International Journal of
Geo-Information

MDPI

Article

Carbon Emission Patterns and Carbon Balance Zoning in Urban Territorial Spaces Based on Multisource Data: A Case Study of Suzhou City, China

Zhenlong Zhang [1,*], Xiaoping Yu [1], Yanzhen Hou [1], Tianhao Chen [1,2], Yun Lu [1] and Honghu Sun [1]

1 School of Architecture and Urban Planning, Suzhou University of Science and Technology, Suzhou 215011, China
2 School of Geography and Planning, Cardiff University, Cardiff CF10 3AT, UK
* Correspondence: zlzhang@usts.edu.cn

Abstract: The concept of green and low-carbon development is integrated into territorial spatial planning and district control research. It is one of the systematic policy tools for emission reduction and carbon sequestration, greatly contributing to achieving the double carbon goal. This paper presents a method for measuring the carbon emissions of urban territorial spaces using multisource big data, aiming to identify the spatial patterns and levels of carbon emissions at microspatial scales. The spatial patterns of carbon emissions were used to construct a carbon balance zoning method to evaluate the regional differences in the spatial distribution of carbon emissions, taking Suzhou as an example to achieve carbon balance zoning at the micro scale of the city. Based on our research, the following was determined: (1) Suzhou's total carbon emissions in 2020 was approximately 240.3 million tons, with the industrial sector accounting for 81.32% of these emissions. The total carbon sink was about 0.025 million tons. (2) In Suzhou City, the high-value plots of carbon emissions are mainly located in industrial agglomeration areas. By contrast, low-value plots are primarily located in suburban areas and various carbon sink functional areas, exhibiting a scattered distribution. (3) The territorial space unit was divided into four functional areas of carbon balance, with 36 low-carbon economic zone units accounting for 37.11%, 29 carbon-source control zone units accounting for 29.90%, 14 carbon-sink functional zone units accounting for 14.43%, and 18 high-carbon optimization zone units accounting for 18.56%. As a result of this study, carbon balance zoning was achieved at the grassroots space level, which will assist the city in low-carbon and refined urban governance. Some ideas and references are also provided to formulate policies for low-carbon development at the micro scale of a city.

Keywords: carbon emissions; spatial pattern; carbon balance zoning; territorial spatial planning; Suzhou City

Citation: Zhang, Z.; Yu, X.; Hou, Y.; Chen, T.; Lu, Y.; Sun, H. Carbon Emission Patterns and Carbon Balance Zoning in Urban Territorial Spaces Based on Multisource Data: A Case Study of Suzhou City, China. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 385. https://doi.org/10.3390/ijgi12090385

Academic Editors: Wolfgang Kainz and Godwin Yeboah

Received: 13 July 2023
Revised: 11 September 2023
Accepted: 15 September 2023
Published: 20 September 2023

1. Introduction

Human activity is primarily concentrated in cities, which are the largest sources of carbon emissions. According to the sixth IPCC report in April 2022, urban carbon emissions in 2020 amounted to 67 to 72% of total global emissions [1], making urban-area carbon emissions an important target in the fight against climate change. Considering that cities are the spatial carriers of various carbon-source activities and carbon emissions, relying solely on industrial policies and emission reduction technologies on the energy supply side is not enough to curb the surge in carbon emissions. To achieve low-carbon development, it is necessary to explore a people-oriented, sustainable, and low-carbon city development model with spatial planning as the breakthrough point [2]. The territorial space carries a variety of carbon sink entities and the carbon emissions of social and economic activities. As a result, territorial spatial planning has become one of the systematic policy tools for coordinating carbon emissions and sinks in order to reduce carbon emissions and sequester carbon [3]. In September 2020, China set the "carbon peaking and carbon neutrality" strategic goal. Considering the construction of ecological civilization and the "double carbon" strategy, it is important to integrate the concept of green, low-carbon development into territorial spatial planning systems. Meanwhile, in view of the differences in urban development levels and natural resource endowments between regions, there is a wide gap in carbon emission and carbon balance states between urban areas. There should be guidance countermeasures involving low-carbon territorial spatial planning using different carbon emission reduction targets, methods, and paths for different carbon balance states in each region. They should also highlight adaptations to local conditions and dynamic adjustments in planning in order to efficiently achieve the "double carbon" target. The division of carbon balance functional zones according to different carbon balance states and creating urban carbon balance zoning is important for reducing carbon emissions and developing low-carbon cities.

Carbon emissions in territorial spaces have been studied by some scholars in recent years. The existing research focuses primarily on measurement methods [4–6], spatial–temporal patterns [7–10], influencing factors [11–13], and planning paths and strategies [14,15]. Carbon emission measurements and spatial patterns are the basis and key to the follow-up field of research. This research was conducted in different urban sectors, such as agriculture [16], transportation [17], construction [18], manufacturing [19], etc., to refine the spatial distribution differences of carbon emissions across sectors. Research areas were primarily concentrated at the national level [20], the regional level [21], and the urban level [22]. In analyzing the current research results, we discovered that scholars have concentrated their efforts on research at a medium–macroscale, whereas measurements and spatial patterns regarding carbon emissions at a micro-scale are underrepresented, especially at the township level. As a consequence of the nonuniformity and inadequacy of territorial space carbon emission data, the accuracy of the relevant calculation results is insufficient to fulfill the high requirements regarding refined governance in territorial space carbon emissions.

Researchers have also researched carbon balance and its zoning methods at various spatial scales in recent years. On the national scale, as a result of land use and climate change, the evolution of the total terrestrial carbon balance pattern in China has been analyzed by calculating changes in carbon storage and carbon sinks (sources) in terrestrial ecosystems [23,24]. At the regional scale, carbon balance zoning at the metropolitan county level was achieved based on regional carbon budget accounting and carbon balance analysis [25]. The empirical results of social network analysis were superimposed on the regional carbon budget analysis, which aims to achieve the carbon balance zoning of the Beijing–Tianjin–Hebei urban agglomeration county unit [26]. Using the PLS–STIRPAT model, some scholars have explored the impacts of population and economic, spatial, and ecological urbanization on carbon emissions and further analyzed the urban carbon balance state in the Middle Reaches of the Yangtze River urban agglomeration of China [27]. At the urban level, they have also explored quantitative structures and spatial pattern optimization in the Beijing green space from the perspective of carbon balance to improve the total carbon sink of the city [28]. In Ensenada, a coastal city in Mexico, the carbon flow and carbon balance of its urban system were estimated by measuring vertical and horizontal carbon fluxes [29]. At the county scale, carbon balance functional zones were divided based on the county carbon balance zoning method in accordance with carbon budget calculations and analyses of the carbon balance state of Huantai township units [30]. At the community level, using spatial and non-spatial data relating to urban form, energy, and carbon emission modeling, the carbon balance state of Vancouver was simulated [31].

Since the influencing factors of carbon emissions are diverse and their external effects are complex, research on carbon balance and its zoning methods has primarily been conducted at a relatively macro-scale, such as in regions, the data from which has been used to make macro-level decisions regarding the development and protection of territorial spaces. The "dual carbon" strategy requires multi-level government input to formulate low-carbon development strategies to reduce carbon emissions, especially for township units, for example, in the grassroots management units of cities, which directly affects the implementation of low-carbon strategies. However, the limitations of data accuracy and method systems prevent research on carbon emission spatial patterns and carbon balance zoning at the micro level, which leads to a lack of guidance on low-carbon planning and grassroots management unit governance, hindering the implementation of low-carbon governance of territorial space. Based on this, this article aims to guide the low-carbon development of cities and assist in the "dual carbon" strategy. Using high-precision carbon emission spatial patterns and carbon balance zoning at the micro-scale of cities as the entry point, a method for calculating territorial space carbon emissions was constructed. Based on multi-source big data, carbon emissions were accurately calculated at the micro-scale to obtain high-precision carbon emission spatial patterns, providing ideas and methods for measuring the high-precision spatial patterns of urban carbon emissions. Furthermore, from the perspective of regional carbon budget balance, a method of territorial space carbon balance zoning was also constructed. Using this method, achieving carbon balance zoning at the urban township level provides a reference for the study of carbon balance zoning at the micro-scale within cities. Finally, based on carbon balance zoning results from urban grassroots units, this article proposes differentiated carbon emission reduction strategies to provide a new perspective on optimizing and adjusting grassroots territorial space units. Thus, it will shape a coordinated, low-carbon, and sustainable development territorial space pattern and help achieve the "dual carbon" goal.

2. Materials

2.1. Overview of the Study Area

Suzhou is located in the south of Jiangsu Province. Taihu Lake lies to the west of Suzhou, and the Yangtze River lies to the north. The city is regarded as one of the most important centers in the Yangtze River Delta and is a famous historical and cultural site (Figure 1). There are five municipal districts and four county-level cities under the jurisdiction of Suzhou, and the city has 97 townships, or street administrative units, with a total area of 8657.32 km^2. By 2020, Suzhou had reached an urbanization rate of 81.72% and a GDP of CNY 20,170.45 billion, making it a leading area in China's economic transformation and development. Furthermore, its industrial output value has consistently ranked in the top three in the nation, with an industrial structure ratio of 1:46.5:52.5. As a national historical and cultural city and an important manufacturing center in China, Suzhou promotes energy conservation, recycling, and low carbon. It also promotes the green transformation of spatial patterns. There are, however, several challenges to overcome, such as continuous population influx, rising energy consumption, land conflicts, etc., creating higher requirements for developing efficient, low-carbon, coordinated, and sustainable land use.

In addition, the township economy is an example of the economic model prevalent in southern Jiangsu. Developing carbon balance zoning and studying the spatial pattern characteristics of carbon emissions at the township level in Suzhou will help us understand how carbon emissions affect social economies under the southern Jiangsu model and provide ideas for green and low-carbon economic development in townships.

2.2. Data Sources

Statistical and spatial data are presented in Table 1. Given Suzhou's statistical yearbook for all districts and counties in 2020, statistics were available on energy, industry, transportation, agriculture, population, and economy. Land use, POIs, mobile phone signaling, and road data were all included in the spatial data. The land use data were derived from the Suzhou Gaofen-2 remote sensing satellite, provided by the China Resources Satellite Application Center (2020); data on mobile phone signaling were obtained from the China Unicom Smart Footprint Platform; POI information was obtained from the Gaode API; and road data for the study area were obtained from the Open Street Map.

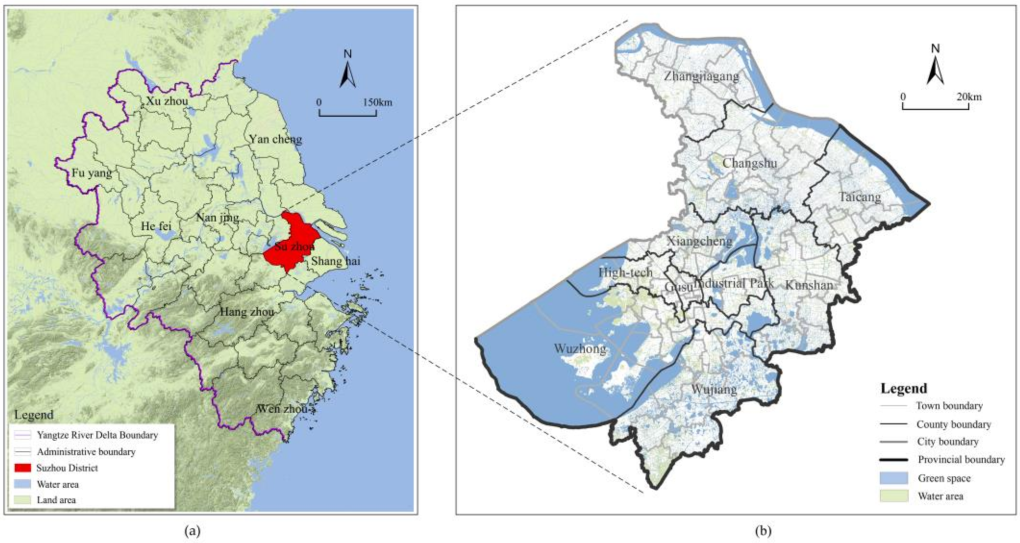

Figure 1. Location of Suzhou City: (**a**) location of Suzhou in the Yangtze River Delta; (**b**) administrative boundary of Suzhou.

Table 1. Description of research data sources.

Data Type	Specific Data	Data Content	Data Source
Statistical data	Energy data	Energy consumed by industrial enterprises; energy consumed by urban residents in daily life	Statistical Yearbook for each urban area (2020) The Seventh Population Census of Suzhou The Fourth National Economic Census of Suzhou
	Industrial data	Production of cement, glass, synthetic ammonia, and other major industrial products	
	Transportation data	Passenger and freight turnover for road, rail, and water transportation; annual mileage of urban public transportation	
	Agricultural data	Quantities of agricultural machinery, pesticides, fertilizers, livestock, crop yields, etc.	
	Demographic data	Population of residents	
	Economic data	GDP data	
Spatial Data	Land use data	Based on interpretations of remote sensing satellite images from Gaofen-2, a classification was made in accordance with the Technical Regulations of the Third National Land Survey	China Resources Satellite Application Center
	POI data	Suzhou area POI data, sorted, filtered, and grouped according to research needs, as well as data cleaning and coordinate transformation	Gaode API
	Cellular signaling data	Data on the presence and movement of populations with specific coordinates	China Unicom Smart Footnote Platform
	Road data	Highways, national roads, provincial roads, county roads, township roads, and other urban sub-grade roads	Open Street Map

3. Method

Based on the corresponding relationship between territorial space and carbon emissions, a measurement method was developed for territorial spatial carbon emissions based on multisource big data. In addition, we calculated the spatial carbon emission levels based on measurement results from various departments in the city to determine the characteristics of urban carbon emission spatial patterns. Lastly, we developed a carbon balance zoning method based on the territorial space carbon emission results to define the carbon balance functional zones (Figure 2).

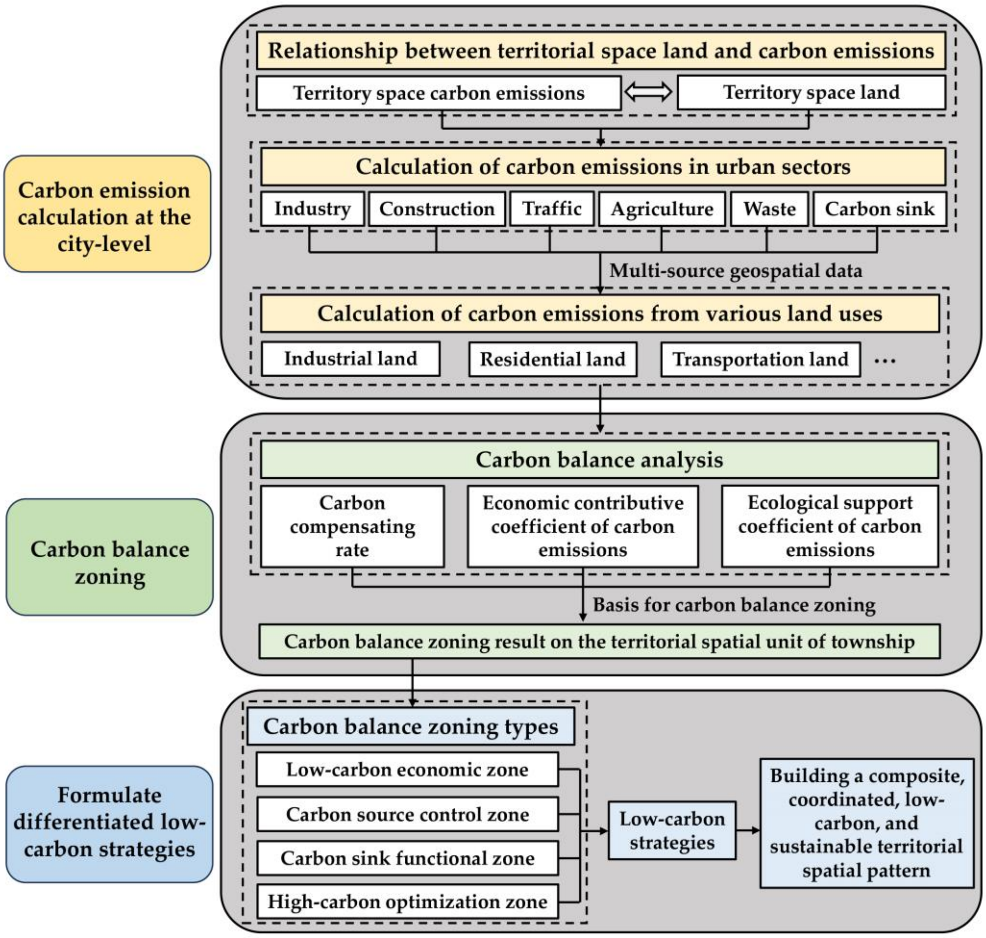

Figure 2. An overview of the methodological flowchart.

3.1. *Method of Carbon Emission Calculation at the City Level*

Quantitative calculation of territorial space carbon emissions is the premise and foundation of studies on regional carbon balances. Some scholars researched calculation methods for carbon emissions closely related to spatial planning in recent years. This includes developing correlation frameworks between land use and carbon emissions [2] and accounting for the carbon emissions of Beijing [32] and Shanghai's overall urban plans [33], thus establishing a greenhouse gas accounting model for the overall planning of territorial space and accounting for greenhouse gas emissions associated with territorial space [34]. However, in the above research, only relying on a single statistical dataset and method to calculate the carbon emission level of land use has resulted in homogenized calculation results from various types of land use, making it challenging to accurately show the spatial pattern characteristics of carbon emissions and regional carbon balance states. This article improves the traditional carbon emission measurement method based on statistical data [2,34], combining multisource big data with statistical data to construct a measurement method for territorial space carbon emissions. By calculating departmental carbon emissions using statistical data, the multisource big data were used to construct a spatialization method for urban carbon emissions, allocating carbon emissions generated by different departments into specific spatial plots. Furthermore, the spatial pattern of carbon emissions is summarized at the micro scale within the city. This method breaks through the limitations of spatial scale and achieves high-precision measurements of carbon emission spatial patterns at an urban microscale. Furthermore, it more accurately reveals the carbon emission spatial pattern and carbon balance characteristics of urban grassroots management units, providing basic support for carbon balance zoning research on microscale grassroots units.

3.1.1. Establishing the Relationship between Territorial Space and Carbon Emissions

Using territorial space as a carrier, this paper links urban carbon emission inventories to territorial space planning, reflecting the influence of economic and social activities. From the perspective of urban consumption, this paper summarizes carbon emission sectors in the IPCC Greenhouse Gas Emission Guidelines and divides them into six categories: industry, construction, transportation, agriculture, waste treatment, and carbon sinks [35]. The corresponding association between the territorial space and carbon emission departments can be determined based on spaces where terminal consuming activities generate carbon emissions (Figure 3).

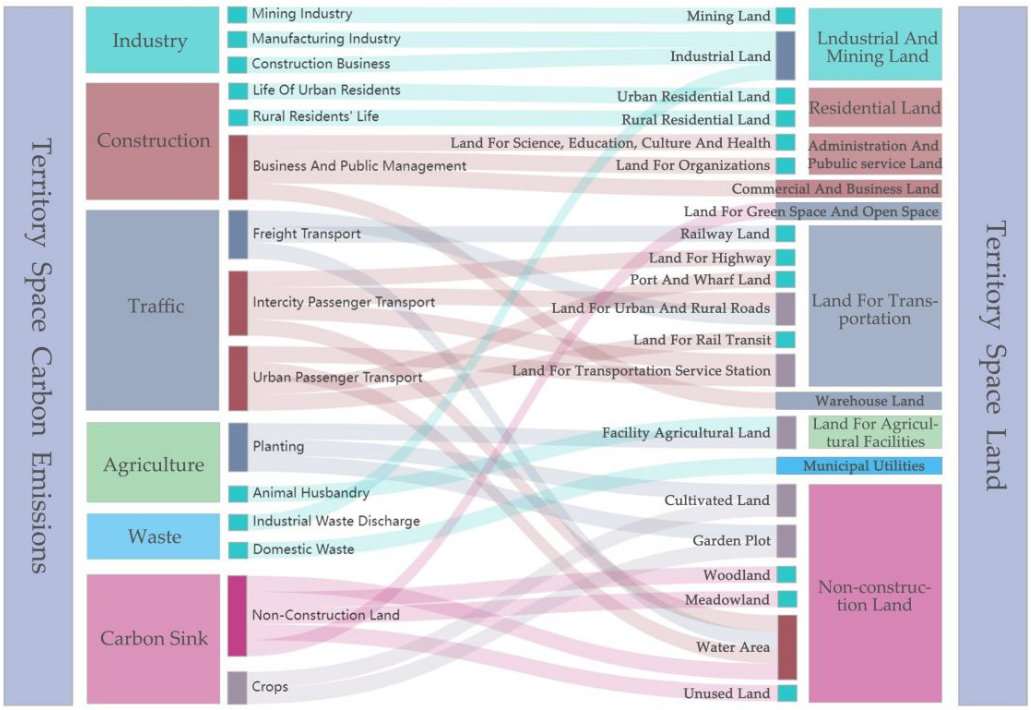

Figure 3. The relationship between territorial space land and carbon emissions.

3.1.2. Carbon Emission Measurement of Urban Sectors

This paper's methodology for measuring carbon emissions mainly draws on the IPCC National Greenhouse Gas Inventories Guidelines and the Provincial Greenhouse Gas Inventories Guidelines. To measure the total urban carbon emissions (C), the level and coefficient of the terminal carbon emission activity are used. There are various sectors, including industry (C_E), construction (C_B), transportation (C_T), agriculture (C_F), waste treatment (C_W), and carbon sinks (C_A). Since CO_2 accounts for most of the greenhouse gases measured, the remaining gases are converted into CO_2 equivalents based on IPCC Global Warming Potential data.

$$C = C_E + C_B + C_T + C_F + C_W + C_A \tag{1}$$

In the industrial sector, carbon emissions are mainly derived from fossil fuel combustion in industrial processes and the chemical or physical conversion of materials. Emissions from industrial power plants are primarily determined by the type and quantity of fuel used in the industry [36]. It is difficult to obtain a correlation coefficient for industrial production because the processes are complex, and carbon emissions are based on cement, steel, glass, and synthetic ammonia production [37].

$$C_E = \sum_{m,n} Ef_{m,n} \times Cf_{m,n} + \sum_k Ep_k \times Cp_k \quad (2)$$

In this formula, C_E represents industrial sector carbon emissions, m represents industrial types, n represents types of energy consumption, $Ef_{m,n}$ represents n-type energy consumption in the m industry, $Cf_{m,n}$ represents the carbon emission coefficients of n-type energy in the m industry, Ep_k represents types of industrial production, and Cp_k represents the carbon emission coefficient of per-unit-weight industrial products.

Construction sector carbon emissions primarily relate to the consumption of natural gas, liquefied petroleum gas, and electrical energy during the operation of residential, commercial, and public buildings.

$$C_B = Eg_{ng} \times Cg_{ng} + Eg_{lpg} \times Cg_{lpg} + \left(Ee_{ep-h} + Ee_{ep-b}\right) \times Ce_{ep} \quad (3)$$

In the formula, C_B represents construction sector carbon emissions; Eg_{ng}, Eg_{lpg}, Ee_{ep-h}, Ee_{ep-b} represent the consumption of natural gas, liquefied petroleum gas, and electricity for residential and commercial buildings; and Cg_{ng}, Cg_{lpg}, Ce_{ep} represent carbon emission coefficients corresponding to energy [38].

The transportation sector's carbon emissions are calculated based on the transportation structure within the city, which includes freight, intercity passenger transport, and urban passenger transportation. The carbon emissions associated with freight and intercity passenger transportation are calculated based on the mode's annual turnover [39]. In urban passenger transportation, carbon emissions are determined by calculating the mileage of different vehicles that people use in their daily commutes [40].

$$C_T = C_{ft} + C_{ipt} + C_{upt} = \sum_f T_{ft} \times c_{ft} + \sum_p T_{pt} \times c_{pt} + \sum_t T_{td} \times c_{td} \quad (4)$$

In the formula, C_T represents transportation sector carbon emissions; C_{ft}, C_{ipt}, C_{upt} represent carbon emissions of freight, intercity passenger transport, and urban passenger transport, respectively; f represents the transportation modes of railways, highways, and waterways; T_{ft} and T_{pt} represent the turnover volume of freight and intercity passenger transportation modes, respectively; c_{ft} and c_{pt} represent the carbon emission coefficient of various modes of transportation; t represents types of transportation vehicles; T_{td} represents the annual mileage of various transportation vehicles; and c_{td} represents the corresponding carbon emission coefficient.

In the agricultural sector, carbon emissions result from agriculture and agricultural materials. In addition, carbon emissions from animal intestinal fermentation and manure management must not be overlooked in the field of animal husbandry. To calculate the carbon emissions generated by agricultural cultivation, the cultivated land area and carbon emissions per unit area are taken into account [41]; the carbon emissions generated by agricultural materials are calculated based on their annual consumption and carbon emission coefficients [10]. To calculate the carbon emissions associated with animal husbandry, the yearly stock of animals and the carbon emission coefficients associated with their related activities are taken into account [36].

$$C_F = C_{cf} + C_{sf} \quad (5)$$

In this formula, C_F represents agricultural sector carbon emissions, C_{cf} represents plantation carbon emissions, and C_{sf} represents carbon emissions from animal husbandry.

CO_2 and CH_4 produced by municipal wastewater and solid waste treatment are also important sources of urban carbon emissions. Industrial wastewater and domestic wastewater produce methane emissions that contribute to carbon dioxide emissions. The term "solid waste" refers to both domestic and industrial waste. Domestic waste treatment results in the emission of carbon dioxide from waste incineration and landfill disposal.

Since industrial waste has a comprehensive utilization rate of 95%, it does not fall within the range of carbon emissions measured. As there is no statistical information regarding the organic content of domestic sewage, methane emissions from industrial wastewater are calculated based on carbon dioxide emissions and their unit CH_4 production capacity [36]. The amount of methane emitted is calculated based on the population and amount of organic matter per capita [42]. To calculate the carbon emissions of domestic waste, its scale and the proportion of municipal waste incineration and landfill treatment are taken into account, as well as the associated parameters [36].

$$C_W = C_{lw} + C_{sw} \tag{6}$$

In this formula, C_W represents waste treatment sector carbon emissions, C_{lw} represents carbon emissions from wastewater treatment, and C_{sw} represents carbon emissions from domestic waste treatment.

City's leading carbon sinks come from non-construction land and crops, such as forest land, grassland, and water areas. Considering that it is difficult to obtain relevant vegetation survey data, this paper uses the carbon absorption per unit area of land use to calculate the carbon sink of forest land [43], water areas [44], and unused land [45]. Based on the carbon absorption rate, economic yield, water content, and economic coefficient of each crop in the city, the carbon sink of agricultural activities can be calculated [46].

$$C_A = C_l + C_{ic} = \sum_j A_j \times Cl_j + \sum_x ca_x \times Y_x \times (1 - wc_x)/HI_x \tag{7}$$

In this formula, C_A represents the total amount of urban carbon sequestration; C_l represents the carbon absorption of crops on non-constructive land; C_{ic} represents the carbon absorption of crops; j represents various types of non-constructive land; A_j represents j-type land areas; Cl_j represents the carbon emission coefficient for corresponding land types; x represents various crop types; and ca_x, Y_x, wc_x, and HI_x represent various crop types for the carbon absorption rate, economic yield, water content, and economic coefficient, respectively.

3.1.3. Carbon Emission Measurement of Territorial Space

The carbon emissions of territorial space can be measured using two main methods. One method involves calculating carbon emissions based on the actual energy consumption of each plot. The other method is the top-down approach. Based on the characteristics of carbon emission activities in different sectors, appropriate spatial allocation methods are employed to allocate carbon emissions to each plot after calculating the carbon emissions of each sector based on statistical data or night-light data [47]. This process is referred to as the "spatialization of carbon emissions" in this paper. As a general rule, the former is used to measure carbon emissions at the microscale or in a sector; however, the latter is used more commonly given the ease of data acquisition, but the accuracy of the results also differs because of differences in spatialization methods. The accuracy of spatial allocation can be improved by relying on big data and spatial models [48]. We calculated sectoral carbon emissions and then spatialized them using a top-down approach. By using the correspondence between carbon emissions and land use types, we can reflect the differences in carbon emissions caused by varying human activity intensities across different spatial elements. For each carbon emission sector, appropriate spatial allocation methods were selected based on the characteristics of carbon emissions on different land types. Methods of spatializing carbon emissions (Table 2) were developed based on multi-source big data in order to distribute the total carbon emissions in territorial space. Finally, the precise spatial patterns of carbon emissions at different spatial scales were obtained via carbon emission spatialization.

Table 2. Correspondence between territorial space types and carbon emission inventories.

Carbon Emission		Territorial Space Types	Data Types	Spatialization Methods
Industry	Mining	Mining land	Industry POI data, and land use data	The carbon emissions of an industrial site are allocated based on the ratio of the number of POIs in the site to the total number of POIs of that type of site
	Industrial manufacturing	Industrial land		
	Supply industry	Municipal utilities		
Construction	Resident life	Urban residential land, and rural homestead	Cellular signaling data, business services POI data, and land use data	The carbon emissions of a residential site are assigned based on the ratio of the number of people on the site to the total population in the area, which are obtained from cellular signaling data
	Business services and public administration	Commercial and business land, as well as administration and public services land		Based on the ratio of the number of POIs of commercial services in commercial land use to the total POIs of commercial services, the carbon emissions of this type of commercial land use are assigned.
Transportation	Freight transportation, Intercity passenger transportation, City passenger transportation	Transportation land	Urban road data, traffic facility POI data, and land use data	Carbon emissions from air, road, and waterway transportation and rail transportation sites are allocated based on the ratio of the road length of each site to the total length of the corresponding transportation type. To measure the carbon emissions from road transportation land, the POI data for transportation facilities are first used to correct the standard length of each road area, and then, the corrected standard length of each road area is used to determine the carbon emission levels.
Agriculture	Plantation	Cultivated land and garden land	Data on land use	Carbon emissions from agricultural land are spatialized based on the ratio of the area of a certain type of parcel to the total area of this type of land.
	Animal husbandry	Agricultural land for facilities		
Waste treatment	Industrial waste Domestic waste	Industrial land Municipal utilities	Data on land use	Carbon emissions from an abandoned sector are spatialized based on the ratio of the plot site's area to the total area of this type of site.
Carbon sink	Non-construction land	Forest land, grassland, water, and unused land	Data on land use	Carbon sequestration in the carbon sink sector is spatialized based on the ratio of the land area of the plot to the total area of this type of land.
	Agricultural crops	Cultivated land and garden land		

3.2. The Method of Carbon Balance Zoning

Carbon balance refers to the situation of carbon emissions and absorption offset by each other in a particular area. A carbon balance is an essential basis for the spatial organization between carbon sources and sinks in territorial spatial planning since it describes the rational relationship between carbon sources and sinks. Using the principle of carbon balance, carbon balance zoning accounts for carbon budget accounting in specific areas and divides regional types based on their respective carbon balance states [30]. The carbon compensation rate measures the balance between regional carbon emissions and carbon sinks. The regional carbon balance state can be intuitively reflected by using the carbon compensation rate, which divides the region into carbon sinks or carbon source areas. Previous studies have mainly used carbon compensation rates as the basis for zoning [49]. However, because most urban areas are carbon source areas, it is difficult for the carbon compensation rate to reflect regional differences in carbon balance states. As far as it goes, the research perspective is relatively singular, making it difficult to reflect the comprehensiveness of zoning. Based on the economic contribution coefficient and ecological carrying coefficient of carbon emissions, regional differences in carbon emissions can be analyzed from economic and ecological perspectives, respectively. In addition to reflecting the regional carbon budget balance in terms of regional environmental and economic development, this can also reflect the degree of economic development, ecological environment foundation, and future development potential in the region [50]. As a consequence, from the perspective of regional carbon budget balance and low-carbon coordinated development, we constructed a territorial space carbon balance zoning method in the economic–ecological composite dimension. Specifically, it uses the carbon compensation rate, the carbon emission economic contribution coefficient, and the ecological carrying coefficient to analyze the carbon balance states of urban grassroots units in order to achieve carbon balance zoning at the urban microlevel.

3.2.1. Carbon Compensating Rate

The carbon compensating rate (CCR) can provide a direct indication of the regional carbon budget balance. Because the carbon compensation rate is not affected by the absolute value of the carbon budget, it is more convenient for horizontal comparisons between regions. The carbon balance states can be more accurately measured from the perspective of the regional balance [51].

$$CCR = E/C \tag{8}$$

In this formula, C represents regional carbon emissions, E represents regional carbon absorptions, and CCR represents regional carbon compensation rates. When CCR is <1, the area is a carbon source; when CCR is >1, the area is a carbon sink zone. The larger the CCR, the stronger the capacity to absorb carbon; when CCR = 1, carbon balance is achieved, carbon neutrality has been achieved, and regional carbon sinks have neutralized regional emissions.

3.2.2. Economic Contributive Coefficient of Carbon Emissions

A carbon emission's economic contribution coefficient (ECC) uses a region's GDP as a reference, measures the benefits that the region produces while generating specific carbon emissions, and illustrates the low carbon efficiency of regional economic development [52].

$$ECC = \frac{G_i}{G} \Big/ \frac{C_i}{C} \tag{9}$$

In this formula, G_i and G represent the regional GDP of each geographic unit and city area, respectively; C_i and C represent the total carbon emissions of each spatial unit and city, respectively.

When ECC is >1, the carbon emission level of the spatial unit is lower than its level of economic development. This implies that it has a higher level of economic efficiency. When ECC is <1, the carbon emission level of the spatial unit is higher than its economic development level. This implies that its carbon emission economic efficiency is lower.

3.2.3. Ecological Support Coefficient of Carbon Emissions

The ecological support coefficient (ESC) of carbon emissions uses the carbon sinks of a spatial unit as a reference to measure the carbon absorption that corresponds to a certain amount of carbon emissions in the region, which represents the ecological carbon sink effect in the spatial unit.

$$ESC = \frac{C_{Ai}}{C_A} \Big/ \frac{C_i}{C} \tag{10}$$

In this formula, C_{Ai} and C_A represent the annual carbon sinks of each spatial unit and city area, respectively; C_i and C represent the yearly carbon emissions of each spatial unit and city area.

If ESC is >1, the region's contribution rate to carbon absorption is more significant than its contribution rate to carbon emissions, indicating a relatively high rate of carbon compensation; if ESC is <1, the region's contribution rate to carbon absorption is less than its contribution rate to carbon emissions, indicating a lower rate of carbon compensation [25].

4. Results

4.1. Calculation and Spatial Pattern of Municipal Territorial Spatial Carbon Emissions

4.1.1. Calculation Results for Carbon Emissions

Based on the previous method for calculating carbon dioxide emissions, Suzhou's total carbon dioxide emissions in 2020 were 240.3 million tons (Table 3). The industrial sector had the highest emissions at 193 million tons, accounting for 81.32% (Figure 4). In this sense, Suzhou's industrial production scale is large, and its energy consumption is high, which is the primary target for reducing carbon emissions. Secondly, carbon emissions from residents' energy consumption reached 29 million tons, representing 12.13% of the total, with electricity production accounting for most of the emissions. A total of 14 million tons of carbon dioxide were emitted because of transportation, accounting for 5.98% of total emissions. There were few carbon sink resources in Suzhou, with a total carbon absorption of approximately 0.02 million tons. Land used for agriculture, forestry, and natural water was the main component of the carbon sink.

Table 3. Carbon emissions in the city's regional space.

Department	Types of Territorial Space	Types of Land Use Carbon Emissions (10,000 Tons)	Departmental Carbon Emissions (10,000 Tons)
Industry	Industrial land Municipal utilities	12,430.46 6905.31	19,334.77
Construction	Urban residential land Rural homestead Commercial and business land Administration and public service land	767.06 537.13 1030.09 548.48	2882.76
Traffic	Transportation land	421.44	1421.44
Agriculture	Cultivated land and garden land Agricultural land for facilities	94.68 6.02	100.70
Waste	Industrial land Municipal utilities	1.02 287.28	288.30
Carbon sink	Cultivated land and garden land Woodland, grassland, and water	−71.96 −179.9	−251.86
	Total	23,776.11	23,776.11

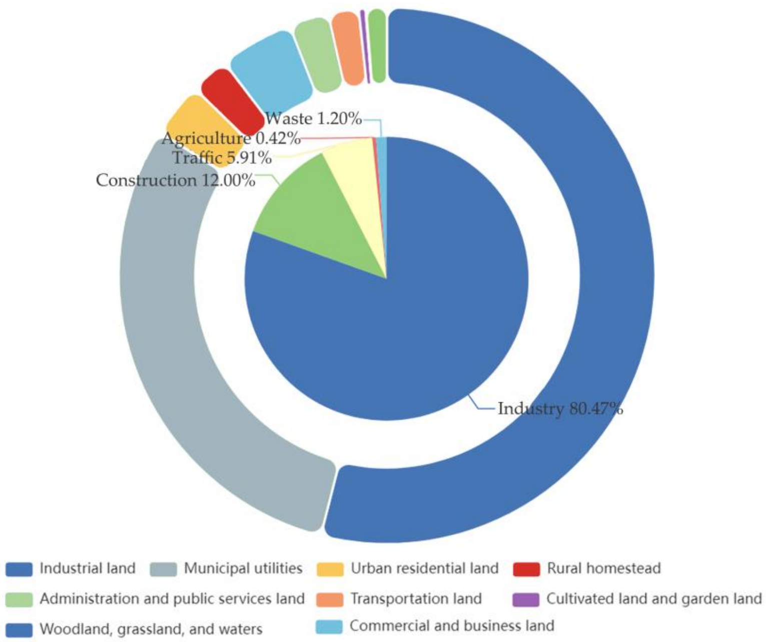

Figure 4. The proportion of carbon emissions by departments and land use.

Given the relationship between territorial space and carbon emissions established above, the carbon emission activities of each department were carried out in the corresponding territorial space land. The industrial department had the most carbon emissions in industrial land and municipal utilities, with 12,430.46 tons and 69.0531 million tons, respectively, accounting for 51.73% and 28.73%. In the construction department, carbon emissions were generated by residential areas; rural homesteads; commercial and business areas; and administration and public service areas. These areas accounted for 12.13% of the total carbon emissions at 767.06, 537.13, 1030.09, and 5.4848 million tons, respectively. As a result of the transportation department's carbon emissions, the transportation land generated 14.2144 million tons of carbon dioxide, or 5.98% of the transportation department's emissions. In terms of carbon absorption activities, cultivated land, garden land, and crops and plants on non-constructive land accounted for 71.96 million tons, while carbon sinks accounted for 1.799 million tons, accounting for 0.30% and 0.76% of the total, respectively.

4.1.2. Spatial Pattern Characteristics of Carbon Emissions

Based on the above spatialization methods of carbon emissions, the total carbon emissions in Suzhou were decomposed into each specific piece of land within the territorial space. The spatial distribution of carbon emissions within the municipal territory is summarized in Figure 5. In the figure, the carbon emissions from the territorial space plots in Suzhou range from −36.05 to 2.5694 million tons. High-emission sites are located primarily in industrial clusters within the city, while low-emission sites are mainly located in suburbs and carbon sink zones. In Suzhou, the carbon sink space is primarily composed of large lakes and hills scattered throughout the city because of its dense water network, but there are no organic connections between the carbon sink spaces.

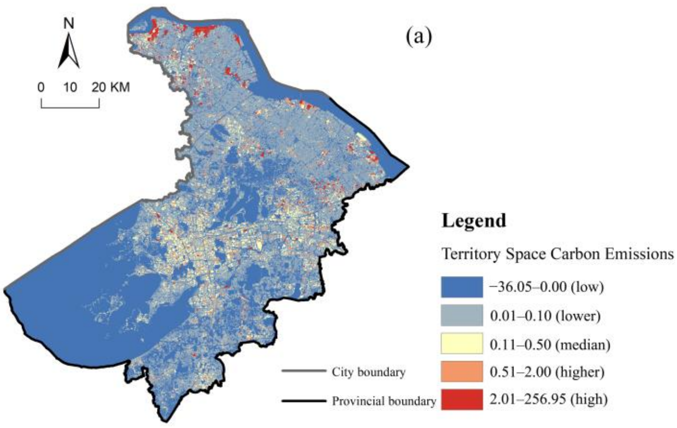

Figure 5. Carbon emissions of Suzhou City: (**a**) carbon emissions from land for the territorial space; (**b**) carbon emissions from a grid for the territorial space.

As there are large differences between the area attributes of land parcels in different territorial spaces, it is difficult to show the spatial structure characteristics of carbon emissions on the spatial distribution map. Carbon emissions can only be expressed in terms of the amount of carbon emitted in land parcels, and it is difficult to express carbon emissions in terms of their intensity. A square grid of 1000 m × 1000 m was used in this study to divide the urban land area evenly, and the total carbon emissions (carbon sinks) of each square grid were tallied to create a carbon emission intensity grid map of each municipal territorial space. We can see that the carbon emissions ranged from −0.15 to 3,964,700 tons (Figure 5). The high-carbon-intensity sites are primarily concentrated in the central urban areas and industrial parks of the Suzhou urban area and its county-level cities, namely the production spaces and living spaces of the cities, with the production space of Zhangjiagang City having the greatest value and distribution, exhibiting an expanding outward trend, which is consistent with the development structure. The majority of low-value plots are found in the suburban areas of Suzhou and its county-level cities, as well as in various carbon sink areas, such as Taihu Lake, the largest carbon sink main area, which displays a scattered distribution.

Using the aggregated administrative boundary vector data at the township level in Suzhou, we calculated the carbon emission (carbon sink) levels for each township territorial space unit (Figure 6). The spatial pattern of carbon emissions can be characterized as follows:

(1) The carbon emissions of territorial space units ranged from 0.2434 to 30.984 million tons, with an average value of 2.4770 million tons. The overall carbon emissions varied greatly, with 80.41% in areas with low and lower carbon emissions, 10.31% in areas with middle emissions, and 9.24% in areas with high and higher emissions, which is characterized by extreme differences. (2) There is a pattern involving one main emission value and two subordinate emission values, with a high value in the north and a low value in the south, in the distribution of carbon emission values for township units; i.e., the high-value industrial town in Zhangjiagang is the core, while the secondary cores in Taicang and Kunshan are located in the north and south, respectively; middle-value areas are openly connected to the high-value areas, exhibiting a stretching trend; and throughout the central city of Suzhou, the lower-value areas are distributed in a continuous distribution around the high-value and higher-value clustering areas. Each street is primarily a low-value area, extending from the townships surrounding large water bodies in a continuous clustering pattern. (3) As Suzhou is the largest manufacturing city in China, it has the highest proportion of industrial carbon emissions, so towns with a high proportion of manufacturing industries will have higher carbon emissions. Although urban areas, particularly the central city streets, have high-intensity population activities, the carbon emissions of the construction and transportation sectors, which are closely related to population activities, are relatively low, thereby resulting in relatively low total carbon emissions; given ecological protection and restrictions on industrial development, towns near large ecological elements such as Taihu Lake also have low carbon emissions.

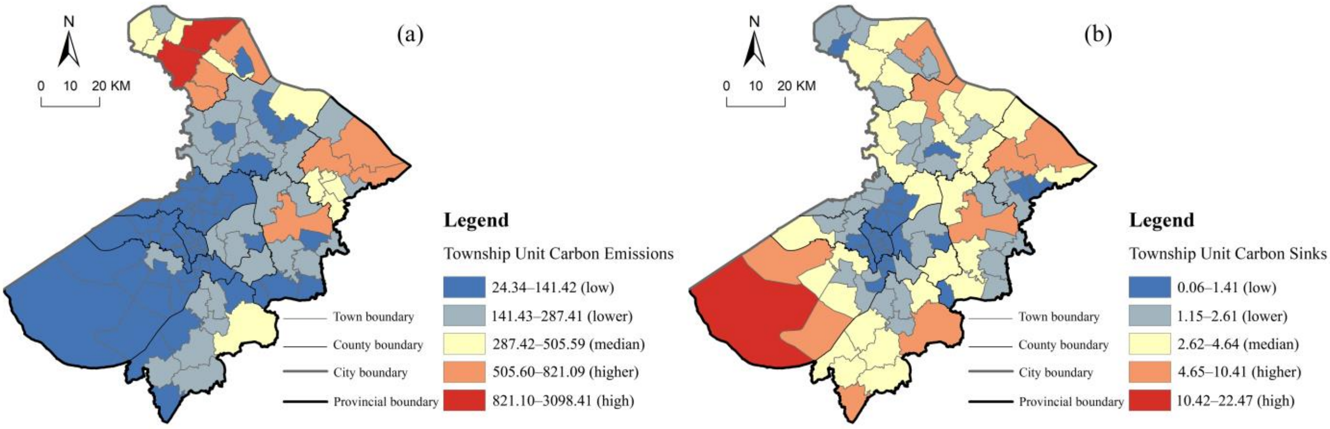

Figure 6. Carbon emissions and sink of township units in Suzhou City: (**a**) carbon emissions; (**b**) carbon sinks.

The following table shows that the pattern and distribution characteristics of carbon sinks within township territorial space units are as follows: (1) The carbon sinks of township and street territorial space units ranged from 700 to 450,400 tons, with a mean value of 67,700 tons. The overall difference in carbon sinks was not significant, with 61.85% in areas with low and lower carbon sinks, 28.87% in areas with median carbon sinks, and 9.28% in areas with high and higher carbon sinks. (2) The spatial distribution of carbon sink values in the township units shows a "low at the center and high at the edges" pattern; i.e., the low-value areas are mainly concentrated in the central city of Suzhou; the lower-value areas are connected in a circle pattern at the periphery of the low-value areas, showing an extension trend; the middle-value areas are distributed throughout Suzhou and its counties; higher-value clusters are located near the municipal boundary areas with abundant ecological resources; and high-value cores are located near Taihu Lake. (3) In the central city of Suzhou, there is a high level of urbanization and a limited amount of unbuilt land and agricultural land, i.e., the main carbon sinks lead to low-value carbon sinks in townships and street units in the central city and form low-value and lower-value clusters with them as the core. Because of the dense network of water in the city, as well as large lakes and hills that serve as major carbon sinks, township units in the area around Taihu Lake and towns with large water bodies or hilly terrain have a high carbon sink, forming high-value and higher-value agglomeration areas.

4.2. Carbon Balance Analysis Based on the Township Territorial Space Unit

4.2.1. Carbon Compensating Rate

A comparative analysis of the total carbon emissions and carbon absorption in Suzhou indicates that its carbon compensating rate is only 1.05%. Thus, the carbon sink level in Suzhou is insufficient to compensate for carbon emissions resulting from human activity, which results in Suzhou, as a whole, being a net carbon source. Given the results for the carbon compensating rates of each township territorial space unit (Figure 7), (1) the average carbon compensating rate of each township land spatial unit ranges from 0.08% to 29.64%, with an average value of 2.19%, and the numerical difference reflects the balance of regional carbon budgets. There is an obvious urban–rural divide in the carbon compensation rate, which is higher in the west and south and lower in the north, middle, and east in spatial terms. There is a core gathering area in the Wuzhong and Wujiang Districts, with high-value and higher-value townships, median openness around the high value, and a higher-value outer circle forming a central agglomeration posture. Lower-value areas are mainly located in the suburbs of each city. Suzhou and county-level downtowns have the highest concentration of low values. (2) The southwest areas of Wuzhong and Wujiang contain large areas of water and hilly terrain, resulting in a large carbon sink area. The amount of carbon sink in this area is relatively large, and the overall carbon emission level is low, so spatial units in this area generally receive high carbon compensation rates. In the central city, there is a high level of urbanization, so there is a smaller distribution of carbon sink land and, thus, a relatively low total amount of carbon sink. The level of carbon emissions in township street units is not low given the concentration of carbon emission factors, such as buildings and transportation, so the carbon compensating rate in urban areas is generally low. In contrast, some township units with relatively high levels of carbon sinks end up with low carbon compensation rates as a result of their high levels of carbon emissions from industrial production.

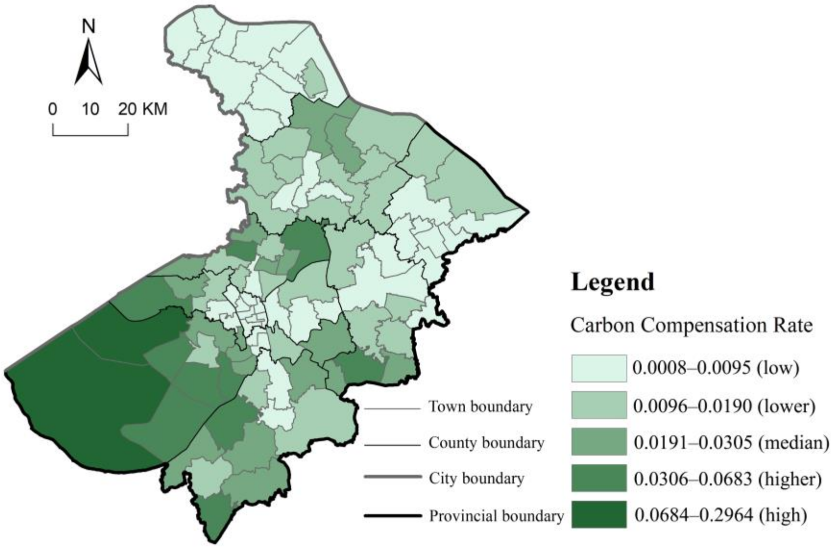

Figure 7. Township territorial space unit carbon compensation rate.

4.2.2. Economic Contributive Coefficient of Carbon Emissions

The economic contributive coefficient of carbon emissions measures the difference between regional carbon emissions from the perspective of economic development. Using the economic contribution coefficient, the following results were obtained for each township territorial space unit (Figure 8): (1) The values of the economic contribution index range from 0.09 and 8.46. The number of townships with an ECC of >1 accounts for 67.01%, while the number of townships with an ECC of <1 accounts for 32.99%. (2) Geographically, this shows that the distribution characteristics can be defined as "high in the middle, low in the north and south, and different between urban and rural areas". Downtown Suzhou and the core streets of Kunshan City are the high-value core; the median area surrounds the outer circle, forming a central agglomeration trend. The contiguous areas of towns and townships in the northern and southern suburbs of the city exhibit low-value agglomeration characteristics. (3) This is because the different functional positions of industries in different townships and streets lead to differences in the economic benefits of carbon emissions in each township. The street units in the urban areas have relatively advanced industrial categories, with a high proportion of production services and advanced manufacturing industries and a high contribution to the carbon emission economy. Marginal towns rely on a relatively low-level industrial structure and traditional energy structure, and the economic contribution of carbon emissions is relatively low.

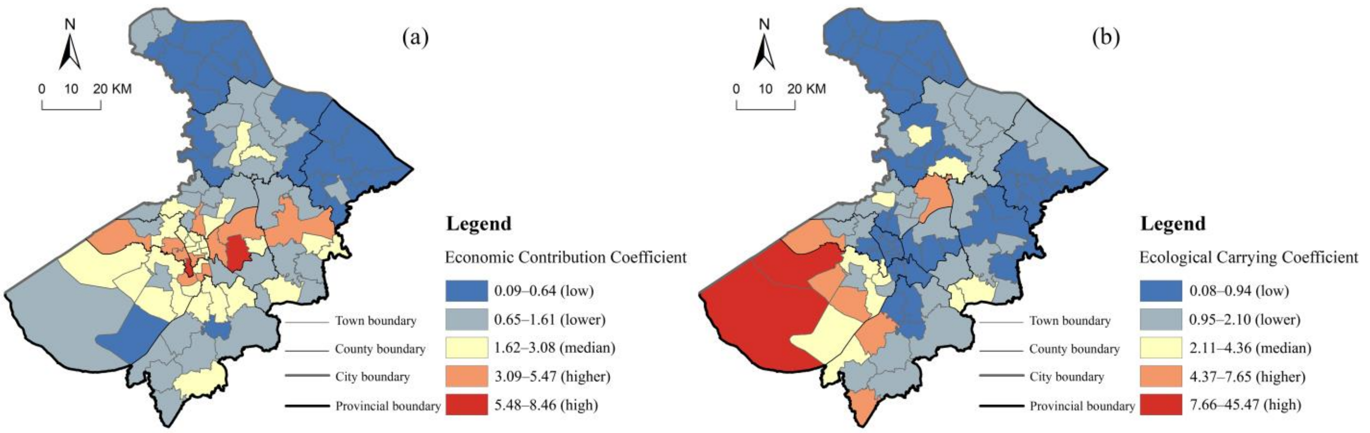

Figure 8. Carbon balance indexes of township units: (**a**) economic contribution coefficient; (**b**) ecological support coefficient.

4.2.3. Ecological Support Coefficient of Carbon Emission

The ecological support coefficient of carbon emissions measures differences in the regional carbon compensation rate and reflects regional carbon sink capacity. Using the ecological support index, the following results were obtained for each township territorial space unit (Figure 8): (1) The values of the ecological support index ranged from 0.09 to 45.47, reflecting the uneven spatial distribution of carbon sinks. The number of townships with an ESC of >1 accounts for 51.55%, while the number of townships with an ESC of <1 accounts for 48.45%. (2) Geographically, this shows that the distribution pattern can be defined as "high in Taihu Lake and low in urban areas, with urban-rural differences", which is similar to the ecological pattern of Suzhou. Near large water bodies, township streets that have a high ecological support index form high-value areas in Taihu Lake, and they also form median areas along the Yangtze River and the southern water network of the city. A majority of the areas with low indexes are located in the central city, surrounding townships, and urban subdistricts. (3) The ecological background, as the main component of carbon sinks, provides the foundation for the spatial ecological carrying capacity, but the lack of ecological network integrity results in obvious differences in it. However, a contiguous agglomeration of urban buildings squeezes the ecological space, affecting the coordination of carbon emissions and absorption and forming low-value contiguous agglomerations.

4.3. Carbon Balance Zoning on the Township Territorial Space Unit

When the economic contribution coefficient for carbon emissions exceeds 1, it indicates that the ratio between the economic output value of the township unit and the total output value is greater than the ratio between the carbon emissions of the township unit and the total carbon emissions, illustrating greater efficiency in energy use and greater carbon productivity. Conversely, it also shows that the efficiency of energy use and carbon productivity of the township unit is relatively low [25]. To characterize the level of energy use efficiency and carbon productivity, 1 is used as a zoning threshold for economic contribution coefficients; when the ecological support coefficient of carbon emission is greater than 1, it means that the ratio between the carbon absorption of the township unit and total carbon sinks is greater than the ratio between the carbon emissions of the township unit and the total carbon emissions, which indicates that it has a higher carbon compensating rate [25] and carbon sink capacity in the ecosystem. In contrast, this indicates that the township units have a relatively low carbon compensation rate and carbon sink capacity; thus, 1 is taken as the zoning threshold of the ecological support coefficients, which represent the levels of the regional carbon compensation rates and the carbon sink capacity.

Based on the calculations for the economic contribution coefficients and ecological support coefficients of each township unit in the previous section, carbon balance zoning was carried out in Suzhou township units to achieve low-carbon coordinated development and regional carbon balance. The township units were divided into four functional zones: a low-carbon economic zone, a carbon source control zone, a carbon sink functional zone, and a high-carbon optimization zone. Table 4 indicates the basis for the division and characteristics of each zone.

Table 4. Characteristics of carbon balance zones.

Carbon Balance Zoning	Classification Basis	Regional Characteristics
Low-carbon economic zone	ECC > 1, ESC > 1	The economic efficiency of carbon emission is high, and the carbon sink capacity of the ecosystem is high.
Carbon source control zone	ECC > 1, ESC < 1	The economic efficiency of carbon emission is high, and the carbon sink capacity of the ecosystem is low.
Carbon sink functional zone	ECC < 1, ESC > 1	The economic efficiency of carbon emission is low, and the carbon sink function of the ecosystem is strong.
High-carbon optimization zone	ECC < 1, ESC < 1	The economic efficiency of carbon emission is low, and the carbon sink capacity of the ecosystem is low.

Figure 9 shows the results of the carbon balance zoning based on the township territorial space unit. Out of these, 36 township units were low-carbon economic zones, accounting for 37.11% of the total, with high economic efficiency in carbon emissions and the carbon sink capacity of the ecosystem. This type of township unit is mainly located in suburban areas around the central urban area, presenting a circular distribution pattern. The economic development and ecological protection of such township units are relatively balanced, and low-carbon industries in these townships should be continuously developed to ensure that the ecological environment achieves high-quality development. They should maintain a high level of carbon sink capacity and adhere to the dual focuses of economic development and ecological protection.

A total of 29 township units were carbon source control zones, accounting for 29.90%, with high economic efficiency in carbon emissions but low carbon sink capacity. Township units of this type are primarily located in the central urban areas of Suzhou and concentrically distributed in the central and eastern regions of the city. The ecological carrying capacity of such township units is a key constraint factor on their socio-economic development. The goal should be to enhance the ecological carbon sink capacity and build an ecological security pattern based on the natural background characteristics of the region. The townships should continuously improve the carrying capacity of the ecological environment for carbon emissions as a future development direction.

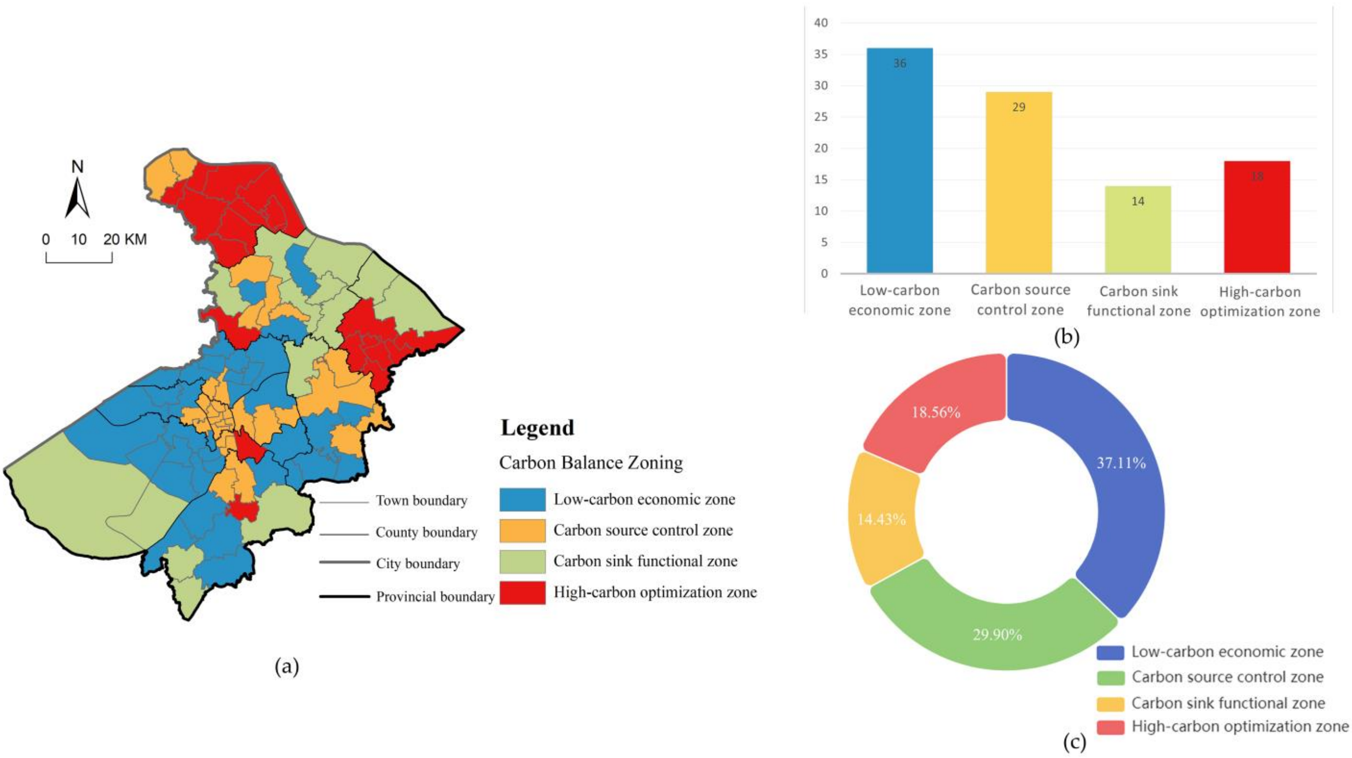

Figure 9. (**a**) Township territorial space unit carbon balance zoning; (**b**) number of carbon balance zoning types; (**c**) the proportion of carbon balance zoning types.

A total of 14 township units are carbon sink functional zones, accounting for 14.43% of the total. Although their carbon emission economic efficiency is low, the ecosystem has a high carbon sink capacity. Township units of this type are predominantly located in the southern areas of Wuzhong and Wujiang, as well as along rivers in the northern areas of Taicang and Changshu, mainly distributed in the north–south edge of the city. The industrial and energy consumption structure of these township units is a key constraint factor on their high-quality development. Efforts should be made to vigorously develop a green and low-carbon economic model and transform the economic growth mode. The townships should accelerate green technology innovations and adjust their industrial structures. They should also optimize and upgrade traditional industries, as well as strengthen the leading role of scientific and technological innovation.

A total of 18 township units are high-carbon optimization zones, accounting for 18.56% of the total, with a low economic efficiency of carbon emissions and carbon sink capacity in the ecosystem. It is mainly industrial towns in Zhangjiagang and Taicang that constitute township units, concentrically distributed in the eastern and northern regions of the city. The imbalance between the economic development and ecological protection of these township units hinders their high-quality development. It is necessary to comprehensively improve the economic efficiency of their carbon emissions and achieve both emission reduction and carbon sequestration. In response to the problem of excessive emissions, efforts should be made to change the urban energy consumption structure and vigorously develop low-carbon industries. Furthermore, it is necessary to consolidate and enhance the carbon sink capacity of the ecosystem, increase carbon sink resources such as forests and grasslands, and increase investment in ecological environment protection to improve the carrying capacity of the ecological environment.

5. Discussion

To the best of our knowledge, there is no unified standard method for measuring city-scale carbon emissions, nor is there an accurate statistical value for urban carbon emissions. The China Emission Accounts and Datasets (CEADs), an authoritative carbon-accounting data platform, did not publish Suzhou's carbon emission data for 2020, but it has published carbon emission data for 290 Chinese cities for 2019, indicating that the total carbon emissions of Suzhou should be 231.2 million tons. As measured in this paper, the Suzhou region's carbon emissions in 2020 were 240.3 million tons. Compared with data from the China Carbon Accounting Database 2019, this represents a slight increase, in line with the development trend of carbon emissions in Suzhou. This data comparison demonstrates that the carbon measurement method and results presented in this paper are scientifically valid and reliable. The results of the carbon emission measurement method can serve as the basis for carbon balance zoning, and the more accurate carbon emissions measured in this paper reflect the scientific and reasonable results of carbon balance zoning.

In this paper, carbon balance zoning in township units was achieved based on a regional analysis of the economic efficiency of carbon emissions and the ecological carrying capacity from the perspective of green and low-carbon development orientation. Compared with studies on the spatial patterns of carbon emissions and carbon balance zoning at the provincial level [53] and those on carbon balance zoning in watersheds [54], this study focuses more on carbon balance zoning at the micro-scale. Additionally, we propose differentiated carbon reduction strategies for grassroots administrative units, facilitating the implementation of strategies related to low-carbon governance in territorial space planning. In contrast to a study on county carbon balance zoning [30], which also focused on the micro-scale, the method used in this study exceeded the traditional measurement method based on statistical data. With more accurate measurement results, the regional differences in the carbon balance states between grassroots units can be revealed more precisely, assisting in propositions for more effective low-carbon governance strategies.

Low-carbon economic zones are typically located at the edges of central urban areas where there is a large amount of ecological land. These regions possess a higher level of carbon sinks and compensation and exhibit good economic efficiency in carbon emissions given their more reasonable industrial structure. Because of the expansion of construction land and reductions in ecological space, township units in central urban areas exhibit a strong carbon emission capacity but a weak carbon sink capacity. This has resulted in a significant disparity between the carbon budget and expenditures of these townships. However, given the high proportion of tertiary industry, its carbon emission economic efficiency is relatively high. Thus, carbon source control zones are typically located in central urban areas. There is a general consistency between the findings of this study and those of other studies concerning the intrinsic mechanism of forming different functional zones [25]. As a result of the scale of regional carbon sink land, the carbon sink capacity can be determined. Thus, carbon sink functional zones are generally located in areas with a concentrated distribution of carbon sink land. Because of factors such as industrial structure and energy structure, industrial towns dominated by traditional manufacturing and energy-consuming industries have excessive carbon emissions, serious carbon deficits, and strong negative ecological effects generated by economic development. These towns are usually high-carbon optimization zones, which are a major point of conflict in the development of regional carbon balance. There are some similarities between the distribution patterns of the above-mentioned functional zones and those discovered in other studies [53].

In terms of guiding future territorial spatial development, carbon balance zoning provides some scientific support for the optimization of grassroots territorial space planning. Taking into account the characteristics of various carbon balance functional zones, it is necessary to adopt differentiated and localized low-carbon development strategies: (1) As low-carbon economic zones, industrial scale should be controlled, industrial agglomeration effects should be strengthened, and larger industries should be developed while maintaining an ecological red line. It is necessary to develop an efficient and low-carbon spatial structure model to enhance the environmental value and carbon sinks. (2) A carbon source control zone should limit the unrestricted spread of production and living space and promote the use of green and clean energy and low-carbon construction technologies. Furthermore, it is necessary to strengthen the ecological environment and steadily improve the regional carbon sink capacity by increasing the scale of carbon sink land and limiting the destruction of the ecological environment. (3) As the primary carbon sinks in the region, carbon sink function zones are responsible for maintaining a high ecological carrying capacity, preventing ecological degradation as a result of economic development. It is necessary to strictly define urban development boundaries, prohibit occupations of ecological land, and prevent pollution and the destruction of the ecological environment to maintain a high degree of ecological quality. (4) The development of carbon balance mainly focuses on high-carbon optimization zones. This should strengthen low-carbon technology innovation in industries, continuously improve the level of energy savings and carbon reduction, and enhance the use efficiency of industrial energy. It is necessary to strictly control the scale of urban construction, accelerate the formation of compact and intensive urban spatial structures to promote a jobs–housing balance, and reduce carbon emissions from the construction and transportation sectors. Additionally, it is necessary to increase urban green areas and balance their distribution, protect the existing ecological environment, and increase the supply of carbon sink products to enhance the ecological carrying capacity. (5) In addition to focusing on the overall coordination involved in developing the regional carbon balance, we should also analyze the carbon circulation process of different spatial units, coordinate goals and policies to reduce carbon emissions in each functional zone, and investigate the mechanism of carbon compensation among townships. To increase regional low-carbon development, we should consider implementing carbon compensation policies between various functional zones based on carbon balance zoning to promote regional synergistic emission reductions.

We constructed a territorial space carbon emission measurement method based on multi-source big data. It can measure carbon emission spatial patterns at the microscale within cities and can make high-precision measurements of carbon emission spatial patterns. Furthermore, high-precision spatial patterns can achieve the carbon balance zoning of urban grassroots units, enriching the research on carbon balance zoning at the microscale of cities. However, there are shortcomings in this article: (1) The carbon emissions of urban agriculture and waste sectors only account for 1.62% of the total amount, and determining their carbon emission spatialization still follows traditional method, which is not precise enough compared with other methods and needs further improvement. (2) Carbon emissions, as greenhouse gases, have the characteristics of flow, diffusion, and cumulative changes. Given limitations in data acquisition, this article only studied the carbon emission spatial pattern and carbon balance zoning of a single period. Based on the perspective of spatiotemporal evolution, research on the characteristics of territorial space carbon emissions and carbon balance zoning still needs to be deepened.

6. Conclusions

Based on the relationship between territorial space and carbon emissions, this paper constructed a calculation method for carbon emissions in urban territorial spaces based on multisource big data and analyzed the spatial patterns of territorial space carbon emissions at the microscale of a city. Furthermore, we constructed a method of carbon balance zoning based on the economic contribution coefficient and ecological support coefficients. Suzhou City's townships were divided into different carbon balance functional zones with this zoning method, which was used to develop targeted and differentiated strategies for reducing carbon emissions.

Suzhou's carbon dioxide emissions in 2020 were estimated to be 240.3 million tons, with the industrial sector being the largest contributor, followed by the construction and transportation sectors. In terms of carbon absorption, there was a total amount of 2,518,600 tons, and the main source of carbon sinks consisted mainly of agricultural and forestry lands and natural waters. In the city, plots that emit high levels of carbon dioxide are mainly concentrated in production and residential areas and show a tendency to expand outward. Most of the low-value plots are located in the suburbs of Suzhou, as well as in the main carbon sinks.

Suzhou has a carbon compensation rate of only 1.05%, which means that the city as a whole is a net carbon source. There is an obvious difference between the urban and rural areas when it comes to the carbon compensating rate within each township unit. This reveals a spatial structural pattern, being higher in the west and south and lower in the north, central, and eastern regions. In each township unit, the economic contribution coefficient for carbon emissions shows a spatial distribution that is higher in the central part, lower in the north and south, and different between urban and rural areas. Because the industrial functional position of each township unit is different, the economic benefits of carbon emissions may vary from one township to another. Carbon emission ecological carrying coefficients for each township unit have spatial distribution characteristics, such as high values in Taihu Lake and low values in urban areas, and there are differences between urban and rural areas. To some extent, this corresponds to the urban ecological patterns of Suzhou.

Based on a carbon balance analysis of township units, we categorized them into four types of carbon balance functional zones, of which 36 township units were low-carbon economic zones, accounting for 37.11%, with high economic efficiency in carbon emissions and the carbon sink capacity of the ecosystem. In total, 29 townships were carbon source control areas, accounting for 29.90% of the total. Township units of this type have high economic efficiency in carbon emissions but low carbon sink capacity. There were 14 township units that were carbon sink functional zones, accounting for 14.43%, with a high carbon sink capacity and low carbon emission economic efficiency. A total of 18 township units were high-carbon optimization zones, accounting for 18.56%, with low economic efficiency in carbon emissions and the carbon sink capacity of the ecosystem.

This paper discusses the spatial patterns of carbon emissions and carbon balance zoning in a single period. Considering the need for "dual carbon" strategies, the dynamic evolution of carbon emissions and carbon balance zoning can be carried out from a time perspective in future research. Furthermore, on based this study, future research can be conducted on the carbon compensation mechanisms of township spatial units. Specifically, such research can examine the mechanisms of compensating carbon between different carbon balance functional zones and propose an overall strategy to protect ecological environment patterns and optimize urban spatial distribution from the perspective of carbon reduction. This will provide scientific support for the coordinated development of urban grassroots units and the development of ecological civilization.

Author Contributions: Conceptualization, Zhenlong Zhang and Xiaoping Yu; methodology, Xiaoping Yu and Zhenlong Zhang; software, Xiaoping Yu and Yanzhen Hou; validation, Zhenlong Zhang and Honghu Sun; formal analysis, Xiaoping Yu and Yanzhen Hou; investigation, Xiaoping Yu, Tianhao Chen, Yun Lu and Yanzhen Hou; resources, Zhenlong Zhang and Yanzhen Hou; data curation, Xiaoping Yu; writing—original draft preparation, Xiaoping Yu, Yanzhen Hou, Zhenlong Zhang and Honghu Sun; writing—review and editing, Tianhao Chen, Yun Lu and Honghu Sun; visualization, Xiaoping Yu and Yanzhen Hou; supervision, Zhenlong Zhang; funding acquisition, Zhenlong Zhang. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Priority Academic Foundation of Jiangsu Higher Education Institutions and the Research Innovation Program for College Postgraduates of Jiangsu Province, grant number SJCX22_1547.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. The Intergovernmental Panel on Climate Change. Climate Change 2022: Mitigation of Climate Change. Available online: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/ (accessed on 4 April 2022).
2. Jiang, Y.; Heng, Y.; Mao, Q.; Chen, S.; He, D. City-level greenhouse gas emission inventory from a spatial planning perspective. *City Plan. Rev.* **2013**, *50*, 56–67.
3. Xiong, J.; Lu, K.; Jiang, Z.; Zhang, C.; Fu, Q.; Jin, Y. Study and Thoughts on Territorial Spatial Planning under the Goal of "Carbon Emissions Peak and Carbon Neutrality". *J. Urban Plan. Forum* **2021**, *4*, 74–80.
4. Montoya-Torres, J.; Akizu-Gardoki, O.; Iturrondobeitia, M. Measuring life-cycle carbon emissions of private transportation in urban and rural settings. *Sustain. Cities Soc.* **2023**, *96*, 104658. [CrossRef]
5. Radonjič, G.; Tompa, S. Carbon footprint calculation in telecommunications companies—The importance and relevance of scope 3 greenhouse gases emissions. *Renew. Sustain. Energy Rev.* **2018**, *98*, 361–375. [CrossRef]
6. Christen, A.; Coops, N.C.; Crawford, B.R.; Kellett, R.; Liss, K.N.; Olchovski, I.; Tooke, T.R.; van der Laan, M.; Voogt, J.A. Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements. *Atmos. Environ.* **2011**, *45*, 6057–6069. [CrossRef]
7. Gao, F.; Wu, J.; Xiao, J.; Li, X.; Liao, X.; Chen, W. Spatially explicit carbon emissions by remote sensing and social sensing. *Environ. Res.* **2023**, *221*, 115257. [CrossRef]
8. Li, J.; Jiao, L.; Li, F.; Lu, X.; Hou, J.; Li, R.; Cai, D. Spatial disequilibrium and influencing factors of carbon emission intensity of construction land in China. *J. Clean. Prod.* **2023**, *396*, 136464. [CrossRef]
9. Chen, X.; Di, Q.; Jia, W.; Hou, Z. Spatial correlation network of pollution and carbon emission reductions coupled with high-quality economic development in three Chinese urban agglomerations. *Sustain. Cities Soc.* **2023**, *94*, 104552. [CrossRef]
10. Liu, M.; Yang, L. Spatial pattern of China's agricultural carbon emission performance. *Ecol. Indic.* **2021**, *133*, 108345. [CrossRef]
11. Yang, X.; Liu, X. Path analysis and mediating effects of influencing factors of land use carbon emissions in Chang-Zhu-Tan urban agglomeration. *Technol. Forecast. Soc. Chang.* **2023**, *188*, 122–268. [CrossRef]
12. Tian, H.; Wang, X. Analysis on the Temporal and Spatial Differences of Carbon Emissions in the Yangtze River Economic Belt and Its Influencing Factors. *J. Xian Univ. Sci. Ed.* **2023**, *26*, 99–104.
13. Dong, J.; Li, C. Structure characteristics and influencing factors of China's carbon emission spatial correlation network: A study based on the dimension of urban agglomerations. *Sci. Total Environ.* **2022**, *853*, 158–613. [CrossRef] [PubMed]
14. Lai, S.; Lu, J.; Luo, X.; Ge, J. Carbon emission evaluation model and carbon reduction strategies for newly urbanized areas. *Sustain. Prod. Consum.* **2022**, *31*, 13–25. [CrossRef]
15. Liu, J.; Peng, K.; Zuo, C.; Li, Q. Spatiotemporal variation of land-use carbon emissions and its implications for low carbon and ecological civilization strategies: Evidence from Xiamen-Zhangzhou-Quanzhou metropolitan circle, China. *Sustain. Cities Soc.* **2022**, *86*, 104083. [CrossRef]
16. Liu, D.; Zhu, X.; Wang, Y. China's agricultural green total factor productivity based on carbon emission: An analysis of evolution trend and influencing factors. *J. Clean. Prod.* **2021**, *278*, 123–692. [CrossRef]
17. Shao, H.; Wang, Z. Spatial network structure of transportation carbon emission efficiency in China and its influencing factors, Chinese Journal of Population. *Resour. Environ.* **2021**, *19*, 295–303.
18. Huo, T.; Cao, R.; Xia, N.; Hu, X.; Cai, W.; Liu, B. Spatial correlation network structure of China's building carbon emissions and its driving factors: A social network analysis method. *J. Environ. Manag.* **2022**, *320*, 115–808. [CrossRef]
19. Wang, L.; You, J. An integrated perspective on the spatial–temporal characteristics of China's manufacturing carbon emissions at the regional and industry levels. *Energy Rep.* **2023**, *10*, 1688–1701. [CrossRef]
20. Liu, X.; Jin, X.; Luo, X.; Zhou, Y. Quantifying the spatiotemporal dynamics and impact factors of China's county-level carbon emissions using ESTDA and spatial econometric models. *J. Clean. Prod.* **2023**, *410*, 137–203. [CrossRef]
21. Zhou, Y.; Chen, M.; Tang, Z.; Mei, Z. Urbanization, land use change, and carbon emissions: Quantitative assessments for city-level carbon emissions in Beijing-Tianjin-Hebei region. *Sustain. Cities Soc.* **2021**, *66*, 102–701. [CrossRef]
22. Cai, M.; Ren, C.; Shi, Y.; Chen, G.; Xie, J. Edward Ng; Modeling spatiotemporal carbon emissions for two mega-urban regions in China using urban form and panel data analysis. *Sci. Total Environ.* **2023**, *857*, 159–612. [CrossRef] [PubMed]
23. Li, J.; Guo, X.; Chuai, X.; Xie, F.; Yang, F.; Gao, R.; Ji, X. Reexamine China's terrestrial ecosystem carbon balance under land use-type and climate change. *Land Use Policy* **2021**, *102*, 105–275. [CrossRef]
24. Zhang, D.; Zhao, Y.; Wu, J. Assessment of carbon balance attribution and carbon storage potential in China's terrestrial ecosystem, Resources. *Conserv. Recycl.* **2023**, *189*, 106–748. [CrossRef]
25. Zhao, R.; Zhang, S.; Huang, X.; Qin, Y.; Liu, Y.; Ding, M.; Jiao, S. Spatial variation of carbon budget and carbon balance zoning of Central Plains Economic Region at county-level. *Acta Geogr. Sin.* **2014**, *69*, 1425–1437.
26. Zhang, Z.; Zhang, D. Spatial connection of CO_2 emission and carbon balance zoning in Beijing Tianjin Hebei counties based on social network. *China Environ. Sci.* **2022**, *43*, 1438–1448.
27. Ma, L.; Xiang, L.; Wang, C.; Chen, N.; Wang, W. Spatiotemporal evolution of urban carbon balance and its response to new-type urbanization: A case of the middle reaches of the Yangtze River Urban Agglomerations, China. *J. Clean. Prod.* **2022**, *380*, 135122. [CrossRef]

28. Liu, Y.; Xia, C.; Ou, X.; Lv, Y.; Ai, X.; Pan, R.; Zhang, Y.; Shi, M.; Zheng, X. Quantitative structure and spatial pattern optimization of urban green space from the perspective of carbon balance: A case study in Beijing, China. *Ecol. Indic.* **2023**, *148*, 110–134. [CrossRef]
29. Bullock, S.H.; Escoto-Rodríguez, M.; Smith, S.V.; Hinojosa, A. Carbon flux of an urban system in Mexico. *J. Ind. Ecol.* **2011**, *15*, 512–526. [CrossRef]
30. Zhang, X. The application of carbon balance zoning method in low carbon spatial plan of Huantai county. *Ind. Constr.* **2021**, *51*, 12–19.
31. Christen, A.; Coops, N.C.; Kellett, R.; Crawford, B.; Heyman, E.; Olchovski, I.; Tooke, T.R.; van der Laan, M.T. *A LiDAR-Based Urban Metabolism Approach to Neighborhood Scale Energy and Carbon Emissions Modeling*; University of British Columbia: Vancouver, BC, Canada, 2010.
32. Wang, Y.; He, Y. Methods for Low-Carbon City Planning Based on Carbon Emission Inventory. *China Popul. Resour. Environ.* **2015**, *25*, 72–80.
33. Li, Y.; Ren, Y. Research on carbon emission accounting method of Shanghai urban master planning. In Proceedings of the 2019 China Urban Plan. Annual National Planning Conference 2019, Chongqing, China, 19 October 2019; pp. 166–175. [CrossRef]
34. Xu, Y.; Xu, L.; Li, T. Greenhouse gas inventory model for territorial spatial master plans. *Adv. Clim. Chang. Res.* **2022**, *18*, 355–365.
35. Zheng, D.; Wu, H.; Lin, C.; Weng, T. The Formulation of Urban Carbon Reduction Unit and Integrated Planning Methodology Based on Carbon Accounting. *Urban Plan.* **2021**, *65*, 43–50.
36. China Business Council for Sustainable Development. Available online: http://www.cbcsd.org.cn/sjk/nengyuan/standard/home/20140113/download/shengjiwenshiqiti.pdf (accessed on 13 January 2014).
37. Hu, Y.; Man, Y. Energy consumption and carbon emissions forecasting for industrial processes: Status, challenges and perspectives. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113–405. [CrossRef]
38. Shi, J.; Tang, H.; Zhou, Q.; Han, L.; Hao, R. High frequency measurement of carbon emissions based on power big data: A case study of Chinese Qinghai province. *Sci. Total Environ.* **2023**, *902*, 166075. [CrossRef]
39. Sun, J.; Zhang, Y.; Xue, R.; Zhang, Y. Modeling carbon emissions from urban traffic system using mobile monitoring. *Sci. Total Environ.* **2017**, *599*, 944–951. [CrossRef]
40. Xia, C.; Xiang, M.; Fang, K.; Li, Y.; Ye, Y.; Shi, Z.; Liu, J. Spatial-temporal distribution of carbon emissions by daily travel and its response to urban form: A case study of Hangzhou, China. *J. Clean. Prod.* **2020**, *257*, 120–797. [CrossRef]
41. West, T.O.; Marland, G. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric. Ecosyst. Environ.* **2002**, *91*, 217–232. [CrossRef]
42. Zhao, R.; Huang, X.; Peng, B. Research on Carbon Cycle and Carbon Balance of Nanjing Urban System. *Acta Geogr. Sin.* **2012**, *67*, 758–770.
43. Liu, J.; Wang, Z.; Duan, Y.; Li, X.; Zhang, M.; Liu, H.; Xue, P.; Gong, H.; Wang, X.; Chen, Y.; et al. Effects of land use patterns on the interannual variations of carbon sinks of terrestrial ecosystems in China. *Ecol. Indic.* **2023**, *146*, 109914. [CrossRef]
44. Duan, X.; Wang, X.; Lu, F.; Ouyang, Z. Carbon sequestration and its potential by wetland ecosystems in China. *Acta Ecol. Sin.* **2008**, *28*, 463–469.
45. Shi, H.; Mu, X.; Zhang, Y.; Lyu, M. Effects of Different Land Use Pattern on Carbon Emission in Guangyuan City of Sichuan Province. *Bull. Soil Water Conserv.* **2012**, *32*, 101–106.
46. Han, Z.; Meng, Y.; Xu, J.; Wu, Y.; Zhou, Z. Temporal and Spatial Difference in Carbon Footprint of Regional Farmland Ecosystem—Taking Jiangsu Province as a Case. *J. Agro-Environ. Sci.* **2012**, *31*, 1034–1041.
47. Cai, M.; Shi, Y.; Ren, C.; Yoshida, T.; Yamagata, Y.; Ding, C.; Zhou, N. The need for urban form data in spatial modeling of urban carbon emissions in China: A critical review. *J. Clean. Prod.* **2020**, *244*, 118–793. [CrossRef]
48. Zheng, Y.; Du, S.; Zhang, X.; Bai, L.; Wang, H. Estimating carbon emissions in urban functional zones using multi-source data: A case study in Beijing. *Build. Environ.* **2022**, *212*, 108–804. [CrossRef]
49. Zhao, R.Q.; Liu, Y.; Ma, L.; Li, Y.; Hou, L.; Zhang, Z.; Ding, M. County-level carbon compensation of Henan province based on carbon budget estimation. *J. Nat. Resour.* **2016**, *31*, 1675–1687.
50. Zhang, W. The Development Thinking about The Key Ecological Functional Areas of Shanxi Province Based on Carbon Balance Zoning. *West. Resour.* **2019**, 198–201. [CrossRef]
51. Li, H. Research on spatiotemporal differentiation and carbon compensation potential of agricultural carbon effects in Shanxi Province. *Shanxi Univ. Financ. Econ.* **2022**. [CrossRef]
52. Wang, Z.; Hu, C.; Zhang, Y.; Liu, H. Characteristics of Carbon Emission Pattern in Hubei Territorial Space and Its Improvement Measures. *Planners* **2022**, *38*, 24–31.
53. Yang, J.; Zhang, M.; Duo, L.; Xiao, S.; Zhao, Y. Spatial Pattern of Land Use Carbon Emissions and Carbon Balance Zoning in Jiangxi Province. *Res. Environ. Sci.* **2022**, *35*, 2312–2321.
54. Wang, Y.; Song, J.; Zhang, K. Spatial-temporal Evolution Trend of Carbon Balance Zoning in Fenhe River Basin. *Sci. Technol. Ind.* **2022**, *22*, 162–169.