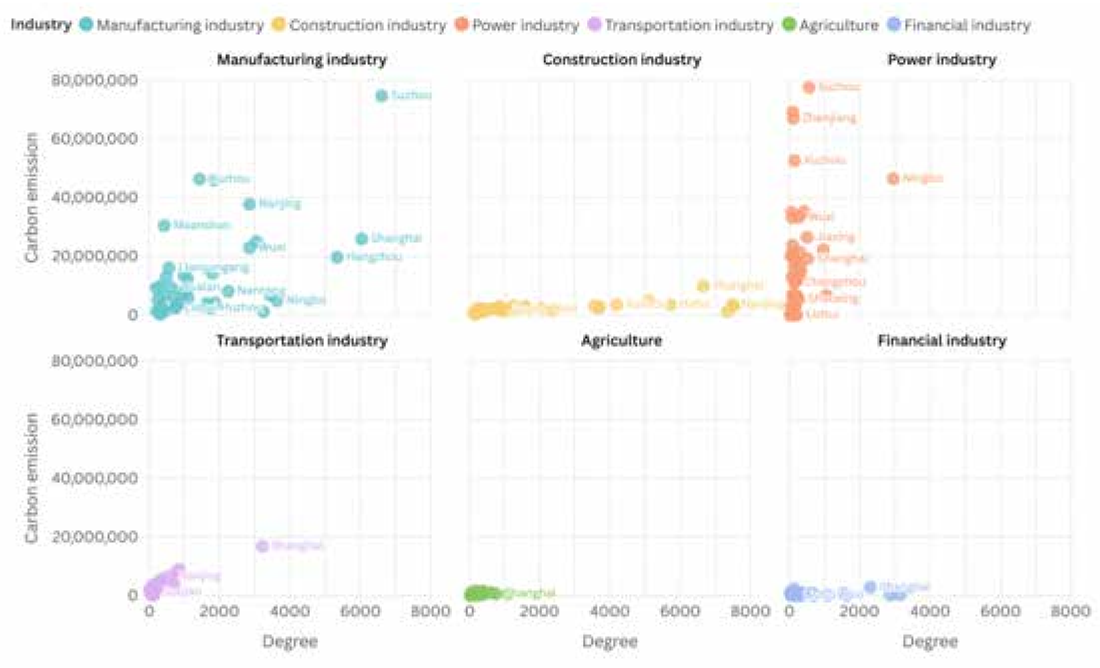

Figure 6 The current situation of multi-industry capital flows and carbon emissions in cities of the Yangtze River Delta region

According to the coupling coordination model, the coupling coordination degree of urban capital flow and carbon emissions in the Yangtze River Delta region in 2022 was calculated (Figure 7). From the perspective of manufacturing, the overall coupling coordination level of cities is relatively low, and most cities are in an uncoordinated state. Only Suzhou is in a high-quality coordination state, Shanghai is in a medium-level coordination state, Changzhou, Nanjing, Hefei, and Hangzhou are in a primary coordination state, Wuxi and Xuzhou are in a barely coordinated state, Tongling and Huaihua are in an extremely imbalanced state. The coupling coordination level of the construction industry is slightly higher than that of manufacturing. Shanghai is in a high-quality coordination state, Suzhou, Yancheng, Nanjing, and Hefei are in a medium-level coordination state, Nantong, Xuzhou, and Hangzhou are in a primary coordination state, Zhenjiang and Huai'an are in a barely coordinated state, and only Tongling is in an extremely imbalanced state. The coupling coordination level of the power industry is relatively low. Only Ningbo is in a good coordination state, Suzhou is in a primary coordination state, Hefei is in a barely coordinated state, and Lishui, Chizhou, and Bozhou are in an extremely imbalanced state. Most cities in the transportation industry belong to uncoordinated areas. Only Shanghai is in a high-quality coordination state, Suzhou is in a primary coordination state, Nanjing and Hangzhou are in a barely coordinated state, and only Huangshan is in an extremely imbalanced state. The regional coupling coordination level of the financial industry is relatively low. Only Shanghai is in a high-quality coordination state, Hefei is in a primary coordination state, Hangzhou is in a barely coordinated state, and Lishui, Suqian, and Suzhou are in an extremely imbalanced state. The overall coupling coordination level of agriculture is relatively high. Most cities are in a coordinated state. Among them, Hangzhou, Hefei, and Fuyang have the highest coupling coordination levels, and they are in a primary coordination state, while only Tongling and Huaihua are in an extremely imbalanced state.

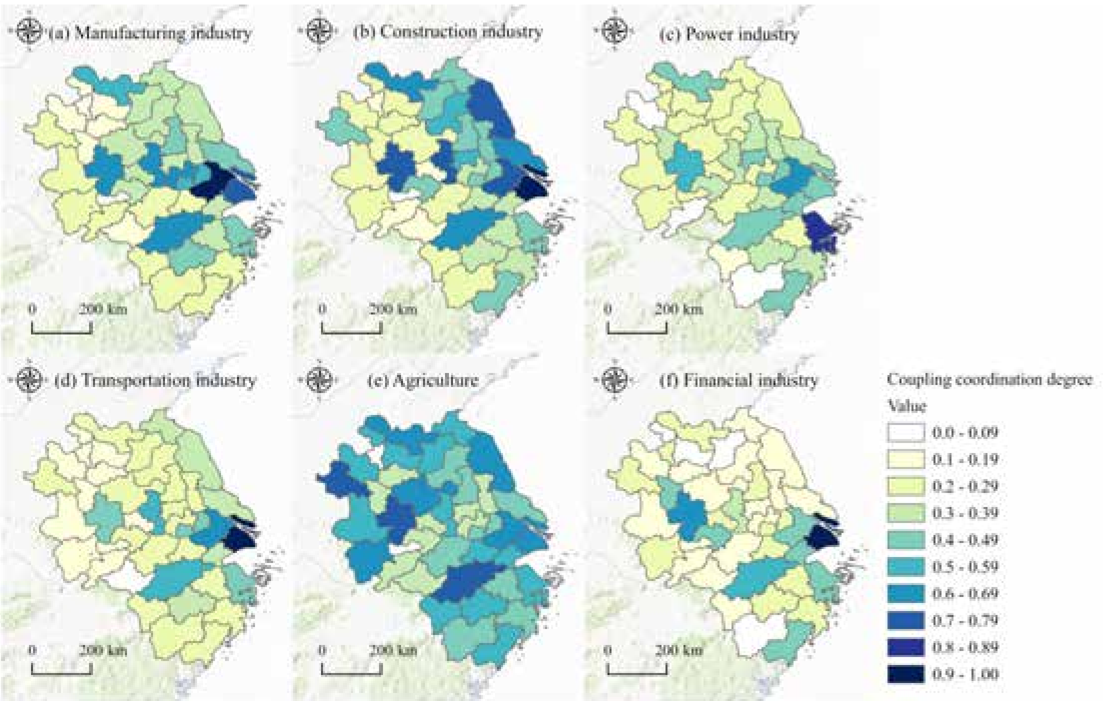

Figure 7 The spatial distribution of the coupling coordination degree between urban capital flows and carbon emissions in the Yangtze River Delta region

5.2 Research on the Coupling Coordination Mechanism of Capital Flow and Carbon Emission System in the Yangtze River Delta Region

Based on multiple perspectives such as social economy, industrial structure, and resource environment, the model was improved through stepwise regression, and the following variables were selected: GDP, urbanization rate of permanent residents, passenger volume, annual average concentration of fine particulate matter (PM2.5), total retail sales of consumer goods, local general budgetary revenue, and local general budgetary expenditure. These indicators were selected as the influencing factors of the coupling and coordination of capital flow and carbon emission system. A multiple linear regression model was used to conduct decomposition analysis of the coupling mechanism for each industry.

From the regression results of the manufacturing industry (Table 2), it can be seen that GDP, local general budgetary revenue and expenditure have a significant impact on the coupling system of manufacturing. Among them, GDP has the greatest impact on the coupling system of manufacturing, and local general budgetary revenue has a relatively significant positive promoting effect on the coupling coordination, while local general budgetary expenditure has an inhibitory effect. For every 1% increase in GDP, the coordination degree of manufacturing increases by 0.114 units, which is lower than that of the construction industry (Table 3), but higher than that of the transportation industry (Table 5), indicating that manufacturing has a moderate dependence on economic scale, but the speed of low-carbon transformation is constrained by the technology lock-in effect, such as the high cost of traditional equipment renewal. The "scissors difference" effect of fiscal revenue lies in that after fiscal revenue increases, it increases subsidies for low-carbon technologies, such as tax incentives for clean production equipment, and due to the preference of fiscal expenditure for infrastructure and projects, it occupies the green investment of manufacturing∆such as insufficient funds for the circular transformation of industrial parks. The reverse effect of fiscal revenue and expenditure on coordination degree reflects the target conflict between local governments in "increasing revenue and reducing expenditure" and "low-carbon investment". Different from the construction industryΔthe failure of PM2.5 and urbanization lies in that manufacturing may be concentrated in high-pollution industriesΔand there is a "compliance is equivalent to compliance" phenomenon in environmental regulationsΔlacking further emission reduction motivation. The coefficient of urbanization is positive but not significantΔwhich may be due to the fact that urbanization drives manufacturing demand but regional industrial homogeneity weakens the efficiency of the capital flow network. The coupling coordination degree of manufacturing is "bidirectionally pulled" by GDP and fiscal revenue and expenditure and it is necessary to solve the predicament of "relying on high-carbon industries for fiscal revenue increase and suppressing low-carbon investment with fiscal expenditure". It is recommended to construct a "fiscal-industry" collaborative policy and embed low-carbon transformation into the hard constraints of local fiscal budgets.

Table 2 Regression results of the impact factors in the manufacturing industry

Y_1	Coefficient	Std.err.	t	P>|t|	[95% conf.interval]	
$\ln X_1$	0.114045	0.037131	3.0700	0.0040	0.038585	0.189505
$\ln X_2$	0.061461	0.037682	1.6300	0.1120	-0.015118	0.138039
$\ln X_3$	0.095169	0.062288	1.5300	0.1360	-0.031414	0.221753
X_4	0.003003	0.002516	1.1900	0.2410	-0.002111	0.008116
X_5	0.000028	0.000023	1.2300	0.2270	-0.000018	0.000075
X_6	0.000151	0.000074	2.0500	0.0480	0.000001	0.000301
X_7	-0.000171	0.000053	-3.2300	0.0030	-0.000279	-0.000063
cons	-2.750605	0.579467	-4.7500	0.0000	-3.928223	-1.572987

In the coupled system of the construction industry (Table 3), GDP, annual average concentration of fine particulate matter (PM2.5), and total retail sales of consumer goods play significant roles. Among them, GDP and the annual average concentration of fine particulate matter (PM2.5) have a relatively large positive promoting effect on it, while the relative influence of total retail sales of consumer goods is smaller, but it can also promote the improvement of the coupled system of the construction industry. The construction industry is highly sensitive to the economic cycle, and economic growth directly drives the efficiency of capital flow and the low-carbon transformation. The coordination degree of the construction industry has the highest elasticity with GDP, possibly due to the large proportion of real estate investment in GDP and the linkage of green building policies and economic stimulus plans. The positive effect of PM2.5 may be because of the policy-driven mechanism. Stringent environmental regulations in high-pollution areas promote the low-carbon transformation of the construction industry, such as mandatory use of environmentally friendly building materials. The positive impact of social retail sales of consumer goods may be due to the increase in demand for commercial real estate, which promotes the optimization of the capital flow network. However, the insufficient application of low-carbon technologies leads to limited improvement in coordination degree. Therefore, priority should be given to strengthening the synergy between economic growth and low-carbon buildings, such as including the coordination degree of the construction industry in local GDP assessment and giving priority to supporting green infrastructure projects. Utilize the policy linkage mechanism for PM2.5 governance to implement building carbon quota trading in high-pollution areas. The second is driven by the consumption end. By providing consumption subsidies to guide the demand for low-carbon buildings, such as green housing purchase discounts, the positive effect of social retail sales of consumer goods can be amplified. The coupling coordination degree of the construction industry is highly dependent on economic growth, and environmental regulations (PM2.5) may indirectly promote the low-carbon transformation through the policy-driven mechanism. A "economic-environment-building" tripartite governance system needs to be constructed to strengthen the driving effect of the consumption end on green buildings.

Table 3 Regression results of the impact factors in the construction industry

Y_2	Coefficient	Std.err.	t	P>|t|	[95% conf.interval]	
lnX_1	0.191559	0.044641	4.2900	0.0000	0.100838	0.282279
lnX_2	-0.031771	0.045302	-0.7000	0.4880	-0.123837	0.060294
lnX_3	0.135850	0.074884	1.8100	0.0780	-0.016334	0.288033
X_4	-0.003030	0.003025	-1.0000	0.3240	-0.009178	0.003117
X_5	0.000048	0.000028	1.7300	0.0920	-0.000008	0.000104
X_6	-0.000039	0.000089	-0.4300	0.6670	-0.000219	0.000142
X_7	-0.000020	0.000064	-0.3100	0.7550	-0.000150	0.000110
cons	-3.041972	0.696655	-4.3700	0.0000	-4.457745	-1.626198

In the power industry (Table 4), GDP and passenger volume have a significant impact on the coupling system of the power industry. Among them, the impact of GDP is greater and it plays a positive promoting role. However, passenger volume has a marginal significant negative effect on the coupling system of the power industry. For every 1% increase in GDP, the power coordination degree increases by 0.171 units, which is significantly higher than that of agriculture (Table 5) and transportation (Table 4). This indicates that the power system is highly bound to the macroeconomy, and economic growth directly drives power investment and supply-demand matching. As a fundamental energy industry, the coordination degree of the power industry is more sensitive to economic fluctuations. Therefore, it is necessary to be vigilant of the resilience risks of the power system during economic downturns. The potential negative impact of passenger volume may lie in the fact that transportation energy consumption competes for power resources. As passenger volume increases, fuel consumption also increases, indirectly reducing investment in clean power, such as charging piles and rail transit electrification lagging behind. At the same time, there may also be investment competition, where local governments may prioritize transportation infrastructure, weakening the funds for upgrading the power system.

The coupling coordination degree of power is highly dependent on economic growth, but it is necessary to prevent the potential inhibitory effect of the expansion of passenger volume. It is recommended to build a "economic-transportation-power" collaborative policy framework, with a focus on enhancing the initiative of local finance in the power system.

Table 4 Regression results of the impact factors in the power industry

Y_3	Coefficient	Std.err.	t	P>|t|	[95% conf.interval]	
lnX_1	0.171417	0.048909	3.5000	0.0010	0.072022	0.270813
lnX_2	-0.092732	0.049634	-1.8700	0.0700	-0.193601	0.008137
lnX_3	0.075229	0.082045	0.9200	0.3660	-0.091506	0.241964
X_4	-0.000920	0.003314	-0.2800	0.7830	-0.007655	0.005815
X_5	0.000032	0.000030	1.0600	0.2980	-0.000030	0.000094
X_6	0.000022	0.000097	0.2200	0.8240	-0.000176	0.000219
X_7	-0.000075	0.000070	-1.0800	0.2880	-0.000217	0.000066
cons	-2.091331	0.763269	-2.7400	0.0100	-3.642481	-0.540181

In the transportation industry (Table 5), the GDP, local fiscal general budgetary revenue and expenditure have a significant impact on the coupling system of the transportation sector. The GDP and local fiscal general budgetary revenue have a positive promoting effect, while local fiscal general budgetary expenditure will inhibit the optimization and improvement of the transportation coupling system. The positive effect of local fiscal revenue may be manifested in the enhanced government financial strength, which can support transportation infrastructure, such as high-speed railways and ports, directly improving the system's coordination. The negative effect of local fiscal expenditure may be due to the expansion of expenditure possibly occupying transportation special funds or reflecting low expenditure efficiency, such as repeated construction and insufficient maintenance. Therefore, considering the priority development of economy and fiscal reform, maintaining GDP growth, and focusing on investing in transportation weak areas, such as rural road networks and multimodal transportation, is necessary. Secondly, optimize the fiscal expenditure structure and establish a transportation special fund to avoid "spreading resources thinly". The coupling coordination degree of transportation is mainly driven positively by economic growth and fiscal capacity, but an unreasonable fiscal expenditure structure will weaken the system's efficiency. It is necessary to promote the coordinated development of "economy - finance - transportation", and focus on optimizing the efficiency of infrastructure investment.

Table 5 Regression results of the impact factors in the transportation industry

Y_4	Coefficient	Std.err.	t	P>|t|	[95% conf.interval]	
$\ln X_1$	0.109253	0.023508	4.6500	0.0000	0.061479	0.157027
$\ln X_2$	-0.012559	0.023856	-0.5300	0.6020	-0.061041	0.035923
$\ln X_3$	0.018781	0.039434	0.4800	0.6370	-0.061359	0.098921
X_4	-0.001719	0.001593	-1.0800	0.2880	-0.004956	0.001518
X_5	0.000013	0.000015	0.8600	0.3940	-0.000017	0.000042
X_6	0.000147	0.000047	3.1500	0.0030	0.000052	0.000242
X_7	-0.000079	0.000034	-2.3700	0.0240	-0.000148	-0.000011
cons	-1.527307	0.366861	-4.1600	0.0000	-2.272859	-0.781756

The most significant influencing factors in agriculture are numerous (Table 6). Factors such as GDP, the urbanization rate of permanent residents, local fiscal revenue and expenditure within the general budget, etc., all have a significant impact on the agricultural coupling system. An increase in GDP and local fiscal revenue within the general budget can effectively promote the improvement of the agricultural coupling system, while an increase in the urbanization rate of permanent residents and local fiscal expenditure within the general budget will reduce and inhibit the improvement of the agricultural coupling system. Among them, the impact of GDP is the greatest, reflecting the significant promoting effect of overall economic development on agricultural modernization, such as technological investment and industrial chain integration. The positive effect of local fiscal revenue can be manifested as enhanced local financial strength possibly supporting agricultural subsidies and infrastructure investment. The negative effect of local fiscal expenditure can be reflected as the expansion of expenditure possibly occupying agricultural resources, such as the flow of funds to non-agricultural fields or the reflection of an unreasonable expenditure structure. The urbanization rate of permanent residents has a significant inhibitory effect on the agricultural coupling degree, possibly manifested as labor loss, the transfer of rural population to urban areas leading to a shortage of agricultural labor force, and weakening of production intensification. The reduction of arable land and the expansion of urbanization occupying farmland directly reduce the scale of the agricultural system. Policy bias, with resources favoring urban areas, relatively insufficient agricultural investment, requires through labor substitution technologies and policies for protecting arable land to counteract its negative impact.

The agricultural coupling degree is significantly influenced by economic growth, environmental quality and fiscal policies. Considerable efforts can be made to enhance the efficiency of the agricultural system through "economic-environment-fiscal" collaborative governance. Meanwhile, GDP growth and increase in fiscal revenue remain the key driving forces for improving the efficiency of the agricultural system.

Table 6 Regression results of the impact factors in the agriculture

Y_5	Coefficient	Std.err.	t	P>|t|	[95% conf.interval]	
lnX_1	0.143406	0.049120	2.9200	0.0060	0.043583	0.243229
lnX_2	0.070262	0.049848	1.4100	0.1680	-0.031042	0.171565
lnX_3	0.072342	0.082398	0.8800	0.3860	-0.095111	0.239795
X_4	-0.010179	0.003329	-3.0600	0.0040	-0.016944	-0.003415
X_5	-0.000001	0.000030	-0.0400	0.9670	-0.000063	0.000061
X_6	0.000254	0.000098	2.6000	0.0140	0.000055	0.000452
X_7	-0.000208	0.000070	-2.9700	0.0050	-0.000351	-0.000066
cons	-2.190231	0.766556	-2.8600	0.0070	-3.748060	-0.632401

In the financial industry coupling system (Table 7), only the local government's general budgetary revenue within the scope of the general budget has a significant impact on it, but the impact is relatively small. For every 1 unit increase in local government's general budgetary revenue, the financial coupling degree may increase by approximately 0.000157 units. An increase in local government's general budgetary revenue can actively promote the optimization of the financial industry coupling system's fiscal and tax policies or help improve the financial coupling degree. The positive impact of local government revenue may be weaker than that of the manufacturing sector due to the increase in fiscal revenue leading to more investment in green finance, such as establishing green industry funds. However, the effect is much weaker. Therefore, it is necessary to leverage specialized financial policy tools, such as including the carbon intensity of financial institutions in the MPA assessment, directly constraining the carbon-oriented capital flow. It is also recommended that a proportion of the increased local government revenue be invested in a green finance risk compensation fund to amplify the weak positive effect of local government revenue.

The financial industry coupling coordination degree is insensitive to macroeconomic variables. It is necessary to break away from the traditional analytical framework and focus on the optimization of financial policy tools and capital network structure, such as carbon financial product innovation. It is suggested to establish a "fiscal-finance" linkage mechanism, incorporate green finance indicators into local government performance assessment, and prioritize the pilot program of carbon flow accounting in the financial industry.

Table 7 Regression results of the impact factors of the financial industry

Y_6	Coefficient	Std.err.	t	P>|t|	[95% conf.interval]	
lnX_1	-0.003506	0.046558	-0.0800	0.9400	-0.098123	0.091112
lnX_2	0.002173	0.047248	0.0500	0.9640	-0.093847	0.098194
lnX_3	0.055253	0.078101	0.7100	0.4840	-0.103468	0.213973
X_4	0.002104	0.003155	0.6700	0.5090	-0.004307	0.008516
X_5	0.000026	0.000029	0.9100	0.3670	-0.000032	0.000085
X_6	0.000157	0.000093	1.7000	0.0990	-0.000031	0.000345
X_7	-0.000098	0.000067	-1.4700	0.1500	-0.000233	0.000037
cons	-0.113044	0.726579	-0.1600	0.8770	-1.589631	1.363543

6. Conclusions and Recommendations

6.1 Conclusions

In terms of regional characteristics, the capital flow networks in multiple industries within the Yangtze River Delta region exhibit differentiated patterns. The manufacturing industry is centered around "Shanghai - Suzhou - Hangzhou", while the construction industry shows a multi-center and dispersed pattern. The power industry, transportation industry, and financial industry have formed network structures of "one main and multiple backups" and "multiple main and multiple backups" respectively, and the agriculture industry has formed a central structure of "combined three cores of Shanghai, Suzhou, and Hangzhou". The analysis of the centrality of the capital flow network shows that cities such as Shanghai, Suzhou, and Hangzhou occupy important positions in multiple industries, and there are significant differences in the range of centrality values for different industries. In terms of spatial distribution of carbon emissions, the total carbon emissions of Suzhou and Xuzhou are prominent, and the carbon emissions of the manufacturing and power industries are significantly higher than those of other industries. The high-value areas of carbon emissions in each industry show obvious urban clustering characteristics, such as the manufacturing industry being concentrated in the "Shanghai - Suzhou - Wuxi - Changzhou - Nanjing - Ma'anshan - Hefei" axis, while the power industry is concentrated in cities such as Suzhou, Zhenjiang, and Huainan.

At the coupling and coordination mechanism level, the coupling and coordination levels of capital flow and carbon emission systems in various industries within the Yangtze River Delta region vary. The overall coupling and coordination levels of manufacturing, power, and finance are relatively low, with most cities being in an uncoordinated state; the coupling and coordination levels of construction and agriculture are relatively higher. The regression analysis results show that the influencing factors of coupling and coordination degrees among different industries have significant differences. GDP has a significant impact on the coupling and coordination of manufacturing, construction, power, transportation, and agriculture, reflecting the important role of economic growth in the development of various industries; local general budgetary revenue and expenditure show different degrees of promotion or inhibition effects in multiple industries; factors such as environmental regulations (such as fine particulate matter concentration), industrial scale (such as social retail sales of consumer goods), and population urbanization also have an impact on the coupling and coordination of specific industries.

6.2 Recommendations

Strengthen regional collaborative governance, optimize the pattern of capital flow and carbon emissions, break administrative barriers, and establish a collaborative governance mechanism for capital flow and carbon emissions in the Yangtze River Delta region. Based on the status of each city in the capital flow network and its carbon emission characteristics, formulate differentiated development strategies. For example, for cities with high capital flow centrality and large carbon emissions (such as Suzhou), guide them to reduce carbon emission intensity through technological innovation and industrial upgrading; for peripheral cities in capital flow, strengthen infrastructure construction and attract low-carbon industry capital inflow to narrow the environmental and development gap between regions and practice the principle of environmental justice.

Build an industry-specific policy implementation system to promote low-carbon transformation, and implement precise policy intervention based on the coupling coordination influencing factors of different industries. Manufacturing needs to break the deadlock of "relying on high-carbon industries for fiscal revenue growth and suppressing low-carbon investment through expenditures", build a "fiscal-industry" collaborative policy, incorporate the low-carbon transformation goal into the hard constraints of local fiscal budgets, and increase fiscal support for green manufacturing technology research and development; the construction industry should build a "economic-environment-building" tripartite governance system, strengthen the backward pressure mechanism of environmental regulations on low-carbon transformation, and at the same time, through consumption-side policies, enhance the demand for green buildings; the power industry needs to build a "economic-transportation-power" collaborative policy framework, optimize the energy structure, and reduce the potential inhibitory effect of passenger scale expansion on the low-carbon development of the power industry; the transportation industry should promote "economic-fiscal-transportation" coordinated development, optimize the fiscal expenditure structure, and improve the low-carbon efficiency of infrastructure investment; the agricultural sector needs to strengthen "economic-environment-fiscal" collaborative governance, through fiscal subsidies and other policies, encourage the application of low-carbon agricultural technologies; the financial industry should build a "fiscal-financial" linkage mechanism, innovate carbon financial products, incorporate green financial indicators into local fiscal performance evaluations, carry out pilot carbon flow accounting in the financial industry, and leverage finance to support the low-carbon economy.

Improve the supervision and assessment mechanism of environmental justice, establish an environmental justice assessment system covering indicators such as environmental rights distribution and regional development fairness, and regularly assess the coordinated development of capital flow and carbon emissions in the Yangtze River Delta region. Strengthen the supervision of environmental risks during capital flow, prevent developed regions from unjustly transferring environmental burdens to less developed regions through capital transfer.

Encourage public participation in environmental governance, ensure the right to information, participation and supervision of residents in each region in environmental decision-making, and ensure that the principle of environmental justice is effectively implemented in the coordinated development of capital flow and carbon emissions.

References

Ahmad, N., & Wyckoff, A (2009). Carbon dioxide emissions embodied in international trade of goods. *OECD Science, Technology and Industry Working Papers*, (1), pp.1-25.

Bullard, R. (2000). Dumping in Dixie: Race, class, and environmental quality. *Westview Press*.

Feldstein, M., Horioka, C. (1980). Domestic saving and international capital flows. *The Economic Journal*, 90 (358), pp.314-329.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics*, 110 (2), pp.353-377.

Jiang WJ., Shan YK (2025). Border Effects on Capital Flows: Evidence from Business Registration Information of 200 Million Enterprises. *Finance & Trade Economics*, 46(3).

Niu G, Yang Y (2024). Research on the carbon reduction effect of regional industrial transfer in China - based on the perspective of factor flow. *Heliyon*,10(14), e33771.

Pan Y., Liang WJ., Ning B., Ye JY (2025). Crossing the Shanhai Pass: Pairing Cooperation, Capital Flow and Coordinated Regional Development. *Journal of Quantitative & Technological Economics*, 42(5).

Panayotou, T. (2003). Economic growth and the environment. *Edward Elgar Publishing*.

Schlosberg, D. (2007). Defining environmental justice: Theories, movements, and nature. *Oxford University Press*.

Sho Hata, Keisuke Nansai, Kenichi Nakajima (2023). Supply Chain Factors Contributing to Improved Material Flow Indicators but Increased Carbon Footprint. *Environmental Science & Technology*, 34(57), pp.12713-12721.

Yan JJ., Guo YQ., Wen FH (2025). Carbon risk and the cost of equity capital: Evidence from China. *International Review of Economics & Finance*, 99, pp.103975.

Zhang J (2002). Capital Formation,Industrialization and Economic Growth:Understanding China's Economic Reform. *Economic Research Journal*, 37 (6), pp.3-13.

Zhao CM., Zhong XH., Ban YH (2025).The Risk of Global Supply Chain and Domestic Capital Flows: Novel Insights into Corporate Cross-Regional Investment. *China Industrial Economics*, (3).

Zhao M., Sun T., Feng Qiang (2021). Capital allocation efficiency, technological innovation and vehicle carbon emissions: Evidence from a panel threshold model of Chinese new energy vehicles enterprises. *Science of The Total Environment*, 784, pp.147104.