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The Impact of Land-Use Structure on Carbon Emission in China

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Abstract: Research objectives: This paper discusses how to support the realization of carbon peak and carbon neutrality through the optimization of national spatial structures by establishing a relationship model between land-use structure and carbon emissions, and then provide theoretical and methodological support for the formulation of relevant policies and plans, as well as the evaluation of implementation effects. Research methods: grid analysis, GIS spatial analysis, double log linear regression model. Results: There is a strong correlation between the spatial structure of land and carbon emissions; the scale of construction land, especially industrial land, directly affects carbon emissions; if the area of construction land is doubled, CO_2 emissions will increase by about 1.7 times. Conclusions: The potential of controlling carbon emission intensity through land structure at the urban level is great, and it is feasible to control carbon emission intensity through territorial spatial planning system. The control elements can be divided into the following levels: land supply control, land structure adjustment, land intensity constraint, and function adjustment of existing land.

Keywords: land-use structure; carbon up to peak; carbon neutral; territorial space

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1. Introduction

Land use is the spatial carrier of various human activities in urban and rural areas. The structure of land use has an important impact on carbon emissions by affecting the level of energy consumption activities. It is an essential and immediate demand of China to promote the reduction of energy consumption and carbon dioxide emissions by optimizing the structure of land use. The impact of land use/cover change (LUCC) on the carbon balance of terrestrial ecosystems has become the focus of current research on global change and terrestrial carbon cycling [1]. However, there is still a lack of the studies on "national spatial land use/land use structure-carbon emission". In recent years, domestic and foreign scholars have carried out research on land use carbon emissions, mainly focusing on the impact of land use change on the carbon cycle of the ecosystem [2–7], the relationship between land use, energy consumption and carbon emissions [8–14], and low-carbon land use models and strategies [15,16]. However, the studies only discussed carbon in terrestrial ecosystems [17], and the influence of anthropogenic carbon emissions was only discussed superficially [18].

Some scholars have investigated the carbon emission effect assessment and low-carbon optimization of land use planning schemes. Zhao Rongqin found that the land-use structure optimization scheme based on the minimization of carbon emissions can have a greater effect on carbon emission reduction [19]. By studying the driving mechanism and factor decomposition of land use carbon emissions, Shi believed that land use carbon emissions were affected by many factors, among which land structure was an important factor causing the growth of land use carbon emissions [20]. Chuai collected various sources of big data and designed a new methodology to examine carbon emissions in Nanjing city at a high resolution of 300 m. In addition, regional differences were compared, and influence factors were analyzed [21]. Xia C explored urban carbon transitions caused by

land use change spatially in Hangzhou [22]. With the territorial space carbon emission intensity of each province and city in 2005 as the dependent variable and the territorial development intensity of each province and city in the same year as the independent variable, Lai Li established simple linear regression model and analyzed samples of 31 cities in the country [23]. It is concluded that due to the huge difference between the carbon budget intensity of construction land and other land types, construction land contributes to the vast majority of carbon emissions in the national land space.

Based on the existing relevant studies at home and abroad, it is known that current research on the spatial land use/land-use structure and carbon emissions in the country is limited and difficult to support the effective implementation of relevant policies. The main consensus is that the increase in the proportion of construction land will increase the concentration of carbon emissions, the proportion of roads and the distribution of industrial land are related to the concentration of carbon emissions in the air, and the increase in the proportion of cultivated land, water areas, grassland, woodland, and vegetation is conducive to reducing the concentration of carbon emissions [24–31]. Low carbon land use optimization can be supported by controlling the expansion of building land and increasing the amount of land available for carbon sinks.

The main shortcomings of these previous studies include the following: (1) The research on GHGs and land-use structure is relatively scarce, with relatively more studies on typical specific regions and relatively weak studies on large sample cities. (2) Land use data are mostly based on remote sensing analysis or the statistical yearbook, the data classification is relatively coarse, and the spatial analysis accuracy is limited; (3) there is still a lack of synergistic analysis of land-use structure and carbon emissions; (4) at present, the relationship between air quality and land use mostly adopts a linear method. Influenced by differences in emission intensity of land use types and location, the response relationship between air quality and land use is complex, and a nonlinear method needs to be used to reveal the process. The quantitative research method is relatively simple and scientifically incorrect.

At present, technical support and work related to climate change and ecological environment protection are still insufficient. It is urgent to carry out research on the impact of territorial spatial land-use structure on carbon emissions. Based on the national land-use data over the years with full coverage of land space, this paper identifies the impact characteristics of land-use structure evolution on urban carbon emissions in the vertical dimension, and constructs a high-resolution carbon emission grid inventory database in the horizontal dimension. Based on the mapping law, a decision-making proposal is made to optimize the land-use structure, thus to reduce carbon emissions and provide support and reference for promoting low-carbon development at the urban, regional, and even national levels from the perspective of territorial spatial planning. The study aims to build a high-precision GIS-based data platform for coupling land-use structure and carbon emissions and a model for correlating land-use structure and carbon emissions, as well as to conduct a hierarchical scenario analysis for the whole country and typical regions.

2. Materials and Methods

2.1. Research Object

Urban industrial land (including cities, established towns, villages, and mining land) and transport land (including railway land, road land, airport land, port and terminal land, and pipeline transport land) under the national classification of construction land are selected as the objects of study, and the industrial land in the above construction land will be further subdivided to explore the correlation between CO_2 and the structure of construction land, as well as the subdivided industrial-type land.

2.2. Data Sources

The basic data used in this paper include the following three aspects: national land-use structure data from 2009 to 2018, nationwide 10 km × 10 km grid carbon dioxide

inventory data in 2015, industrial POI (point of interest) training transformation AOI (area of interest) + smart industrial land identification data.

Specifically, the national land-use structure data in this paper are mainly based on the results of the second national land survey. On the basis of the national standard of land-use status classification, obtained the urban unit land-use structure data and 10 km × 10 km precision land-use data; the carbon dioxide inventory data came from CHRED (China high resolution emission gridded database) that organized by the Environmental Planning Institute of the Ministry of Ecology and Environment, EDGAR (emission database for global atmospheric research) and MEIC (multi-resolution emission inventory for China) data; industrial POI training transformed AOI + smart industrial land identification data are aimed at industrial land use, an in-depth analysis of the industrial land was carried out using the location information of the polluting enterprises in the pollutant discharge permit database of the Ministry of Ecology and Environment, and nearly 100,000 industrial POI points were converted into the AOI (area of interest) training set. POI points are classified as enterprises corresponding to M1, M2, and M3, and then 35 industries are subdivided by industry, and the average land area of POI points is calculated based on remote sensing images. The results are further aggregated to the grid industrial land-use categories, compared and verified with the land survey data, and the coefficients are adjusted to obtain the final industrial land-use composition of the 10 km × 10 km grid.

2.3. Methods

This paper conducts an empirical study on the correlative influence between national territorial space and carbon emissions at the national scale. Based on the analysis of the national territorial spatial land-use structure and the research on the grid inventory of carbon dioxide emissions by grid analysis and GIS spatial analysis, a correlation framework between the national territorial spatial land-use structure data and carbon dioxide emissions is established. Also, the spatial land-use characteristics and emission characteristics of the country are described and correlated, and a regression model (mainly double log linear regression model) of land-use structure-carbon emissions is established to provide support for the application of policy scenario analysis of the relationship between land use and emissions.

Existing studies mostly take separate and independent discussions on land-use structure and carbon dioxide emissions, and lack linkage analysis. In addition, limited by the quality of basic data, existing research mainly focuses on a certain city or region, and the accuracy of spatial analysis is limited. This paper is the first to carry out an empirical study at the national scale, which establishes the national territorial spatial land-use structure data and carbon dioxide emission grid inventory data, and then carries out a multi-scale correlation model study. Through the pilot evaluation, the study verifies the feasibility of the model and provides policy recommendations. The technical route of this study is shown in Figure 1.

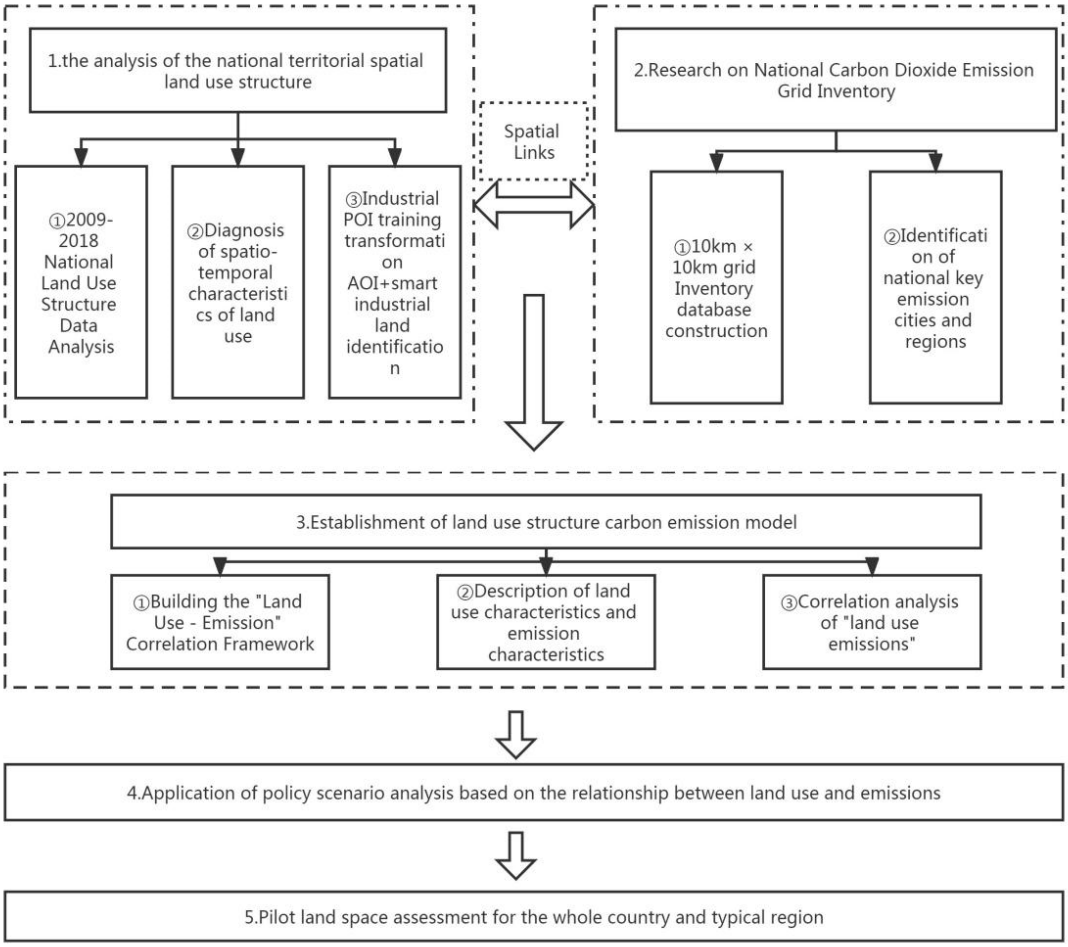

Figure 1. Research technology itinerary map.

3. Results

3.1. National Level Construction and Land Use and Emission Characteristics

3.1.1. National Level

The types of construction land used in this study include the following: rural roads, cities, towns, villages, mining land, railway land, highway land, airport land, port land, and pipeline transportation land. The predominant proportion of built-up land is in villages, towns, and highways, which account for more than 90% of the total built-up area; the proportion of built-up land by whether it is industrial or not is 4% for industrial land, 20% for non-industrial land, and 76% for other land.

According to the national emission distribution map (Figure 2), the distribution of carbon dioxide emissions has obvious characteristics of "high in the east and low in the west, high in the north and low in the south", and the emissions in the mid-eastern regions are significantly higher than other regions, emissions are low across the western region. The emissions of eastern regions are significantly higher than those of the western regions. Most of the regions with higher carbon dioxide emissions are concentrated in the eastern and northern regions, with the emissions of Shandong being the most significant. The emissions of Shandong alone account for 9.3% of the country. Several provinces in northern China, such as Shandong, Inner Mongolia, Hebei, Henan, Shanxi, and Liaoning, account for almost half of the country's total emissions. The Tibet Autonomous Region, Xinjiang Uygur Autonomous Region, Qinghai Province in western China are all low-emissions areas. For example, the area of Tibet Autonomous Region is more than 70 times that of Beijing, but its carbon dioxide emissions are less than one-thirtieth than that of Beijing.

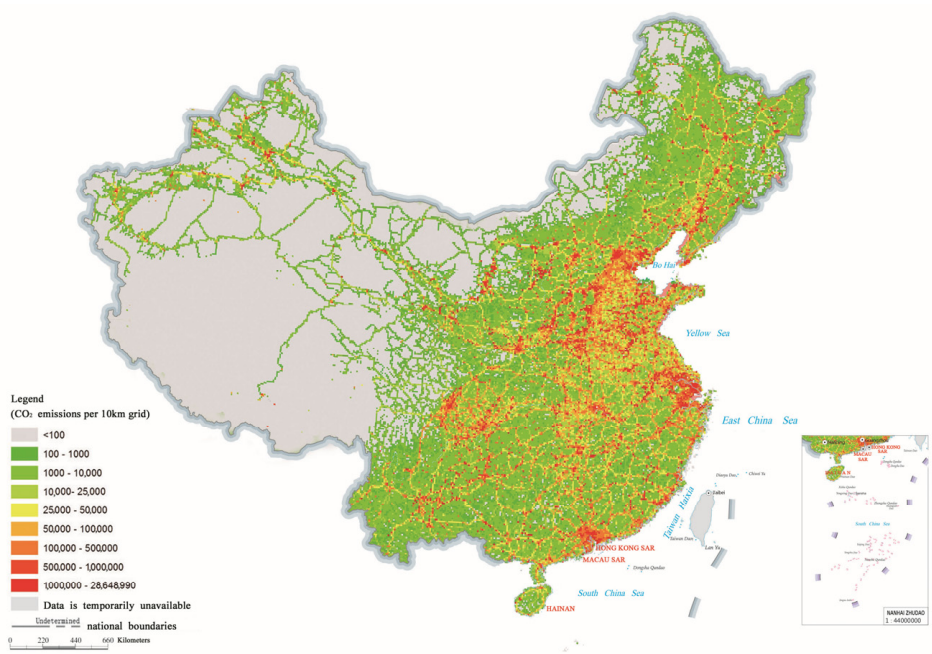

Figure 2. Distribution map of national carbon dioxide emissions.

3.1.2. Partition Level

According to the scope of China's economic zoning, the grids are aggregated into four regions: the northeast, eastern, central and western regions, and statistics are made on the composition of construction land, total CO_2 emissions, and emission intensity. In terms of total construction land, the eastern region is the highest, and the northeastern region is the lowest; the land use intensity is the highest in the eastern region, followed by the central region, and the western region is the lowest; in terms of land-use structure, the proportion of villages in the central region is relatively high, and the proportion of urban land in the eastern and northeastern regions is relatively high.

The total emission of carbon dioxide is the highest in the eastern region, followed by the western region, and the lowest in the northeastern region; the emission intensity (emissions/construction land area) is the highest in the eastern region, followed by the central region, and the lowest is in the western region. The difference in quantity and emission intensity is relatively insignificant, as shown in Figure 3.

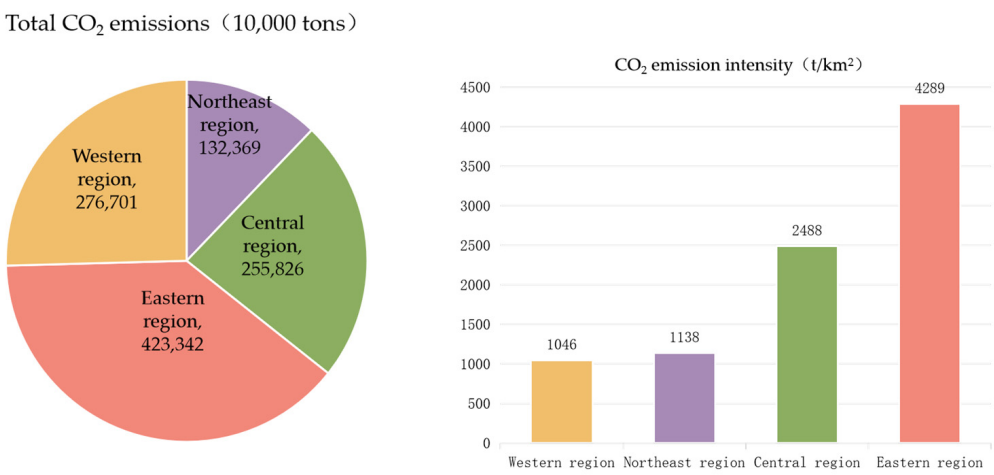

Figure 3. National Subregional Emissions and Emission Intensities.

3.1.3. Urban Agglomeration Level

At the urban agglomeration level, five typical urban agglomerations were selected for the study, namely, the Pearl River Delta urban agglomeration, the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration, the middle reaches of the Yangtze River, and the Chengdu-Chongqing urban agglomeration. At the urban agglomeration scale, the aggregation is performed to count CO_2 emissions, and the average value of land-use structure data. The five major urban agglomerations possess 39% of the country's population and generate 50% of the country's GDP; in terms of carbon dioxide emissions and the scale of construction land, the five agglomerations are similar and the Yangtze River Delta urban agglomeration is the highest among them.

In terms of the total amount of construction land and the intensity of land use, the Yangtze River Delta region is the highest; in terms of land-use structure, the proportion of urban construction land in the Pearl River Delta region is much higher than that of other urban agglomerations, and the proportion of mining land in the Beijing-Tianjin-Hebei region is relatively large. The carbon dioxide emission intensity of the urban agglomerations also shows a similar pattern (Figure 4), the Yangtze River Delta urban agglomeration is the highest, followed by Beijing-Tianjin-Hebei, and the Pearl River Delta urban agglomeration is the lowest.

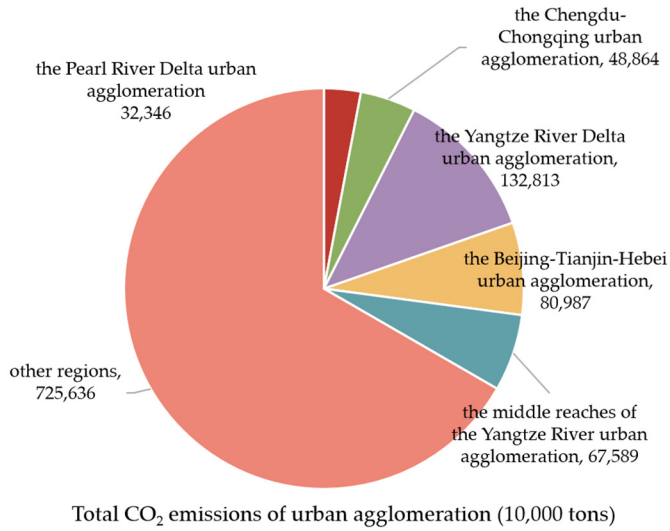

Figure 4. Total carbon dioxide emissions of urban agglomerations.

3.1.4. City Level

In this paper, the 346 major cities in the country are ranked according to the CO_2 emission intensity from smallest to largest (Figure 5). It can be seen that, in general, the cities with higher land use intensity show a higher trend of CO_2 emissions; in terms of the land-use structure, the higher the proportion of urban land is high, the higher the CO_2 emissions.

3.1.5. Grid Level

The distribution of construction land at the grid level of 10 km × 10 km across the country is shown in Figure 6, and the carbon dioxide emissions are shown in Figure 2. Through the visualization of carbon emissions at the national level, it is found that there are a large number of grids that do not emit CO_2. In the subsequent analysis, the kilometer grids with CO_2 emissions less than 1 t are removed. Spatial placement without grids: grids are mainly located in mountainous areas or deserts. There are 97,132 grids in the country, and 58,229 CO_2 grids remain after removal.

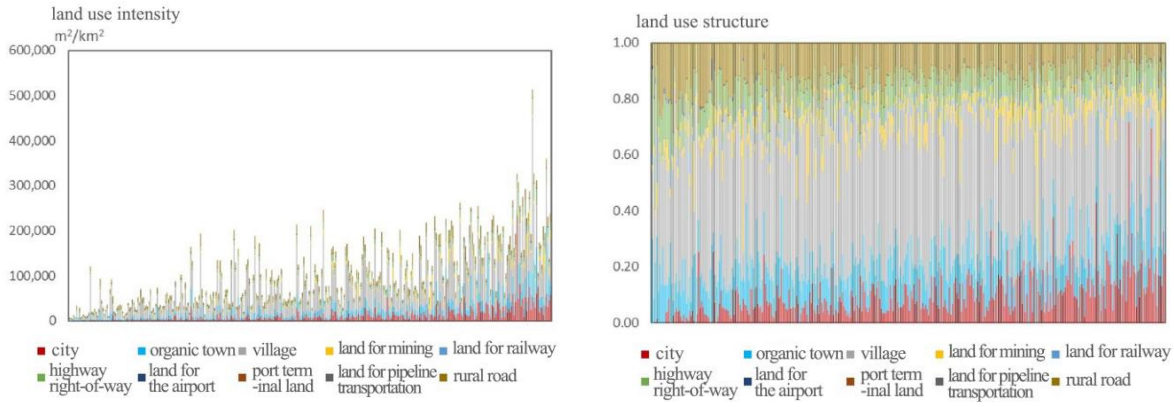

Figure 5. Land use intensity and land-use structure in major cities (in order of CO_2 emission intensity).

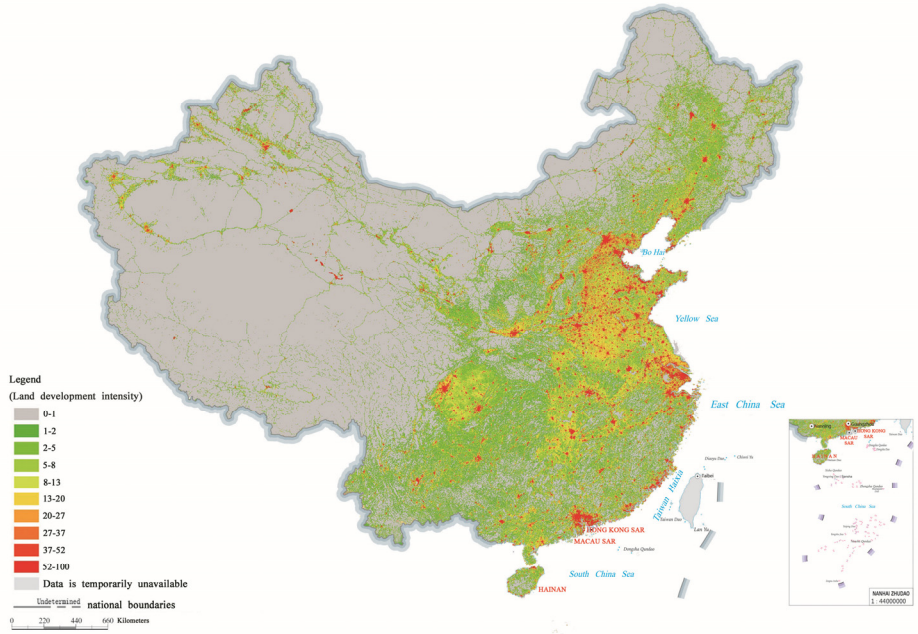

Figure 6. Distribution of construction land at grid level.

With the assistance of the cumulative distribution curves of construction land and CO_2 emissions for each grid (Figure 7), it is found that 4.38% of the grids correspond to 90% of the total emissions, and the corresponding grids have a construction land area of only about 110,000 square kilometers, accounting for 27.94% of the national construction land and about 1.2% of the national land area. Since the vast majority of CO_2 emissions are concentrated in a few grids, it is very important to control emissions in key areas.

There are also significant differences in CO_2 emissions for grids with similar land-use structures. Among the 58,229 grids in the country, the grids with urban land area accounting for 20–21% were selected for analysis, as shown in Figure 8. There are significant differences in grid emissions in different regions, especially in the central region. Some grid emissions are similar to other regions. Therefore, it is necessary to control both the land type and the land carbon emission intensity for the carbon emission of the national land space.

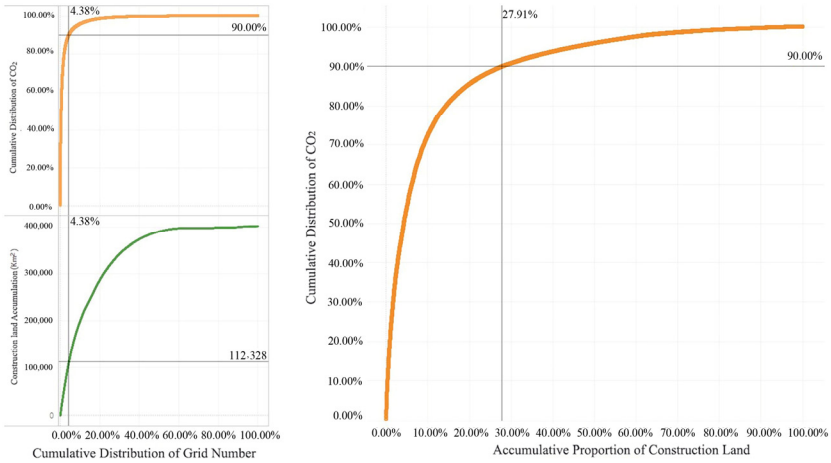

Figure 7. Grid construction land and cumulative distribution curve of carbon dioxide.

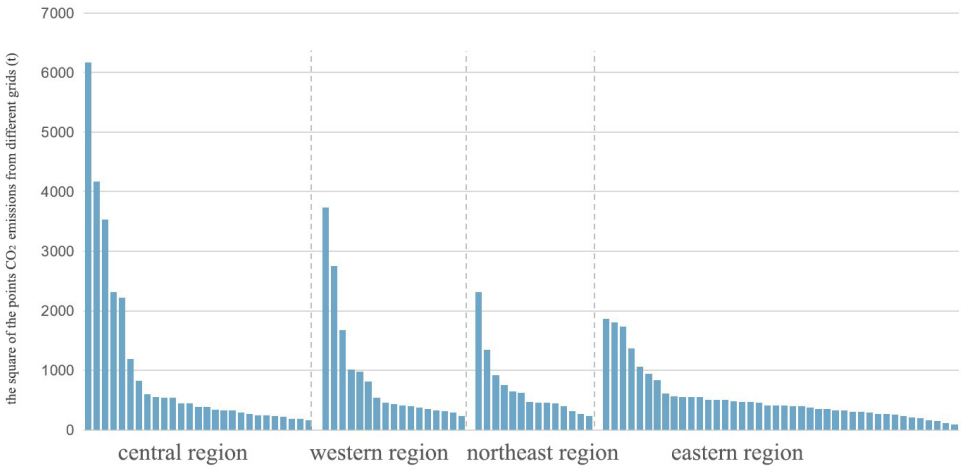

Figure 8. Distribution of carbon dioxide emissions in grids with similar land-use structures.

3.2. Coupling Analysis of "Land Use-Carbon Emission"

In this study, 10 km × 10 km grids were divided nationwide, and a total of about 97,000 grids were obtained, but there are a large number of grids in these grids that do not produce or produce very little CO_2 emissions. The carbon emissions visualization revealed that such grids are mainly located in areas such as mountains or deserts where human activity is minimal, so grids with CO_2 emissions of less than 1 ton were removed from the CO_2 emissions analysis, leaving 58,229 grids.

3.2.1. The Relationship between the Area and Type of Construction Land and CO_2 Emissions

In order to intuitively analyze the relationship between the area and type of construction land and CO_2 emissions, this study firstly divided 58,229 grids into 20 levels according to the level of CO_2 emissions, each level is set with 2911 grids. The average area of different construction land types in the grid is demonstrated in Figure 9. The 20 columns in the figure represent the average construction land type and corresponding area of the grids in different sets. The points in the black broken lines in the figure represent the CO_2 emissions of the grids with the lowest CO_2 emissions in each set. It can be seen that with the increase in the construction land area, especially the urban (city + organic town) construction land area, the CO_2 emission generally shows an upward trend. Particularly when the construction land area accounts for more than 15% of the grid area, the CO_2 emission increases rapidly with the increase in the construction land area.

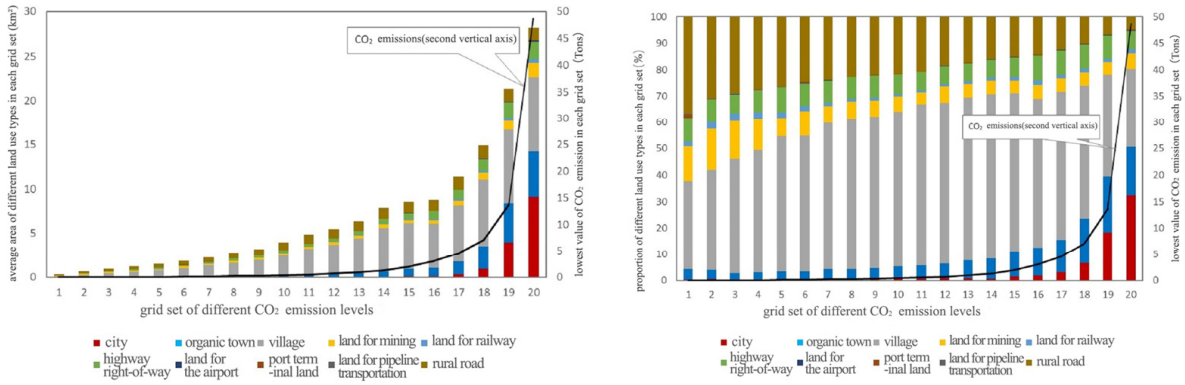

Figure 9. Relationship between the area and proportion of different land use types and the CO_2 emission level.

Figure 9 is obtained by plotting the average proportions of different construction sites for the 2911 grids in the above 20 sets. The 20 columns in the figure represent the proportion of different types of construction land in different sets. It can be seen that the CO_2 emission increases significantly with the increase in the urban area, indicating that the relationship between urban land and CO_2 emission is significant. The larger the proportion of urban land, the more it is necessary to consider how to control CO_2 emissions.

3.2.2. Double Logarithmic Model of Built-Up Land Area and Carbon Emissions

Based on the preliminary analysis of the correlation between construction land and CO_2 emissions, in order to obtain the quantitative relationship between construction land and CO_2 emissions, a variety of data analysis methods were tried, and finally it was found that the double logarithmic linear relationship between the total area of construction land and CO_2 emissions was significant. That is, after removing the grid with the construction land area of 0 from the 58,229 grids, the remaining 57,607 grids were subjected to a double logarithmic linear regression of CO_2 emissions per unit area and the proportion of construction land (Figure 10). The coefficient $R^2 = 0.5983$, the linear relationship is significant, and the obtained regression equation is:

$$\log(y) = 1.4272\log(x) + 3.9636, \quad (1)$$

where y is the CO_2 emission per unit area, unit t/km^2; x is the proportion of construction land in the grid.

According to this regression equation, when the scale of construction land doubles, the corresponding CO_2 emission increases by about 1.7 times, that is, the increase in construction land promotes the accelerated growth of CO_2 emissions.

According to the above method, the double logarithmic linear fitting of CO_2 emissions per unit area and the proportion of construction land was performed for 31 provincial-level administrative regions, and the results are shown in Figure 10. Except for that of Xinjiang, the regression coefficient of determination R^2 value of 30 provinces is greater than 0.4, and the linear fit is great. Without considering Xinjiang for the time being, according to the regression equations of the 30 provinces, when the construction land area doubles, the corresponding increase in carbon emissions is calculated. The results are shown in Table 1, where large differences among provinces are found. When the construction land is doubled, the added value of CO_2 emissions in each province ranges from 1.1 times to 3.9 times. Among them, the 10 provinces with the largest increase are Qinghai, Tibet, Guizhou, Shandong, Shanxi, Jilin, Henan, Liaoning, Fujian, Ningxia, and the 10 provinces with the smallest increase are Inner Mongolia, Sichuan, Hainan, Anhui, Beijing, Hubei, Hunan, Yunnan, Gansu, and Hei Longjiang. Different provinces have different spatial land-use structures and different levels of technological development, resulting in significant differences in the increase in carbon emissions with construction land.

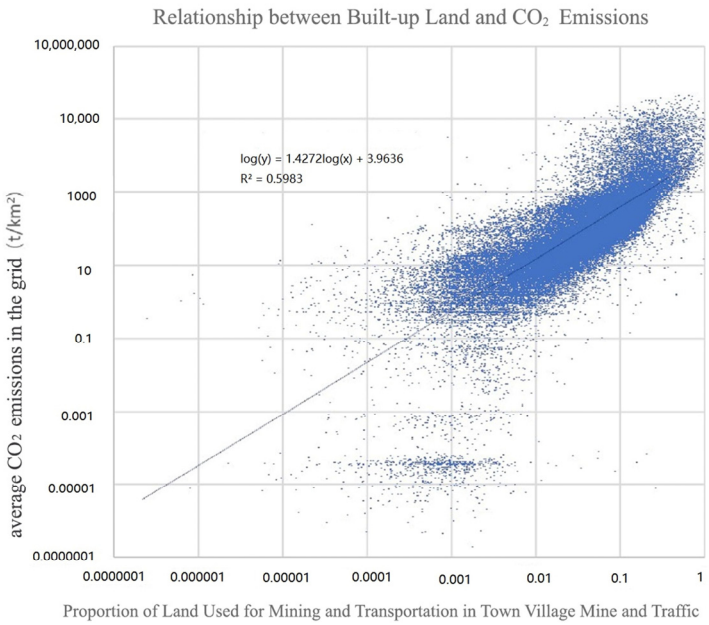

Figure 10. Double logarithmic regression results of national construction land area and carbon emissions.

Table 1. Double logarithmic regression results by province.

Province	Regression Coefficient	Determination Coefficient R^2	Number of Valid Grids	The Added Value of Carbon Emissions When the Area of Construction Land is Doubled
Xinjiang	0.730	0.374	4547	66%
Inner Mongolia	1.057	0.559	6801	108%
Sichuan	1.160	0.620	4024	123%
Hainan	1.240	0.448	360	136%
Anhui	1.287	0.413	1402	144%
Beijing	1.387	0.797	213	162%
Hubei	1.466	0.610	1888	176%
Hunan	1.467	0.549	2113	176%
Yunnan	1.468	0.565	3618	177%
Gansu	1.484	0.551	2763	180%
Heilongjiang	1.494	0.694	3962	182%
Guangdong	1.495	0.593	1844	182%
Zhejiang	1.527	0.706	1167	188%
Shanghai	1.548	0.541	104	192%
Chongqing	1.580	0.561	965	199%
Guangxi	1.599	0.540	2356	203%
Shaanxi	1.613	0.584	1938	206%
Hebei	1.613	0.688	1981	206%
Jiangsu	1.651	0.473	1126	214%
Jiangxi	1.664	0.565	1675	217%
Tianjin	1.668	0.596	148	218%
Ningxia	1.671	0.503	354	218%
Fujian	1.672	0.607	1325	219%
Liaoning	1.672	0.606	1520	219%
Henan	1.674	0.554	1589	219%
Jilin	1.760	0.656	1883	239%
Shanxi	1.805	0.647	1612	249%
Shandong	1.918	0.462	1600	278%
Guizhou	1.989	0.499	358	297%
Xizang	2.002	0.465	115	300%
Qinghai	2.284	0.410	2256	387%

The double logarithmic model of construction land area and carbon emission is an empirical model, and it is also a quantitative presentation of qualitative analysis results, which mainly reflects the characteristics of accelerated growth of carbon emission with the increase in construction land area. However, this model cannot well reflect the specific factors affecting carbon emissions. Therefore, this study further explores in detail and obtains the following coupling model.

3.2.3. Double Logarithmic Model of Land Area and Carbon Emissions by Sub-Sector

Industrial production, including the energy industry, contributes most of the anthropogenic CO_2 emissions. As a result, it is necessary to study the relationship between industrial land and carbon emissions.

When the carbon emissions of industrial land in the context of industry segmentation is studied, it is found that the fitting method using non-negative least squares is the most robust. From the national results of the correlation analysis, it can be indicated that the industries most closely related toCO_2 are gas production and supply, electricity and heat production and supply, warehousing and logistics, and petroleum processing, coking, and nuclear fuel processing.

In order to further study the coupling relationship between land use and carbon emissions in different industries, nearly 100,000 industrial POI points were converted into AOI, and the distribution of 35 subdivided industries in the grid was obtained. After trying a variety of data mining methods, we finally chose to use a 10 km × 10 km grid as the basic unit to conduct multiple linear regressions between CO_2 emissions and different types of industrial land. In order to achieve the best regression effect, some industries in the 35 sub-industries were selectively merged to obtain 19 industry types as shown in Table 2.

Table 2. Industry types for multiple linear regression.

Serial Number	Industry or Industry Collection
1	Gas production and supply industry
2	Electricity and heat production and supply industry
3	Water production and supply industry
4	Paper and paper products industry
5	Petroleum processing coking and nuclear fuel processing industries
6	Chemical fiber manufacturing
7	Chemical raw materials and chemical products manufacturing
8	Ferrous metal smelting and rolling industry
9	Non-metallic mineral products industry
10	Warehousing and logistics industry
11	Non-ferrous metal smelting and calendering industry
12	Animal husbandry
13	Non-ferrous metal mining and dressing industry
14	Leather, fur and feathers and their products and footwear
15	Village

The final regression equation is:

$$E = b0 + b1A1 + b2A2 + \ldots \ldots + b19A19 \quad (2)$$

Among them, E is the CO_2 emissions of the grid, unit t; bn is the CO_2 emission coupling coefficient (emission intensity) of the industry, unit t/km^2; An is the area of the nth industry in the grid, unit km^2.

The above regressions were performed on the data of 31 provinces in mainland China, and the multivariate linear regression equation of carbon emissions in different provinces and industrial land were obtained. The results showed that the linear relationship was significant. According to the regression equation of 31 provinces, a box plot of carbon emission intensity of different industries is made, as shown in Figure 11.

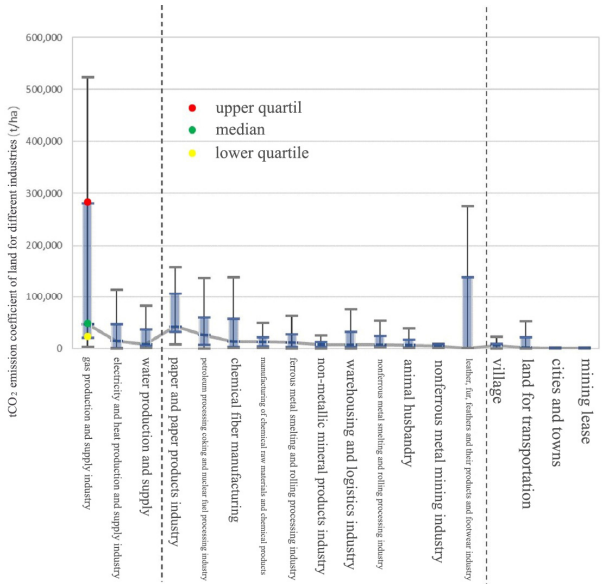

Figure 11. Box diagram of CO_2 emission coefficients for different industries.

According to the "China Carbon Emissions Trading Report (2017)", in 2009, the industry with the largest carbon emission in China was the supply of electricity, gas, and water. Judging from the results of this study, the gas, electricity, and water industries have high carbon dioxide emission intensity, and the carbon emission intensity of different provinces varies greatly, so their emission reduction potential is large. It can be seen from Figure 11 that other industrial lands other than water, electricity, and gas are significantly related to carbon emissions (in ascending order of median emission intensity) paper and paper products, petroleum processing, coking, and nuclear fuel processing industry, chemical fiber manufacturing, chemical raw material and chemical product manufacturing, ferrous metal smelting and rolling processing industry, non-metallic mineral product industry, warehousing and logistics industry, non-ferrous metal smelting and rolling processing industry, animal husbandry, non-ferrous metal mining industry selection, leather, fur, feather and its products, and footwear.

The paper industry has the highest carbon intensity. Statistics show that in 2015, China's paper industry accounted for 1.67% of carbon emissions. Among them, more than 80% of the emissions come from the combustion of fossil fuels, especially coal. Almost all coal in paper making enterprises is used in small self-provided power plants and heating boilers. The scale of power generation/heating is small, energy utilization efficiency is low, and carbon emissions are large [32]. Therefore, the decarbonization of the paper industry should first focus on banning/upgrading self-provided power plants/boilers, and at the same time, other measures should be taken to reduce corporate energy consumption and carbon emissions [33]. The carbon emission intensity of chemical fiber and leather industries varies greatly among provinces, and the larger emissions may also be related to self-provided power plants/boilers. Heavy industries such as petroleum, chemical, metal, and non-metal are traditional large carbon emitters, and their corresponding land-use emission intensity is also high. On the one hand, production capacity should be strictly controlled and efficiency should be improved to reduce carbon emissions; on the other hand, if deep decarbonization is to be achieved, fundamental technological changes and carbon capture technologies are often required. The emission intensity of warehousing, logistics, and animal husbandry land is also relatively large, and has developed rapidly in the past decade. The studies on carbon emissions in these two industries are extremely limited, and more in-depth research is needed in the future to establish a modern green warehousing logistics industry and animal husbandry to reduce greenhouse gas emissions.

Excluding industrial land, village and town land, as well as transportation land and mining land have low emission intensity, but these areas account for about 79% of total

construction land. Hence, the industries also contribute to total emissions. As can be seen from the overall coupling results, according to the method similar to the multiple linear regression of the above 31 provinces, the multiple linear regression is carried out with all the data of the 31 provinces as a whole. The results show that the linear relationship is significant, and the multivariate linear regression equation of carbon emissions and land use in different industries is obtained. According to this equation to analyze the coupling relationship between construction land and carbon emissions, it is found that urban and organic town land (referred to as urban land) accounts for 1% of the total land area, but carbon emissions account for nearly 90% of the country's total emissions. Among the nearly 90% of carbon emissions, the carbon emissions from industrial land (about 17% of urban land) and the carbon emissions from non-industrial land account for about half. Therefore, the optimization of the spatial structure of urban areas is the top priority to achieve peak carbon dioxide emissions and carbon neutrality.

According to the overall coupling results, the multivariate linear regression equations of the overall carbon emissions of 31 provinces and the land use of different industries are obtained, and then the lower quartile of the statistical results of carbon emission intensity of different industries in the 31 provinces and sub-provinces is taken as the advanced value. The carbon emissions when the carbon emission intensity of industrial land is reduced to the advanced value, and it is found that the overall carbon emissions of 31 provinces can be reduced by half. It can be seen that the emission reduction potential of urban land is large, accounting for 46% of such emission reduction. What is followed are chemicals, power, non-metals, ferrous metals and warehousing and logistics, which account for 14%, 12%, 12%, 6%, and 5% of such reductions, respectively. These should be the key areas for carbon emission control in the future.

3.2.4. Carbon Emissions Forecast

Based on the multiple linear regression results of the overall carbon emissions of 31 provinces across the country and land use in different industries, different control scenarios are considered to predict carbon emissions scenarios. The five scenarios are set as follows:

BAU Scenario (no control scenario): Similar to the past decade, 600,000 hectares of construction land will be added each year without structural adjustment or emission intensity controls.

Control Scenario 1: The annual increase in construction land is reduced to 210,000 hectares, but no structural adjustment or emission intensity control is carried out.

Control Scenario 2: On the basis of Control Scenario 1, adjust the land-use structure is adjusted, and new land use for industries with excess capacity are reduced or canceled.

Control Scenario 3: On the basis of Control Scenario 2, the carbon emission intensity of different industries in the newly added construction land is reduced, so that it can be reduced to the advanced value of the industry year by year within five years (lower than the lower quartile of the statistical results of carbon emission intensity of different industries in 31 provinces and sub-provinces).

Control Scenario 4: On the basis of Control Scenario 3, the carbon emissions from previous land use are controlled and the carbon emission intensity is reduced by 0.2% year by year.

The carbon emission forecast results under the five scenarios are shown in Figure 12. It can be seen that with the deepening of the control, the carbon emissions will gradually decrease, and finally achieve the carbon peak in 2030. That is to say, without considering carbon sequestration and carbon capture, the target of peak carbon dioxide emissions can still be achieved by 2030 through land use supply control, land-use structure adjustment, land use intensity constraints, and functional adjustment of existing land use. The carbon emission reduction in 2030 in the control scenario is about 14%. Figure 12 shows the specific calculation of the carbon emission reduction effect achieved by each control measure in 2030 under different scenarios.

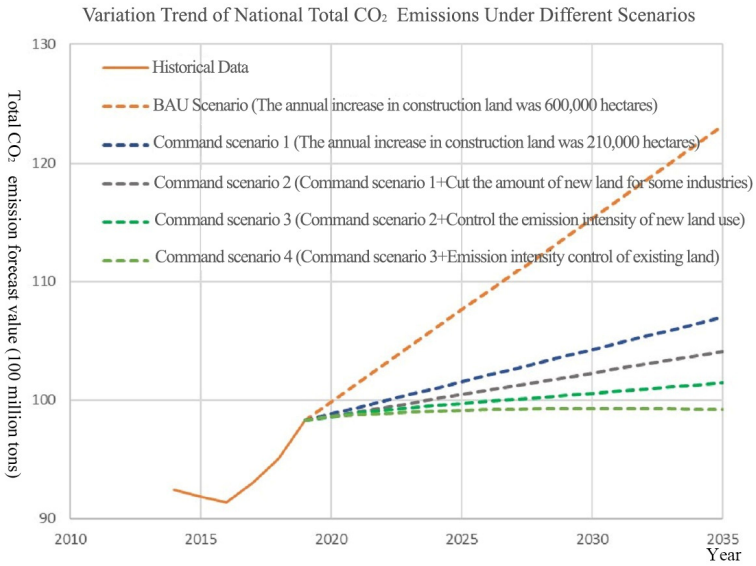

Figure 12. Predicted total CO_2 emissions under different scenarios.

According to the existing state-owned space structure, carbon emissions will continue to grow without any control measures. The carbon emission forecast results for 2030 show that if construction land continues to grow at an average annual growth rate of about 600,000 hectares in the past decade, and measures such as land-use structure adjustment and carbon emission intensity constraints are not taken, then carbon dioxide emissions will continue to grow. A 16% increase is expected in 2030 compared to 2020. Controlling the area of new construction land can significantly reduce CO_2 emissions. In the past ten years, the construction land has maintained an annual increase of about 600,000 hectares, of which the new industrial and mining storage land accounts for about 1/4, the new real estate land accounts for about 1/4, and the remaining half left and right are new infrastructure and other land. If the area of newly added construction land drops from 600,000 hectares per year to 280,000 hectares per year, the model predicts that carbon emissions will drop significantly. Compared with the uncontrolled scenario, emissions in 2030 will drop by about 10%. However, under the background that the urbanization rate will continue to increase, the control of the total amount of construction land cannot be achieved without practical control measures. Therefore, on the basis of steady economic growth, in order to achieve the decline or even negative growth of new construction land, it is necessary to further tap the potential of the existing construction land, to improve the land use control standard system, to develop and apply land-saving technologies, and to reduce the use area of construction land per unit of GDP, etc.

Adjusting the new land-use structure can further reduce CO_2 emissions. Fossil energy industry, petrochemical, chemical, metal, non-metal, and other industries have high carbon emission intensity, and the land used for such industries should be strictly controlled in the newly added land, and even zero growth of land used in some industries should be achieved, so as to adjust the structure of new land use and reduce the carbon emission targets.

Fossil energy can be replaced by renewable energy: according to the International Renewable Energy Agency (IRENA), under the target of global warming of less than 2 degrees Celsius, global electricity consumption will account for half of global final energy consumption in 2050, and 86% of the electricity from non-fossil energy. It is predicted in the report of Goldman Sachs that renewable energy is the most important technology to achieve decarbonization in China, and the decarbonization contribution rate can reach 50%; it is estimated that Chinese power generation in 2060 will triple the current amount, mainly from solar energy, wind energy, nuclear energy and hydrogen energy.

China's petrochemical, chemical, metal, non-metal, and other heavy industries are facing certain problems of overcapacity and backward production capacity. The control of the new land use in such industries is consistent with the needs of resolving excess production capacity, eliminating backward production capacity and accelerating the release of high-quality production capacity. It is conducive to achieving high-quality development of the industry while reducing carbon emissions.

The carbon peak can be achieved to further control the carbon emission intensity of new land and reduce the carbon emission intensity of existing land. Reducing the carbon intensity of construction land has great potential to reduce emissions. For newly added construction land, carbon emission constraints for newly added projects can be considered with the industry advanced value. For existing construction land, the industry advanced value can be used as the target to formulate a carbon emission intensity reduction plan.

4. Discussion

The research is based on grid scale, and different scales will have a significant impact on the research results. This study uses a 10 km × 10 km grid as the research unit, divides the land area of the country into more than 90,000 grids, and conducts correlation statistics on land use and carbon emissions. The statistical results show that: the average carbon dioxide emission intensity (y) in the grid and the proportion of construction land (x) are fitted in double pairs, and the fitting function is log (y) = 1.4272log(x) + 3.9636, R^2 = 0.5983. If the research unit changes, the fitting function will change accordingly, so the research conclusion in this article is expressed as "based on the statistical data display under the grid scale of 10 km × 10 km". Later, the author will further study the correlation between land use and carbon emissions at different scales, and explore the establishment of a cross scale quantitative analysis model.

There is a strong correlation between the spatial structure of land use and the concentration of carbon emissions, and the refined land use planning based on environmental capacity is imperative. Taking into account the new requirements of peak carbon dioxide emissions by 2030 and carbon neutrality by 2060 proposed by the state, this study puts forward the following policy recommendations: (1) We should strengthen the management and control of national land space based on carbon emissions, and strictly control the land supply, especially the land supply with high energy consumption, for regions and provinces and cities with relatively large carbon emissions, relatively extensive development, and high carbon emission intensity of construction land. (2) The new round of territorial space planning should be based on the management and control of the nature of land functions. We should strictly control the disorderly, blind expansion of construction land, and the supply of high-energy-consuming industrial land in some areas, optimize the structure and layout of land and space, guide the adjustment of industrial land structure, promote clean and high value-added industrial upgrading, and further put forward control constraints on the intensity of land carbon emissions. (3) In the new territorial and spatial planning and management system, the requirements for peak carbon dioxide emissions and carbon neutrality should be combined, and the requirements for land supply scale and structural adjustment should be clearly put forward in the overall planning of territorial space at all levels. The entry threshold for construction and development should be elevated. (4) We should introduce climate change and environmental capacity constraints in the preparation of territorial space planning, conduct special discussion and evaluation, and use it as a planning basis. (5) The implementation evaluation and monitoring index system of carbon emissions and capacity in the "dual evaluation" and "dual evaluation" system of land and space planning should be included, and the land evacuation and reduction of high-energy-consuming industries should be guided. We should build a model system for the relationship between land space use and carbon emissions, evaluate the synergistic relationship between land space use development and carbon-neutral development scenarios, and ensure the realization of carbon-neutral scenarios. (6) We should adjust the spatial land-use structure of the country, optimize the layout, synergize carbon sink ecosystems, set national

carbon sink capacity targets, gradually increase carbon absorption and storage capacity, and identify key carbon sink areas and conservation and promotion policies. Territorial spatial planning should guide the intensive and low-carbon development model of cities. An efficient, intensive, low-carbon, and livable urban spatial system should be created. We should promote green travel and guide residents' behavior towards green and low carbon. (7) Based on the "one map" of land and space planning, we should integrate the management and control requirements of relevant departments such as development and reform, environmental protection, etc. We should also achieve precise management and control of carbon emissions space under the linkage of multiple data sources.

5. Conclusions

With the establishment of a model on the relationship between spatial land-use structure and carbon emissions, this study explores how the optimization of spatial land-use structure can support the achievement of carbon peaking and carbon neutrality, and provides theoretical support for the formulation of relevant policies and plans, as well as the evaluation of their implementation effects. The main conclusions reached include: (1) There is a strong correlation between the spatial structure of land and carbon emissions; the scale of construction land, especially industrial land, directly affects carbon emissions; if the area of construction land is doubled, CO_2 emissions will increase by about 1.7 times. (2) The analysis by province shows that the provincial land-use structure is directly related to carbon emissions, and the correlation coefficients of different provinces vary from each other, reflecting the distinction in carbon emissions caused by different provincial land-use structures; the area of construction land doubled, and carbon emissions in different provinces increased by 1.1 to 3.9 times. (3) Grids with similar land structures are selected for analysis. The grid carbon emissions in different provinces have a certain degree of dispersion, and the eastern region is significantly better than other regions, reflecting the impact of technical and management factors on carbon emissions. (4) The analysis at the city level shows that in the case of similar land GDP output, the land carbon emission intensity is still quite different, indicating that the city level has a great potential to control the carbon emission intensity through the land structure. (5) Analysis from the type of industrial land: the carbon emission intensity of different industries is quite different, among which the carbon intensity of the land used for basic energy such as water, electricity, and municipal supply is the largest, followed by the industrial land, urban living, and production land. However, the urban living and production land covers a large area, which should also be paid attention to; the carbon emission intensity of different regions in the same industry is also quite different, reflecting the role of technology and management factors in carbon emission control. The analysis results of subdivided industries can set carbon emission benchmarks for industrial land use and provide a basis for introducing carbon intensity indicators into future land supply. (6) It is efficient and feasible to control carbon emissions through the territorial spatial planning system. The elements of control can be divided into the following levels: land supply control, land-use structure adjustment, land use intensity constraints, and functional adjustment of existing land use. These means of control should be required and considered in future territorial and spatial planning at all levels. (7) According to the above analysis in the research, this paper conducts a scenario analysis of land use control in national land spatial planning. The results show that through the above control methods, without considering carbon sinks and carbon capture, it is still possible to achieve the national carbon peak in 2030. In 2030, compared with the uncontrolled scenario, the emission reduction ratio will be 14%.

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