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Decoupling Characteristics between Coupling Coordination Degree of Production-Living-Ecological Function and Carbon Emissions in the Urban Agglomeration of the Shandong Peninsula

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Abstract: Under the dual carbon goals, the relationship between land production-living-ecological function and carbon emissions points to a new direction for land spatial planning. This study compiles and analyzes carbon emissions and the production-living-ecological function coupling coordination degree of 16 cities in the Shandong Peninsula urban agglomeration for the years 2001, 2006, 2011, 2016, and 2021. Furthermore, it introduces the Tapio decoupling model to calculate the decoupling index between carbon emissions and the coupling coordination degree. The spatiotemporal evolution characteristics of production-living-ecological function coupling coordination, carbon emissions, and the decoupling index were analyzed. The results indicate that (1) from 2001 to 2021, the production-living-ecological function coupling coordination degree in Shandong Peninsula urban agglomeration increased overall, with an obvious "high in the east and low in the west" feature in the spatial pattern. That is caused by the difference in resource endowment between the east and the west and the gap in the process of urbanization, industrial structure transformation, and ecological governance. (2) During the study period, overall carbon emissions increased, with a significantly reduced growth rate. A polarization phenomenon of increase and decrease trends within the urban agglomeration was observed. The spatial distribution characteristics of land use carbon emissions showed significant production-living-ecological coupling coordination degree heterotropism. (3) From 2001 to 2021, the decoupling relationship between production-living-ecological coupling coordination degree and carbon emissions mainly exhibited three patterns: strong negative decoupling, expansion negative decoupling, and strong decoupling, maintaining a good decoupling trend overall. These results indicate that the coordinated development level of production, living, and ecological functions in the study area has improved during the research period, and its decoupling relationship with carbon emissions has also shown a positive trend. However, there is still a problem of uneven regional development. In the future, the production-living-ecological development of Shandong Peninsula urban agglomeration should adhere to the development pattern of "two circles and four regions", which aims to promote resource sharing and complementary advantages through specific regional divisions, and achieve coordinated development within the region. This involves optimizing land use structure and function, encouraging innovation and development of green industries, and deepening ecological environment restoration and protection to realize the coordinated development of the production-living-ecological function of land use under the dual carbon goal.

Keywords: production-living-ecological function coupling coordination degree; carbon emissions; Tapio decoupling index; Shandong Peninsula urban agglomeration; land use; dual carbon goals

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1. Introduction

National development depends on the multiple functions of land space [1]. Aligned with the strategic goal of achieving high-quality development, the coordination between the production-living-ecological functions within land space plays an important role [2].

With the rapid development of the social economy and the continuous advancement of industrialization and urbanization, competition for urban agglomeration's production-living-ecological space has intensified [1]. The production-living-ecological function has changed significantly, with transformations between functions diversifying in direction and speed. Specifically, the production and living functions have continuously improved, often at the expense of hindering and depleting ecological functions. At the same time, pollution emissions from production and living spaces impact the internal stability of ecological space, exacerbating coordination contradictions among production, living, and ecological functions. Consequently, this leads to a cascade of negative effects, including ecological degradation and environmental pollution [3]. Among these pollutants, the emission of carbon dioxide, which is classified as a greenhouse gas because of its heat-trapping properties, contributes to global warming and has a particularly negative effect on ecological functions. At the 75th United Nations General Assembly, the Chinese government solemnly announced that China aims to reach its carbon peak by 2030 and achieve carbon neutrality by 2060 (referred to as the "dual carbon" goal). In recent years, against the backdrop of dual carbon imperatives, carbon emissions have emerged as an important factor causing social, economic, and ecological problems. Research shows that carbon dioxide emissions resulting from land use changes account for one-third of urban carbon emissions, making them a key driver of global and regional carbon emission changes [4]. Therefore, it is crucial to pay attention to the spatiotemporal evolution pattern of the production-living-ecological (PLE) function from the perspective of dual carbon and improve its current status quo, which prioritizes economic and social aspects over ecological and green ones. The aim of this study is to facilitate the comprehensive utilization of land and space and promote environmentally sustainable, high-quality development within urban agglomerations [4].

The coupling and coordination of production life ecology (PLE) functions has been a hot topic in urban planning and land management in recent years. With the acceleration of urbanization, the functional differentiation of urban space and land use changes have had a significant impact on the ecological environment, which has prompted scholars to explore how to achieve multifunctionality and coordination of land use. Scholars have proposed in their research the process and mechanism of the impact of land use function transformation on the ecological environment, emphasizing the importance of land use function transformation on ecological services and ecosystem health in the context of urbanization [5]. Scholars have also explored the land use model based on PLE function from the perspective of sustainability and revealed the impact of different land use types on ecosystem service functions through case studies [6]. In exploring the evaluation methods of PLE functional coupling coordination, some scholars have adopted a multi-indicator comprehensive evaluation method to quantify the PLE functional coupling coordination relationship at the county level and proposed optimization strategies [7].

In terms of the application of the coupling coordination model, some scholars have predicted the spatiotemporal evolution of the "production life ecology" functional coupling in the Yellow River Basin, demonstrating the potential application of this model in macro-regional planning [8]. In addition, some scholars have studied the spatiotemporal coordination and conflict of production, life, and ecological land functions in the Beijing Tianjin Hebei region, revealing the complexity of the interactions between different functions [9].

Previous studies on carbon emissions have primarily analyzed the impact of carbon emissions from an industrial or spatial perspective, evaluating the mechanisms and effects of policies and regulations related to carbon emissions. Additionally, these studies have advocated for the "dual carbon" development pathway. From an industrial perspective, scholars have mostly focused on energy-intensive sectors, such as heavy industry and transportation, measuring carbon emissions and investigating the carbon emission effects of industrial dynamics. They have also proposed paths for achieving carbon peaks and carbon neutrality through industrial transformation [10]. In the study of spatial carbon emissions, scholars have adopted a multi-level spatial perspective, examining characteristic

geographical regions, urban agglomerations, and administrative divisions at various levels as research units [11]. Furthermore, they have integrated variables such as innovation, population, and the digital economy into the analysis of factors influencing carbon emissions. Policy research on carbon emissions mainly focuses on the benefits of carbon trading policies and mechanisms, the financial aspects of carbon trading, and the formulation of supporting legal regulations [12]. Among these, taking urban agglomerations as research units to observe the temporal and spatial evolution of carbon emissions provides theoretical insights for this paper. Regarding the relationship between land multifunctionality and carbon emissions, research has mostly focused on the relationship between single land functions and carbon emissions. Scholars have employed methods such as area transfer matrices, spatial change rate coefficients, and land use change dynamic indices to conduct such research. This includes analyzing carbon metabolism and carbon flow within the framework of urban carbon metabolism theory, studying changes in carbon metabolism caused by the changes in the strength of the production-living-ecological function, or separately measuring the carbon emissions of the PLE function and comprehensively comparing it with the regional carbon emissions growth rate. However, few studies have delved into the relationship between land multifunctionality, especially the coordination of various functions, and carbon emissions [13]. As a result, the socio-economic drivers and consequences of land function coordination and their links to carbon emissions have not been adequately studied, which is critical to understanding the broader context of land use decisions.

To address the aforementioned problems, the decoupling theory was employed, and the decoupling model was introduced following the examination of the production-living-ecological function coupling coordination [14]. The decoupling model refers to a conceptual framework used to analyze and quantify the relationship between two or more variables, typically in the context of their growth or change over time. In the field of environmental economics and sustainable development, decoupling models are often employed to examine the relationship between economic growth (or other drivers) and environmental impacts, such as carbon emissions. Decoupling, in this context, occurs when there is a change in the rate of one variable that is not mirrored by an equivalent change in the other variable. The Tapio decoupling index method is the current authoritative approach for assessing the decoupling relationship between the two systems [15]. The decoupling relationship between the two systems is obtained using the elasticity coefficient of different system changes to avoid the dilemma of base period selection encountered in the OECD decoupling index method. Through the application of the coupling coordination degree model, this study aims to observe the evolution of the production-living-ecological function pattern from the perspective of comprehensive land use [16]. Furthermore, the decoupling model is employed to analyze the decoupling relationship between coordinated land use and carbon emissions, providing a new approach to comprehensive land use and green development [17].

2. Materials and Methods

2.1. Theoretical Framework

The purpose of this study is to explore the decoupling relationship between the coupling coordination level of land production-living-ecological function and carbon emissions and analyze its spatiotemporal evolution characteristics.

The production-living-ecological function constitutes the three primary functions of land space [18]. The production function involves the direct acquisition of various materials by humans with land as the labor object or social production and service with land as the spatial bearer, thereby providing material support for human life maintenance [19]. The living function ensures basic material existence, encompassing various spatial functions such as residence, transportation, consumption, and entertainment generated by humans in the process of land use. It represents the role that land can play in human life and reinforces the production function [5]. The ecological function refers to the role of ecosystems and

ecological processes in maintaining ecological balance, meeting humans' basic ecological needs, and ensuring the basic environmental conditions necessary for human production and living [6].

The differentiation law of the PLE function in land space fundamentally depends on the development of regional natural resources and environment, production, and life [20,21]. Optimizing land use patterns and enhancing the coordination degree of land multifunctionality will change the process of carbon cycle change, thereby reducing surface carbon emissions, enhancing vegetation carbon sequestration capacity, and reducing atmospheric CO_2 concentration, ultimately yielding a positive impact on global climate change [22]. Carbon emissions generated by different land use types vary, and changes in land use structure may also affect the carbon source and carbon sink functions of different types [23]. Therefore, this study establishes an evaluation index system for the PLE function based on its definition and examines its spatiotemporal evolution and coupling coordination (Figure 1). From the perspective of dual carbon, it investigates the effect of the coordinated evolution of land function on carbon emissions.

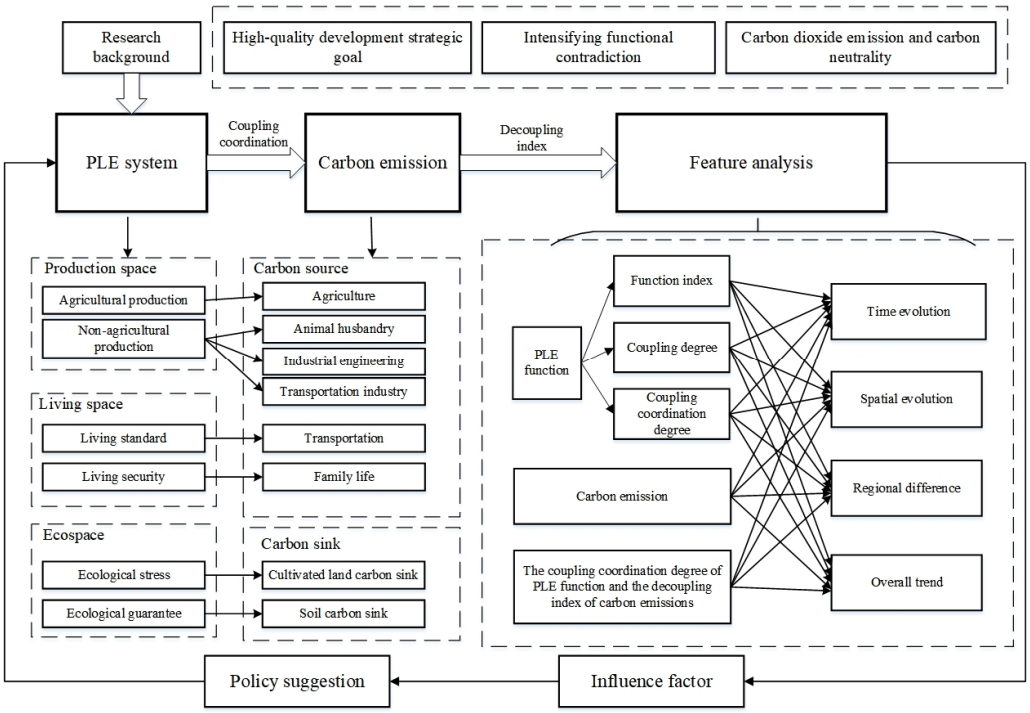


Figure 1. Theoretical framework illustrating the relationship between land multifunctionality and carbon emissions.

2.2. Study Area and Data Sources

The production-living-ecological function of the land in the Yellow River Basin is rich and diverse, which is of great significance to the local and national economic and social development and ecological security. In terms of production function, the Yellow River basin is an important agricultural, forestry, and animal husbandry area in China, mainly distributed in the upper and middle reaches. In terms of living function, the Yellow River basin flows through a number of densely populated provinces and regions that are the living and residential areas for a large number of people, and urban and rural construction land is mainly concentrated in the middle and lower reaches. In terms of ecological function, the ecosystem of the Yellow River Basin provides a variety of ecological services, such as food supply, water conservation, soil conservation, and climate regulation.

The Shandong Peninsula urban agglomeration is selected as the study area (Figure 2) as it is the only urban agglomeration with a population exceeding 100 million in the Yellow River Basin [24]. This region leads in major economic indicators such as gross domestic

product, total industrial output value, and total import and export volume, ranking first among urban agglomerations in the Yellow River Basin [25]. This economic prominence makes it a critical area for studying the interplay between economic development and environmental concerns. In terms of strategic location, The Shandong Peninsula Urban Agglomeration is located in the lower reaches of the Yellow River and along the coast of the Bohai Sea and Yellow Sea. It is an important component of the eastern coastal region of China and has a geographical advantage in connecting North China, East China, and Northeast China, making it a typical example of how urban areas can impact and be impacted by their surrounding regions. At the same time, the Shandong Peninsula city cluster faces common challenges related to rapid economic growth and urbanization, such as resource shortage and ecological degradation. These challenges are typical of many urban agglomerations around the world, making the Shandong Peninsula urban agglomeration a relevant case study for exploring solutions and strategies. Notably, the region's comprehensive advantages, including its market potential, innovation capacity, and opening potential, contribute to its increasing influence and driving force within the Yellow River Basin. However, existing literature lacks investigations into the relationship between land use and carbon emissions within the Shandong Peninsula urban agglomeration [26]. Therefore, this study holds significant implications for shaping a path of high-quality development for the Shandong Peninsula urban agglomeration and cities across the Yellow River Basin.

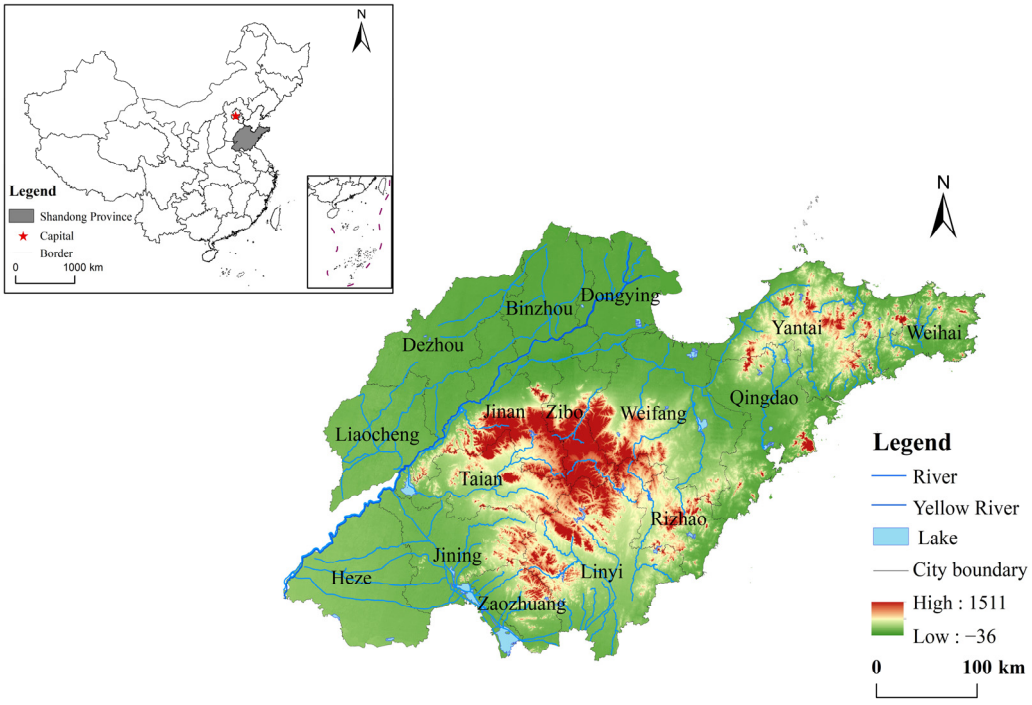


Figure 2. Map of the research area.

This article takes 16 cities in the Shandong Peninsula urban agglomeration as the research object. Considering the lag relationship between urban land use and carbon emissions, it is more reasonable to use time periods as the research scale for relevant measurements. At the same time, considering the connection with the five-year plan for national economic development, five time nodes in 2001, 2006, 2011, 2016, and 2021 are selected as the research period. The research data primarily consist of land use and land cover remote sensing monitoring data, resource and environmental data, and socio-economic statistical data. Urban carbon emission data is sourced from China Carbon Accounting Database (CEADs). The socio-economic data mainly comes from the Shandong Statistical Yearbook from 2001 to 2021 and the Statistical Yearbooks of various cities. For some missing data, adjacent year data is used instead. The land use and land cover

remote sensing monitoring data are sourced from the land use/land cover remote sensing detection database (CNLUCC). Resource and environmental data are required from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (see: http://www.resdc.cn/, accessed on 1 October 2023). On the basis of obtaining various types of data, the ArcGIS platform is used to unify the data coordinate system and perform spatial correction, establishing an integrated database of urban system elements in the research area.

2.3. Comprehensive Evaluation of Production-Living-Ecological Function

The refinement of the production-living-ecological function is essential for exploring the coordinated use of production-living-ecological space [27]. The subclassification and expansion of the PLE function at the sub-functional level can form a functional classification and evaluation system suitable for the scale of urban agglomerations [9]. This system facilitates the comprehensive development and utilization of land surrounding the evaluation system.

At the core of human life and social progress, the growth and development of cities are affected by population size and structure [28], thereby shaping population distribution patterns. The quality of life for residents, including living comfort and satisfaction of basic needs, serves as the key indicator for measuring urban life function. Therefore, the urban living function is further divided into the population-carrying function and the public service function. The population-carrying function is measured by population density and the proportion of the urban population in the total population [29]. The public service function is evaluated using metrics like per capita road area, number of beds per capita, number of educational institutions per capita, per capita domestic water consumption, and per capita domestic electricity consumption [30].

Economic vitality is the driving force behind urban development, mainly relying on the city's production function. As the social and economic structure evolves, urban economic growth primarily depends on the secondary and tertiary industries. Accordingly, the production function of cities is categorized into the industrial production function and the commercial production function. The industrial production function is reflected by the average gross industrial output value, the proportion of secondary industry in GDP, and the average investment in fixed assets. On the other hand, the commercial production function is reflected by the proportion of tertiary industry in GDP and the average investment in real estate development.

With the introduction of the eco-friendly concept and the establishment of construction standards, urban ecological protection has become an important link in regional development. To maintain the ecological balance of cities, it is necessary to strengthen environmental management and ensure sustainable development [31]. Therefore, the ecological functions of the city are divided into ecological cultivation function and environmental governance function. Ecological cultivation function includes green coverage rate of built-up areas, per capita green area, and proportion of built-up area in urban land area [32]. Environmental governance function includes average investment in environmental governance, sewage treatment rate, and harmless treatment rate of domestic waste [33,34].

Therefore, the principles of logic, hierarchy, comprehensiveness, rationality, and science guide the selection of 18 indicators (Table 1). Subsequently, the extreme value standard method is used to normalize the evaluation indicators, and the entropy weight method is employed to determine the weight of each indicator [7]. Finally, a multi-indicator model evaluated the production-living-ecological function of the Shandong Peninsula urban agglomeration. The methods are as follows.

Table 1. Comprehensive evaluation index system for production-living-ecological function.

Function	Factor	Factor Weight (WI)	Index	Indicator Description	Attribute	Indicator Weight (Wij)
Production Function	Industrial Production Function	0.42	Average gross industrial output value	Gross industrial output value/urban area	+	0.31
			Proportion of secondary industry in GDP	Directly from the statistical yearbook	−	0.27
			Average investment in fixed assets	Investment in fixed assets/urban area	+	0.42
	Commercial Production Function	0.58	Proportion of tertiary industry in GDP	Directly from the statistical yearbook	+	0.68
			Average investment in real estate development	Investment in real estate development/urban area	+	0.32
Living Function	Population-carrying Function	0.48	Population density	Total urban population/urban area	−	0.32
			Proportion of the urban population in the total population	Urban population/total urban population	+	0.68
	Public Service Functions	0.52	Per capita road area	Directly from the statistical yearbook	+	0.16
			Number of beds per capita	Number of sickbeds/total urban population	+	0.28
			Number of educational institutions per capita	Number of primary and secondary school students/number of primary and secondary schools	+	0.22
			Per capita domestic water consumption	Total domestic water/total urban population	−	0.18
			Per capita domestic electricity consumption	Total domestic electricity consumption/total urban population	−	0.16
Ecological Function	Ecological Cultivation Function	0.46	Green coverage rate of built-up area	Directly from the statistical yearbook	+	0.32
			Per capita green area	Green area/total urban population	+	0.42
			Proportion of built-up area in urban land area	Built-up area/urban land area	−	0.26
	Environmental Governance Function	0.54	Average investment in environmental governance	Investment in environmental treatment/urban area	+	0.38
			Sewage treatment rate	Directly from the statistical yearbook	+	0.27
			Harmless treatment rate of domestic waste	Directly from the statistical yearbook	+	0.35

Considering the inconsistency of the properties and dimensions of each indicator, positive and negative indicators are standardized separately. For positive indicators, where higher values indicate greater system development benefits, Equation (1) is applied. Conversely, for negative indicators, where lower values suggest enhanced system development benefits, Equation (2) is used [35]:

$$X''_{ij} = \frac{X_{ij} - min\{X_j\}}{max\{X_j\} - min\{X_j\}} \quad (1)$$

$$X''_{ij} = \frac{max\{X_j\} - X_{ij}}{max\{X_j\} - min\{X_j\}} \quad (2)$$

After dimensionless processing, the data will have a value of 0, causing a shift in the overall index. Thus, all sample observations after dimensionless processing are increased by 1, as shown in Equation (3):

$$X'_{ij} = X''_{ij} + 1 \quad (3)$$

Normalizing the probability of a sample observation value appearing in an index subsystem facilitates measuring the uncertainty of the index subsystem using the information entropy formula, as depicted in Equation (4):

$$Y_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}} \quad (4)$$

In multi-index comprehensive evaluation, the entropy method typically employs relative information entropy to measure the relative difference among different index subsystems. Furthermore, it reflects the impact intensity of each index on the ranking of investigated samples and serves as the basis for further weighting. The calculation equations are as follows:

$$e_j = -k\sum_{i=1}^{m}(Y_{ij} \times lnY_{ij}), k = \frac{1}{lnm} \quad (5)$$

$$d_j = 1 - e_j \quad (6)$$

where e_j denotes the relative information entropy, and d_j represents the relative information entropy redundancy.

Subsequently, the weight and comprehensive evaluation score of the PLE function are computed, as shown in the following equations:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (7)$$

$$F_i = \sum w_j \times Y'_{ij} \quad (8)$$

where w_j represents the weight and F_i represents the production, living, and ecological function indexes, respectively.

2.4. Coupling Coordination Degree Model

An interactive coupling relationship characterized by mutual promotion and influence exists among the production-living-ecological functions of land. Utilizing the coupling coordination degree model of the PLE function developed by established research institutes [2,8], the coupling degree types for the PLE function (Table 2) and the coupling coordination type table (Table 3) for the Shandong Peninsula urban agglomeration were established. The specific calculation formula is as follows.

Table 2. Types of production-living-ecological function coupling degree.

Coupling Type	Low Coupling	Antagonism	Running-in	Coordinated Coupling
Coupling degree (c)	(0, 0.3]	(0.3, 0.5]	(0.5, 0.8]	(0.8, 1.0]

Table 3. Types of coupling coordination degree for production-living-ecological function.

Coupling Coordination Type	Extreme Maladjustment	Severe Maladjustment	Moderate Maladjustment	Mild Maladjustment Type	Near Dysfunctional Type	Reluctantly Coordinated	Primary Coordination Type	Intermediate Coordination Type	Well-Coordinated	High-Quality Coordination Type
Coupling coordination degree (d)	(0, 0.1]	(0.1, 0.2]	(0.2, 0.3]	(0.3, 0.4]	(0.4, 0.5]	(0.5, 0.6]	(0.6, 0.7]	(0.7, 0.8]	(0.8, 0.9]	(0.9, 1.0]

$$C_{ple} = \left[(F_p \times F_l \times F_e) / \left(\frac{F_p + F_l + F_e}{3} \right)^3 \right]^{1/3} \quad (9)$$

In Equation (9), $F_p F_l$ F_e represent the indices of production, living, and ecological functions, respectively; C_{ple} represents the functional coupling degree of production (P)-living (L)-ecology (E) [35].

$$D_{ple} = \sqrt{C_{ple} \times T_{ple}} \quad (10)$$

$$T_{ple} = aF_p + bF_l + cF_e \quad (11)$$

In Equation (10), D_{ple} represents the coupling coordination degree of production (P)-living (L)-ecological (E) functions. In Equation (11), T_{ple} indicates the comprehensive evaluation score of production (P)-living (L)-ecological (E) functions, where a, b, and c are the undetermined coefficients of production, living, and ecological functions, respectively. Considering the relationship between production, life, and ecology, the undetermined coefficients are determined as $a = 1/3$, $b = 1/3$, and $c = 1/3$.

2.5. Decoupling Index

The Tapio decoupling index method is an authoritative approach commonly used to measure the decoupling relationship between two systems [15]. It uses the elasticity coefficient of different system changes to determine the decoupling relationship between the two systems, thereby avoiding the dilemma of base period selection encountered by the OECD decoupling index method. Based on this, this study calculates the ratio of the change in carbon emissions to the change in the coupling coordination degree of the production-living-ecological function, constructing the decoupling index between carbon emissions and the PLE function coupling coordination degree [14,36–38]. The specific expression is as follows:

$$E_{it} = \frac{(C_{it} - C_{it-1})/C_{it-1}}{(D_{it} - D_{it-1})/D_{it-1}} = \frac{\Delta C/C}{\Delta D/D} \quad (12)$$

In Equation (12), E_{it} represents the decoupling coefficient between the coupling coordination degree of the PLE function and the carbon emissions of city i in year t; C_{it} denotes the carbon emissions of city i in year t; D_{it} signifies the PLE function coupling coordination degree of city i in the t year; $\Delta C/C$ represents the rate of change in carbon emissions; $\Delta D/D$ indicates the change rate of the coupling coordination degree of the PLE function.

The decoupling relationship can exhibit varying degrees of strength and direction, ranging from strong to weak and from positive to negative. The Tapio classification of the decoupling relationship between emissions and economic growth, based on the direction and rate ratio of change, serves as a crucial foundation for identifying the type of the decoupling relationship. Based on the Tapio classification standard and existing research, this study applies it to discern the state of the decoupling relationship between the coupling coordination degree of the PLE function and carbon emissions (Figure 3).

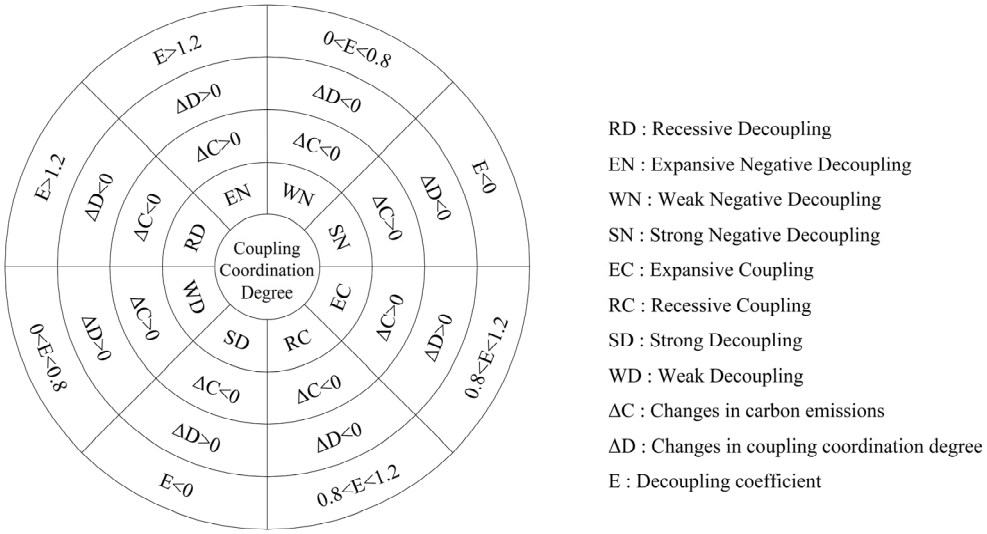


Figure 3. Quadrant diagram illustrating discrimination of decoupling relationship types.

In line with the research requirements, this study divides and defines the decoupling relationship between the coupling coordination degree of the PLE function and carbon emissions. When $\Delta C < 0$ and $\Delta D > 0$, it indicates the optimal state of strong decoupling, where carbon emissions decline while the degree of the PLE function coupling coordination increases. Conversely, strong negative decoupling represents the worst scenario: carbon emissions rise while the coordination degree of the PLE function coupling decreases, contradicting the concept of green coordinated development. The progression, from strong negative decoupling to expansion negative decoupling, expansion connection, expansion relative decoupling, and finally strong decoupling, represents the path of green coordinated development of land use. The research period spans 2001–2006, 2006–2011, 2011–2016, and 2016–2021, respectively. During the research period, only three decoupling states are observed: strong negative decoupling, expansion negative decoupling, and strong decoupling (Table 4). Therefore, this study only considers these three decoupling states.

Table 4. Criteria for decoupling types.

Decoupling State	Judgment Criteria			Evaluation Connotation
Strong negative decoupling	$\Delta C > 0$	$\Delta D < 0$	$E < 0$	Increased carbon emissions. Functional coupling coordination degree decreases.
Expansion negative decoupling	$\Delta C > 0$	$\Delta D > 0$	$E > 1.2$	Increased carbon emissions. Coordination degree of functional coupling rises slowly.
Strong decoupling	$\Delta C < 0$	$\Delta D > 0$	$E < 0$	Reduction of carbon emissions. Functional coupling coordination increased.

3. Results

3.1. Spatiotemporal Evolution Characteristics of Production-Living-Ecological Function

From 2001 to 2021, the overall performance of the production-living-ecological function in the Shandong Peninsula urban agglomeration showed improvement (Figure 4d–f). The production function index increased from 51.14 to 61.75 but experienced periodic declines between 2001 and 2011. This trend might be attributed to the relatively backward industrial structure of the Shandong Peninsula urban agglomeration, with an overly high proportion of manufacturing industries and insufficient industrial diversification, leading to a lack of power for production development. However, from 2011 to 2021, the production

function steadily improved, possibly due to the gradual optimization of the three industrial structures and enhanced production competitiveness. The living function index increased from 51.43 to 66.44. The rapid urbanization in the study area resulted in a significant influx of people into the city, leading to a considerable expansion of urban living areas and a notable enhancement in living standards from 2011 to 2021. However, the rapid expansion of urbanization and population scale also led to increased pollutant emissions and severe resource consumption. Additionally, inadequate attention to ecological environment protection and restoration resulted in periodic declines in ecological function. Subsequently, initiatives such as the "Ecological Shandong" projects and the "13th Five-Year Plan" for ecological and environmental protection in Shandong Province focused on promoting green production and lifestyle, strengthening ecological protection and restoration efforts, and cultivating residents' environmental awareness. These efforts gradually shaped the ecological construction pattern of the Shandong Peninsula urban agglomeration, leading to steady progress in ecological function levels from 2006 to 2021.

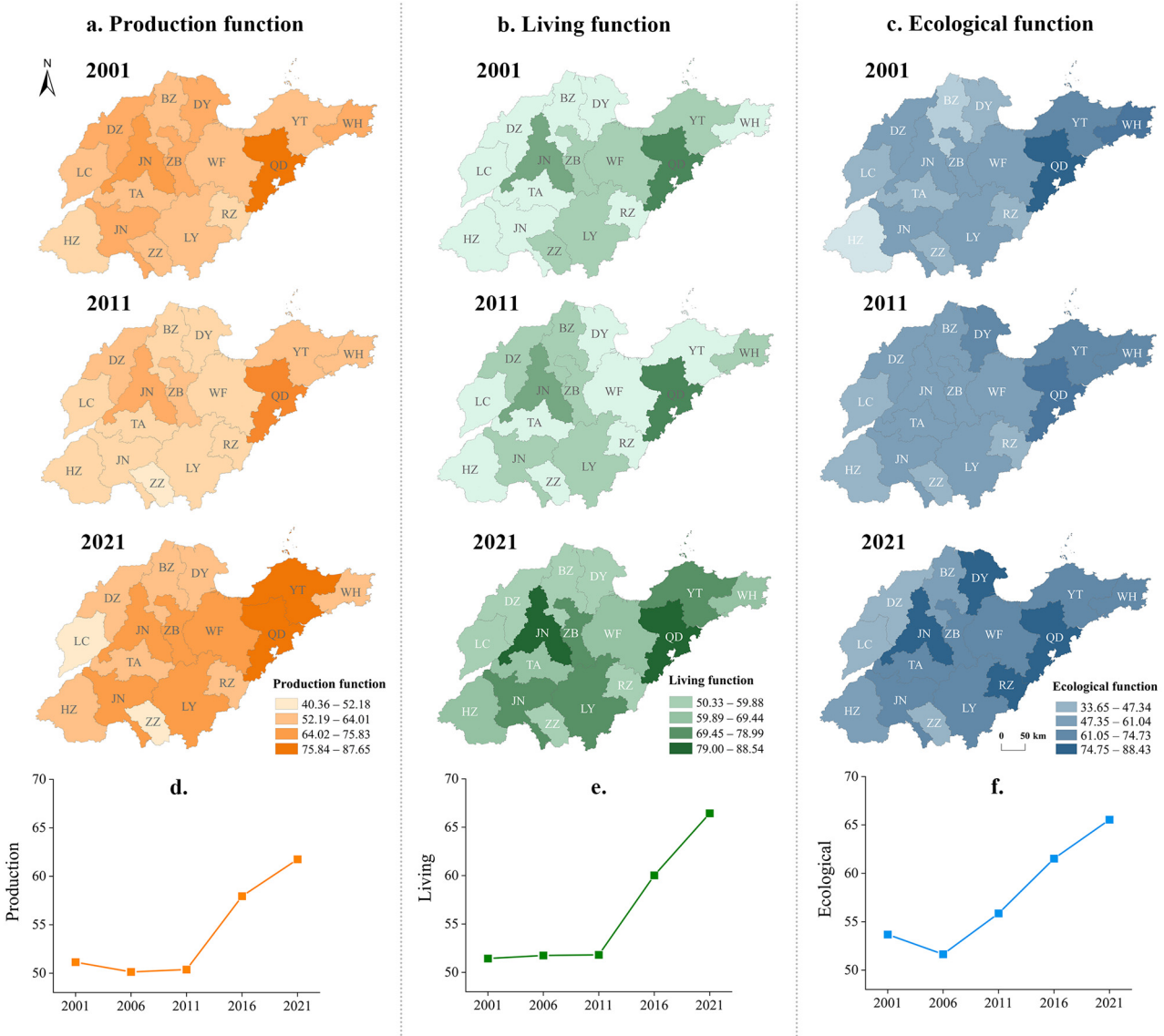


Figure 4. Spatial and temporal evolution of production-living-ecological function in Shandong Peninsula city cluster for 2001, 2011, and 2021: (**a**–**c**). The spatial evolution of production, living and ecological functions; (**d**–**f**). The temporal evolution of production, living and ecological functions.

In terms of spatial distribution, Qingdao and Jinan play a leading role in production, with the production function of eastern and central Shandong significantly surpassing that of western Shandong (Figure 4a). In terms of living function, Qingdao has the highest function index, being the only city in Shandong Province with a living function index exceeding 70. Jinan, Zibo, Weifang, and Linyi follow suit with high indices, while Heze records the lowest. The spatial distribution of the living function across the 16 cities in Shandong Province reflects a pattern where central cities drive the development of surrounding cities (Figure 4b). The "dual-core" cities, Jinan and Qingdao, are urbanization hubs with exceptional levels of living function. During the study period, they have been pivotal in radiating development to surrounding cities, thereby minimizing internal differences within urban agglomerations caused by urbanization. However, the speed and quality of urbanization in Zaozhuang, Binzhou, and other areas require improvement, with their living function levels lagging. After experiencing the periodic decline in ecological function from 2006 to 2011, the growth rates of ecological function indices vary significantly across different regions and cities. The central and eastern regions of Shandong Province have witnessed notable improvements in ecological function, characterized by higher levels in the east and lower levels in the west (Figure 4c).

3.2. Spatiotemporal Characteristics of Coupling Coordination Degree of Production-Living-Ecological Function

From 2001 to 2021, the coupling coordination degree of the production-living-ecological function within the Shandong Peninsula urban agglomeration showed different growth trends (Figure 5). Notably, the coupling degree among cities surpassed that of coupling coordination. While the coupling degree reflects the degree of correlation among the three subsystems of production, life, and ecology, the coupling coordination degree places greater emphasis on the quality of these subsystems. Therefore, the comparative results show ample opportunities for enhancing the coordinated development of the PLE function in various cities.

During the study period, the average coordination degree of PLE function coupling increased from 0.72 to 0.80, transitioning from an intermediate coordination type to a good coordination type. In 2001, the coupling coordination degree ranged between 0.57 and 0.90, with Heze City registering the lowest and Qingdao City the highest. Coordination types varied from reluctant coordination to primary coordination, intermediate coordination, and good coordination. By 2021, the coupling coordination degree ranged between 0.64 and 0.93, encompassing primary coordination, intermediate coordination, good coordination, and high-quality coordination types. Zaozhuang City exhibited the lowest coupling coordination, while Qingdao City recorded the highest. The distribution among coordination types was 2, 5, 8, and 1, respectively, showing distinct differences between the east and the west. The differences between the east and the west stem from initial differences such as location, resource factors, human capital, and policy frameworks. Since the reform and opening up, the eastern coastal region with rich resources has become the forefront of urban agglomeration development, while the western inland areas have faced challenges in development. These initial differences have widened the gap in urbanization, industrial restructuring, and ecological governance between the east and west of the Shandong Peninsula urban agglomeration over the past two decades. Therefore, reducing the differences between them and promoting the coordinated development of urban agglomerations is a key priority for future endeavors.

Overall, from 2001 to 2021, the coupling coordination degree of the three functions in the study area has shown steady improvement, reflecting synchronized and coordinated growth across all functions. At the prefectural and city levels, the majority have experienced coordinated growth in production and living functions. Therefore, the evolution trend of the ecological function has become the main factor affecting the growth of the coupling coordination degree of the PLE function. This phenomenon is particularly significant in prefectures and cities where there have been significant increases or decreases in the coupling

coordination degree. For example, Rizhao and Heze have witnessed a significantly higher growth rate in ecological function compared to production and living functions, resulting in a significant increase in the coupling coordination degree overall. Conversely, Liaocheng has seen steady progress in production and living functions but a significant deterioration in ecological function, leading to an overall decline in the coupling coordination degree. In Qingdao, ecological function has shown improvement levels in production and living functions, maintaining a consistent trend in the overall coupling coordination degree.

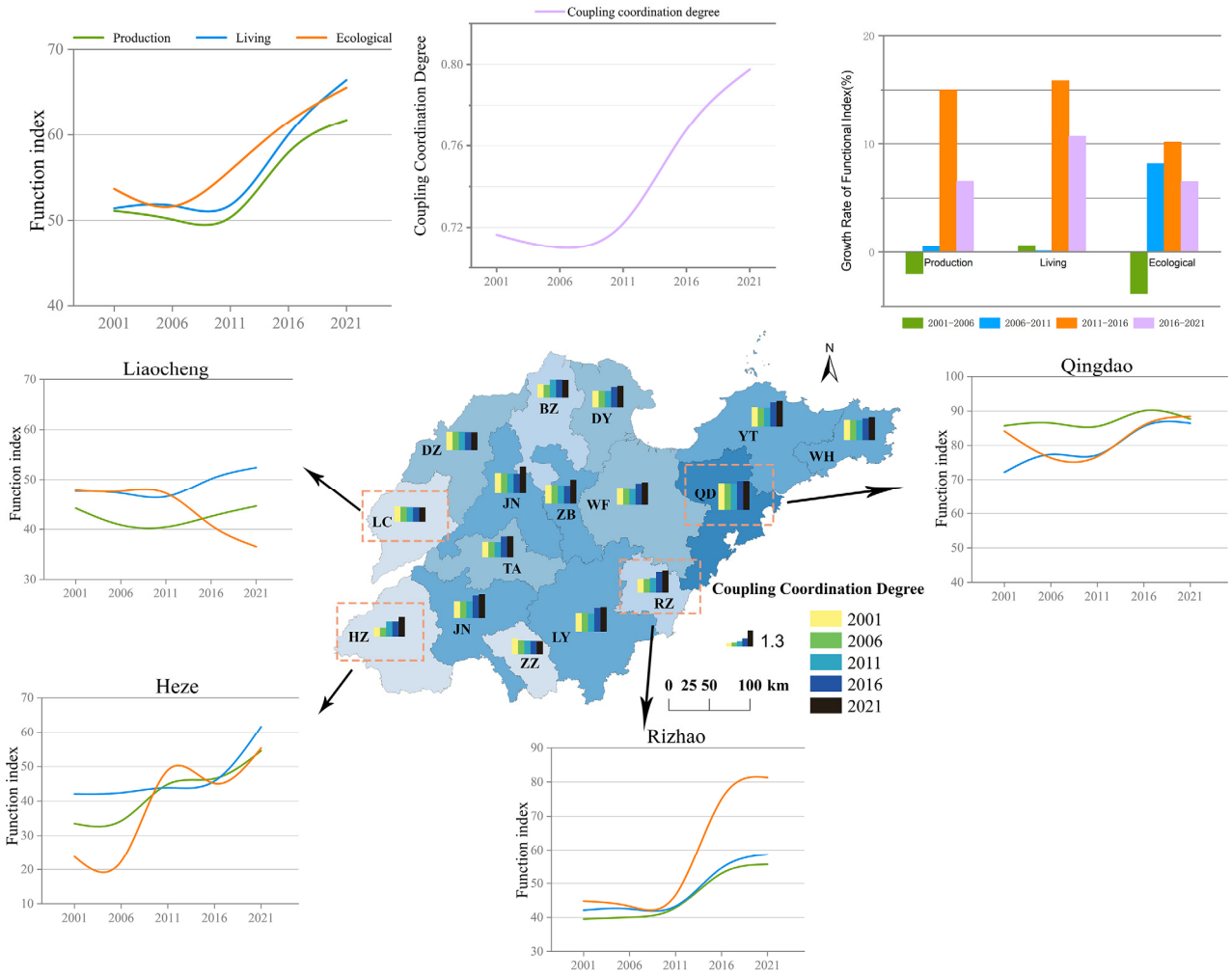


Figure 5. Spatial changes in coupling coordination degree in different characteristic units in Shandong Province.

Compared to 2001, the coupling coordination degree of the PLE function in the study area has overall improved. This progress can be attributed to the implementation of the master plan for the Shandong Peninsula urban agglomeration, which has established a network development framework consisting of "two circles and four districts" to foster coordinated development among other cities under the dual-core influence of Jiqing. Additionally, Shandong Province's efforts to build a high-level urban agglomeration with advanced technology, sustainable development, and ecological preservation present a significant historic opportunity for its new development phase.

3.3. Analysis of Temporal and Spatial Characteristics of Carbon Emissions

In 2021, the total carbon emissions from land use in the Shandong Peninsula urban agglomeration reached 430,052,500 tons, marking an increase of 80.21% compared to 2001. The overall carbon emissions of the urban agglomeration experienced an upward trend

(Figure 6a). From 2001 to 2016, carbon emissions nearly doubled, reflecting the region's economic development and population growth over the past two decades. The surge in carbon emissions can be attributed to the industrialization process, where economic growth led to a substantial increase in emissions. However, from 2016 to 2021, the region experienced a notable shift. Because of the lag effect brought about by the industrial restructuring and advancement in technology, carbon emissions were effectively managed. Total carbon emissions stabilized around 430 million tons, with the rate of increase dropping from 25% to 2%.

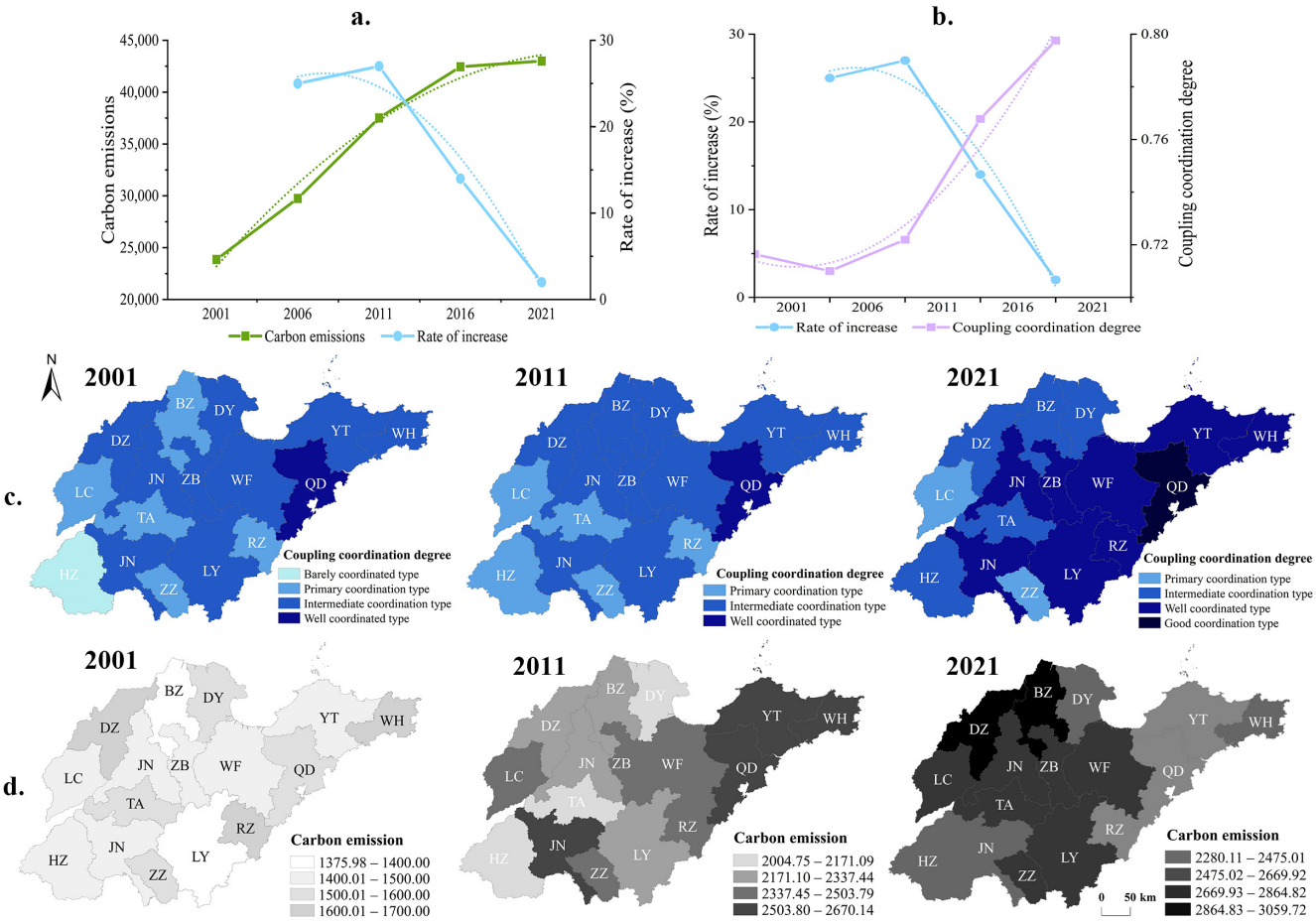


Figure 6. Changes in carbon emissions and growth rate of Shandong Peninsula urban agglomeration from 2001 to 2021: (**a**). Changes in carbon emissions; (**b**). Changes in the coupling coordination degree; (**c**). The spatial evolution of the coupling coordination degree; (**d**). The spatial evolution of carbon emissions.

At the spatial level, there is a polarized trend in the change in carbon emissions (Figure 6b). In areas where industrial restructuring is progressing rapidly, like Qingdao and surrounding cities, carbon emissions show a downward trend. However, in older industrial cities such as Jinan, Zibo, and others, along with Binzhou and Zaozhuang, where industrial transformation is sluggish, carbon emissions continue to fluctuate and rise.

The spatial distribution of carbon emissions from land use shows significant PLE function coupling coordination degree anisotropy (Figure 6c,d). From 2001 to 2021, high-value areas of carbon emissions in the study area generally followed a "west to east to west" trajectory, while high-value areas of PLE function were mainly concentrated in the eastern part of Shandong Province, gradually extending westward. This shift is attributed to the implementation of green development, technological revolution, and industrial transformation and upgrading in the production sector. As a result, while productivity has improved, carbon emissions have been effectively controlled. In addition, the promotion of

green lifestyles and efforts to protect and restore the ecological environment have intensified. At the same time, heavily polluting enterprises have been deregistered and relocated.

3.4. Decoupling Relationships between Coupling Coordination Degree of Production-Living-Ecological Function and Carbon Emissions

3.4.1. Analysis of Temporal and Spatial Characteristics of Decoupling Relationship in Urban Agglomeration

From 2001 to 2011, the decoupling relationship between the coupling coordination degree of the PLE function and carbon emissions in Shandong Peninsula urban agglomeration mainly exhibited strong negative decoupling (Table 5). During this period, the extensive economic development model prioritized increasing factor inputs and expanding production scale, neglecting innovation in production technology and the coordinated development of land multi-function, resulting in a poor decoupling relationship. From 2011 to 2021, there was a significant improvement trend towards transitioning to strong decoupling. Carbon emission levels decreased, and the coupling coordination degree of the PLE function improved, reaching the optimal state in the decoupling relationship.

Table 5. Decoupling index between coupling coordination degree of production-living-ecological function and carbon emissions in Shandong Peninsula urban agglomeration from 2001 to 2021.

City	2001–2006	2006–2011	2011–2016	2016–2021
Jinan	−18.98	−133.59	−39.66	−0.05
Qingdao	−89.67	−210.67	−1.06	−19.84
Zibo	−59.47	−79.28	−25.10	−0.16
Zaozhuang	−5.46	−14.48	−5.80	−46.66
doy	−81.25	−28.65	3.50	−3.08
Yantai	−12.98	34.39	−0.08	−0.63
Weifang	−29.18	−77.91	1.95	−2.74
Jining	−96.88	188.39	−0.03	−0.22
Tai'an	−337.79	−9.34	2.41	−1.31
Weihai	−47.21	−2422.09	−0.91	−0.10
sunshine	−30.44	16.04	−0.09	−0.39
Linyi	109.72	−30.90	1.43	−1.92
Texas	54.60	−37.89	−11.80	−100.95
Liaocheng	−16.79	−47.77	−12.12	−50.80
Binzhou	−13.95	1.24	−82.01	−18.67
Heze	−95.71	−0.16	−1001.52	−0.76

During the study period, the types of decoupling relationships observed include strong negative decoupling, expansion negative decoupling, and strong decoupling, with an overall favorable decoupling trend (Figure 7). Benefiting from the implementation of the 13th Five-Year Plan for ecological and environmental protection in Shandong Province, cities have managed to maintain steady economic growth while adjusting energy and industrial structures to promote greener production and lifestyles. Spatial control systems for the ecological environment have been established, efforts to strengthen ecological protection and restoration have been intensified, and endeavors to promote coordinated green development have been pursued. At the same time, the development planning of the Shandong Peninsula urban agglomeration has been steadily progressing.

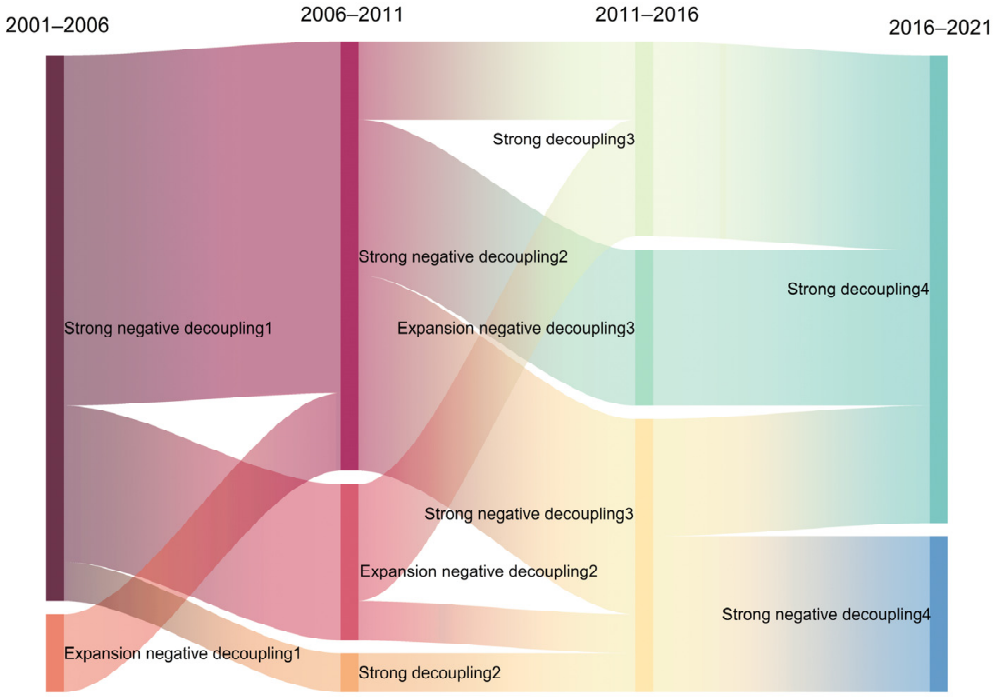


Figure 7. Evolution of decoupling types between the coupling coordination degree of production-living-ecological function of the Shandong Peninsula urban agglomeration and carbon emissions from 2001 to 2021.

3.4.2. Analysis of Spatiotemporal Characteristics of Decoupling Relationship between Cities and Regions

From 2001 to 2011, most cities in the Shandong Peninsula urban agglomeration exhibited a strong negative decoupling state between the coupling coordination degree of the three functions and carbon emissions. The evolution process of decoupling can be categorized into four trends at the local city level. The first category comprises the high-speed evolution group, primarily coastal cities such as Qingdao, Yantai, Jining, Weihai, and Rizhao (Figure 8a). These cities generally started with a relatively high initial level of coupling coordination for the PLE function, which greatly improved from 2011 to 2016, predominantly achieving strong decoupling during this period. The second category is the medium-speed evolution group, including Jinan, Zibo, Dongying, Weifang, and Tai'an (Figure 8b). Most of these cities maintained a strong negative decoupling level for a long time, achieving strong decoupling from 2016 to 2021. The third category, the retrogressive evolution group, mainly experiences backward decoupling levels during the decoupling evolution process (Figure 8c). The main representatives are Linyi and Heze, both of which experienced a fluctuating retrogression of decoupling levels from 2011 to 2016, eventually reaching a strong decoupling state from 2016 to 2021. The fourth category is the lag evolution group, including Zaozhuang, Dezhou, Liaocheng, and Binzhou (Figure 8d). The coupling coordination degree of the PLE function in these cities generally declined overall, failing to reach the ideal level of strong decoupling during the research period. The transformation and upgrading of industrial structures in this group lag behind, and land use coordination requires further improvement.

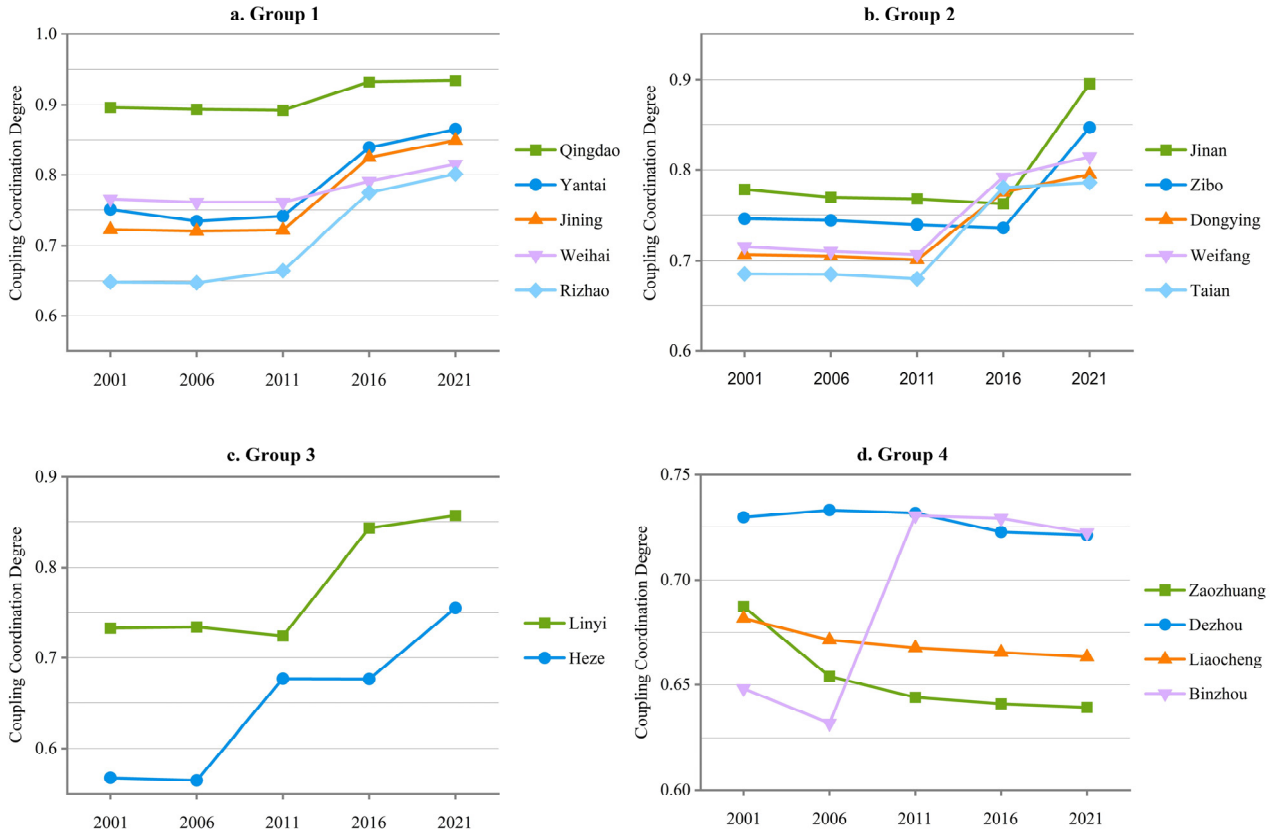


Figure 8. Temporal changes in coupling coordination degree in different characteristic units in Shandong Province from 2001 to 2021.

During the process of decoupling relationship transformation, most cities have experienced a transitional phase where the coupling coordination degree initially decreased and then increased, while carbon emissions first increased and then decreased. This suggests that the coordinated use of land functions is crucial for reducing carbon emissions. The path of decoupling from strong negative decoupling to expansion negative decoupling and then to strong decoupling represents the trajectory for low carbon coordinated and optimized development.

4. Discussion

With the advancement of industrialization and urbanization, urban agglomerations, as spatial organization forms, serve as important platforms for realizing major national development strategies in the new developmental phase. Shandong Peninsula urban agglomeration, being the most developed among urban agglomerations in the Yellow River Basin, has encountered a series of problems, such as resource scarcity and ecological degradation stemming from its rapid economic growth and urbanization. The Shandong Peninsula urban agglomeration is facing a problem of balancing resource utilization and sustainable development. This study addresses this problem through the following three aspects.

First, based on research results and system theory related to the production-living-ecological function and guided by principles of science, practical applicability, operational feasibility, and regionality, an evaluation index system for the PLE function, including production function, living function, and ecological function indices is constructed. Secondly, based on the decoupling theory and models, the decoupling relationship between the PLE function coupling coordination system and the carbon emission system is analyzed using the elasticity coefficient to measure changes within the two systems. By calculating the ratio of carbon emission changes, a decoupling index between carbon emissions and

PLE function coupling coordination is constructed. Finally, using the previously described method, the PLE function coupling coordination, carbon emissions, and decoupling index of Shandong Peninsula urban agglomeration is dynamically evaluated for the years 2001, 2006, 2011, 2016, and 2021. Subsequently, the dynamic evolution, distribution pattern, and influencing factors of these parameters are analyzed.

Shandong Peninsula urban agglomeration, ranked among the top 10 national urban agglomerations, should catch up with the advancement of leading urban agglomerations while serving as a link for promoting regional coordinated development. From 2001 to 2021, the urban agglomeration experienced phased industrialization and urbanization, leading to significant changes in its land PLE function pattern and exhibiting a favorable decoupling trend with carbon emissions. Previous studies have suggested an enhancement in the coupling coordination degree between the intensity of the PLE function and land use carbon emissions in urban agglomerations [1,39,40]. This study further verified this conclusion by using different models across different research areas, aligning with recent policy guidance aimed at achieving national high-quality development goals. The positive evolution of the decoupling relationship is attributed to the implementation of sustainable development strategies. By adhering to the principles of the scientific development concept, we can maintain economic growth, improve innovation capabilities, and achieve both economic restructuring and energy conservation with emissions reduction.

4.1. Formation Mechanism of Decoupling of Coupling Coordination of Production-Living-Ecological Function and Carbon Emissions

The positive decoupling relationship between the coupling coordination degree of the PLE function and carbon emissions can be fundamentally attributed to the transformation of the human-land relationship. This transformation is evident in the organized allocation and spatial reconstruction of limited urban land resources among different dominant functions. As the external manifestation of comprehensive spatial utilization of land for multifunctional purposes, the coupling and coordination of the PLE function serve as central points along this transmission path. The factors that promote its spatiotemporal evolution are the problems and dilemmas faced during the process of social and economic development. To maintain rapid economic growth, an extensive development model was adopted, characterized by high investment and consumption at the expense of the ecological environment. In addition, the rapid progress of industrialization and urbanization has stimulated the expansion of production functions and increased the demand for living functions, often at the expense of ecological functions. This has led to an alarming depletion of resources and a continuous deterioration of the living environment, prompting a shift in human–land relationships from one-way utilization to interdependence. From 2001 to 2021, the Shandong Peninsula urban agglomeration has undergone stages of industrialization and urbanization. In this process, the intensive use of land and the optimization of urban planning have reduced the encroachment on ecological space and improved the versatility of land. At the same time, with the transformation of the industrial structure from agriculture to industry and services within the Shandong Peninsula city cluster, more environmentally friendly and resource-saving industries have been developed. This transition reduces the negative impact on ecological functions while improving production efficiency and quality of life, contributing to the reduction of carbon emissions. During the study period, these major changes experienced by the Shandong Peninsula urban agglomeration not only improved the coupling coordination degree of PLE function but also reduced carbon emissions caused by land use change. In general, in terms of production and livelihood, the overall industrial structure has shifted from agriculture to industry and service sector. In terms of ecology, urbanization has progressed towards large-scale, intensive development, gradually eliminating small-scale urbanization and improving urban land use and energy consumption efficiency. This transformation has significant implications for the urban spatial carbon cycle, improving the carbon metabolism efficiency of the land system and ultimately reducing land carbon emissions.

4.2. Policy Recommendations

Based on the above research results, two major problems emerge regarding land use in the Shandong Peninsula urban agglomeration. First, there is a lack of harmony in the development of the three functions within the prefecture. Second, there is an imbalance in the overall east–west development of the urban agglomeration. Therefore, based on the evolution pattern of land function coupling coordination degree and the decoupling trend of carbon emissions observed during the study period, the following policy suggestions are proposed in accordance with the development characteristics of the study area.

Considering the uncoordinated development of the PLE function within cities and prefectures, several measures can be taken. In the industrial sector, there should be a focus on promoting industrial upgrading and transformation, fostering industrial cooperation, and encouraging the division of labor between cities and prefectures. This involves transforming traditional industries into high-end and intelligent ones while simultaneously developing green and circular economies. In the social aspect, efforts should be made to optimize the urban-rural structure, promote the integrated development of urban and rural areas, and improve the quality of urbanization. Ensuring equal access to public services and living standards for urban and rural residents is paramount. Regarding the ecological environment, two main strategies can be pursued. First, the formulation and strict implementation of the ecological protection red line policy is essential to safeguard important ecological function areas, sensitive ecological environments, and areas rich in biodiversity. Second, research and development should be encouraged, as well as the application of green energy and clean technology to reduce carbon emissions and facilitate the industry's transition towards sustainability.

Given the differences between the eastern and western regions of urban agglomerations, several strategies can be implemented to address these discrepancies. First, regarding the economy, increased investment should be directed towards the western region, particularly in infrastructure, high-tech industries, education, and research and development, to stimulate local industry growth and economic development. Second, implementing tailored industrial policies can facilitate the mitigation of mature industries from the eastern to the western region, thus promoting a more balanced distribution of industries. Third, supporting the development of distinctive economic sectors in the western region, such as agricultural processing and cultural tourism, can help build regional brands and attract external investment. In terms of environmental governance, strict environmental protection policies should be established to ensure that the western region adheres to principles of green and sustainable development during its process of development. Additionally, promoting cooperation between the eastern and western regions in environmental protection technology and resource utilization can yield synergistic effects in environmental governance. As a leader in ecological protection within the Yellow River Basin, Shandong Peninsula urban agglomeration should actively demonstrate its exemplary role in ecological preservation and high-quality development. A comprehensive regional development plan should be formulated to clarify the development orientations and goals of both the eastern and western regions, ensuring their complementary development. Establishing a regional coordinated development mechanism, including fiscal transfers, tax incentives, and industrial support policies, can help narrow the development gap between the two regions. Furthermore, strengthening the construction of regional transportation networks and improving interconnectivity between the eastern and western regions will promote the seamless flow of personnel, capital, information, and other resources. Encouraging collaborative relationships between cities in the eastern and western regions, along with resource and market sharing, can foster mutual benefits and promote the integration of industrial chains, thus forming closer economic bonds between cities within the region.

The study of urban agglomerations is a starting point for examining national macro development strategies. Expanding and applying the research insights from urban agglomerations to the national and provincial levels can fully utilize the advantages of different levels of government, form a policy environment of linkage and coordinated promotion, and more effectively achieve sustainable development of society, economy, and environment. At the national level, establish unified land use and carbon reduction standards, clarify carbon emission

benchmarks and targets for land use, and provide guidance for provincial policy formulation. Promote the research and application of low-carbon technologies, support the research and development of low-carbon technologies through national scientific research projects and innovation funds, and promote their application in land use and urban planning. Establish and improve a national carbon trading market and incentivize enterprises and regions to reduce carbon emissions through market mechanisms. At the provincial level, based on the actual situation of the province, formulate land use plans that are in line with local characteristics, emphasizing ecological protection and land multifunctionality. Based on the overall national goals, establish provincial-level carbon emission quotas and implement quota management for key emitting enterprises. Through the implementation of these policies, a joint effort can be formed at the national and provincial levels to promote the rational use of land resources and effective control of carbon emissions, achieving coordination and unity between economic and social development and ecological environment protection. This not only responds to the country's dual carbon goal but also provides specific paths for local governments to achieve sustainable development.

4.3. Limitations and Future Prospects

Constrained by data collection limitations and quantitative processing methods, the measurement of the production-living-ecological function to a certain extent overlooks the objective conditions that shape various indicators. The validity of the results may be affected by objective differences such as regional resource endowments and subjective differences such as residents' diverse functional needs. It is worth noting that peripheral city areas within the urban agglomeration still lag in terms of urbanization. Future research could delve into these areas to explore the underlying causes and developmental paths of their backwardness, thereby leveraging the pivotal role of central cities in driving progress. In addition, this study explores the impact and mechanisms of the overall coordination degree of the PLE function on carbon emissions. Moving forward, it is important to deepen research by analyzing the internal components of production, life, and ecology. This will aid in uncovering the underlying drivers for carbon emission reduction, thus paving the way for a better development path towards green, coordinated, and sustainable development.

5. Conclusions

In this study, the Shandong Peninsula urban agglomeration, one of China's top 10 urban agglomerations, serves as the research focus. The Tapio decoupling model is employed to analyze the interplay between the production-living-ecological function coupling coordination degree and regional carbon emissions. The decoupling relationship between these two systems is analyzed as follows:

(1) From 2001 to 2021, the overall trajectory of the PLE function level in Shandong Peninsula urban agglomeration showed an upward trend. However, significant differences were observed between the eastern and the western regions.
(2) From 2001 to 2021, carbon emissions in Shandong Peninsula urban agglomeration showed a trend of initial increase followed by subsequent decrease. Notably, the spatial distribution of carbon emissions from land use showed significant heterogeneity in the PLE function coupling coordination degree.
(3) From 2001 to 2021, the decoupling relationship between the PLE function coupling coordination degree and carbon emissions in Shandong Peninsula urban agglomeration transitioned from strong negative decoupling to strong decoupling, maintaining a good decoupling trend overall. However, decoupling regressed in certain cities, resulting in significant regional differences in decoupling dynamics.
(4) The findings of this study underscore the positive implications of coordinated land function utilization for carbon emission reduction. Simultaneously, it also proposes a low-carbon coordinated and optimized development path, characterized by the sequence: a transition from strong negative decoupling through expansion negative decoupling to strong decoupling.

The results of this study not only emphasize but also expand the positive impact of coordinated land use on carbon reduction. Specifically, the research findings reveal the relationship between production and living ecological functions and carbon emissions in different urban areas within the Shandong Peninsula urban agglomeration. The comprehensive analysis of this study, including a detailed study of the spatiotemporal evolution of PLE functional coupling coordination and carbon emissions, provides a more refined understanding of complex dynamics. In addition, the study identified different decoupling patterns throughout the region, ranging from strong negative decoupling in rapidly developing coastal cities to lagging decoupling progress in some inland areas. These insights contribute to a more comprehensive exposition of the potential for low-carbon and sustainable development within urban agglomerations, laying the foundation for more targeted and effective policy interventions.

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