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Carbon Balance Zoning and Spatially Synergistic Carbon Reduction Pathways—A Case Study in the Yangtze River Delta in China

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Abstract: The concept of major function-oriented zones is highly compatible with the idea of spatially synergistic carbon reduction. In this study, 2005–2020 is taken as the research period, and 305 counties in the Yangtze River Delta (YRD) region are taken as the research unit. The S0M-K-means clustering model and GeoDetector are adopted on the basis of carbon emission/absorption accounting to analyse the spatial and temporal variations in the carbon balance in the YRD region. Furthermore, carbon balance zoning and influencing factors are analysed. Then, a regional spatially synergistic carbon reduction pathway is proposed. The results show that carbon absorption in the YRD region struggles to offset carbon emissions; the regional carbon imbalance is gradually becoming worse; and each county's carbon emission/absorption shows a significant spatial imbalance. Optimised development zones and key development zones are high-value agglomerations of carbon emissions, while the main sources of carbon sinks in the YRD region are the key ecological functional zones. The YRD region has 87 high carbon control zones, 167 carbon emission optimisation zones, and 51 carbon sink functional zones, which are further subdivided into 9 types of carbon balance zones in accordance with the major function-oriented zones (MFOZs). Based on the driving factors of carbon balance changes in the YRD region, this study proposes differentiated spatially synergistic carbon reduction paths for each zone in accordance with the carbon balance zones. As the Yangtze River Delta is an essential engine for China's economic development, the study of its carbon balance is highly relevant in formulating differentiated low-carbon development pathways for each functional zone and promoting regional spatially synergistic carbon reduction to realise the target of "dual-carbon" development.

Keywords: major function-oriented zoning; Yangtze River Delta; carbon budget; carbon balance zoning; spatially synergistic carbon reduction pathways

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1. Introduction

As the most important factor causing global climate change, anthropogenic greenhouse gas emissions have caused ecological and environmental problems that have severely constrained the sustainable development of human civilization [1]; furthermore, contradictions between economic growth and ecological conservation have become more and more prominent. Controlling and reducing carbon emissions has become important for countries worldwide [2]. Since the beginning of this century, driven by industrialisation and urbanisation, China's economy has made great progress, but increased fossil energy consumption and the destruction of surface vegetation often go hand in hand with rapid economic growth, leading to a rapid increase in the regional carbon emissions, a corresponding shift in the spatial pattern of carbon sources and sinks, and a growing imbalance between regional carbon revenues and expenditures [3,4]. As the world's economic and demographic power, China's CO_2 emissions account for nearly 30% of global CO_2 emissions [5]. Against this background, the Chinese government has proposed the goal of "carbon peak and carbon neutrality" by 2030. This measure is not only important for implementing an ecological civilisation and promoting the green transformation of economic and social development, it is also important for committing to addressing and responding to global climate change. The imbalance between carbon emissions and carbon absorption is a major obstacle to achieving regional carbon reduction and carbon neutrality [6,7]. China's "dual-carbon" goal involves both achieving effective control of the overall amount of carbon emissions and realising synergies and equity in carbon emission reduction between regions [8,9].

With the intensification of global warming, studies related to carbon emissions have become increasingly abundant, and numerous studies have been conducted from different perspectives on carbon emission/absorption accounting [10,11], carbon balance/compensation zoning [8,12], and carbon efficiency [13]. These studies reveal the features of the spatial and temporal evolution of carbon emission/absorption at different scales and regions, as well as their driving factors [14,15]. Carbon emission/absorption accounting provides the basis for these relevant studies. The emission factor method based on the carbon emission factors provided in the Guidelines for National Greenhouse Gas Inventories compiled by the Intergovernmental Panel on Climate Change (IPCC) is considered the basic reference for carbon emission accounting [16]; methods of accounting for carbon emissions based on remotely sensed interpreted data, such as land use data and night-time lighting data, have also been widely applied [17,18]. In terms of accounting for carbon absorption, most of the studies that have been conducted have used inventory, modelling, or atmospheric inversion methods to assess and account for ecosystem carbon absorption [19,20]. In addition, some scholars and research institutes have constructed and released carbon emission and absorption datasets [21,22], which provide data support for macroscale studies. Chinese scholars have carried out a wealth of studies on the characteristics of the temporal and spatial evolution of carbon revenues and expenditures on the basis of carbon accounting at different geographical scales, such as the provincial, prefectural, and watershed scales; the results of this research show that China's carbon emissions have significant spatial differentiation and agglomeration effects and that the imbalance between carbon sources and sinks in the national territory is considerable [23,24]. The differences among regional carbon budgets stem mainly from complex interactions among economic, social, policy, technological, and ecological systems [25]. Some scholars have explored the roles of different socioeconomic factors in driving changes in regional carbon emissions via the logarithmic mean divisia index model (LMDI) [26], the stochastic impacts by regression on population, affluence, and technology model (STIRPAT) [27], and the extended Kaya's constant [28]. Furthermore, the population size, economic model, energy consumption structure, and emission reduction measures are the main factors driving regional carbon budget changes [29].

To alleviate the imbalance between carbon sources and sinks in China, much research has been conducted on carbon compensation; a consensus exists on the importance of interregional carbon compensation systems in promoting regional low-carbon development and achieving carbon neutrality [30,31]. Furthermore, the division of carbon balance zones or carbon offset zones based on the scales of regional carbon budgets and spatial differences is the key to establishing these systems and promoting spatially synergistic carbon reduction [32,33].

Major function-oriented zoning (MFOZ) is a comprehensive geographic zoning method with applicability, innovation, and foresight that was introduced by the Chinese government in 2010 [9,33]. Based on the differences in regional resource and environment carrying capacity, existing development intensity, and future development potential, the plan groups state territories into four categories: optimised development zones (ODZs), key development zones (KDZs), restricted development zones (RDZs), and prohibited development zones (PDZs). Among them, RDZs are subdivided into agricultural production zones (APZs) and key ecological functional zones (EFZs). Defining the main function of each geographical unit and determining the development or protection methods for it according to local conditions are highly important for building a spatial development pattern of the national territory that is in harmony with the socioeconomic and ecological environment [31,34]. Research on carbon balance involves characterising the balance between sources and sinks of carbon in a specific region within a certain period [35,36]. Regional differences in natural ecosystems and socioeconomic activities result in different patterns of territorial space development, which directly or indirectly cause changes in regional carbon emission/absorption [37–39]. Objectively, differences in carbon revenues and expenditures among regions occur and are manifested mainly in the strengths or weaknesses of regional carbon sources/sinks and the imbalance of the spatial distribution of carbon emissions/absorption at different geographic scales; therefore, exploring spatially synergistic carbon reduction pathways can promote the dual-carbon goal [34,40]. Moreover, major function-oriented zoning is highly compatible with spatially synergistic carbon reduction. Specifically, the differentiated spatial planning policies of different functional zones can guide and control human activities, thus affecting regional carbon emissions and carbon absorption [41,42]. Therefore, an analysis of regional carbon balances from a MFOZ perspective is highly significant for realising regional carbon equity and synergistic carbon reduction [8].

Generally, research on carbon balance has received extensive attention from academics and achieved rich research results, but some deficiencies still exist. First, most city- or county-level research focuses only on carbon emissions, though some do estimate regional carbon absorption via the coefficient estimation method; however, due to differences in the climate and environment of each region, estimation data based on the same coefficient have large errors, which affects the accuracy of carbon balance research. Second, the resource endowment and development paths of county units are somewhat different; the county is the fundamental unit of China's MFOZs, and the existing studies are still relatively limited and urgently need to be enriched. In addition, most research on the influencing factors related to carbon balance has utilized the STIRPAT, the LMDI, and other models to portray the extent of each factor's influence; research on the analysis of influencing factors combined with spatial heterogeneity needs to be strengthened.

The Yangtze River Delta (YRD) region is the most economically active and integrated region in China and has the closest regional cooperation. The levels of economic development, industrialisation, urbanisation, and population concentration in the region are all at high levels, and imbalances in the spatial distribution of carbon sources and sinks within the region are increasing; therefore, how to contribute to low-carbon development through spatial synergies is an important topic that needs to be addressed urgently in the region. We take 305 county units in the YRD region of China as the study area and 2005–2020 as the study period. On the basis of carbon emission/absorption accounting, we explore the spatial and temporal evolution characteristics of the carbon balance in the YRD region; propose a carbon balance zoning scheme based on the perspective of MFOZs; quantitatively analyse the factors influencing the changes in the carbon balance; and propose a path of spatially synergistic carbon reduction on this basis. The findings provide practical ideas and policy inspiration for the green and low-carbon transition and the realisation of the dual-carbon target in the YRD region.

2. Study Area and Methodologies

2.1. Study Area

The YRD region is located in the region where the Yangtze River and seas meet, is an impact plain formed by the sedimentary action of rivers, and has a flat topography and a dense river network, making it among the most economically vibrant regions in China. The geographical area includes the Shanghai, Jiangsu, Zhejiang, and Anhui provinces, totalling 305 county study units (see Figure 1). With a long history of development, a densely populated area, and a relatively high level of development, the urbanisation rate of the YRD region increased from 50.92% to 70.85%, and the gross domestic product (GDP) increased by a factor of 5.31, from 2005 to 2020. As of 2020, the region accounts for 16.67% of China's population and 24.12% of its GDP output, but less than 4% of China's territory. Regional resources are abundant and environmental pressures are high, and the contradictions of ecological conservation and economic growth are very prominent. The 305 counties in the YRD region vary substantially in their resource endowment and development level, and there is significant spatial heterogeneity in the scale of carbon emissions and carbon absorption. Therefore, analysing the differences in the carbon balance characteristics of the counties in the YRD region based on major function-oriented zoning and exploring spatially synergistic carbon reduction pathways can help in building a new territorial spatial pattern in line with the dual-carbon goal.

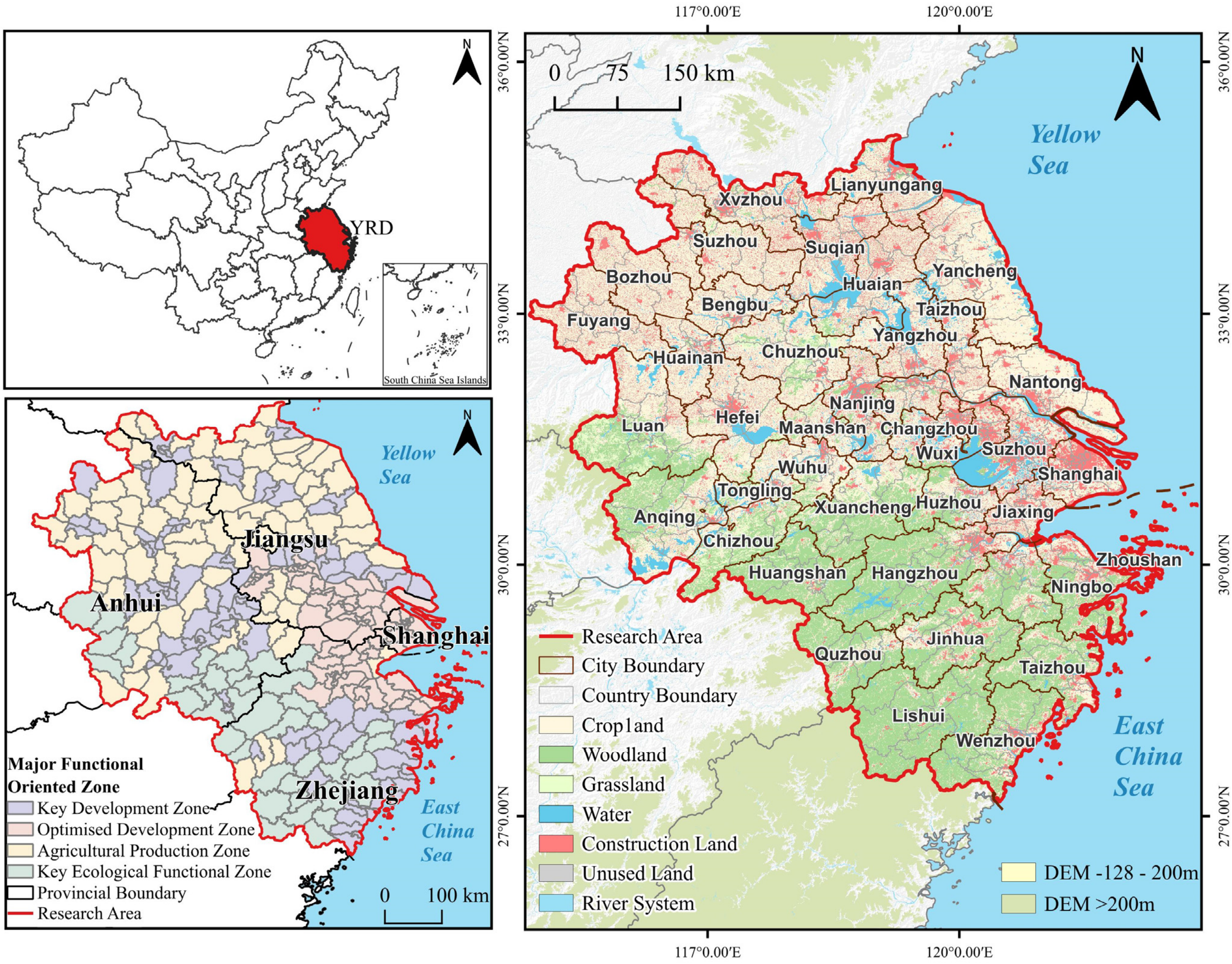


Figure 1. Location Map of YRD Region.

2.2. Data Sources

The administrative division data required for this paper were obtained from the National Platform for Common GeoSpatial Information Services (https://www.tianditu.gov.cn, accessed on 29 April 2024). The land use data were obtained from the Resource and Environment Science Data Platform [43]. The net primary productivity (NPP) of vegetation was obtained by extracting the MOD17A3GV6 product from the Google Earth Engine. The soil-related data were obtained from HWSD v2.0 [44]. Climate data such as precipitation and temperature data were obtained from the National Tibetan Plateau Scientific Data Centre [45,46]. The number of medium and large industrial enterprises were obtained from the website of Qichacha (https://www.qcc.com, accessed on 4 February 2024). The economic and social development data required for this paper were obtained mainly from county and city statistical yearbooks or statistical bulletins, with some missing data made up using linear interpolation. The energy consumption data were obtained from the China

Energy Statistical Yearbook. The MFOZs were obtained from the draft of provincial major function-oriented zoning for Shanghai, Jiangsu, Zhejiang, and Anhui.

2.3. Methods

2.3.1. Carbon Emission Accounting

As the current statistical unit of China's energy consumption data is province-based, it is difficult to directly account for carbon emissions in counties; furthermore, some scholars believe that the difference in energy use efficiency within a province is larger among cities and smaller among counties within a city [47]. Therefore, drawing on the methodology of existing studies, under the premise of ensuring that the total carbon emissions of the counties in the province are equal to the provincial carbon emissions and that the total subsectoral carbon emissions of the counties in the province are equal to the provincial subsectoral carbon emissions, we introduce city-level indicators to indirectly account for the carbon emissions of the counties; the calculation steps are as follows [47,48]:

With reference to the accounting method used by relevant scholars to decompose regional carbon emissions into four sectors [48,49], this paper groups the seven categories of economic sectors in the energy end-consumption section of the China Energy Statistical Yearbook into four categories (see Table 1). The accounting is carried out based on the statistical data of various types of energy consumption in different economic sectors of provincial-level administrative regions in the YRD region with the help of the reference methodology provided by the IPCC. The formula is as follows [16]:

$$rCE = \sum_{i}\sum_{j} EC_{i,j} \times K_i + \sum_{i} EC_{i,p} \times K_p \tag{1}$$

$$K_i = NCV_i \times CC_i \times 10^{-3} \times COF_i \tag{2}$$

where rCE denotes the provincial carbon emissions; i denotes the energy type; j denotes the three industries; p denotes the residential sector; $EC_{i,j}$ and $EC_{i,p}$ denote the consumption by the corresponding energy i for industrial sector j and the residential sector p, respectively; K_i and K_p denote the carbon emission factor for energy i and the residential sector p; NCV_i denotes the net caloric value of energy i; CC_i denotes the CO_2 emissions per net caloric value produced by energy i; and COF_i denotes the oxidation ratio during energy i combustion. In this study, we use the carbon oxidation rate of each type of energy published by the IPCC [16], and the net caloric value and the CO_2 emissions per net calorific value of each type of energy based on China's actual measurement [49] (see Table 2).

Table 1. Economic sectoral division.

Economic Sectors in the China Energy Statistics Yearbook	Economic Sectors Delineated in This Paper
Farming, forestry, animal husbandry and fishery	Primary industry
Industry and construction	Secondary industry
Transportation, logistics and postal	Tertiary industry
Wholesale and retail trade services	
Accommodation and catering services	
Consumption for living	Residential sector

Carbon emissions per unit of output value and per capita living carbon emissions are calculated for the three industries at the provincial level according to the provincial three-industry output value and population. Then, they are multiplied by the city three-industry output value and population to get the hypothetical carbon emissions of each city. The theoretical carbon emissions of each city are accounted for with the help of city-level data on energy consumption per unit GDP; the ratio of the two types of carbon emissions is utilised to correct the carbon emission intensity of each sector of the economy at the city scale. The formula is as follows [47]:

$$COCE = \frac{sTCE}{sHCE} = \frac{EI \times tGDP \times ACC}{\sum_j \frac{rCE_j}{rGDP_j} \times sGDP_j + \frac{rCE_p}{rGDP_p} \times sP} \tag{3}$$

$$ACC = \frac{\sum_j EC_j \times K_i}{\sum_k EI_k \times GDP_k} \tag{4}$$

where $COCE$ denotes the city carbon emission correction coefficient; $sTCE$ denotes the city theoretical carbon emission; $sHCE$ denotes the city hypothetical carbon emission; EI denotes the energy consumption per unit of GDP; $tGDP$ denotes the total regional GDP; ACC denotes the average carbon emission coefficient of each type of energy; rCE_j denotes the provincial carbon emissions from sector j; $rGDP_j$ is the GDP of industry j at the provincial level; $sGDP_j$ denotes the GDP of industry j at the city level; rCE_p denotes the per capita carbon emission at the provincial level; $rGDP_p$ denotes the provincial GDP per capita; sP denotes the city population size; EC_j denotes the energy consumption of industry j; k_i denotes cities in the province; EI_k is the energy consumption per unit of GDP in city k; and GDP_k is the GDP in city k.

Table 2. Energy types and emission factors.

Fuels in This Study	NCV (PJ/10^4 t, 10^8 m^3)	CC (tC/TJ)	COF	Carbon Emission Coefficient
Raw coal	0.21	26.32	0.94	1.91
Cleaned coal	0.26	26.32	0.93	2.33
Other washed coal	0.15	26.32	0.93	1.35
Briquettes	0.18	26.32	0.90	1.56
Coke	0.28	31.38	0.93	2.30
Coke oven gas	1.61	21.49	0.98	1.24
Other gas	0.83	21.49	0.98	0.64
Other coking products	0.28	27.45	0.98	2.76
Crude Oil	0.43	20.08	0.98	3.10
Gasoline	0.44	18.90	0.98	2.99
Kerosene	0.44	19.60	0.98	3.10
Diesel oil	0.43	20.20	0.98	3.12
Fuel oil	0.43	21.10	0.98	3.26
Other petroleum products	0.51	17.20	0.98	3.15
Liquefied petroleum gas	0.47	20.00	0.98	3.38
Refinery gas	0.43	20.20	0.98	3.12
Nature gas	3.89	15.32	0.99	2.16

Note: Briquettes in the table include briquettes and gangue from the China Energy Statistical Yearbook; other gasses in the table include blast furnace gas, converter gas, and other gas from the China Energy Statistical Yearbook; other petroleum products in the table include naphtha, lubricants, paraffin, white spirit; bitumen asphalt, petroleum coke and other petroleum products from the China Energy Statistical Yearbook.

Accounting for carbon emissions in counties is conducted with the help of the corrected carbon intensity for city-level economic sectors. The calculation formula is as follows [47]:

$$xCE = \sum_j COCE \times \frac{rCE_j}{rGDP_j} \times xGDP_j + COCE \times \frac{rCE_p}{rGDP_p} \times xP \tag{5}$$

where xCE denotes county carbon emissions, $xGDP_j$ denotes county j-industry GDP, and xP denotes the county population size.

2.3.2. Carbon Absorption Accounting

Net ecosystem productivity (NEP), a key indicator of carbon absorption, is used to characterise regional carbon absorption. The formula is as follows [50]:

$$CS = NPP - RH \tag{6}$$

$$RH = 0.6163RS^{0.7918} \tag{7}$$

$$RS = 1.55e^{0.031T} \times \frac{P}{P + 0.68} \times \frac{SOC}{SOC + 2.23} \tag{8}$$

$$SOC = SC \times \gamma \times H \times (1 - \delta_{2\mathrm{mm}}) \times 10^{-3} \tag{9}$$

where CS denotes the regional annual carbon absorption; NPP denotes the regional annual net primary productivity of vegetation; RH denotes the regional annual soil heterotrophic respiration; RS denotes the annual soil respiration; T denotes the annual mean temperature; P denotes the annual precipitation; SOC denotes the density of soil organic carbon within a depth of 20 cm; SC denotes the organic carbon content of the top soil layer from 0 to 20 cm; γ denotes the soil bulk weight; H denotes the thickness of the soil; and $\delta_{2\mathrm{mm}}$ represents the percentage of gravel in the soil smaller than 2 mm.

2.3.3. Carbon Balance Analysis and Zoning Methods

The economic contribution coefficient (ECC) of carbon emissions is the ratio of the economic contribution rate to the regional carbon emission rate; it reflects the size of the regional carbon production capacity from the economic perspective. The ecological support coefficient (ESC) of carbon emissions is the ratio of the regional carbon absorption rate to the regional carbon emission rate; it reflects the ecological carbon capacities of the area from the ecological perspective [8]. The formula for the calculations is as follows:

$$ECC = \frac{GDP_i}{GDP_s} \Big/ \frac{CE_i}{CE_s};\ ESC = \frac{CA_i}{CA_s} \Big/ \frac{CE_i}{CE_s} \tag{10}$$

where GDP_i and GDP_s denote the GDP of county i and the YRD region, respectively; CE_i and CE_s denote the carbon emissions of county i and the YRD region, respectively; and CA_i and CA_s denote the carbon absorption of county i and the YRD region, respectively. An $ECC > 1$ means that the county unit's economic contribution is higher than its carbon emission contribution, and the reverse is true for an $ECC < 1$; $ESC > 1$ indicates that a county unit has a strong offsetting capacity for regional carbon emissions, and the reverse is true for $ESC < 1$.

Referring to the literature, we adopt the SOM-K-means cluster analysis method to carry out zoning studies and select indicators from four dimensions—scale of total carbon emissions, socioeconomic development level, resource-environmental carrying capacity, and territorial exploitation degree—as the basis for zoning [8,51] (see Table 3). The calculation of these indicators is based on data from 2020. The regional main functional areas were overlaid on top of the zoning results to further subdivide the carbon balance zones. The calculation formula is as follows:

Table 3. Economic sectoral division.

Dimensions	Indicators
Carbon emission	Total carbon emissions
Socioeconomic development level	Economic contribution coefficient of carbon emission (ECC)
Resource-environment carrying capacity	Ecological support coefficient of carbon emission (ESC)
Territorial exploitation degree (TED)	Share of built-up land area in the area of national territory space

Note: The calculations of relevant indicators are based on the 2020 dataset.

The normalised revealed comparative advantage index (NRCA) is useful for measuring and identifying the dominant attributes of carbon balance zones [52]. The formula is as follows:

$$NRCA_{ij} = \frac{X_{ij}}{X} - \frac{X^{i} \times X_j}{X^2} \tag{11}$$

where $NRCA_{ij}$ denotes the NRCA of attribute j in county i; X_{ij} denotes the indicator value of attribute j in county i; X_i denotes the sum of the indicator values of all attributes in county

i; X_j denotes the sum of the indicator values of attribute j in each county unit of the YRD region; and X denotes the total indicator of all county units and attributes.

The self-organizing map (SOM) is an unsupervised artificial neural network [53]. K-means is a cluster analysis algorithm with an iterative solution using the sum-of-squares-of-errors criterion function as the clustering criterion function. The SOM-K-means is a hybrid cluster analysis method for spatial partitioning; it combines the advantages of the SOM algorithm in terms of self-organisation and adaptivity and the advantages of K-means in terms of easy interpretation, fast convergence, and high efficiency.

2.3.4. Analysis of Factors Affecting Carbon Compensation Rates

The carbon compensation rate refers to the proportion of carbon absorption to carbon emission, which can more accurately reflect the current status of the regional carbon balance. Therefore, the dependent variable is the carbon compensation rate, and 10 indicator variables in five dimensions, including urbanisation, industrialisation, ecological foundation, agricultural production, and governance-technological level, are selected to detect the driving factors that affect the regional carbon balance. The selected indicators are shown in Table 4.

Table 4. Regional carbon balance influencing factors: indicator system and interpretation.

Dimensions	Indicators	Interpretation of Indicators
Urbanisation	Urbanisation rate (X_1)	Urban population/Total population
	Territorial exploiting degree (X_2)	Construction land area/Total territorial area
Industrialisation	Secondary industry share of GDP (X_3)	Added value of secondary industry/Gross domestic product (GDP)
	Number of medium and large industrial enterprises (X_4)	Number of medium and large industrial enterprises in the region
Ecological foundation	Vegetation richness (X_5)	Normalised difference vegetation index
	Vegetation cover (X_6)	Area of vegetation cover/Total territorial area
Agricultural production	Primary industry share of GDP (X_7)	Added value of primary industry/Gross domestic product (GDP)
	Share of cropland (X_8)	Cropland area/Total territorial area
Governance-technological level	General public budget expenditure (X_9)	General public budget expenditure in the region
	Number of patents received for inventions (X_{10})	Number of patents received for inventions in the region

GeoDetector (GD) can be used to effectively measure spatial heterogeneity; it is a set of statistical methods for detecting the causes of spatial heterogeneity and revealing the driving forces of different influencing factors, and is widely used at different research scales, such as the national, provincial, city, and township scales, as well as in various research fields, like the eco-environment, land use, regional planning, and public health fields [54]. The factor detector measures the degree to which different influences explain spatial heterogeneity; its expression is as follows:

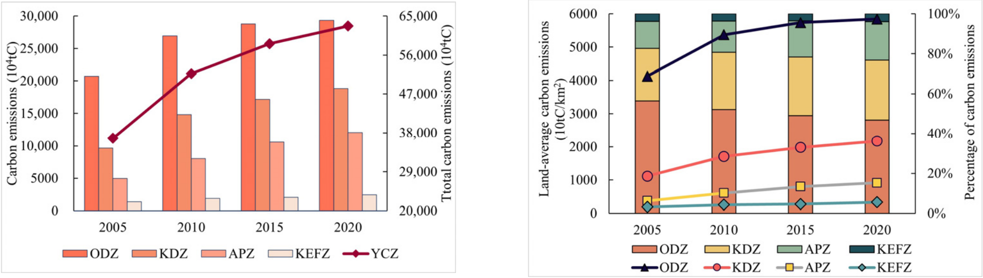
$$q = 1 - \frac{\sum_i n_i \theta_i^2}{n\theta^2} \tag{12}$$

where q denotes the explanatory power of the influencing factors; it is a number between 0 and 1, and larger values have more explanatory power. i denotes the number of strata of the independent variables; n and n_i denote the sample size and the sample size of the ith stratum, respectively; and θ and θ_i denote the variance in the dependent variable in the research zone and the variance in the dependent variable in stratum i, respectively.

3. Results

3.1. Characteristics of the Spatial-Temporal Evolution of the Carbon Balance

Carbon emissions in the YRD region have shown a significant growth trend over time, but with the implementation of green and low-carbon development in recent years, the growth of regional carbon emissions has gradually levelled off. At the county scale (see Figure 2), the YRD region’s carbon emissions show a significant spatial imbalance, with overall high values in the northeast and low values in the southwest. During 2005–2020, the high-value zone expanded outwards along the “Shanghai–Nanjing–Hangzhou–Ningbo” line, while the northern part of the YRD was also an area of rapid growth in carbon emissions. The "Shanghai–Nanjing–Hangzhou–Ningbo" line, with its high population concentration, high level of economic development, and highly developed manufacturing industry, is an important economic engine of the YRD region, and its energy consumption is higher than that of other areas in the YRD region; thus, it is a high carbon emission area in the YRD region. Northern Jiangsu and northern Anhui have rich mineral resources and a good base for industrial development, so carbon emissions in the region are growing rapidly. The spatial structure of carbon emissions in the YRD region has gradually evolved from a "core-periphery" structure with Shanghai, Nanjing, and Hangzhou as the high-value areas in 2005 to a polycentric structure with Shanghai, Nanjing, Suzhou, Wuxi, Xuzhou, Hefei, Hangzhou, and Ningbo as the core cities.



(**a**) (**b**)

Figure 2. Changes in carbon emissions in the YRD region. (**a**) Changes in carbon emissions from the MFOZs of the YRD region; (**b**) carbon emissions share and land-average carbon emissions of each MFOZ.

From the perspective of major function-oriented zoning (see Figure 3), the YRD region's carbon emissions are mainly concentrated in optimised development zones (ODZs) and key development zones (KDZs), which are important high-population and economically dense areas. They are responsible for absorbing industrial agglomeration and driving regional development. Due to the optimisation and escalation of the industrial structure, the share of carbon emissions in the optimised development zones shows a decreasing trend but still accounts for nearly half of the carbon emissions in the region as a whole; the land-average carbon emissions of this zone are much greater than those in other regions. Furthermore, as a key development area for current and future industrialisation and urbanisation, carbon emissions in this area are increasing as a proportion of the YRD region. Key development zones, which are the focus of current and future industrialisation and urbanisation, have seen their shares of carbon emissions in the region increase. The carbon emissions from the agricultural production zones and key ecological functional zones have remained at a low level; among them, with the advancement of mechanised cultivation and the strengthening of regional development, carbon emissions from the agricultural production zones have increased, while carbon emissions from the restricted development zones, such as key ecological functional zones, have remained basically the same as in previous years.

Between 2005 and 2020, changes in carbon absorption in the YRD region continued to grow over time, but the growth trend was relatively flat. After 2010, the construction of an ecological civilisation gradually became a key issue of concern in China, with effective improvement in the eco-environment and significant growth in carbon absorption. At the county scale (see Figure 4), carbon absorption in the YRD region as a whole shows a spatial feature of being higher in the southwest and lower in the northeast. The high carbon absorption zones in the region are consistently clustered in southwestern Zhejiang and southern Anhui, which have a wide distribution of hilly and mountainous terrain, high vegetation cover, and a relatively low level of industrialisation, making them important ecological spaces in the YRD region; therefore, the carbon absorption in this region is greater than what it is in other regions of the YRD region. In addition, the coastal area of Jiangsu is a high-value area for carbon absorption due to its rich wetland resources. The low-value areas are concentrated primarily along the “Shanghai–Nanjing–Hangzhou–Ningbo” line, which has a high level of urbanisation and industrialisation; furthermore, the space for carbon sinks has been reduced and encroached upon by construction land. In addition, the centres of city administrative regions are low carbon-absorption areas, which increase outwards from the core. The regions with the greatest changes in carbon absorption from 2005 to 2020 are concentrated mainly in the northern region of Anhui, where carbon absorption has been effectively enhanced as a result of the steady progress of ecological restoration.

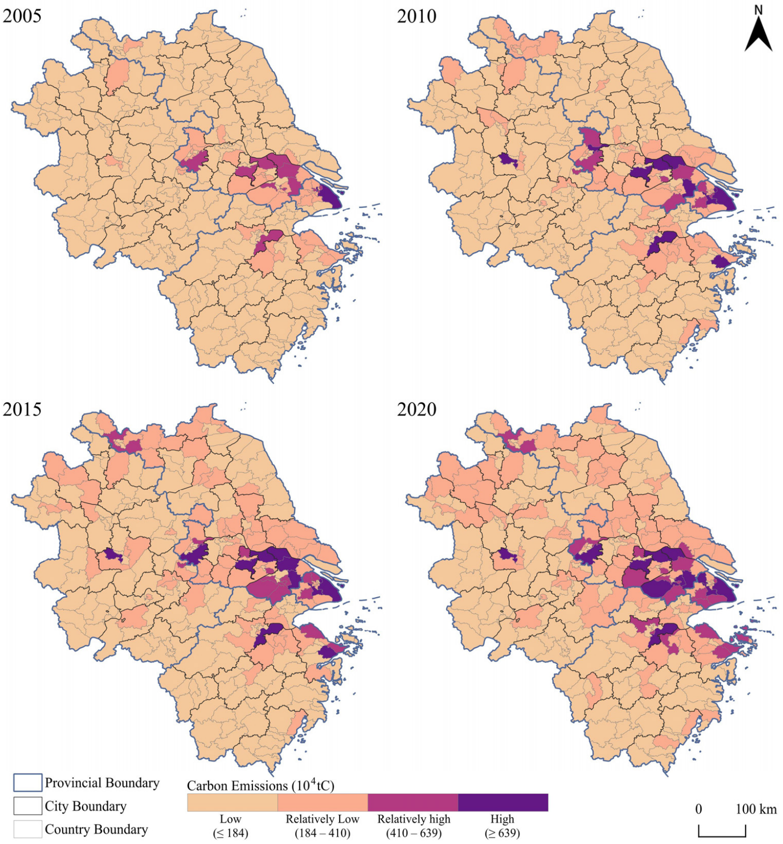
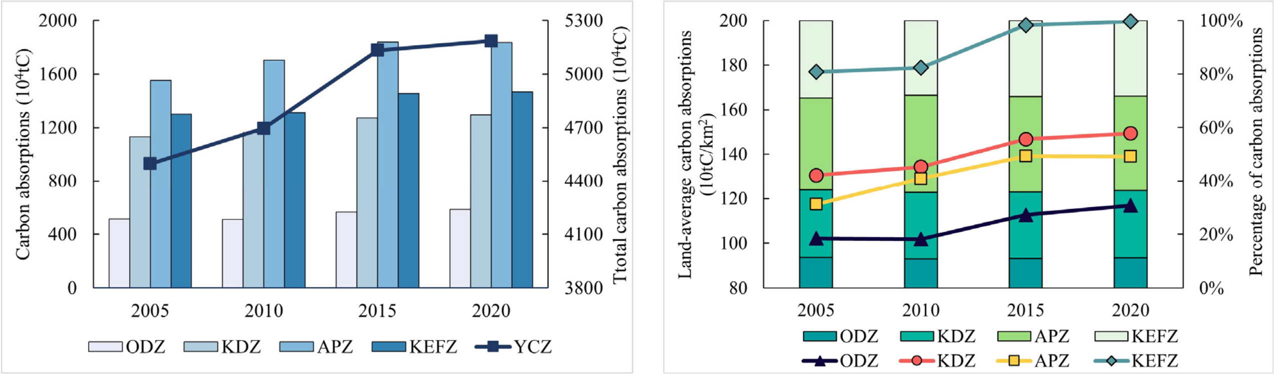


Figure 3. The YRD region’s carbon emissions, 2005–2020.



(**a**) (**b**)

Figure 4. Changes in carbon absorption in the YRD region. (**a**) Changes in carbon absorption from the MFOZs of the YRD region; (**b**) carbon absorption share and land-average carbon absorption of each MFOZ.

From the perspective of MFOZs (see Figure 5), the carbon absorption in the YRD region is concentrated mainly in agricultural production zones and key ecological functional zones, which are responsible for guaranteeing food security and ecological safety; high-intensity industrialisation and urbanisation are restricted in these zones. Therefore, the ecological environment of these zones is relatively good, and the space for carbon sinks is relatively rich, as these zones account for more than 60% of the YRD region's carbon absorption; furthermore, they are the main spatial carriers of carbon absorption in the YRD region. In addition, because of the relatively weak carbon sink function of cropland, the land-average carbon absorption in the main agricultural production areas where cropland is widely distributed is relatively low. The key development zones in the YRD region likewise contribute a certain extent of carbon absorption due to their high resource and environmental carrying capacity, but due to the small land area of the region, the land-average carbon absorption is relatively high.

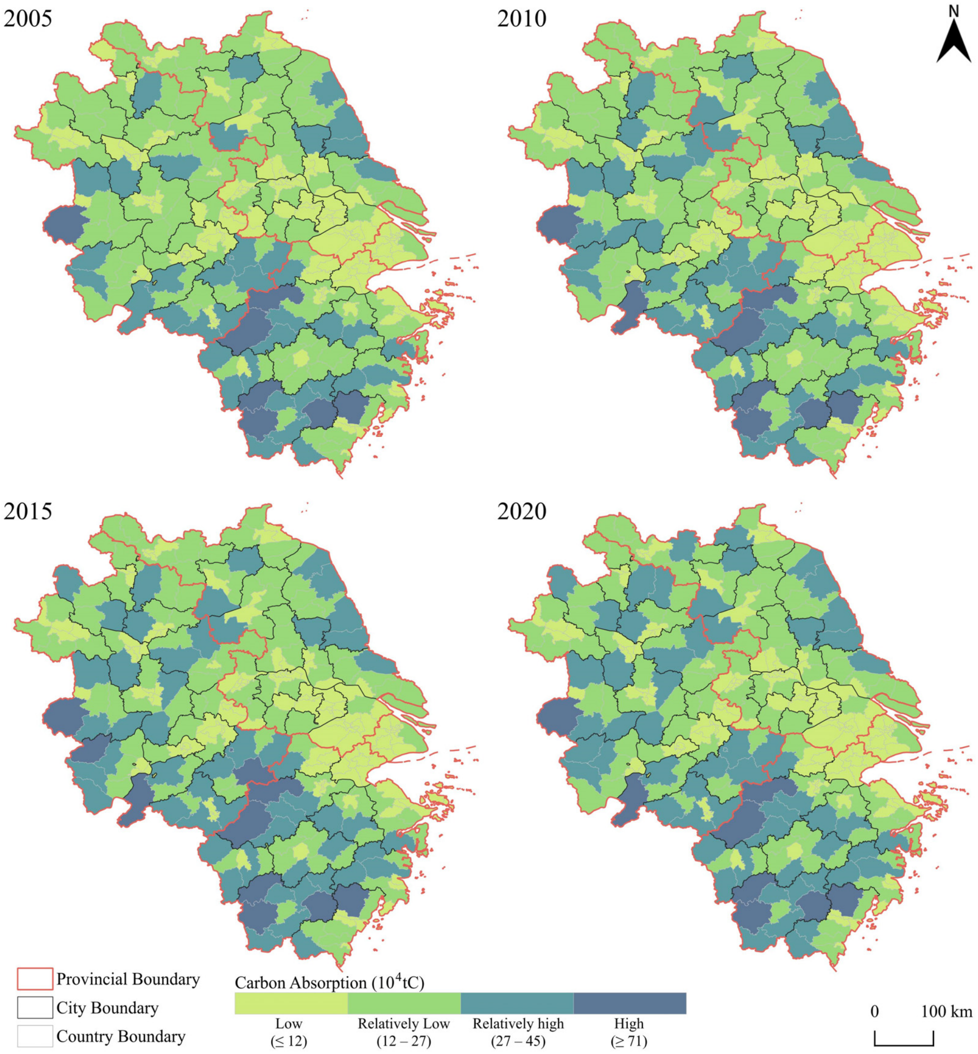


Figure 5. The YRD region's carbon absorption, 2005–2020.

3.2. Carbon Balance Zoning Results

On the basis of the NRCA index, with the help of the SOM-K-means algorithm, the 305 county units in the YRD region were classified into three types of carbon balance zones—high carbon control zones (I), carbon emission optimisation zones (II), and carbon sink functional zones (III), which were overlaid with major function-oriented zoning and further classified into nine types of zones (see Table 5 and Figure 6).

Table 5. Main indicators of the different carbon balance zones.

Carbon Balance Zoning (Number of Units)		Share of GDP/%	Share of Carbon Emissions/%	Share of Territory /%	ECC	ESC	TED /%
High carbon control zone	Optimised development zone (32)	30.41	30.14	9.77	1.01	0.27	25.46
	Key development zone (34)	13.56	16.22	12.43	0.84	0.76	14.06
	Agricultural production zone (21)	5.03	7.79	9.23	0.65	1.09	11.20
Carbon emissions optimisation zone	Optimised development zone (49)	22.95	16.15	4.65	1.42	0.21	34.59
	Key development zone (70)	13.95	14.19	12.90	0.98	0.89	17.30
	Agricultural production zone (4)	8.96	9.91	21.13	0.90	1.89	17.90
	Key ecological function zone (44)	0.49	0.90	1.33	0.54	1.79	3.91
Carbon sink functional zone	Agricultural production zone (14)	1.79	1.68	8.44	1.06	4.67	8.15
	Key ecological function zone (37)	2.87	3.00	20.12	0.96	8.87	2.15

1. **High Carbon Control Zones.** The high carbon control zones consist of 87 county units, accounting for 31.43% of the YRD's land area, generating 48.99% of the YRD's GDP, and 54.15% of the YRD's carbon emissions. These zones are located mainly in the eastern part of Shanghai, the southern part of Jiangsu, the Ningbo-Hangzhou line in Zhejiang, and surrounding the central urban areas of some cities in Anhui, which are the most important area of the YRD region in terms of carbon emissions. Among them, the high carbon control zone-optimised development zones include 32 county units, which are the concentrated distribution areas of the manufacturing industry, and account for 30.14% of the YRD region's carbon emissions. The ECC (1.01) of this kind of zone is less than that of other optimised development zones, as is the ESC (0.27), indicating that the economic benefits of carbon emissions and the ecological support capacity of these zones are at relatively low levels. The high carbon control zone-key development zones include 34 county units, which are the current key areas for industrialisation and urbanisation development in the YRD region. The ECC (0.84) and ESC (0.76) of this type of zone are lower than those of the YRD region, which shows that the high carbon emissions in these zones do not bring about a better economic benefit and have a low ecological support capacity for carbon emissions. The high carbon control zone-agricultural production zone includes 21 county units, which are more disturbed by human activities, and the economic efficiency and ecological support capacity of carbon emissions of these zones are lower than those of other agricultural production zones.
2. **Carbon Emission Optimisation Zones.** The carbon emission optimisation zones, with a total of 167 county units, are the most numerous carbon balance zones in the YRD region, accounting for 40.01% of the YRD region's land area and 46.34% of the YRD's GDP, and generating 41.16% of the YRD's carbon emissions. These zones are located mainly in the northern part of Jiangsu, the northern and central parts of Anhui, the Taihu Lake basin, and the central urban areas of some cities. Among them, the carbon emission optimisation zone-optimisation development zones include 49 county units. These zones have a long history of development; some high carbon emission industries have been transferred to other regions; and their industrial structures have been optimised and upgraded. The ECC (1.42) of this type of zone is the highest in the YRD region, and the ESC (0.21) is the lowest in the YRD region, which indicates that the economic efficiency of carbon emission in these zones is high, but the carbon ecological support capacity is lower than that of other zones due to the high degree of territorial spatial development. The carbon emission optimisation zone-key development zones comprise 70 county units, which have an ECC of 0.98, an ESC of 0.89, and a low level of territorial spatial exploitation, indicating that the economic benefits of carbon emissions and the ecological function of carbon sinks are in a relatively matched state in these zones. The carbon emission optimisation zone-agricultural production zones and the carbon emission optimisation zone-key ecological functional zones comprise 48 county units, which account for 10.82% of

the YRD's carbon emissions. The carbon ecological support capacities of these two types of zones are relatively high, but the economic efficiency of carbon emissions is low, especially in the key ecological functional zones, where the ECC is only 0.54. Regional carbon emissions should be optimised in the future development process; furthermore, the regional economy needs to be improved through the development of green industries in the future.

3. **Carbon Sink Functional Zones.** There are 51 county-level units in the carbon sink functional zones, which account for 28.56% of the territorial space of the YRD region but produce only 4.6% of the YRD's carbon emissions. These zones are primarily situated in the southwestern part of Zhejiang and the southern part of Anhui and have the strongest carbon sink functions in the YRD region. Among them, the carbon sink functional zone-agricultural production zones include 14 county units, and have an ECC and ESC greater than 1; the economic efficiency of carbon emission and carbon ecological support capacity are at a high level. The carbon sink functional zone-key ecological functional zones comprise 37 county units, primarily situated in hilly and mountainous regions, with high vegetation cover and ESCs as high as 8.87. These zones have the highest carbon ecological support capacity in the YRD region and are important ecological barriers in the YRD region.

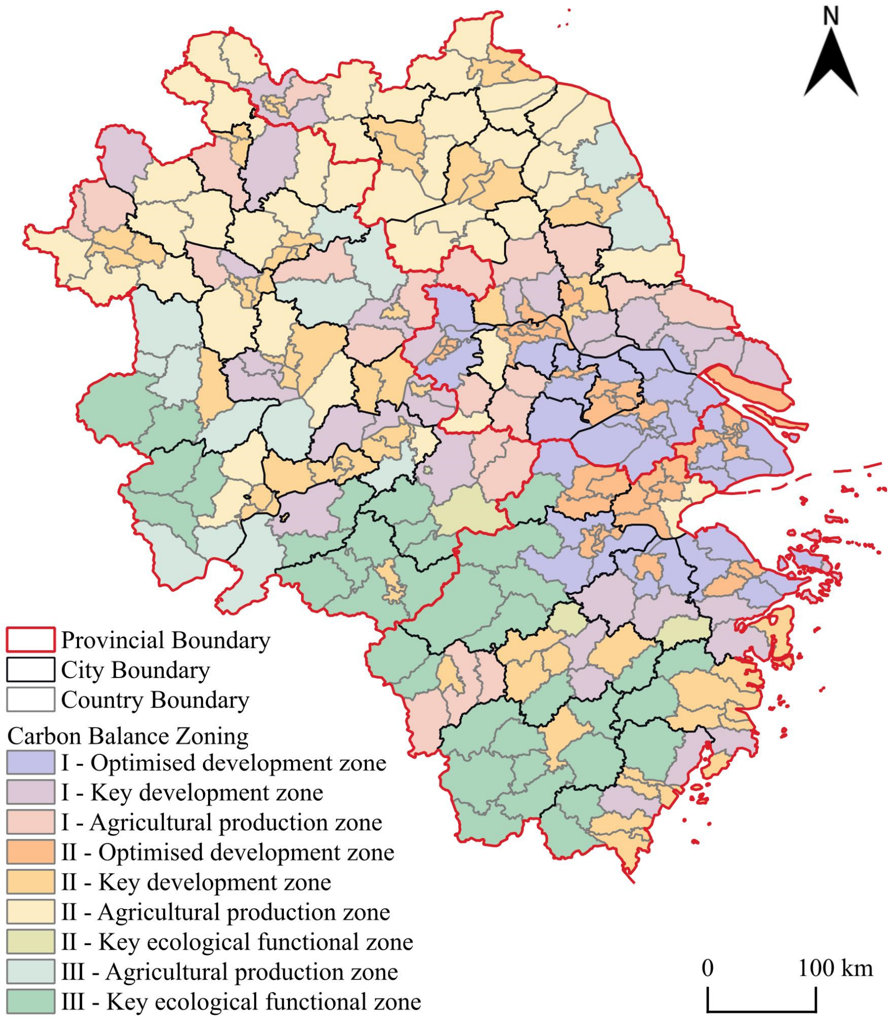


Figure 6. Carbon balance zoning in the YRD region.

3.3. Results of Geodetector Analyses

Using the GeoDetector algorithm package in R [55], the carbon compensation rate of each county unit is taken as the dependent variable, and 10 indicators selected from the urbanisation, industrialisation, ecological foundation, agricultural production, and governance-technological level of each county unit are taken as independent variables, which are inputted into the GeoDetector model together; the capacity value of each driver is calculated to influence the regional carbon compensation rate. The results of the analysis are displayed in Table 6.

Table 6. Detection of carbon compensation rate drivers in the YRD region and its major functional zones.

Carbon Balance Zoning	**Year**	***q*-Value of the Driving Indicators**									
		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
Yangtze River Delta	2005	0.22 ***	0.44 ***	0.15 ***	0.16 ***	0.29 ***	0.61 ***	0.20 ***	0.24 ***	0.17 ***	0.08 ***
	2010	0.25 ***	0.46 ***	0.13 ***	0.19 ***	0.43 ***	0.63 ***	0.16 ***	0.23 ***	0.37 ***	0.15 ***
	2015	0.19 ***	0.47 ***	0.10 ***	0.18 ***	0.62 ***	0.69 ***	0.16 ***	0.21 ***	0.45 ***	0.16 ***
	2020	0.18 ***	0.65 ***	0.11 ***	0.23 ***	0.58 ***	0.65 ***	0.19 ***	0.22 ***	0.38 ***	0.21 ***
Optimised development zone	2005	0.41 ***	0.50 ***	0.16 **	0.15 **	0.67 ***	0.30 ***	0.61 ***	0.24 **	0.35 ***	0.21 ***
	2010	0.45 ***	0.60 ***	0.22 ***	0.12 *	0.62 ***	0.29 ***	0.57 ***	0.24 **	0.11	0.22 ***
	2015	0.53 ***	0.74 ***	0.16 **	0.17 **	0.68 ***	0.36 **	0.59 ***	0.24 **	0.05	0.12
	2020	0.71 ***	0.52 ***	0.12 **	0.09	0.51 ***	0.26 **	0.83 ***	0.26 **	0.09	0.10
Key development zone	2005	0.32 ***	0.31 ***	0.20 ***	0.06	0.39 ***	0.23 ***	0.38 ***	0.16 ***	0.10 *	0.07
	2010	0.32 ***	0.45 ***	0.15 ***	0.13 **	0.44 ***	0.37 ***	0.39 ***	0.14	0.12	0.08
	2015	0.26 ***	0.53 ***	0.06	0.14 **	0.34 ***	0.47 ***	0.17 ***	0.16 *	0.11	0.06 *
	2020	0.31 ***	0.54 ***	0.11 *	0.10	0.42 ***	0.31 ***	0.41 ***	0.08	0.21 ***	0.05
Agricultural production zone	2005	0.21 ***	0.14	0.33 ***	0.20 **	0.04	0.20 ***	0.39 ***	0.11	0.24 ***	0.08
	2010	0.17 **	0.21 **	0.41 ***	0.29 ***	0.07	0.17 *	0.40 ***	0.08	0.34 ***	0.16 **
	2015	0.21 **	0.35 ***	0.21 *	0.28 ***	0.07	0.22 **	0.38 ***	0.11	0.34 ***	0.07
	2020	0.24 ***	0.24 ***	0.35 ***	0.28 **	0.11	0.22 *	0.48 ***	0.06	0.32 **	0.18 **
Key ecological function zone	2005	0.28 *	0.42 **	0.38 ***	0.30	0.28 *	0.47 ***	0.27	0.45 ***	0.64 ***	0.19
	2010	0.34 **	0.39 **	0.41 **	0.31 **	0.35 **	0.49 ***	0.24	0.40 **	0.70 ***	0.32 **
	2015	0.21	0.50 ***	0.44 **	0.28 **	0.54 ***	0.57 ***	0.34 **	0.40 *	0.55 ***	0.19
	2020	0.13	0.39 **	0.48 ***	0.29 *	0.46 ***	0.53 ***	0.24	0.49 ***	0.74 ***	0.29 *

Note: ***, **, and * denote 1%, 5%, and 10% significance levels, respectively. X_1 denotes the urbanisation rate; X_2 denotes the territorial exploiting degree; X_3 denotes the secondary industry share of GDP; X_4 denotes the number of medium and large industrial enterprises; X_5 denotes the vegetation richness; X_6 denotes the vegetation cover; X_7 denotes the primary industry share of GDP; X_8 denotes the share of cropland; X_9 denotes the general public budget expenditure; X_{10} denotes the number of patents received for inventions.

At the YRD regional level, the degrees of territorial exploitation (X_2), vegetation richness (X_5), and vegetation cover (X_6) are the main drivers influencing the regional carbon compensation rate; among them, the effect of the degree of territorial exploitation (X_2) increases over time, while the effect of vegetation cover (X_6) is always at a high level.

In terms of optimised development zones, the urbanisation rate (X_1), territorial exploitation degree (X_2), vegetation richness (X_5), and primary industry share of GDP (X_7) are the main factors influencing changes in the regional carbon compensation rate, while the influence of factors related to industrialisation, such as the secondary industry share of GDP (X_3) and the number of medium and large industrial enterprises (X_4), gradually decreases or is not significant over time. In terms of key development zones, the influence of each driver of the regional carbon compensation rate varies less, and the main driver is similar to that of the optimised development zones; however, the influence of the urbanisation rate (X_1) is much lower than that of the optimised development zones, and the influence of the degree of territorial exploitation (X_2) gradually strengthens over time, becoming the most dominant driver. In terms of agricultural production zones, the primary industry share of GDP (X_7), the secondary industry share of GDP (X_3), the general public budget expenditure (X_9), and the number of medium and large industrial enterprises

(X_4) are the most important driving factors. The influence of the primary industry share of GDP (X_7) gradually strengthens with time, and the influence of factors in the area of industrialisation, such as the secondary industry share of GDP (X_3) and the number of medium and large industrial enterprises (X_4), is relatively stable, which is in line with the major functional characteristics of the region. In terms of key ecological function zones, the general public budget expenditure (X_9), vegetation cover (X_6), and share of cropland (X_8) are the main driving factors, and the secondary industry share of GDP (X_3), degree of territorial exploitation (X_2), and vegetation richness (X_5) are also at high levels, while the influence of the other factors has low significance.

4. Discussion

4.1. Characteristics of Carbon Balance Evolution and Carbon Balance Zoning in the YRD Region

This study, as an empirical study, reflects the evolution process and current situation of the carbon balance in the YRD region, and provides a reference case for similar regions to carry out carbon reduction and emission reduction work.

This study shows that the spatial structure of carbon emissions in the YRD region has gradually evolved from a "core-periphery" structure with Shanghai, Nanjing, and Hangzhou as the high-value areas in 2005 to a polycentric structure with the central city of the region as the core, while carbon absorption has always shown a spatial characteristic of being high in the southwest and low in the northeast, which is basically consistent with previous studies [13,37]. In addition, this study used the SOM-K-means algorithm to divide the carbon balance zones under the perspective of the main functional areas. This study finds that optimised development zones and key development zones are the key areas in the YRD region in which to promote carbon reduction, while key ecological functional zones are the dominant areas for carbon sink functions in the YRD region, which indicates that the concept of MFOZs is highly compatible with spatially synergistic carbon reduction.

4.2. Analysis of the Drivers of Changes in the Regional Carbon Balance

Previous studies have generally concluded that regional carbon emission/absorption changes are affected by the integrated impacts of natural ecosystems and human economic activities [38,56], and that the total and spatial-temporal differences between carbon emissions and carbon absorption directly affect the regional carbon balance status, which is further confirmed by this study. The results of the GeoDetector analysis are shown in Table 6; the YRD region's carbon compensation rate was influenced mainly by factors such as the territorial exploiting degree (X_2) and the vegetation cover (X_6), which indicates that territorial spatial development and utilisation in the YRD region have profound impacts on the regional carbon emissions and carbon absorption. As a major engine of China's economic growth, construction land expansion in the YRD region has resulted in increases in carbon emissions while fragmenting the original land cover and weakening the region's carbon sequestration capacity; thus, the incremental increase in carbon absorption is much lower than the incremental increase in carbon emissions, and the imbalance of the regional carbon balance has become more and more prominent.

This study also further supports some of the previous studies, which suggested that different MFOZs have differentiated drivers of carbon balance changes [31,37], which is verified in this study through empirical analyses. As the results in Table 6 show, the main driving factors affecting the change in the carbon compensation rate in the optimized development zone and the key development zone are mainly urbanisation (X_1, X_2) and ecological foundation (X_5, X_6); this indicates that this type of region, as the core area for the development of the YRD, has a high degree of population concentration driven by urbanisation, with a large amount of natural cover and cropland converted to construction land, seriously squeezing the space for agricultural production and the space for carbon sink. This leads to the fragmentation and low-quality of land for carbon sinks, and difficulty for the carbon absorption capacity to offset the continuous growth of carbon emissions, resulting in the continuous decline in the regional carbon compensation rate. Variations in the carbon compensation rate of the agricultural production zones are mainly affected by the secondary industry share of GDP (X_3), the primary industry share of GDP (X_7), and the general public budget expenditure (X_9), that is, the improvement in the infrastructure and industrialisation aggravate the carbon imbalance of the region, which is in line with the characteristics of some of the agricultural production zones of the YRD region that combine the important tasks of industrialisation, urbanisation, and agricultural modernisation. Due to the special functional position and ecological vulnerability of key ecological function zones, ecological improvement, over-exploitation, industrialisation, and urbanisation will all affect the carbon balance status of the region [11,17]. This study shows that the general public budget expenditure (X_9), vegetation cover (X_6), share of cropland (X_8), and secondary industry share of GDP (X_3) are the main driving factors for the change in carbon balance, which, to some extent, validates the relevant viewpoints; however, they still need to be further analysed and explored.

4.3. Spatially Synergy Carbon Reduction Pathways in the YRD Region

Through the above analysis, we can see that there are significant carbon balance differences among different functional zones in the YRD region, and the regional carbon imbalance phenomenon is prominent. Therefore, how to explore the differentiated economic development mode, spatial development mode, and carbon neutralisation path of each region with the help of carbon balance zoning in the YRD region is a key question that should be resolved urgently. To this end, we propose the following differentiated spatial synergistic carbon reduction pathways for different functional zones.

Optimised Development Zones. These zones represent growth poles for economic development in the YRD region, with sound urban systems and strong regional competitiveness. These zones are classified in carbon balance zoning as high carbon control zones or carbon emission optimisation zones. Among them, high carbon control zones should place the transformation of the development mode as their highest priority; actively absorb the high concentration of innovative elements; create an advanced manufacturing base; and improve the region’s economic efficiency in terms of carbon emissions. Carbon emission optimisation zones are mostly central urban areas, which are at the forefront of economic transformation and development by virtue of their first-mover advantages in terms of market environment, science and education, and infrastructure. The future of this type of area should focus on the development of modern service and high-tech industries and explore the construction of innovative and ecological cities.

Key Development Zones. These zones have good foundations for economic development, with greater development potential and greater resource and environmental carrying capacities. They are important for undertaking regional population and industrial transfers. These zones are classified in carbon balance zoning as high carbon control zones or carbon emissions optimisation zones. High carbon emission zones should focus on constructing a regional innovation system; enhancing the capacity of industrial clustering; increasing the economic efficiency of carbon emissions of existing industries; strengthening the protection and restoration of the eco-environment; and enhancing the capacity for carbon sequestration in the region. Carbon emission optimisation zones need to explore the spatially synergistic carbon reduction paths of the two types of regions. First, for the urban centres of some cities, efforts should be made to give full play to the advantages of location; focus on the construction of strategic emerging industries and high-tech industrial bases; and actively expand green space at the same time. Second, some areas with better ecological bases and agricultural production conditions should give full play to the ecological advantages of the region in accordance with the characteristics of the lead; and optimise the development of green industries and modern agriculture and other low-pollution industries.

Agricultural production zones. These zones have good conditions for agricultural production, with the supply of agricultural products as their main function. They guarantee the security of production and the supply of agricultural products. These zones are classified in carbon balance zoning as high carbon control zones, carbon emission optimisation zones or carbon sink functional zones. Among them, the high carbon control zones should be careful to avoid the development of high-polluting and high-energy-consuming industries; focus on the development of green industries; and explore the development of low-carbon agriculture. Carbon emissions optimisation zones need to focus on improving agricultural infrastructure, guiding the development of advantageous agricultural products, and building nationally important production bases for cereals and advantageous agricultural products. Carbon sink functional zones need to safeguard the ecological advantages of their regions; enhance the comprehensive production capacity of cereals; and avoid excessive industrialisation and urbanisation.

Key Ecological Functional Zones. These zones possess high ecological sensitivity and a low resource and environmental carrying capacity, which makes them unsuitable for large-scale development and construction; as a result, they bear the important responsibility of maintaining the ecological security of the YRD region. These zones are classified as carbon emission optimisation areas or carbon sink functional areas in carbon balance zoning. Carbon emission optimisation zones should promote ecological restoration, strengthen ecological protection efforts, and explore the potential for realising the value of ecological products. Carbon sink functional zones should focus on enhancing their carbon sequestration capacity, develop characteristic industries that can be supported by resources and the environment according to local conditions, and guide the orderly transfer of overloaded populations.

5. Conclusions

In this paper, a carbon balance zoning study was conducted based on the estimation of carbon emissions and carbon absorption in the YRD region during 2005–2020. The driving factors of the regional carbon balance were analysed via GeoDetector, the impacts of various drivers on the regional carbon compensation rate were revealed, and spatially synergistic carbon reduction pathways for carbon balance zoning were proposed. The main conclusions are as follows:

1. In 2005–2020, the YRD region's carbon emissions and carbon absorption continued to increase, but the rise in carbon absorption did not offset the rise in carbon emissions. Consequently, the regional carbon imbalance will become increasingly prominent, and a significant spatial imbalance in the spatial development trend will occur. The high-value carbon emission zones are clustered in the optimised development zones and key development zones along the "Shanghai–Nanjing–Hangzhou–Ningbo" line, while the high-value carbon absorption zones are distributed mainly in the key ecological functional zones in the southeastern mountainous areas;
2. Based on the carbon accounting results and the NRCA index of each county unit attribute, the YRD region is divided into 87 high carbon control zones, 167 carbon emissions optimisation zones, and 51 carbon sink functional zones. Carbon emissions from the high carbon control zones account for 54.15% of the total carbon emissions in the YRD region, and the economic benefits of carbon emissions and carbon ecological support capacity are at a low level. The county units in the carbon emissions optimisation zones either have high levels of economic benefits related to carbon emissions or have compatible levels of economic benefits related to carbon emissions and ecological functions related to carbon sinks; the carbon sink functional zones contribute to 36.45% of the carbon sequestration, and they have a stronger carbon ecological support capacity;
3. From 2005 to 2020, there were spatial and temporal differences in the drivers of carbon balance changes in the YRD region. Furthermore, the main influences on the carbon compensation rate varied in the different functional zones due to regional differences in the direction of economic development and resource utilisation patterns. Overall, it is one of the most economically active regions in China, changes in territorial exploitation and utilisation patterns in the YRD region are the major drivers of changes in the regional carbon balance.

Considering the carbon balance zoning of the YRD region, differentiated spatially synergistic carbon reduction paths are proposed with respect to the carbon balance characteristics of different zones and the locations of the main functions to serve as a reference for realising sustainable low-carbon development in the YRD region.

Furthermore, because of limited access to county-level data, the county-level carbon emission estimations in this study are determined via an indirect method; the accuracy of carbon accounting still has room for improvement. Although the study of carbon balance zoning in the YRD region can offer ideas for regional low-carbon development, the realisation of China's dual-carbon goal needs to be based on the national scale, and appropriate spatially synergistic carbon reduction pathways need to be explored; therefore, the study of carbon balance zoning and drivers of carbon balance at the national scale should be strengthened in the future.

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