Pol. J. Environ. Stud. Vol. 32, No. 6 (2023), 5389-5402
DOI: *10.15244/pjoes/169514* ONLINE PUBLICATION DATE: 2023-09-11

Original Research

A Study on Influence of Land Morphology on Carbon Emissions: The Case of Yangtze River Delta Region

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Received: 15 April 2023
Accepted: 12 July 2023

Abstract

This study focuses on the impact of regional land use land morphology on carbon emissions from a regional perspective. The study first quantifies the land morphology of the Yangtze River Delta region from 2005 to 2017 by calculating a series of parameters. These parameters include city scale, shape complexity, shape fragmentation, spatial aggregation and spatial diversity. Then, a panel data model of these parameters and overall urban carbon emissions was developed and analyzed by multiple linear regression. It was found that city scale spatial diversity had significant positive effects on carbon emissions in the Yangtze River Delta region, while the complexity of urban shape had a negative effect. Based on these findings, the study proposes that in terms of overall urban structure, it is necessary to strengthen and improve the degree of compact clustering of morphology and functions, and advocate a highly connected "polycentric" agglomeration cluster model; within cities, the complexity and fragmentation of land morphology should be reduced through a "narrow roads and small blocks" transportation model.

Keywords: carbon emission, land morphology, Yangtze River Delta region

Introduction

The climate crisis is a serious challenge that the world is currently facing. According to “Global Climate 2020”, despite the cooling effect of the La Nina event, 2020 was still one of the hottest years on record, and 2015-2020 was the hottest six-year period on record. The global average temperature is about 1.2ºC higher than the period from 1850 to 1900, before industrialization. The Intergovernmental Panel on Climate Change (IPCC) stated in its Sixth Assessment Report that human activities have caused a large amount of greenhouse gas emissions since industrialization, and cities where production and living activities are concentrated have become the main source of global carbon emissions [1]. Cities consume a lot of energy while creating economic growth. Therefore, cities are not only the places that are affected by climate change and bear risks, but also the key components for solving this crisis.

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In the 2015 Paris Climate Conference, participating countries adopted the "Paris Agreement", which proposed to limit the global average temperature increase to within 2ºC above pre-industrial levels. Since then, some important countries and regions in the world, such as Russia, the United States, and the European Union, have already published their timetables for "peak emissions" and "carbon neutrality". In 2020, the Chinese president, for the first time, proposed China's goals of "peak emissions" and "carbon neutrality" at the United Nations General Assembly, that is, China will strive to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 [2]. In the context of the goals of "peak emissions" and "carbon neutrality", reducing carbon emissions is China's long-term strategy, and cities are the main sources of energy consumption and greenhouse gas emissions. Therefore, "carbon emission reduction" in cities is key to China's achievement of the goals of "peak emissions" and "carbon neutrality". There are many factors that affect the total amount of carbon emissions in cities. Existing research shows that the level of economic development, industrial structure, energy intensity, and population density will significantly affect the total carbon emissions in cities [3].

In the past few decades, with the rapid development of urbanization in China, the land and spatial forms of many cities have undergone structural changes. Previous studies have shown that changes in land use types and the size of built-up areas can affect the scale and agglomeration effects of economic development, the construction of urban transportation systems and networks, and thus have an impact on energy use and carbon emissions in cities [4, 5]. So, what other factors related to urban land forms can affect carbon emissions? At the same time, China's urbanization will continue to grow at a high speed in the future. Therefore, the optimization and adjustment of land forms to meet the requirements of emissions reduction and the implementation of China's " emission peak and carbon neutrality" strategy are the starting points of this article.

This article takes 41 cities in the Yangtze River Delta region as the research object, analyzes the characteristics of urban land form changes based on relevant indicators and carbon emission data, and explores the coupling relationship between land form indicators and urban carbon emissions through regression analysis and other methods. By studying the impact mechanism of land form indicators such as urban scale, form characteristics, and agglomeration degree on carbon emissions, this article proposes optimization strategies for land forms in future urban development to help China achieve its " emission peak and carbon neutrality" goals.

Related Concepts and Research

Land Morphology

Land Morphology refers to the material form of landuse. When it comes to the form and distribution characteristics of built-up areas in region, it means "Land Morphology" in English, which is the deep-seated structure of landuse under the comprehensive influence of natural environment, history and culture, social economy and other factors in a certain period of time [6, 7], and its development and evolution is one of the main forms of man-land relationship. Land Morphology generally includes the external geometric form of urban land use, the functional layout of internal elements and the architectural organization pattern [8, 9].

The research on the theory of Land morphology began earlier in the 1950s when March and Martin founded the "Research Center for Urban Form and Land Use" at Cambridge University in England. They proposed that cities are composed of basic spatial elements, which are combined to form different open and enclosed spaces, and at the same time produce traffic links [10-12]. The study of Land morphology analyzes the basic spatial geometric elements of cities from different scales and perspectives, so as to describe these elements and their relationships by quantitative and qualitative methods [13, 14]. In the process of development, Gradually absorbed by urban planning, architecture, geography and other disciplines, Formed a relatively extensive theoretical system of Land morphology. It can be divided into the development history of Land morphology [15], the evolution and mechanism of Land morphology [16], the study of urban spatial structure model [17], the analysis method of spatial form [18, 19], etc. The research ideas and methods are constantly expanding, and the importance of Land morphology to human settlement environment is also rising.

Urban Carbon Emissions

The research on urban carbon emissions has become a hot topic under the background of global climate crisis. Urban carbon emissions refer to the general name of carbon dioxide emissions generated by energy consumption in the process of operation of urban related industries, residents' lives, transportation and other factors [20]. City is the concentration of life and economic activities, which needs to consume a lot of energy to meet the needs of production and life. IPCC pointed out that the main cause of global warming is carbon dioxide produced by human activities, in which the carbon emissions caused by living, transportation and industrial production in urban areas account for about 75% of the total global carbon emissions, and cities have become the most important source of global carbon emissions.

Related Research

Land morphology is related to carbon emissions through some media elements, that is, Land morphology reflects urban expansion through transportation and infrastructure layout, which indirectly has a long-term and root-cause impact on carbon emissions. In recent years, with more and more media elements discovered by researchers, the influence of Land morphology on carbon emissions has been paid more and more attention.

The research on carbon emission effect based on Land morphology can be roughly divided into three different aspects. The first is to discuss the impact of spatial forms of different cities on carbon emissions of the whole city or region. Ou et al. [21] quantitatively analyzed the relationship between urban form and carbon emissions through panel data modeling, and pointed out that compact and multi-core urban pattern is conducive to carbon emission reduction. Yi Yanchun et al. [22] quantified the Land morphology with the density of residential areas. Through empirical analysis, it was found that the residential density greatly affected carbon emissions, and the compact Land morphology was conducive to low-carbon development. Shu Xin et al. [23] constructed the corresponding panel data model by analyzing the carbon emission center shift of the Yangtze River Delta urban agglomeration and its relationship with urban land growth, and found that the urban form is compact, but the unreasonable function layout and configuration will have a negative effect on carbon emission reduction. Shi et al. [24] analyzed and concluded that the irregularity and complexity of urban form were significantly correlated with urban carbon emissions from the perspectives of urban government policy, region, population and economic scale. Macro-scale studies mostly quantify Land morphology through different model construction, and the conclusion is that compact and reasonable Land morphology and functional layout are conducive to low-carbon development of cities, and the "multi-center" development model is more conducive to the realization of carbon neutrality [25, 26].

Second, at the meso level, it discusses the influence of Land morphology on carbon emissions of different urban sectors such as construction, transportation and industry. Ye Yuyao et al. [27] pointed out that the Land morphology friendly to low-carbon transportation is to use green wedge green space system to divide traffic corridors by combing and summarizing the cases of the impact of urban spatial structure on traffic and carbon emissions. Yang Yanfang et al. [28] analyzed the factors affecting Beijing's building carbon emissions through STIRPAT model based on building life cycle theory. The results showed that population urbanization, per capita building living area and other factors greatly affected carbon emissions. Xia et al. [29] built a geographically weighted regression model with the mixed level of urban residential density and land use as independent variables, and analyzed that the urban residential density in Hangzhou has the most significant impact on traffic carbon emissions. The related research at the meso-scale level simplifies the research object, and puts forward more specific and targeted suggestions and references for the development of low-carbon cities by studying the relationship between urban form and carbon emissions in a single sector, which is beneficial to the formulation of carbon neutral technical routes in relevant departments.

The third is to study the impact of Land morphology on carbon emissions caused by residents' living, traveling, working and activities from the micro level. Shao Ran et al. [30] calculated the carbon emissions of residents' communities based on the questionnaire statistics of energy consumption behaviors such as travel of Beijing residents, and concluded that factors such as building density and land use pattern significantly affected the direct carbon emissions of residents' behaviors. Ma Jing et al. [31] made an empirical study on the relationship between urban form and individual travel carbon emissions from the perspective of micro-individual behavior, and pointed out the importance of building a low-carbon city and guiding low-carbon travel. Qi Bin et al. [32] found through questionnaire survey that there is a curve correlation between household income and carbon emissions of residential buildings, while population density is negatively correlated with carbon emissions of residential buildings. In addition to ordinary urban form indicators, micro-level research usually introduces other control variables such as population and economy, and analyzes the impact of urban form on carbon emissions caused by individual behavior of residents in a more comprehensive and detailed way, which is helpful to guide individual low-carbon awareness and promote the construction of low-carbon cities.

On the whole, the existing related literature start with different dimensions, different scales of research objects and various research methods. The relationship between Land morphology and carbon emissions is deeply studied, and most of them quantify the indicators and establish reliable models. The conclusions are very convincing, which provides a good reference for the optimization and upgrading of Land morphology under the background of carbon emission reduction. However, the index dimension of characterizing Land morphology is relatively single, and most of them start from compactness, centrality and sprawl, and need to add more comprehensive variable indicators; Secondly, under the background of carbon neutrality after empirical research, the optimization and control strategies of Land morphology are weak and need further discussion. Therefore, this paper quantitatively describes the Land morphology through landscape pattern index, by selecting city size, shape complexity, shape fragmentation, spatial aggregation and spatial diversity as five dimensions. In addition, this paper studies the influence of Land morphology on carbon emissions and its deep mechanism through regression analysis, and provides suggestions for optimizing urban form to achieve the purpose of carbon emission reduction.

Material and Methods

Overview of Research Subjects

The Yangtze River Delta is located in the eastern coast of China, with a total area of 358,000 square kilometers. It now has jurisdiction over Shanghai, Zhejiang, Jiangsu and Anhui provinces, with a total of 41 cities and towns densely distributed. It is one of the regions with the fastest economic development, the most vitality and innovative ability in China. In recent years, with the rapid development of urbanization, great changes have taken place in the Land morphology of the Yangtze River Delta, and the regional energy consumption and carbon emissions have increased year by year, which has a negative impact on the sustainable development of regional economy and society. Especially during the period from 2002 to 2005, the Yangtze River Delta region vigorously promoted industrialization and urbanization, with rapid economic growth, and the consumption of energy and carbon emissions also increased greatly. After 2006, people paid more and more attention to environmental problems, energy consumption was gradually controlled, and the growth rate of carbon emissions gradually slowed down [33].

Data Sources

In this study, the land use/cover information (CLCD) and total carbon emission data of 41 cities in the Yangtze River Delta region from 2005 to 2017 were selected (Table 1). The land use/cover information comes from the annual China Land Cover Data Set (CLCD), which contains nine types of land use, including cultivated land, woodland, shrub, grassland, water, ice and snow, wasteland, impervious water and wetland [34]. The total carbon emission data of cities in the Yangtze River Delta region comes from the carbon emission data of counties and districts in China from 2005 to 2017 inversion through night light data [35], and the required data are calculated by summation according to city division.

Research Methods

Measurement of Land Morphology: Landscape Pattern Index

Urban form can be characterized by a variety of indicators from different angles, including physical indicators such as the proportion of construction land, road area per capita and geometric indicators represented by landscape pattern index. Landscape pattern refers to the type, number, spatial distribution and configuration of landscape components, which is the concrete embodiment of landscape heterogeneity [36]. Landscape pattern index is a quantitative index obtained by remote sensing (RS) technology and geographic information system, which can describe landscape pattern information in a highly concentrated way, and reflect some characteristics of its structural composition and spatial configuration. It is divided into three levels: patch level index, patch type level index and overall landscape level index. Through the calculation and analysis of landscape pattern index, we can effectively quantify the Land morphology, evaluate its characteristics such as aggregation, centrality and fragmentation, and study the evolution differences and mechanisms of Land morphology in different time dimensions such as structure and function [37].

Compared with other indicators to measure urban form, landscape pattern index can describe different types of urban form objectively and comprehensively at the micro level independently and uniformly, and explore the internal relationship between landscape structure and urban form changes, which has great advantages in urban form measurement.

In this paper, combined with the highly dense regional characteristics of the Yangtze River Delta region, referring to the index selection rules of related research, five dimensions are selected to characterize the Land morphology: city scale, shape complexity, shape fragmentation, spatial aggregation and spatial diversity. City size represents the capacity of a city, which is closely related to the expansion of urban construction land and population size; Shape complexity measures the properties of boundaries and shapes of different elements in cities; Shape fragmentation can describe the fragmentation degree of patches in cities and measure the accessibility between patches; Spatial aggregation degree reflects the connectivity and aggregation degree of each functional structure of the city, which is related

Table 1. Research data types and sources.

Data name	Data type	Data source
Administrative division data	Vector data	National Basic Geographic Information Center
Land use/cover data	Raster data	China Land Cover Data Set (CLCD) [28], selecting data from 2005, 2010, 2015 and 2017
Total carbon emissions	Attribute data	Carbon Emission Data of Counties and Districts in China from 2005 to 2017 [29]

Table 2. Landscape pattern index and its description.

First-class index	Secondary index	Indicator significance
City size	(CA) Total patch area (CA)	The total area of urban impervious patches reflects the scale of urban construction land
Complexity of city shape	(SHAPE_MNv Average shape index (SHAPE_MN)	It reflects the complexity of Land morphology, SHAPE_MN>0, the larger the value is, the more complex the shape is
City shape fragmentation	(NP) Patch number (NP)	It represents the total number of patches and reflects the fragmentation degree of landscape. NP ≥ 1, the larger the value, the higher the fragmentation degree of landscape
Urban spatial aggregation degree	(COHESION) Binding degree index (COHESION)	It measures the spatial connectivity of landscape types, 0<COHESION ≤ 100, and the larger the value, the higher the degree of patch aggregation
Urban spatial diversity	Shannon diversity index (SHDI)	It reflects landscape heterogeneity, SHDI≥0, the larger the value, the richer the land use and the higher the fragmentation degree

3.3.2 Coupling of Land morphology and Carbon Emissions: Multivariate Linear Regression Analysis

to the development and expansion mode of the city; Spatial diversity describes the richness of urban form, which is closely related to the mixed use of land. The five dimensions comprehensively start from different emphases of Land morphology, and give attention to describing the characteristics of Land morphology structure and layout, each with its own emphasis and close relationship.

According to the characteristics of the above five dimensions, based on the overall principle of objectivity, accuracy and synthesis, five landscape pattern index indexes CA, SHAPE_MN, NP, COHESION and SHDI (Table 2) are selected to quantitatively describe the urban spatial morphological characteristics of the Yangtze River Delta region, and the calculation is completed by FragStats4 software.

Coupling of Land Morphology and Carbon Emissions: Multivariate Linear Regression Analysis

In this study, the carbon emission data of cities in the Yangtze River Delta in 2005, 2010, 2015 and 2017 and the landscape pattern index that quantitatively describes the spatial form are selected to build a panel data model. Using statistical software StataSE16, the correlation analysis of variables is carried out at first, and whether there is multicollinearity among variables is detected to ensure that the model is not pseudo-regression. Then, F test is carried out on the model to determine whether the indicators such as significance of the model are suitable for selecting mixed regression. If the test does not conform, the Hausmann test is further carried out to determine whether the fixed effect model or the random effect model is used. Finally, through the panel data to build an appropriate multiple linear regression model, we can get the relationship between Land morphology and carbon emissions. The basic model takes the form of:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \varepsilon \quad (1)$$

Among them, y represents the explained variable urban carbon emissions, x1-x5 represents the total area of impervious patches (CA), average shape index (SHAPE_MN), patch number (NP), COHESION index and Shannon diversity index (SHDI) respectively, and ε represents the random disturbance term except the above variables. Because the carbon emission data of the explained variables used in this study are inversion

Table 3. Variable types and names.

Variable type	Variable name	Specific indicators	Unit
Dependent variable	Carbon emissions	CO2E(y)	Million tons
Explanatory variable	City size	CA(x1)	ha
	Complexity of city shape	SHAPE_MN(x2)	/
	Fragmentation of urban patches	NP(x3)	unit
	Urban spatial aggregation degree	COHESION(x4)	/
	Urban spatial diversity	SHDI(x5)	/

from night light data, which are strongly correlated with control variables such as urban economic development level, in order to avoid false regression, this study does not use other factors affecting carbon emission such as economic development level, energy intensity and industrial structure as control variables to participate in regression.

Results and Discussion

Spatial Distribution Characteristics of Carbon Emissions

The changes of carbon emissions of cities in the Yangtze River Delta region from 2005 to 2017 are shown in Fig. 1. Most cities show an increasing trend year by year. The spatial distribution of carbon emissions is obviously different, with obvious spatial agglomeration characteristics, showing the overall characteristics of the highest in the central and eastern regions and gradually decreasing outward (Fig. 2). According to the average level of cities in administrative regions, the order of carbon emissions from high to low is Shanghai>Jiangsu>Zhejiang>Anhui. Shanghai's carbon emissions are always at the highest level, followed by Jiangsu, followed by Zhejiang and Anhui. From the distribution in the province, the carbon emissions of eastern cities of Anhui Province such as Chuzhou and Hefei are the highest in the province, while those of Zhejiang Province are concentrated in Hangzhou and Ningbo, while those of southern Jiangsu Province such as Suzhou and Nantong are the highest in the province.

There are obvious differences in carbon emissions among different cities in the same period. In 2005, the city with the highest carbon emissions in the Yangtze River Delta region was Shanghai, it reaches 170.8 million tons (Mt), which is the only city with more than 100 Mt, followed by Chuzhou and Suzhou with carbon emissions above 50Mt, Ningbo, Hangzhou and Nanjing with carbon emissions exceeding 40Mt, which decreases from near to far with the distance from Shanghai, while most cities with carbon emissions less than 10 Mt are located in Anhui Province, among which Zhoushan City in Zhejiang Province has the smallest carbon emissions, only 3.7 Mt; In 2010, the total carbon emissions of Shanghai increased rapidly and far exceeded those of other cities, reaching 230.7 Mt, accounting for about 15% of the total carbon emissions of 41 cities in the Yangtze River Delta region. The carbon emissions of Chuzhou and Suzhou exceeded 100 Mt, while the carbon emissions of Ningbo, Hangzhou, Nanjing, Wuxi, Hefei, Nantong, Xuzhou, Yancheng and Jiaxing all exceeded 40 Mt from large to small, and Tongling ranked last with about 6 Mt; In 2015, Shanghai still ranked first with 190 Mt of urban carbon emissions, but compared with 2010, it decreased significantly. Chuzhou and Suzhou both exceeded 100Mt, and there were 10 cities exceeding 40 Mt from high to low, namely Nanjing, Ningbo, Wuxi, Nantong, Hefei, Hangzhou, Xuzhou, Jiangsu, Yancheng, Changzhou, Yangzhou and Zhoushan ranked last; in 2017, the carbon emissions of cities in the Yangtze River Delta region were basically similar to those in 2015, except that Taizhou was added to cities exceeding 40 Mt. Generally speaking, the spatial distribution characteristics of carbon emissions in the Yangtze River Delta region are highly consistent with its overall economic development pattern and population distribution pattern.

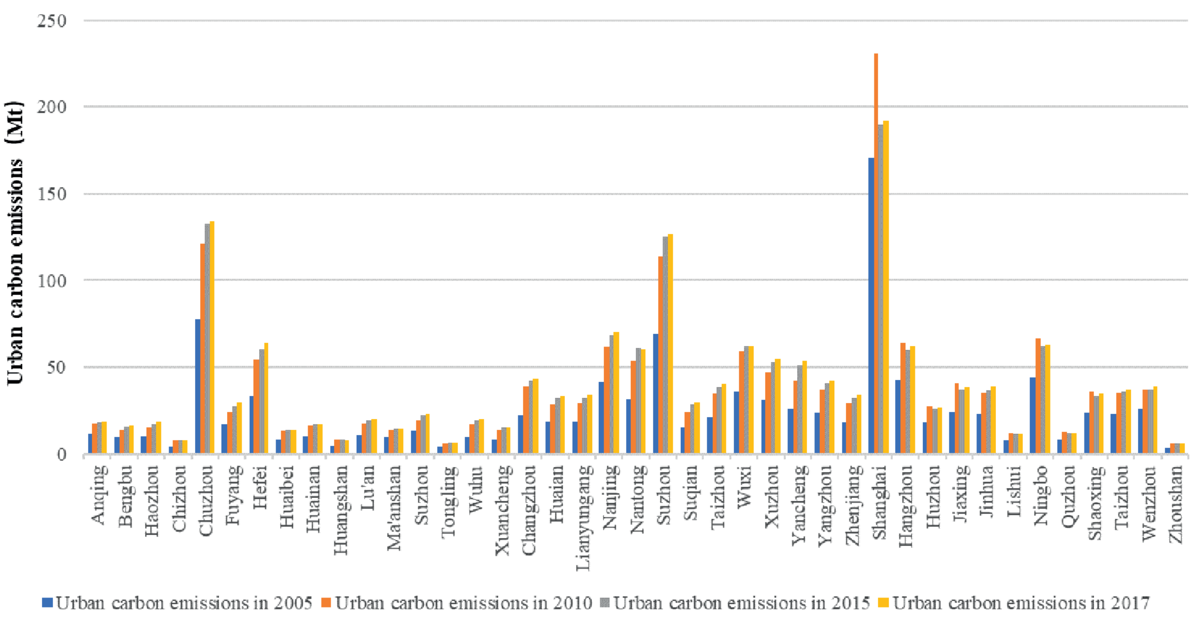

Fig. 1. Changes of urban carbon emissions in the Yangtze River Delta region from 2005 to 2017.

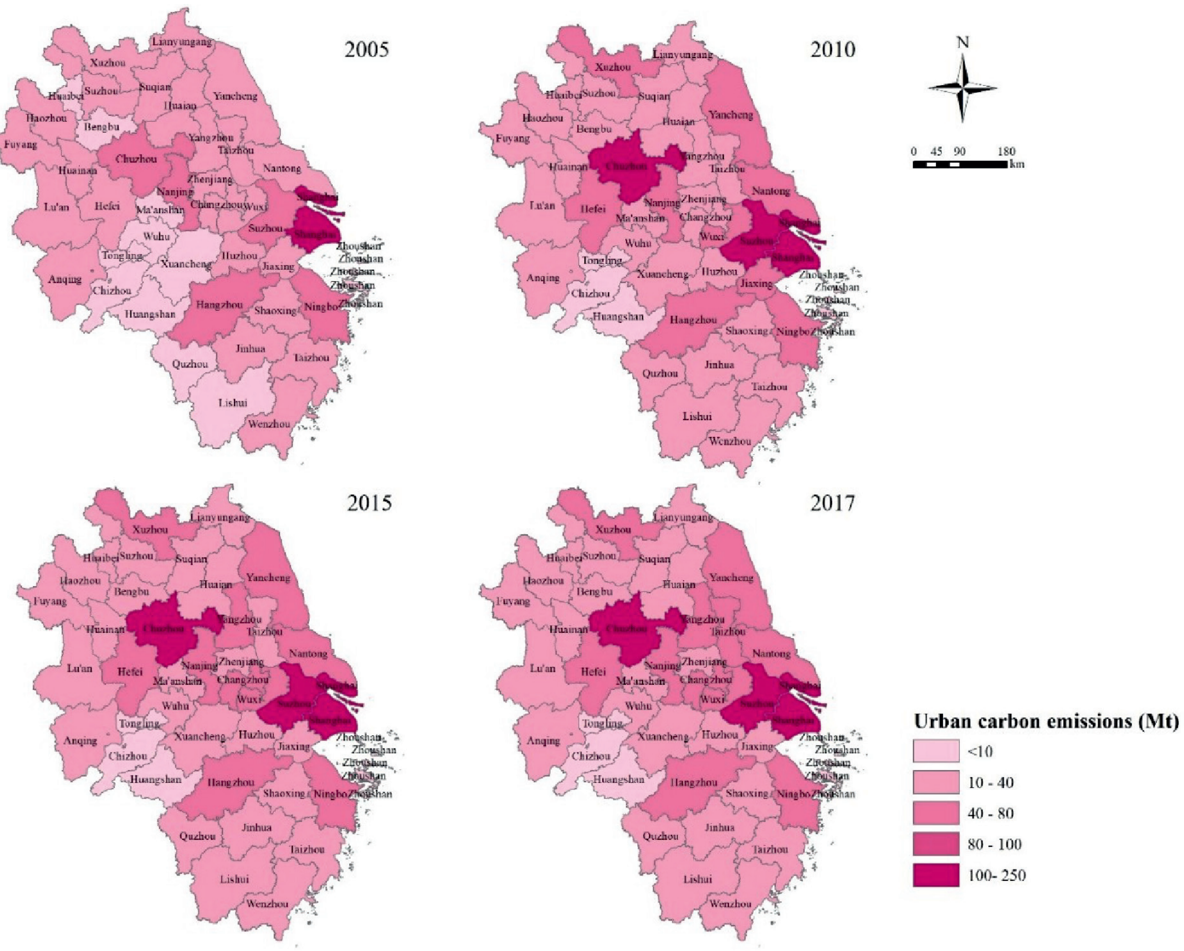

Fig. 2. Urban carbon emissions in the Yangtze River Delta region.

Dynamic Change Characteristics of Land Morphology

From 2005 to 2017, the urban form in the Yangtze River Delta region has changed significantly. The impervious patch area CA of 41 cities in the Yangtze River Delta region showed a rapid growth trend (Fig. 3), and the total area increased from 28,500 square kilometers to 41,600 square kilometers. During this period, the Yangtze River Delta region experienced rapid urbanization development, and the land use situation changed obviously, which was mainly manifested in the rapid expansion of urban land use scale. Among them, Xuzhou, Shanghai, Yancheng, Suzhou and Suzhou, which ranked the top five in impermeable patch area, had a particularly significant change in land use

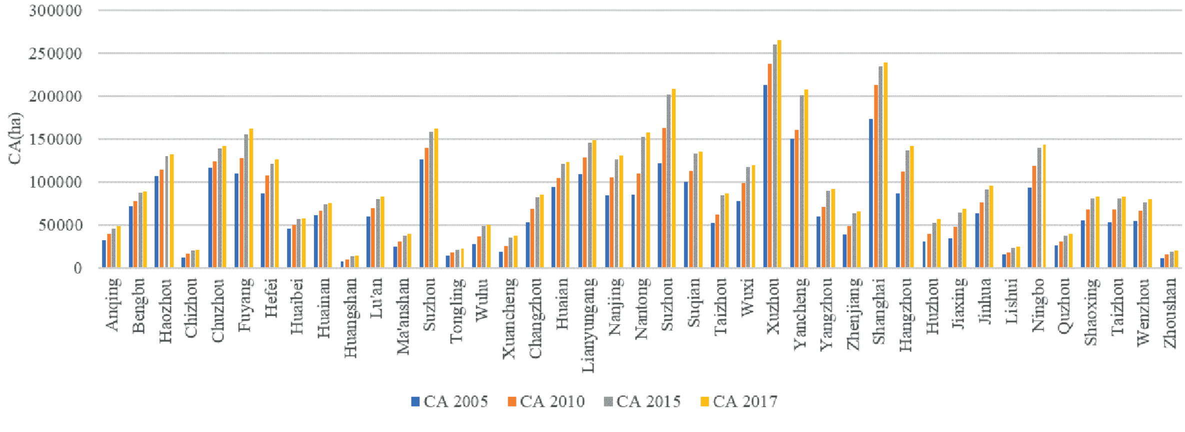

Fig. 3. Changes of total patch area (CA) of urban impervious land in Yangtze River Delta region.

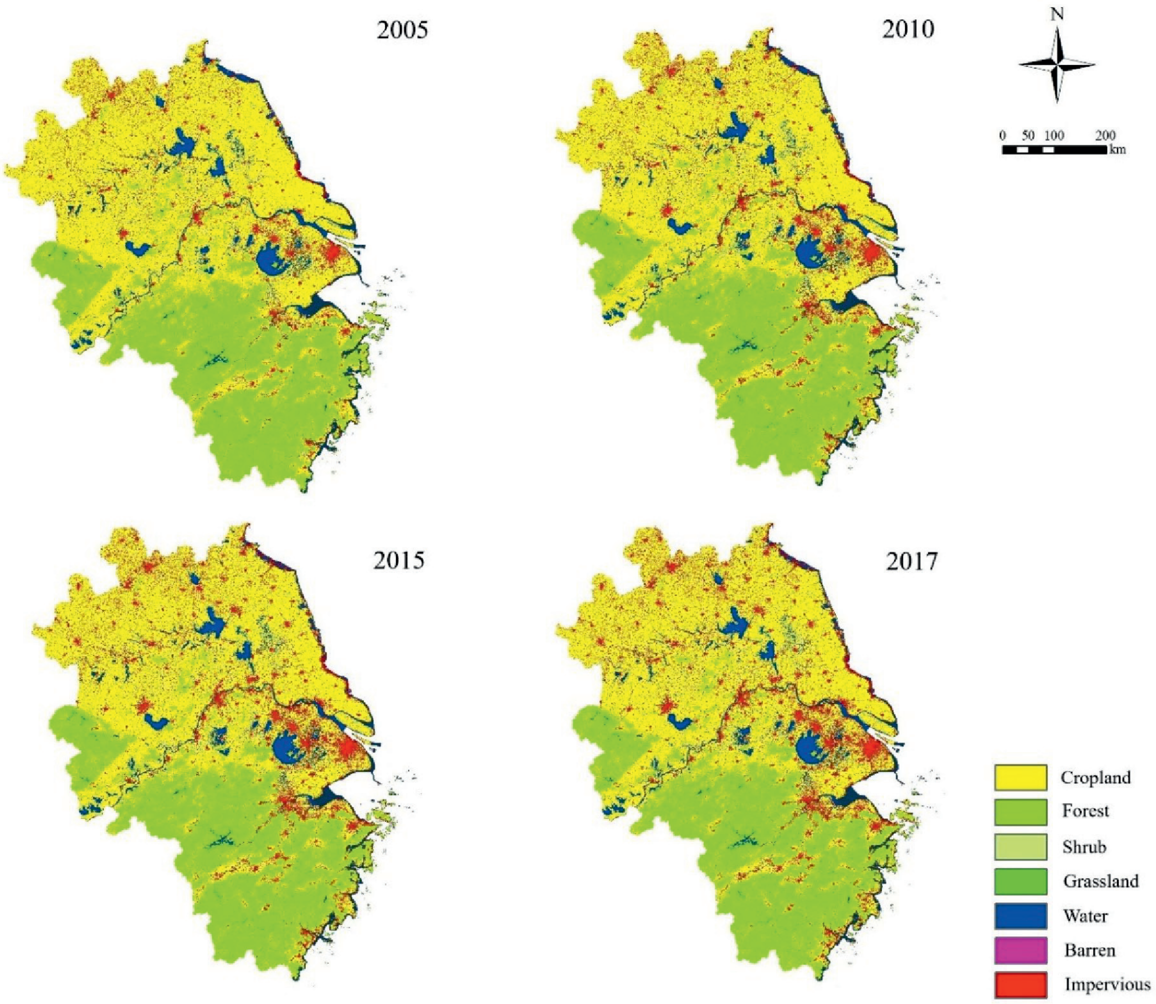

Fig. 4. Land use change in Yangtze River Delta region.

expansion, and the area of urban built-up areas increased significantly (Fig. 4).

Generally speaking, the average shape index (SHAPE_MN) of cities in the Yangtze River Delta is increasing year by year (Fig. 5), which shows that with the continuous construction and expansion of cities, the spatial form of each sample city becomes more complex and the boundary becomes more irregular. Among them,

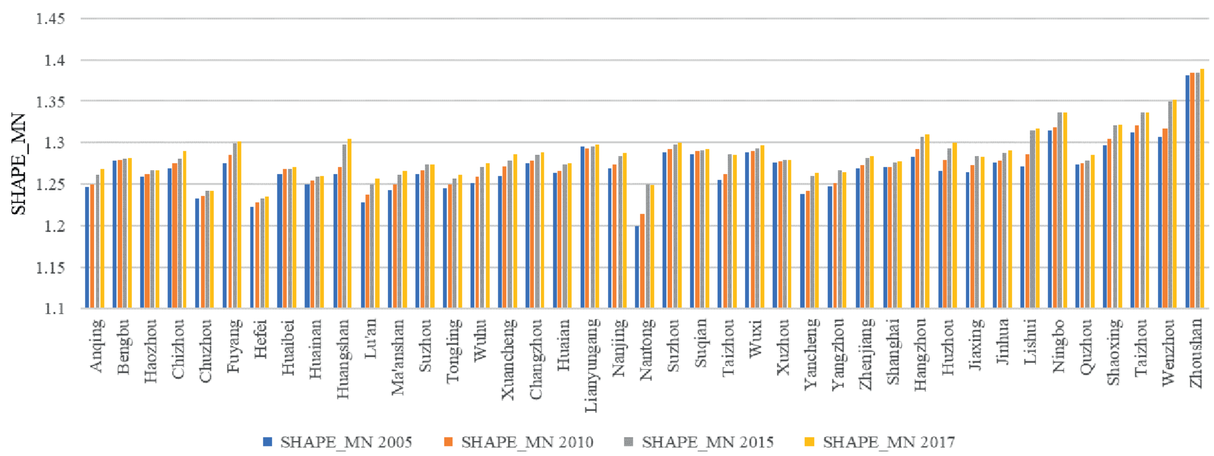

Fig. 5. Changes of average shape index (SHAPE_MN) in Yangtze River Delta region.

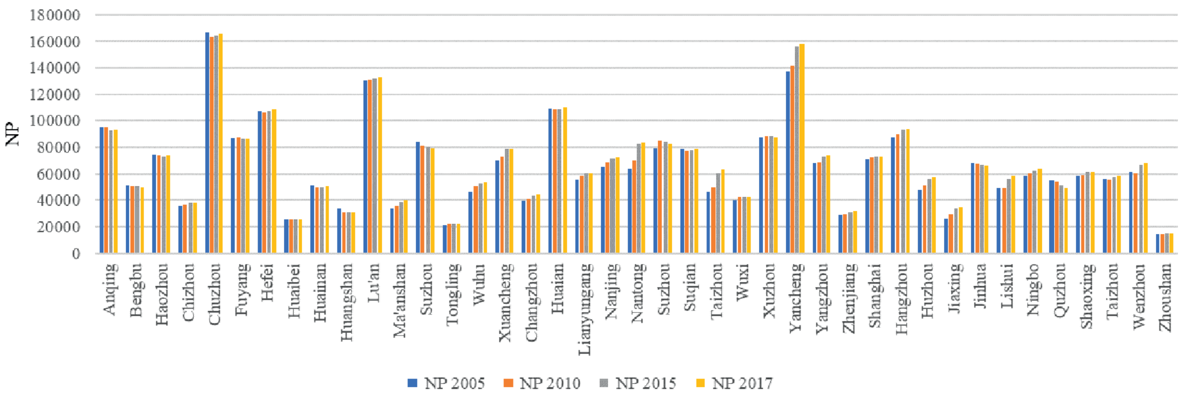

Fig. 6. Variation of patch number (NP) in Yangtze River Delta region.

the city with the largest SHAPE_MN value is Zhoushan City, and its urban form is the most complex because of its islands; Nantong, Taizhou, Yancheng and Yangzhou in Jiangsu Province, Lishui, Ningbo, Wenzhou and Hangzhou in Zhejiang Province, Fuyang and Huangshan in Anhui Province increased greatly in 2010-2015. It shows that under the impetus of the Yangtze River Delta integration policy since 2010, the economic and urbanization level of cities in the Yangtze River Delta region has made a qualitative leap, and the urban form, boundary and functional layout are more diversified and complex.

The number of patches NP varies from city to city (Fig. 6), and Chuzhou, Yancheng and Lu'an in Anhui Province have the largest number of patches. The NP values of Ma'anshan, Wuhu and Xuancheng in Anhui, Changzhou, Nanjing, Nantong, Taizhou, Yancheng and Yangzhou in Jiangsu, Hangzhou, Huzhou, Lishui and Ningbo in Zhejiang are on the rise as a whole, which shows that while the space is connected, the urban form is inevitably becoming more and more fragmented, and the dominance of a single landscape type is constantly declining. The NP value of Suzhou, Anhui Province, Jinhua, Quzhou, Zhejiang Province shows a downward trend as a whole, which indicates that the degree of urban fragmentation decreases. When urbanization develops to a certain extent, the filling degree of urban space increases, and patches tend to connect into patches, so the number of patches decreases. The NP value of other cities is basically the same.

The COHESION index is higher than 99.5 and approaches 100 except Zhoushan City (Fig. 7), which shows that the patch connectivity of cities in the Yangtze River Delta region is extremely high and the function distribution is relatively concentrated. The COHESION values of Suzhou in Anhui Province, Nantong, Suzhou, Taizhou and Wuxi in Jiangsu Province, Huzhou, Ningbo and Zhoushan in Zhejiang Province showed a slight downward trend, indicating that in the process of rapid urbanization, the same type of patches were scattered, which led to the decrease of concentration and physical connectivity in some cities. The COHESION value of other cities changed little and remained at a high level, which indicated that the compact level of Land morphology and functional layout in the Yangtze River Delta region had reached a high level and was gradually changing to an ideal urban spatial development model.

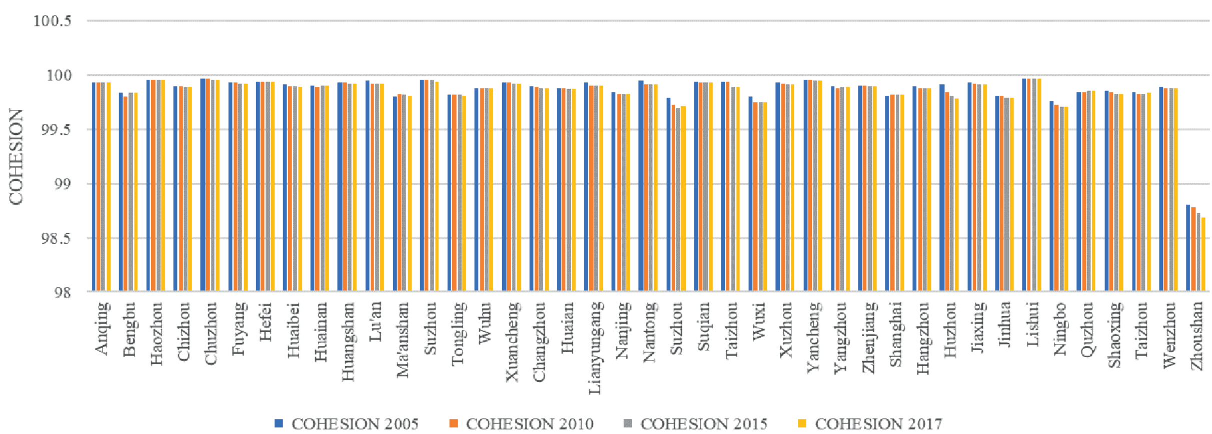

Fig. 7. Changes of COHESION index in Yangtze River Delta region.

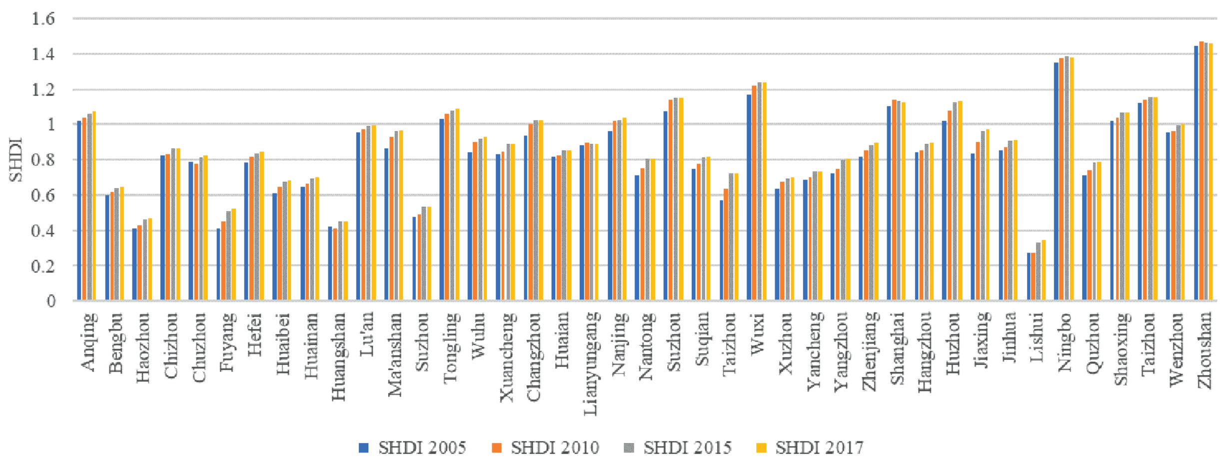

Fig. 8. Changes of Shannon Diversity Index (SHDI) in Yangtze River Delta.

Shannon Diversity Index SHDI is on the rise in most cities in the Yangtze River Delta region as a whole (Fig. 8), which means that landscape heterogeneity becomes more significant and land use richness increases accordingly. SHDI values of Shanghai, Zhoushan, Ningbo, Taizhou, Shaoxing, Huzhou, Wuxi, Suzhou, Nanjing, Changzhou, Tongling, Anqing, Anhui and other cities all exceed 1, indicating that landscape types are richer, various types of patches show a more balanced trend distribution in the landscape, and the combination and functional distribution patterns of different types of patches are more reasonable and efficient.

Coupling Analysis of the Influence

Before the regression analysis, the correlation analysis of variable data is carried out to judge whether there is multicollinearity among variables. The results are shown in Table 4, and the absolute values of correlation coefficients are all less than 0.8, which indicates that there is no multicollinearity among variables, and a panel data regression model can be constructed.

Then test whether the model has individual effect, the results show that P value is 0, individual effect is extremely significant, is not suitable for mixed regression model. Further Hausmann test shows that P value is 0.0016, less than 0.05 rejects the original hypothesis, that is, it is more suitable to choose the fixed effect model. In order to make the regression model more intuitive and robust, the explanatory variables and the explained variables are logarithmic, and the final fixed effect panel data model is constructed. The expression is as follows:

$$\ln y = \beta_0 + \beta_1 \ln x_1 + \beta_2 \ln x_2 + \beta_3 \ln x_3 + \beta_4 \ln x_4 + \beta_5 \ln x_5 + \varepsilon \quad (2)$$

The fixed effect model is used to calculate the panel data of this study by multiple regression linear calculation (Table 5). R2 is 0.765, which indicates that the regression model has a high degree of fitting, and the influence of explanatory variables on carbon emissions is as high as 76.5%. It shows that Land morphology will have an impact on the total amount of urban carbon emissions to a great extent. In addition, economic development level, energy intensity, industrial structure and other factors may also affect carbon emissions together. This study will focus on analyzing the influencing factors of Land morphology on carbon emissions. Finally, the expression of urban carbon emissions about spatial pattern is as follows:

Table 4. Correlation analysis among variables (*, **, *** represent 10%, 5% and 1% significance level test, respectively).

	co2e	CA	SHAPE_MN	NP	COHESION	SHDI
co2e	1					
CA	0.667***	1				
SHAPE_MN	-0.0450	-0.0660	1			
NP	0.375***	0.560***	-0.380***	1		
COHESION	0.0290	0.170**	-0.642***	0.350***	1	
SHDI	0.298***	-0.0170	0.434***	-0.144*	-0.577***	1

$$\ln y = 152.490 + 1.269\ln x_1 - 8.604\ln x_2 - 0.833\ln x_3 - 32.988\ln x_4 + 1.186\ln x_5 \quad (3)$$

Among them, the total area of impervious patch CA has the most significant positive impact on carbon emissions in the Yangtze River Delta region, which shows that the larger the city scale, the greater the energy consumption of living and production activities on the construction land, and the more carbon emissions will be generated. Since the 21st century, cities in the Yangtze River Delta region are in a stable and rapid development stage of urbanization, guided by the policy of urbanization with Chinese characteristics in 2002, The Yangtze River Delta region has formed regional megacities as economic growth poles, radiate the urban agglomeration structure of surrounding core large, medium and small cities, therefore, the scale of core cities represented by Shanghai, Suzhou and Hangzhou and the scale of land use increased significantly during this period. The process of urban infrastructure construction has been accelerated. For example, the amount of investment in urban infrastructure in Shanghai increased from 88.574 billion yuan in 2005 to 142.508 billion yuan in 2015 [38]. The improvement of urbanization and infrastructure level has attracted more people to the Yangtze River Delta region, and the city scale has been expanding in terms of population and land use, resulting in more carbon emissions from residents' daily life and urban production activities.

The Shannon Diversity Index SHDI has a very significant positive impact on carbon emissions, which shows that the stronger the heterogeneity of spatial form, the more fragmented the space is, which means that economic activities are correspondingly divided into different patches, thus indirectly increasing infrastructure costs and transportation costs, and inevitably generating more energy consumption activities. Under the background of regional integration in the Yangtze River Delta, the comprehensive transportation system has been continuously improved, and intra-city transportation, inter-city transportation and inter-provincial passages within the region have become the focus of regional comprehensive transportation integration development. At present, the density of railway network in Yangtze River Delta region is 1.5 km/100 km^2, which is about twice the national level; The highway density is 71.7 km/100 km^2, which is about 3.7 times of the national level [39]. The heterogeneity of urban space in the Yangtze River Delta region promotes the rapid development of traffic to a certain extent, which leads to the increase of carbon emissions.

The average shape index SHAPE_MN has a significant negative impact on carbon emissions in the Yangtze River Delta region, indicating that the more complex the urban spatial form, the less carbon emissions, which may result from the fact that there is the emergence of a "multi-center" urban development model after the urban spatial form has become complex and diverse; the inner functional areas of the city adopt flexible and flexible layout structure around multiple centers, and do not pursue the regularity of urban boundaries; each city unit meets the balance of occupation and residence; several small patches gather to form a compact, efficient and continuous "multi-center" large patch, thus reducing ineffective waste of resources and contributing to urban carbon emission reduction.

Patch number NP has a negative impact on carbon emissions, but it is not significant, which may result from the fact that even if the large number of patches means that the Land morphology is broken. However, it cannot accurately and comprehensively describe the layout and compactness of production activities in cities. Therefore, the number of patches can not play a decisive role in urban carbon emissions, and the morphological fragmentation caused by excessive number of patches can be compensated by optimizing the internal functional structure of cities. The reasonable and efficient spatial morphological development and

Table 5. Panel data regression results (*, **, *** represent 10%, 5% and 1% significance level test, respectively).

VARIABLES	y (lnco2e)
$\ln x_1$ (lnCA)	1.269***
	(8.71)
$\ln x_2$ (lnSHAPE_MN)	-8.604**
	(-2.21)
$\ln x_3$ (lnNP)	-0.833*
	(-1.83)
$\ln x_4$ (lnCOHESION)	-32.988
	(-0.34)
$\ln x_5$ (lnSHDI)	1.186***
	(2.71)
Constant	152.490
	(0.34)
Observations	164
Number of cityname	41
R-squared	0.765
Company FE	YES
F test	0
r2_a	0.758
F	66.26
Hausman	19.36
p-value	0.0016

evolution model of cities is the key to reduce carbon emissions.

COHESION has no obvious influence on carbon emissions, which may be because the COHESION value in the Yangtze River Delta region changes little and basically approaches 100, and the Land morphology has been in a high-level stage of urbanization with high concentration and stability. In the process of rapid urban development, people tend to gather in areas with high urbanization level, which leads to the increase of corresponding infrastructure, and several small patches gradually gather together into large patches that can gather successfully. Taking Shanghai as an example, The combination index of Shanghai shows a trend of increasing first and then decreasing, However, the increase or decrease is not large. The urbanization rates of Shanghai in 2005, 2010 and 2017 are 84.5%, 88.86% and 87.7%, respectively, indicating that after the urbanization development reaches a high level, the Land morphology tends to be stable and a compact and clustered development model suitable for itself has been found. Therefore, COHESION cannot constitute the leading factor of Land morphology affecting carbon emissions in the Yangtze River Delta region.

As can be seen from the above analysis, City scale and spatial diversity have a significant positive impact on carbon emissions in the Yangtze River Delta region by affecting population, land use and transportation. Urban shape complexity and patch fragmentation have a negative impact on carbon emissions, but the significant degree is not high. The key to sustainable low-carbon development of cities lies in effective planning of reasonable, compact and efficient spatial form and functional layout.

Suggestions

A city is a complex space integrating culture, entertainment, commerce, administration and residence. In the process of urban development and renewal, agglomeration effect will spontaneously occur around the living and production functions, forming different functional groups, and the compact spatial form can efficiently play this spatial combination and agglomeration effect, greatly improve the convenience in living and production, and reduce the carbon emissions caused by unnecessary daily traffic. By quantifying the Land morphology in the Yangtze River Delta region, combined with the total amount of carbon dioxide emissions in cities, regression analysis shows that the mechanism of Land morphology for carbon emissions is mainly realized by affecting the carbon emissions of land use, transportation and other departments. High compact Land morphology can greatly improve the efficiency of carbon emissions, which is conducive to the sustainable development of low-carbon cities.

Considering that the city scale and spatial diversity which is represented by the total patch area and Shannon Diversity Index have a significant positive impact on urban carbon emissions, the suggestions on urban spatial structure could be given. In terms of the overall urban structure, it is suggested to strengthen and improve the compact agglomeration degree of form and function, and advocate the "polycenteric" agglomeration group mode with high connectivity. To form diversity urban units and emphasize the mixed use of diversified land types, with striving to achieve a balance between occupation and residence, so as to decompose the carbon emission pressure brought by the expanding urban population. It is suggested to implement the progressive space development strategy and pay attention to the low carbon development of built-up areas with certain infrastructure. Taking Shanghai as an example, the city has proposed the "15-minute living circle" urban development model for decades, and has placed various facilities within a 15-minute walking distance of residential areas, greatly reducing unnecessary traffic trips.

Given that the complexity of urban shape and patch fragmentation represented by average shape index and patch number will have a negative impact on carbon emissions. This means that the uneven distribution of functional areas due to the complexity and fragmentation of land forms will cause carbon emissions will increase. Therefore, under the premise that the existing urban functional layout is established, whether the functional organization can be rationalized to transform "complexity and fragmentation" to "diversity and order" is an effective strategy for the future low-carbon urban development. Existing research shows that the disorderly and fragmented spatial form will lead to an increase in the consumption of infrastructure such as roads and pipe network systems, thereby aggravating carbon emissions [40]. To avoid this phenomenon, it is suggested to change the traditional construction mode of "wide roads and big blocks" into "narrow roads and small blocks", to reduce the complexity and fragmentation of Land morphology. And the road grades and scales are appropriately adjusted according to factors such as functional distribution, traffic load and use characteristics of plots, so as to establish a green and comfortable slow-moving system that is convenient for non-motor vehicles to travel and form a walking-oriented road system. At the same time, improve the construction of public transportation system including rail transit and improve the transfer efficiency. In addition, when adjusting the existing unreasonable roads and land parcel structure, the small-scale gradual adjustment method is emphasized to avoid energy waste, and at the same time, it can protect and continue the distinctive urban texture in the Yangtze River Delta region.

Conclusion

Quantitative analysis and research on the relationship between Land morphology and carbon emissions can provide a new way of thinking and coping for spatial planning under the requirement of "emission peak and carbon neutrality". As the main body of carbon emission, constructing ideal Land morphology through reasonable urban planning will become an important method to achieve the goal of "emission peak and carbon neutrality".

In this study, city scale, shape complexity, shape fragmentation, spatial aggregation and spatial diversity are selected as five dimensions. Corresponding to five parameters as the total patch area, average shape index, patch number, binding index and Shannon diversity index. By calculating the above parameters, the Land morphology of 41 cities in the Yangtze River Delta region in 2005, 2010, 2015 and 2017 was quantitatively analyzed, and the regression analysis was carried out combined with the total urban carbon dioxide emission data to study the impact of Land morphology on carbon emissions and its mechanism.

According to this research, the city scale represented by total patch area and the spatial diversity represented by Shannon Diversity Index in Yangtze River Delta region are positively correlated with urban carbon emissions. This means that a reasonable, compact and efficient spatial form and functional layout are more conducive to the sustainable and low-carbon development of cities. A polycenteric and group-connected development model to improve the compact agglomeration degree of urban structure could be implemented. However, the complexity of urban shape represented by the average shape index and the patch fragmentation are negatively correlated with carbon emissions in the Yangtze River Delta region. We should make up for it through rational planning of transportation system at different scales, turn to the spatial organization mode of "narrow roads and small blocks", adjust the road system in a small scale and gradually, make up for the adverse effects of complex and broken Land morphology on traffic carbon emissions, and create favorable conditions for the improvement of slow-moving system and public transport system.

It is found that Land morphology affects carbon emissions through many factors. Therefore, the planning control and guidance of Land morphology will effectively reduce carbon emissions and help China achieve the strategic goals of "emission peak" and "carbon neutrality" at an early date.

Acknowledgment

This research is supported by China National Social Science Fund (No, 19BJY063).

Conflict of Interest

The authors declare no conflict of interest.

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