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Research on the Impact of Carbon Emissions and Spatial Form of Town Construction Land: A Study of Macheng, China

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Abstract: In the context of low-carbon construction, reducing carbon dioxide emissions from town construction land is the key to mitigating the problems caused by global warming. The influence of spatial form on carbon emissions has been generally recognized, but its influence at the level of town construction land is less explored. Therefore, in this study, in order to investigate the relationship between the spatial form of town construction land and carbon emissions, the relationship between them was analyzed, taking Macheng town of Bengbu city as the research object, selecting spatial form elements and quantifying them, and characterizing and accounting for the carbon emissions from the town construction land by each building's energy consumption. The study demonstrates that the spatial form elements such as building area and building storeys are important factors affecting the carbon emissions of residential land. Likewise, the building area, building shape coefficient, and floor area ratio are crucial factors impacting the carbon emissions of public lands. This research offers spatial form optimization strategies from a carbon reduction perspective by delving into the inherent relationship between spatial form and carbon emissions in town construction land. Consequently, it provides valuable scientific guidance for quantifying spatial planning and formulating carbon reduction strategies within a low-carbon framework.

Keywords: carbon emissions; spatial form; town construction land; building energy consumption

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1. Introduction

Since the onset of the industrial revolution, fossil fuels have been extensively exploited, resulting in massive greenhouse gas emissions, primarily carbon dioxide. Consequently, severe climate-related issues have arisen, significantly jeopardizing human society's survival and development [1]. Due to climate change, one of humanity's most significant challenges, countries worldwide have reached a consensus regarding the need to reasonably reduce CO_2 emissions, respond to climate change, and develop a low-carbon sustainable development strategy. For example, in the 2015 Paris Agreement, countries such as Sweden [2], France [3], the United Kingdom [4], and New Zealand [5] proposed actions to address climate change beyond 2020. China, currently the world's largest emitter of carbon, has pledged to peak its carbon emissions by 2030 and to achieve carbon neutrality (i.e., offsetting the carbon dioxide produced in the form of carbon sequestration, carbon offsets, etc., to achieve relative "zero emissions" by 2060) [6,7].

Town construction land serves as a spatial platform for human activities, encompassing various aspects of daily life, work, and leisure. However, it also plays a significant role as a primary source of carbon emissions. Human activities substantially contribute to carbon emissions, particularly within different categories of town construction land, including residential and public areas [8]. Statistics indicate that approximately 80% of global CO_2 emissions originate from town construction land [9]. In the case of China, carbon emissions from the energy consumption of town construction sites accounts for about 73% of China's total carbon emissions [10]. It can be seen that reducing carbon dioxide emissions from town construction land is the key to solving the global warming problem, but scholars mostly calculate carbon emissions from construction land as a whole, at the scale of urban agglomerations, provinces, and cities, and do not study town-level construction land; therefore, it is crucial to explore carbon emissions at the scale of town construction land. The energy consumption of buildings emerges as the primary source of carbon emissions within urban construction sites. Relevant studies indicate that building energy consumption comprises approximately 40% of global energy consumption at present. In developed countries such as the United States, buildings' energy consumption already surpasses 60% of the total energy consumption [11]. Furthermore, as living standards improve, the proportion of building energy consumption is expected to increase further. Therefore, measuring CO_2 emissions on town construction land, in terms of building energy consumption, is essential to reducing carbon emissions. Existing studies in the field have predominantly focused on the microscopic perspective of a building's energy consumption, specifically examining aspects such as the heating [12], lighting [13], and materials [14] of individual building units. This study focuses on the plot scale in towns and takes building energy consumption as the entry point, which is used to represent the carbon emission levels of town construction land. This not only excludes the influence of other disturbing factors but also can analyze the relationship between spatial form and carbon emissions at the micro-level more directly and effectively.

As a product of the urbanization process, spatial form significantly influences the living environment [15] and transportation patterns, among other factors. These factors, in turn, directly impact the energy consumption and carbon emissions of town residents [16]. Since the 1980s, there has been a growing interest among scholars in researching the relationship between carbon emissions and spatial form. Initially focusing on analyzing building-scale elements such as building shape coefficient [17] and building orientation [18], the research has evolved to explore the coupling relationship between spatial morphology and carbon emissions at broader scales. This expansion includes investigating elements such as the floor area ratio [19] and population density [20] of spatial scale and the carbon emissions of construction land. For example, using Grasshopper, Natanian J et al. (2019) conducted an iterative simulation of energy consumption in the Mediterranean region. Their study revealed that factors such as window-opening and building volume ratios significantly impact energy consumption [21]. Oh M et al. (2021) discovered that the relationship between building bulk factor, obstacle angle, and building orientation significantly influenced energy consumption. Their analysis indicated that building bulk factor and obstacle angles significantly impacted energy use [22]. Xu C (2019) et al. investigated the energy footprints and greenhouse gas emissions in 28 EU member states. Their findings revealed that a high population density and mixed-use urban development were desirable approaches to reducing energy footprints and greenhouse gas emissions [23]. Faroughi M et al. (2020) employed statistical methods to investigate the factors influencing community carbon emissions. They compared their findings with ground surface temperature (LST) remote sensing data and identified that variables such as population density and vegetation cover had the most significant impact on energy consumption [24]. The above studies show that the configuration of spatial form can have a great impact on carbon emissions, and a reasonable spatial form is conducive to reducing energy consumption in human activities, but scholars mostly analyze its impact from the micro- or macro-perspective of spatial form alone, failing to combine the macro- and micro-perspectives. Additionally, scholars mostly study this impact from a certain perspective, for example, focusing on cities [25], residential areas [26], building structures [27], or transportation [28], while analyses from the perspective of town construction land are lacking. Therefore, this study combines macroscopic and microscopic perspectives, and explores the correlation between the spatial forms of land and building from two scales, which is relevant to the effective reduction in carbon emissions and could help to optimize the spatial form of towns [29].

At present, carbon emissions are mostly calculated at the national, provincial, and urban cluster levels and are not sufficiently discussed at the town and village levels. Moreover, scholars mostly discuss the relationship between spatial form and carbon emissions from the perspective of cities, residential areas, or buildings, and not enough research has been conducted focusing on the different types of construction land in towns. Therefore, this study uses Macheng town in Bengbu City as the research object. It screens and quantifies spatial form elements and uses building energy consumption as the starting point to calculate carbon emissions. The study analyzes the impact of spatial form elements on carbon emissions in different types of construction land in the town. The main objective of this study is to investigate the relationship between carbon emissions from town construction land and spatial form and to propose specific strategies for optimizing spatial form from a carbon reduction perspective.

2. Materials and Methods

2.1. Study Area and Data Sources

This study uses Macheng town in Bengbu City as an example. It is located on the south bank of the middle reaches of the Huaihe River, with a latitude of 32°43′–33°30′ N and longitude of 116°45′–118°04′ E. It belongs to the transition zone between the humid monsoon climate of the northern subtropical zone and the semi-humid monsoon climate of the southern temperate zone. The area of the Macheng inter-town is 176.03 km^2, and the subject of this study is the town construction land, so the town area of Macheng was used as the study area, with an area of about 5.62 km^2 and a resident population of 8009, as shown in Figure 1.

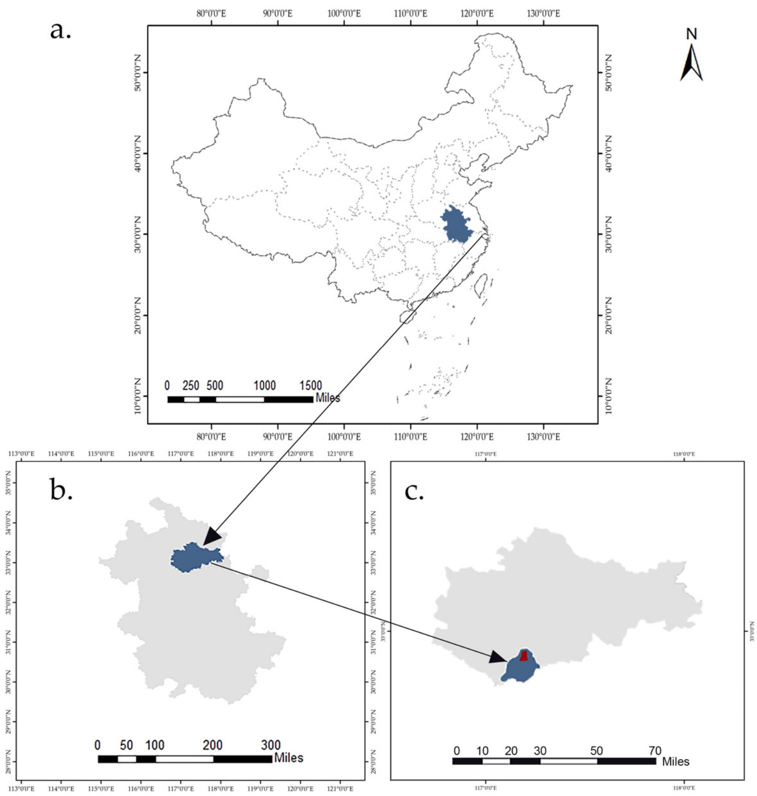


Figure 1. Location of the study area. (**a**) The location of Anhui Province in China. (**b**) The location of Bengbu in Anhui Province. (**c**) The location of Macheng inter-town and town area in Bengbu.

The study of the town's spatial form and carbon emission needed accurate data support. The spatial data used in this study were obtained from the 2021 administrative district map, geographic information data, and 2021 topographic mapping data of Bengbu City, Macheng Town.

2.2. Methods

The following work was conducted in this study. The details are shown in Figure 2 and will be introduced in the following sections.

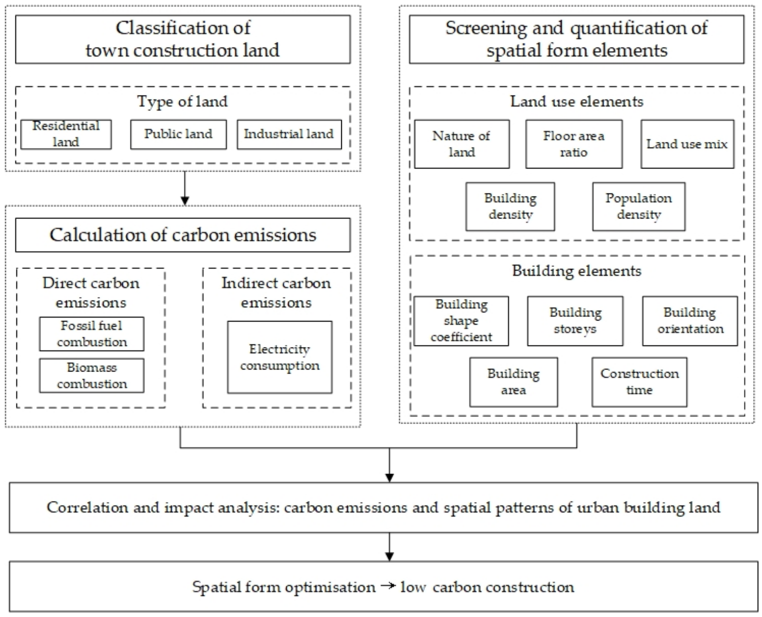


Figure 2. Research framework diagram.

Firstly, according to the relevant norms and the current situation of the study area, the classification of town construction land was determined: it was divided into residential land, public land, and industrial storage land according to the current situation of the study area.

Secondly, the spatial form elements affecting the carbon emission of town construction land were screened and divided into two scales: land-use elements and building elements.

Thirdly, using building energy consumption as a characterization, the carbon emissions of different types of construction land in towns were calculated using direct and indirect methods.

Fourthly, the correlation between the spatial form of town construction land and carbon emissions was analyzed. A regression-fitting analysis of the relationship between each index of spatial form and carbon emissions was carried out to further explore the quantitative relationship between them.

Finally, specific spatial form optimization suggestions for reducing carbon emissions in towns were proposed.

2.2.1. Classification and Screening of Town Construction Land

According to the terminology of urban and rural planning issued by the National Committee for the Examination of Scientific and Technical Terms in 2020, town construction land is defined as "all kinds of land used for town construction within the planning area" [30]. Town construction land refers to the land occupied for the implementation of town planning within the scope of the town construction land, which is determined by the general land-use planning, including land for town residential and public buildings, as well as land for industrial and mining storage, commercial land, and other special land. In this study, the above norms are used to define the urban construction land under study, which mainly includes construction land such as residential land, public land, and industrial storage land.

This study aims to characterize the carbon emission levels of different types of construction land in towns and cities by building energy consumption at the plot scale. In contrast, the main body of building energy consumption is the different types of buildings. Town construction land is the carrier of different types of buildings. To measure carbon emissions from urban construction land, it is first necessary to match the different functions of buildings with the nature of urban construction land. There are currently more standards and codes for classifying building functions. This study draws on the "Standard for energy consumption of buildings (2016)", "Uniform standard for design of civil buildings (2019)" and the classification of the China Building Energy Model (CBEM) developed by the Energy Conservation Research Centre of Tsinghua University, as well as the relatively authoritative database on building function classification with the Commercial Building Energy Consumption Survey Database (CBECS) in the United States for comparison buildings, which are classified according to their main functions. Its official website is https://www.eia.gov/consumption/commercial/building-type-definitions.php (accessed on 10 April 2023). This study's classification of building functions is determined comprehensively, covering the main building types in towns. Using the classification of land use in the Ministry of Natural Resources November 2020 Guidelines on Land and Sea Use Classification for Land Spatial Survey, Planning, and Use Control, combined with the classification of building functions, a table is presented correlating the different types of construction land and building functions in towns (Table 1).

Table 1. Correlation between different types of building sites and building functions in towns.

Major Categories of Land Type	Medium Category of Land Type	Building Function
Residential land	Urban residential land	Urban residential buildings
	Rural residential land	Rural residential buildings
Public land	Commercial services land	Commercial services buildings
	Administrative office land	Administrative office buildings
	Cultural land	Cultural buildings
	Educational land	Educational buildings
	Medical land	Medical buildings
	Municipal utilities land	Municipal utilities buildings
Industrial storage land	Industrial land	Industrial production buildings
		Production auxiliary room buildings
	Storage land	Storage buildings

It should be noted that, in the building function classification used in this study, some buildings with similar functions are divided into one category, such as medical buildings, including medical and technical buildings, inpatient buildings, and outpatient buildings, which are uniformly classified as hospital buildings in the study, and elementary schools, junior high schools, high schools, and research institutes, which are uniformly classified as cultural buildings. As building energy consumption is the main source of carbon emissions from town construction land, this study is mainly based on the perspective of building energy consumption, so the dynamic traffic energy consumption was not considered, and the main carrier of traffic energy consumption is town road land. Therefore, town road land was not included in the classification of the town construction land in this study. Therefore, road land and land to be studied in depth were not considered for building energy consumption.

2.2.2. Screening and Quantification of Spatial Form Elements

There is no unified understanding of spatial form in academic circles, and there are many different uses of the term "spatial form" alone. From an architectural perspective, some scholars consider the area in which a building is located to be a spatial form. Others argue that spatial form is not a single architectural component but an integrated collection of landscapes and realities. This extends spatial form to urban form, which is measured and analyzed from a spatial perspective [31]. With the continuous development of spatial morphology research in various disciplines, the constituent elements of spatial morphology have expanded, ranging from the material elements of road networks, land use, and spatial structures to non-material elements such as human behavioral characteristics and economic factors. In urban design at the neighborhood scale, the elements of spatial form mainly include material elements such as layout and form, land use, urban transport, and infrastructure [32].

Cervero and Kockelman have proposed the famous "3D" theory of spatial form elements, which has been extensively studied by many scholars and has produced more mature and accepted results [33,34]. These are divided into three dimensions: density, diversity, and design [35]. The density refers to the building area, building density, and population density of the plot, the diversity refers to the mix of the site, and the design refers to the building form and built environment [36,37].

Table 2 summarizes the indicators of spatial forms that may influence carbon emissions in the studies of different scholars, which have strong applicability and recognition.

Table 2. Study of the spatial form indicators affecting carbon emissions.

Spatial Pattern Indicators	Medium Category of Land Type
Floor area ratio	Javanroodi K (2018) [38], Mao, Y (2018) [19]
Building area	Jinpei Ou (2013) [39], Rong P (2020) [40], Zhang X (2021) [41], Alhorr Y (2014) [42], Zheng S (2022) [43]
Population density	PWG Newman (1989) [44], Y Yi (2017) [45], Alhorr Y (2014) [42], Li J (2017) [46], Liang, D (2023) [20]
Travel behavior	Jinpei Ou (2013) [39], Shen Y S (2022) [25], Li J (2017) [46]
Building density	Y Yi (2017) [45], Khaled Alawadi (2022) [37], Robert Cervero (1997) [35], Shen Y S (2022) [25],
Building storey	Zhang X (2021) [41], Alhorr Y (2014) [42], Li X (2018) [47]
Landscape metrics	G Wang (2019) [48], Y Zhang (2023) [49], Faroughi M (2020) [24]
Land use mix	Robert Cervero (1997) [35], Shen Y S (2022) [25]
Nature of land	Shen Y S (2022) [25], Zhang X (2021) [41], Alhorr Y (2014) [42], Filogamo L (2014) [50]
Building shape coefficient	Zhang X (2021) [41], Liao Q (2022) [51], Bringas E N (2022) [52], Javanroodi K (2018) [46], Carpio, M (2021) [17]
Construction time	Alhorr Y (2014) [42], Liao Q (2022) [51], Li X (2019) [53]
Building orientation	Sun, C (2022) [18], Oh, M (2021) [22], Filogamo L (2014) [50]

This study investigates the influence of spatial morphology on the carbon emissions of construction land at the town level and screens out the spatial morphological elements that may influence the carbon emissions of town construction land according to relevant norms, 3D theory, and other scholars' studies. Since this study is mainly conducted from the perspective of building energy consumption, the dynamic transportation energy consumption was not considered, and the travel behavior index was considered to be deleted; The town construction land does not cover green land, forest land, grassland, and water, so the landscape metrics index was considered to be deleted. Therefore, in this study, the indicators of travel behavior and landscape metrics index were deleted, and 10 spatial form factors were considered. Their concept, explanation, and measurement methods are shown in Table 3.

Table 3. Spatial form indicator description.

Classification of Elements	Elements of Spatial Form	Equation	Description	Definition
Land use elements	Nature of land	$L = U_i$ (i = 1,2,3 . . . . . . ,9)	U_i is the type of land use in category i; 1 is urban residential land; 2 is rural residential land; 3 is commercial services land; 4 is administrative office land; 5 is cultural land; 6 is educational land; 7 is medical land; 8 is municipal utilities land.	Nature of land refers to the specific use of a building site, as defined by the planning authority following the relevant land use classification standards and in response to urban and rural development needs.

Table 3. *Cont.*

Classification of Elements	Elements of Spatial Form	Equation	Description	Definition
	Floor area ratio	$F = \frac{A}{U}$	A denotes the total building area within the plot; U denotes the total site area of the plot.	The floor area ratio refers to the ratio of the total building area to the site area within a plot. It provides a measure of the intensity of development of the land.
	Land use mix	$M = \frac{-\sum P_i \ln P_i}{\ln L}$ (i = 1,2,3 . . . . . . , n)	L is the number of building types; P_i is the percentage of the building area of type i; n is the number of building types on the plot.	Land use mix refers to the proportion of other functional floor space mixed on a single nature of the building site.
	Building density	$D = \sum_{i=1}^{n} \frac{s_i}{U}$ (i = 1,2,3 . . . . . . , n)	s_i denotes the building footprint of the ith building on the plot; U indicates the total site area of the plot; n is the number of buildings on the plot.	Building density refers to the ratio of the total basement area of all buildings to the total site area within a certain plot of land, and can reflect the open space ratio and building density within a certain site.
	Population density	$P = \frac{R}{U}$	R denotes the number of people living on the plot; U denotes the total land area of the plot.	Population density refers to the number of people living on a unit of building land and is a true reflection of the distribution of the population within the building site.
	Building shape coefficient	S = $\sum_{i=1}^{n} \frac{B}{T}$ (i = 1,2,3 . . . . . . , n)	B denotes the sum of the exterior areas of the building; T denotes the sum of the volume of the building.	The building shape coefficient is the ratio of the surface area of a building to its volume. At this stage, the building form factor is an essential parameter in characterizing the morphological features of a building and an important factor in the energy consumption of a building.
	Building storey	C = C_i (i = 1,2,3 . . . . . . , n)	C_i denotes the number of storeys of the ith building; n is the number of building blocks on the plot.	Building storey refers to the natural storey of the building, which is generally calculated based on the interior floor level ±0 or more, including semi-basements with light windows above the exterior floor level, whose interior storey height is above 2.20 m (excluding 2.20 m); the natural storey is calculated, while others, such as attics and stairwells, are not calculated.
Building elements	Building orientation	$O = \sum_{i=1}^{n} \frac{J_i}{Z_i} (\alpha \leq 15°)$ $O = \sum_{i=1}^{n} \frac{\lvert\cos \alpha J_i\rvert}{Z_i} (\alpha > 15°)$	J_i denotes the length of the south elevation of the ith building; Z_i denotes the perimeter of the ith building; α indicates the angle between the south and north azimuth of the building.	Building orientation is the ratio of the length of the south-facing façade of a building plan to the perimeter of the building plan. In this study, building orientation refers to the ratio of the length of the south-facing elevation of all building planes on the site to the perimeter of all building planes.
	Building area	$A = \sum_{i=1}^{n} s_i h_i$ (i = 1,2,3 . . . . . . ,n)	s_i denotes the building footprint of the ith building on the plot; h_i denotes the building height of the ith building on the plot; n is the number of buildings on the site.	Building area refers to the total above-ground construction scale on a building site and represents, to some extent, the intensity of development on that building site.
	Construction time	$Y = Q_i$ (i = 1,2,3 . . . . . . ,8)	Q_i denotes represents the construction time of the first building; 1 before 1980; 2 for the period 1980–2000; 3 for the period 2000–2010; 4:2010–2015; 5 for 2015–today.	Construction time refers to the development and construction of the building on which the construction site is located. In turn, the date of development and construction of a building specifies the materials used in its construction, the external envelope of the building, the form of the building, and other characteristics.

2.2.3. Calculation of Carbon Emissions

Due to the limited sample size of industrial storage land in Macheng town, it is difficult to explore the interconnections between spatial form elements and draw valid conclusions, so only residential land and public land are involved in the calculation of carbon emissions from urban construction land in this study. Since the carbon emissions from residential land and public land are mainly generated by the energy consumption in the operation phase of buildings, and the energy consumption in the operation phase of buildings accounts for about 90% of the energy consumption in the whole life cycle of buildings [54,55], this study uses the energy consumption in the operation phase of buildings to express the carbon emissions from town construction land. The energy consumption in the building operation phase mainly comes from the consumption of electricity, coal, natural gas, and other energy sources, and the carbon emissions can be divided into direct emissions and indirect emissions according to the energy use or consumption mode. Direct emissions refer to greenhouse gas emissions from fossil energy combustion activities such as coal, natural gas and oil, and industrial production processes; indirect emissions refer to the emissions implied by the use and consumption of purchased electricity, heat, and steam, and mainly refer to the carbon emissions generated inside buildings.

In this study, direct carbon emissions are mainly based on fossil fuel combustion and biomass combustion, calculated as follows:

$$E_{\text{Direct}} = E_{\text{Fossil fuel combustion}} + E_{\text{Biomass combustion}} \quad (1)$$

Among them,

$$E_{\text{Fossil fuel combustion}} = \sum_{i=1}^{n} \left(FC_i \times C_{ar,i} \times OF_i \times \frac{44}{12} \right) \quad (2)$$

In Equation (2), $E_{\text{Fossil fuel combustion}}$ is emissions from the combustion of fossil fuels; FC_i is the consumption of fossil fuel I; $C_{ar,i}$ is the received elemental carbon content of fossil fuel i; OF_i is the carbon oxidation rate of fossil fuel i; 44/12 is the ratio of the relative molecular mass of carbon dioxide to carbon; and i is the fossil fuel type code in which the carbon content of the received base element is given. The equations are:

$$C_{ar,i} = NCV_{ar,i} \times CC_i \quad (3)$$

In Equation (3), $C_{ar,i}$ is the received−based elemental carbon content of fossil fuel I; $NCV_{ar,i}$ is the received–based low-level heat content of fossil fuel i; CC_i is the carbon content per unit calorific value of fossil fuel i. Referring to the Ministry of Ecology and Environment's Guidelines for Accounting and Reporting of Greenhouse Gas Emissions from Enterprises and the Guidelines for Accounting and Reporting of Greenhouse Gas Emissions from Coal Producers in China, the fossil fuel combustion in this study is mainly natural gas, liquefied petroleum gas, and anthracite coal, and the default values of the relevant parameters are shown in Table 4.

$$E_{\text{Biomass combustion}} = F_{Biomass} \times EF_{Biomass} \quad (4)$$

In Equation (4), $E_{\text{Biomass combustion}}$ is the emissions from biomass combustion; $F_{Biomass}$ is the amount of biomass fuel consumed; $EF_{Biomass}$ is the emission factor for the combustion of biomass fuels; for this study, only charcoal combustion was involved, and an emission factor of 6.0 was used for charcoal, referring to provincial guidelines for the preparation of GHG inventories.

Table 4. Default values for fossil-fuel-related parameters.

Energy Name	Low-Level Heat Content [d]	Carbon Content per Unit Calorific Value	Carbon Oxidation Rate (%)
Liquefied Petroleum Gas	50.179 [a]	0.0172 [c]	98 [b]
Natural gas	389.31 [a]	0.01532 [b]	99 [b]
Anthracite	20.304 [a]	0.02749 [b]	94 [b]

[a] Data taken from the China Energy Statistics Yearbook 2019. [b] Data taken from the "Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (Trial)". [c] Data taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. [d] Data taken from GB/T 2589-2020 "General Rules for Calculating Comprehensive Energy Consumption" [56].

Since this study area does not involve the outsourcing of heat and heating, this paper uses an indirect method to calculate the electricity-based GHG emissions in building energy consumption, which are calculated as follows:

$$E_{\text{Indrect}} = E_{\text{Electricity}} = AD_{\text{Electricity}} \times EF_{\text{Electricity}} \quad (5)$$

$E_{\text{Electricity}}$ is emissions from t*he* purchased use of electricity; $AD_{\text{Electricity}}$ is purchased electricity consumption; $EF_{\text{Electricity}}$ is the grid emission factor. Referring to the Ministry of Ecology's Guidelines for the Accounting and Reporting of Corporate Greenhouse Gas Emissions, a grid emission factor of 0.5810 was used.

3. Results

3.1. The Relationship between Spatial Form Elements and Carbon Emissions from Town Construction Land

The carbon emissions of each parcel in the town of Macheng were obtained by adding up the direct and indirect carbon emission values, as shown in the Figure 3. The cumulative carbon emissions of the town of Macheng in 2021 were 5,336,091.271 kg of CO_2, of which 3,775,335.627 kg was for residential land and 1,860,755.645 kg was for public land (the spatial distribution of the carbon emission index in Macheng is shown in Table 4).

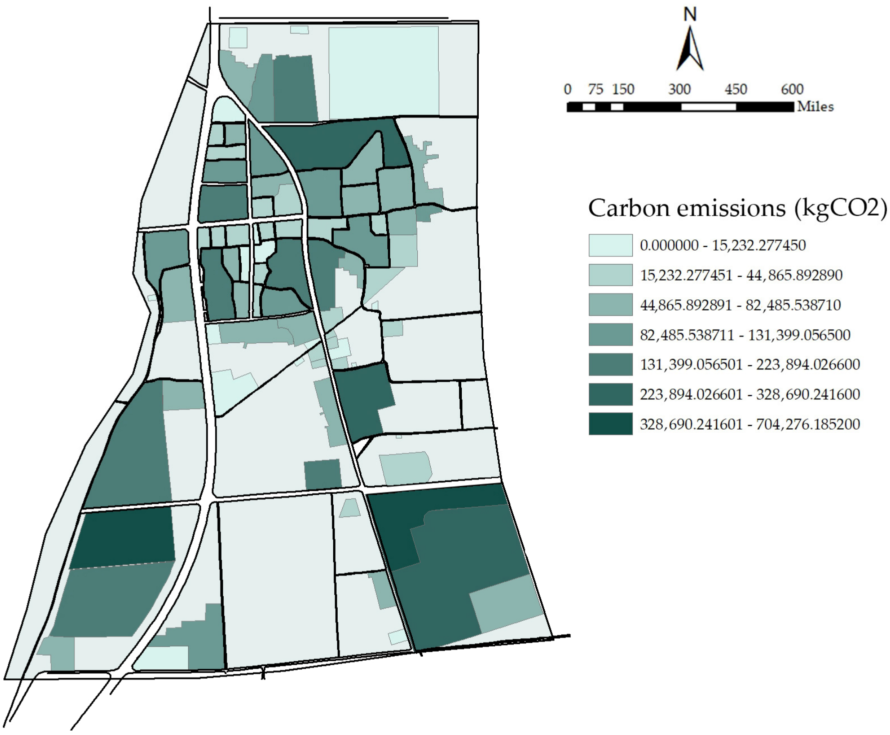


Figure 3. Spatial distribution of carbon emission index in Macheng.

Pearson correlation analysis is a quantitative analysis method to analyze the correlation between two variables, which can filter out the influencing factors of the dependent variable, and is also the basis for multiple regression analysis. Pearson correlation analysis applies to two quantitative variables that obey a normal distribution, and if a linear trend is found between the two variables by plotting a scatter plot, the linearity of the two variables can be described by calculating the Pearson correlation coefficient correlation. The Pearson correlation coefficient matrix for all variables is shown in Figures 4 and 5.

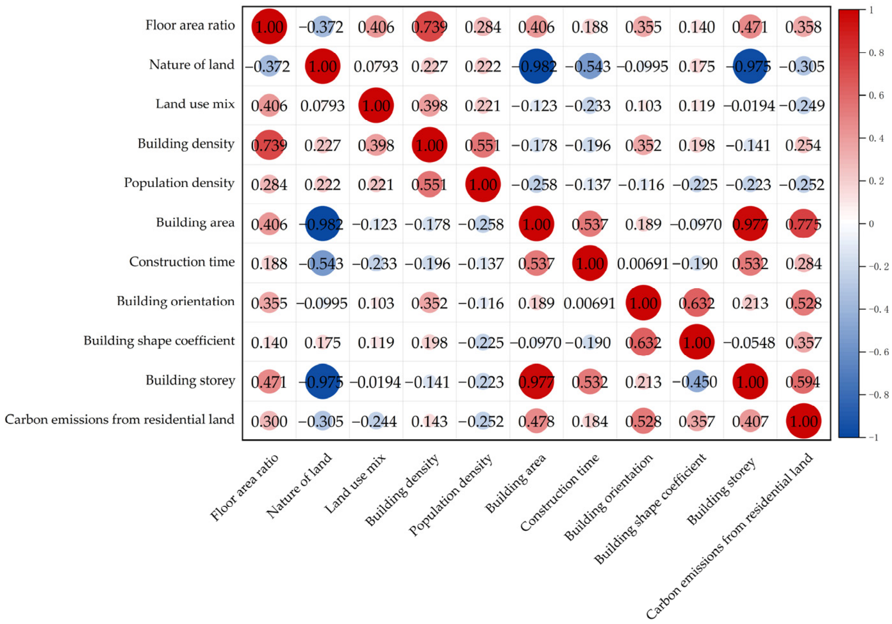


Figure 4. Matrix of Pearson correlation coefficients between the spatial form elements and carbon emissions from residential land.

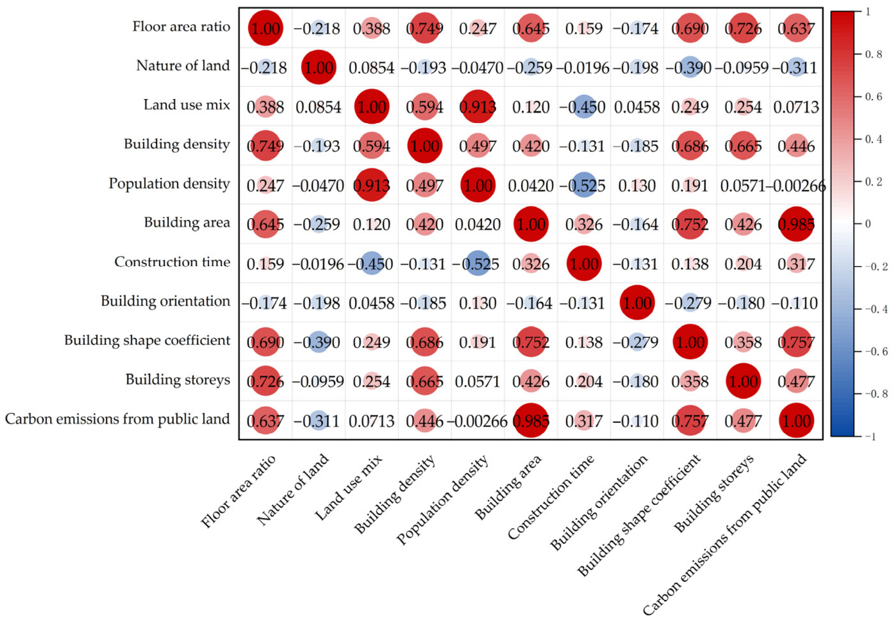


Figure 5. Matrix of Pearson correlation coefficients between the spatial form elements and carbon emissions from public land.

According to the Pearson correlation matrix, the elements with a significant correlation with the carbon emission of town construction land were filtered out, as shown in Table 5. The elements with a significant correlation with the carbon emissions of residential land

and the degree of influence are building area > building storey > building orientation > floor area ratio > building shape coefficient > nature of land > construction time > building density > population density, and the elements with a significant correlation with the carbon emissions of public land and the degree of influence are building area > building shape coefficient > building storey > floor area ratio > building density > nature of land.

Table 5. Correlation coefficients between the spatial patterns and carbon emissions from urban building sites.

Type	Variable Name	Residential Land		Public Land	
		Correlation Coefficient	Significance Level	Correlation Coefficient	Significance Level
Land use elements	Nature of land	−0.305 ***	0.000	−0.311 **	-
	Floor area ratio	0.358 ***	0.00	0.637 **	0.011
	Land use mix				
	Building density	0.254 **	0.329	0.446 **	0.095
	Population density	−0.252 **	0.027		
Building elements	Building shape coefficient	0.34 ***	0.007	0.757 ***	0.001
	Building storeys	0.596 ***	0.000	0.542 ***	0.000
	Building orientation	0.518 ***	0.000		
	Building area	0.728 ***	0.000	0.985 ***	0.000 ***
	Construction time	0.284 **	0.049		

Note: *** and ** represent 1% and 5% significance levels, respectively.

3.2. Analysis of the Impact of Spatial Form Elements on Town Construction Land

To study the relationship between the spatial form elements with a significant correlation and the carbon emissions of town construction land, the correlation and trend analysis of the scatter plot between the two variables were used to determine their linear or nonlinear influence relationship.

3.2.1. The impact of spatial form elements on residential land

The nine significantly correlated elements of the nature of the land, floor area ratio, building density, population density, building storey, building shape coefficient, building orientation, building area, and construction time were used as independent variables, and carbon emissions from the residential land use were used as dependent variables, to be fitted separately (as shown in Table 6).

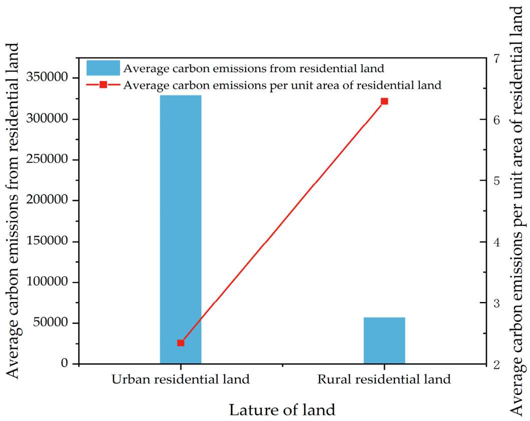
(1) Nature of land

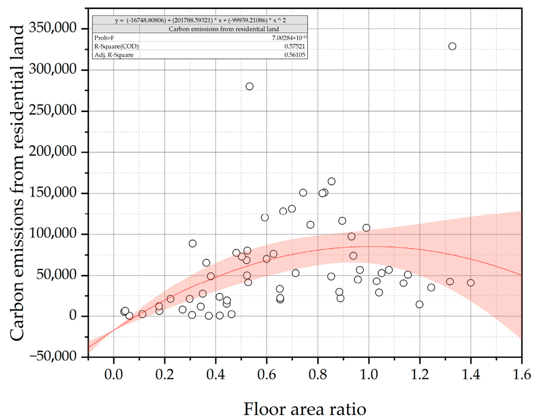
As shown in Table 6 (chart 1), in the residential land use category, the average carbon emissions from urban residential land (328,690.2416 kgCO_2/a) were more significant than the average carbon emissions from rural residential land (56,502.3834 kgCO_2/a). The average carbon emissions from the urban residential land (2.3467 kgCO_2/m^2.a) were lower than those from rural residential land (6.2915 kgCO_2/m^2.a), which is related to the actual situation in the town of Macheng, where only one housing estate is in use on urban residential land (one under construction). The population capacity and usage rate were lower compared to rural residential land, and rural residential land involves the consumption of energy such as gas and biomass (firewood), which, to some extent, increases CO_2 emissions.

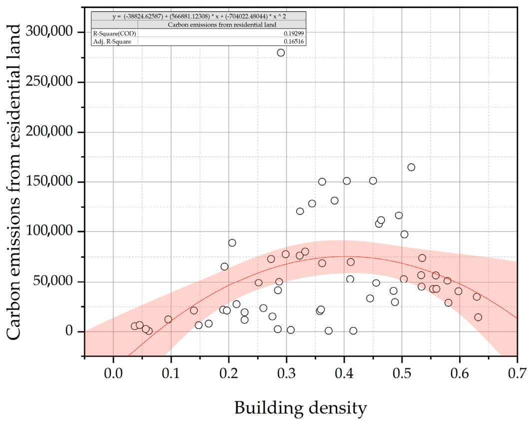
(2) Floor area ratio

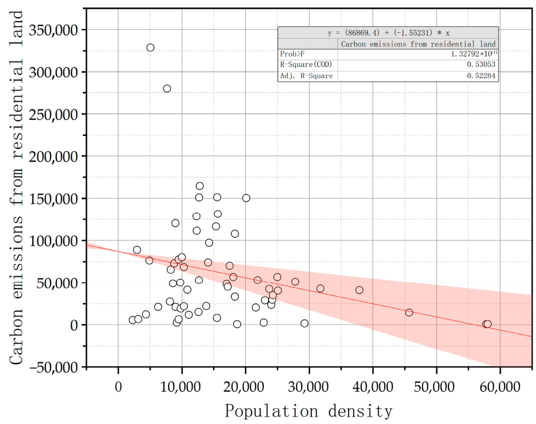
The degree of explanation for the quadratic polynomial trend line of floor area ratio and carbon emissions from the residential land use has an R-squared of 0.57521. When the floor area ratio was in the interval of [0,1.01], the carbon emissions from the residential land use increased with the increase in floor area ratio, while they decreased with the increase in floor area ratio when the floor area ratio was greater than 1.01.

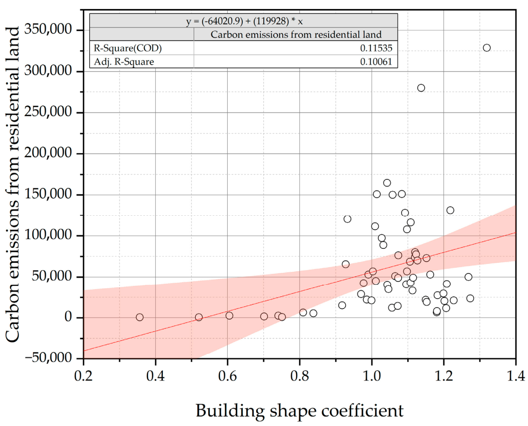
Table 6. Analysis of the spatial form and the impact of carbon emissions from residential land.

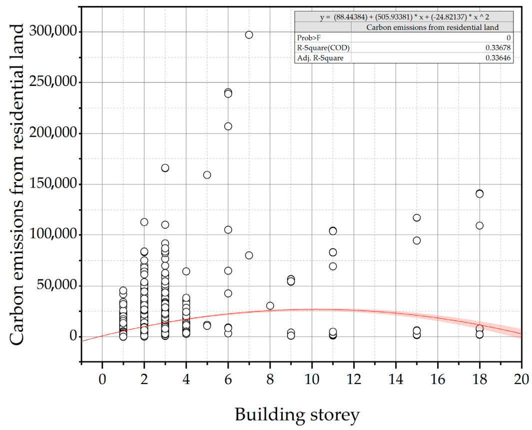
<table>
<tr><th>Spatial Form Elements</th><th colspan="2">Analysis Chart</th></tr>
<tr><td rowspan="2">Land use elements</td><td>


(1) Nature of land</td><td>


(2) Floor area ratio</td></tr>
<tr><td>


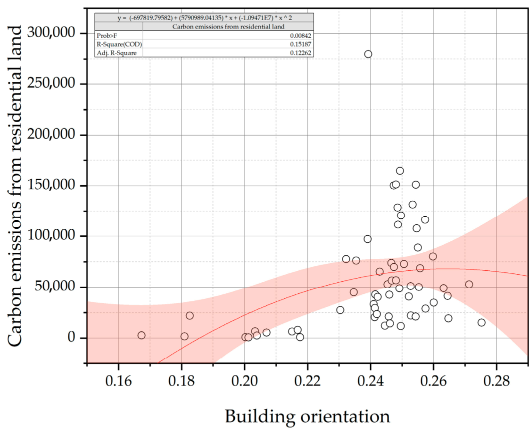
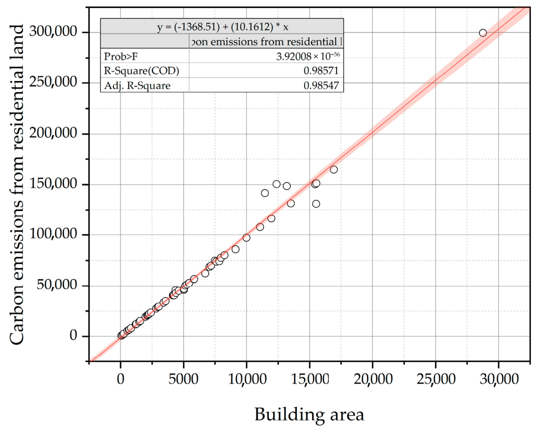
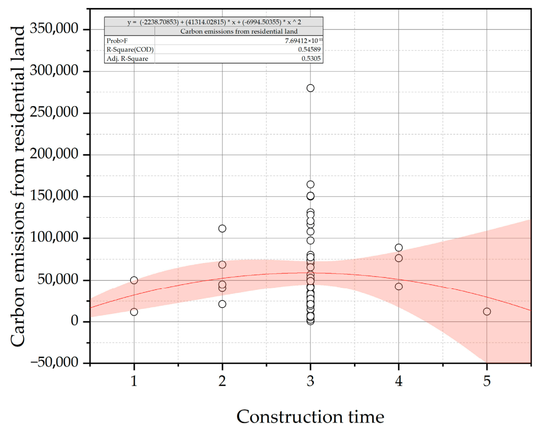
(3) Building density</td><td>


(4) Population density</td></tr>
<tr><td>Building elements</td><td>


(5) Building shape coefficient</td><td>


(6) Building storey</td></tr>
</table>

Table 6. *Cont.*

Spatial Form Elements	Analysis Chart
	 (7) Building orientation  (8) Building area  (9) Construction time
Notes:	○ Carbon emissions from residential land Fitted Y of Carbon emissions from residential land 95% Confidence Band of Carbon emissions from residential land

(3) Building density

The degree of explanation for the quadratic polynomial trend line of the building density and carbon emissions from residential land R-squared was 0.19299. By analyzing the trend line Table 6 (chart 3), building density and residential land use carbon emissions show an inverted U-shaped trend that increased and then decreased. When the building density was less than 0.40, the carbon emissions of the residential land correspondingly increased with the increase in building density, while they decreased with the increase in building density when the building density was greater than 0.40.

(4) Population density

The R-squared used for the degree of explanation of population density and carbon emissions from residential land was 0.53053. By analyzing the fitted curve in Table 6 (chart 4), carbon emissions from residential land decreased with increasing population density.

(5) Building shape coefficient

The building shape coefficient and residential land use showed a linear relationship, and the degree of explanation for the carbon emissions from residential land was 0.11535. An analysis of the scatter plot in Table 6 (chart 5) shows that the carbon emissions from residential land increasde with the increase in the building shape coefficient.

(6) Building storey

The R-squared of the degree of explanation between the building storey and carbon emissions from residential land was 0.33678. By analyzing the trend line in graph (6), building storey and carbon emissions from the residential land showed an inverted U-shaped trend that increased and then decreased. When the number of building storeys was less than 10, the carbon emissions of the residential land increased correspondingly with the increase in building storey; when the number of building storey was greater than 10, MaCheng town has urban residential buildings, which do not lead to greenhouse gas emissions from anthracite coal and biomass combustion, and, to a certain extent, will reduce the overall carbon emissions, leading to a decrease with the increase in building storey.

(7) Building orientation

Building orientation and residential land carbon emissions showed a one-to-one quadratic linear regression relationship, with the trend line showing an R-squared degree of 0.15187. By observing the scatter plot in Table 6 (chart 7), residential land carbon emissions showed an inverted U-shaped change trend that first increased and then decreased. When the building orientation was less than 0.2645, the carbon emissions from residential land increase correspondingly with the increase in building orientation, while they decreased with the increase in building orientation when the building orientation was greater than 0.2645.

(8) Building area

The building area and the carbon emissions of different types of town construction land showed a one-dimensional linear relationship, in which the degree of explanation, R-squared for the carbon emissions of rural residential land, was 0.98571. This passed the 0.01 significance level. Observing the scatter plot, Table 6 (chart 8) shows that, with the increase in building area, the carbon emissions of residential land showed an increasing trend.

(9) Construction time

The degree of explanation of the quadratic polynomial trend line between the construction time and carbon emissions from residential land had an R-squared score of 0.54589 and over a 0.01 significance level, as shown in Table 6 (chart 9). When the construction time finished before 2000, the carbon emissions of residential land increased with the construction time; when the construction took place after 2010, it decreased with the construction time.

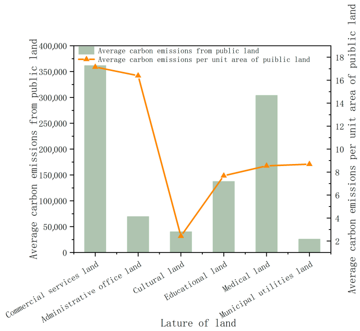
3.2.2. The Impact of Spatial Form Elements on Public Land

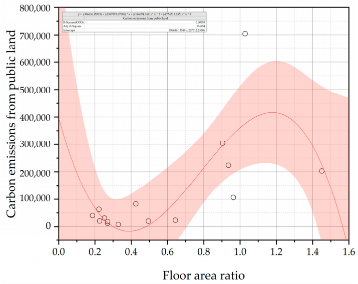
The six significantly correlated elements of site nature, floor area ratio, building density, building storey, building shape coefficient, and building area were used as independent variables, and carbon emissions from public land were used as dependent variables and fitted separately (as shown in Table 7).

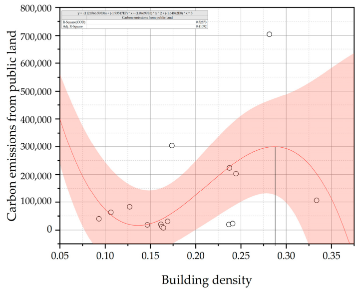
(1) Nature of land

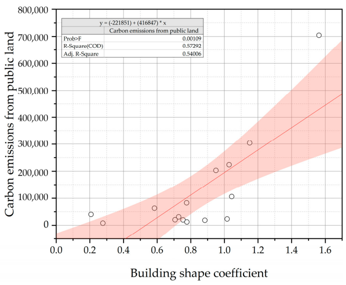
As shown in Table 7 (chart 1), among the public land types, the overall changes in the average carbon emissions are, in descending order, commercial service land (361599.6924 $kgCO_2/a$), medical land (303994.9139 $kgCO_2/a$), educational land (137339.8212 $kgCO_2/a$), administrative office land (69549.7745 $kgCO_2/a$), cultural land (40177.0587 $kgCO_2/a$), and municipal utilities land (25791.4314 $kgCO_2/a$). The average value of carbon emissions per unit area also varied greatly: cultural land (2.4237 $kgCO_2/m^2.a$), educational land (7.6778 $kgCO_2/m^2.a$), medical land (8.5426 $kgCO_2/m^2.a$), municipal utilities land (8.6851 $kgCO_2/m^2.a$), administrative office land (16.3981 $kgCO_2/m^2.a$) and commercial service land (17.1510 $kgCO_2/m^2.a$). By comparing the SE with the average value of carbon emissions per unit area of public land in general, it can be determined that the commercial service land, administrative office land, municipal utilities land, and medical land were relatively "high carbon emission" types of urban construction land. We can identify commercial service, administrative office, public utility, and medical land as relatively "high carbon emission" town construction land types, and education and cultural land as relatively "low carbon emission" town construction land types.

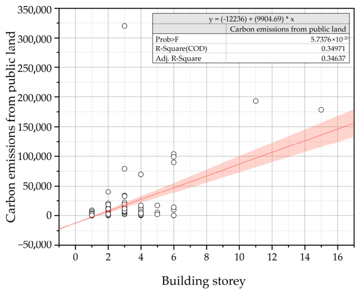
Table 7. Analysis of spatial form and the impact of carbon emissions from public land.

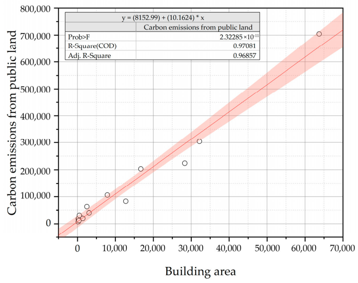
<table>
<tr><th>Spatial Form Elements</th><th colspan="3">Analysis Chart</th></tr>
<tr><td>Land use elements</td><td>

(1) Nature of land</td><td>

(2) Floor area ratio</td><td>

(3) Building density</td></tr>
<tr><td>Building elements</td><td>

(4) Building shape coefficient</td><td>

(5) Building storey</td><td>

(6) Building area</td></tr>
<tr><td colspan="4">Notes: ○ Carbon emissions from public land
Fitted Y of Carbon emissions from public land
95% Confidence Band of Carbon emissions from public land</td></tr>
</table>

(2) Floor area ratio

The degree of explanation for the cubic polynomial trend line of floor area ratio and public land carbon emissions' R-squared value was 0.60353. Table 7 (chart 2) shows that when the floor area ratio was at (0.38, 1.18) for public land carbon emissions, they increased with the increase in the floor area ratio and decreased with the increase in the floor area ratio at (0, 0.38) and (1.18, 1.6).

(3) Building density

The degree of explanation for the cubic polynomial trend line of building density and public land carbon emissions had an R-squared score of 0.52873. According to the trend changes in line Table 7 (chart 3), with the increase in building density, public land carbon emissions showed a roughly inverted N-shaped trend of decrease–increase–decrease for building density (0, 0.14), and public land (0, 0.14) and (0.29, 0.35). Public land carbon emissions increased with increases in building density. In contrast, at (0, 0.14) and (0.29, 0.35), public land carbon emissions decrease with increasing building density.

(4) Building shape coefficient

The building shape coefficient showed a linear relationship with public land, and the degree of explanation for carbon emissions from public land was 0.57292. By analyzing the fitted curve in Table 7 (chart 4), the carbon emissions from public land increased with the increase in building shape coefficient.

(5) Building storey

The building storey showed a linear relationship with the carbon emissions of public land, and the degree of explanation for the carbon emissions of public land was 0.34971. In Table 7 (chart 5), it can be seen that the carbon emissions of public land increased with the increase in building storey.

(6) Building area

The degree of explanation for the carbon emissions from public land had an R-value of 0.97081; the fitted curve in Table 7 (chart 6) shows that the carbon emissions from public land tend to increase with the increase in floor area.

3.3. Random Forest Regression of Spatial Form and Carbon Emissions from Town Construction Land

The nonlinear relationship between spatial form and carbon emissions from town construction land was further investigated using random forest regression. We used the sklearn machine learning library in Python programming to build regression models based on elements with significant correlations in SPSS.

3.3.1. Model Regression Results for Residential Land

Based on the nine spatial form elements with a significant correlation and the carbon emissions of residential land, a random forest model was established, and regression prediction was performed to obtain the fitting effect graphs of the test set and training set (Figure 6). A specific analysis of the results in the above Figure 6 shows that the consistency between the training and prediction sets was high, which indicates that the prediction performance of this model was good and can be used for the efficient and accurate prediction of the carbon emissions of such projects. The performance of the stochastic model for the test set and training set is presented in Table 8. The mean squared error (MSE) represents the expected value of the difference between the predicted and actual values, and the mean absolute error (MAE) represents the mean value of the absolute value of the error, which reflects the error of the predicted value. The smaller this value, the better. The coefficient of determination (R^2) was 0.9813 and 0.9738, which was close to 1. The accuracy of the model was high, which indicates a good fitting effect.

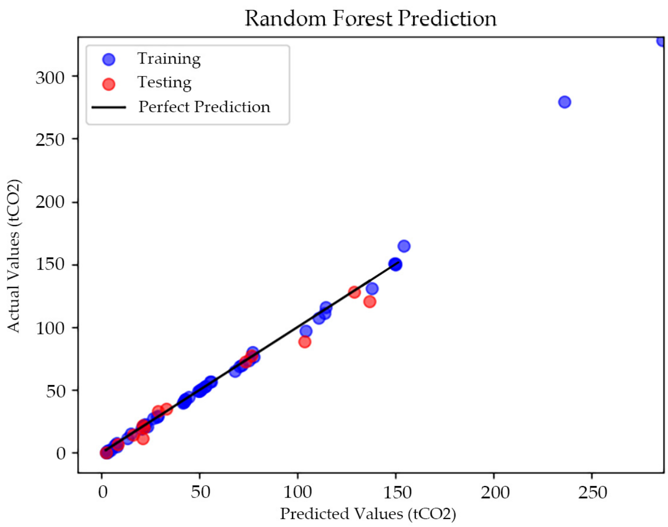


Figure 6. The effect of fitting the full dataset of carbon emissions and the spatial form of residential land.

Table 8. Residential land use model evaluation results.

	R2 Score	Mean Squared Error	Mean Absolute Error
Training	0.9813	0.4117	0.3249
Testing	0.9738	0.4639	0.4240

We also discovered the significance of every spatial form factor in the above random forest model, as shown in Figure 7. Building area, floor area ratio, and building storeys are the most important drivers of carbon emissions for residential land, similar to the results of person-related tests.

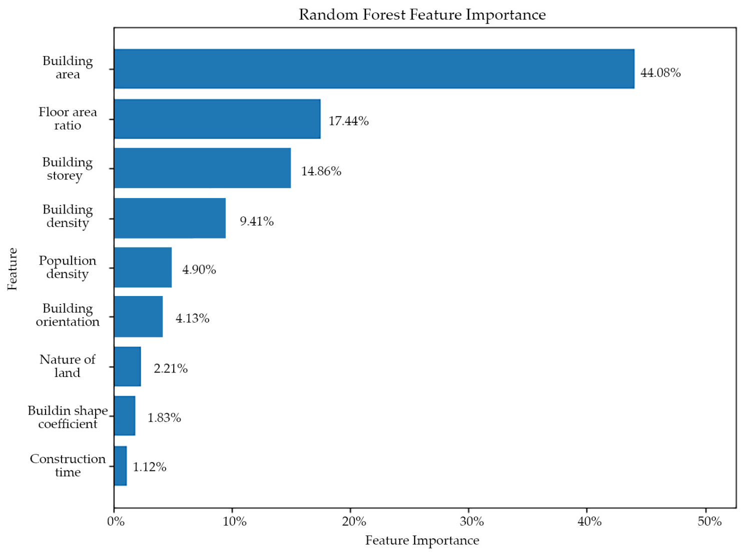


Figure 7. Importance of the spatial form characteristics in residential land.

3.3.2. Model Regression Results for Public Land

Based on the six spatial form elements with a significant correlation and the carbon emissions of residential land, a random forest model was established, and regression prediction was performed to obtain the fitting effect graphs of the test set and training set (Figure 8). The specific analysis of the results in the above Figure 8 shows that the consistency between the training and prediction sets was high, which indicates that the prediction performance of this model was good and could be used for the efficient and accurate prediction analysis of carbon emissions of such projects. The stochastic model performance of the test and training sets are listed in Table 9. The error cases of the prediction values of both MSE and MAE were small, and the coefficient of determination R^2 was close to 1. Therefore, it can better explain the carbon emissions of public land after considering a series of spatial form elements.

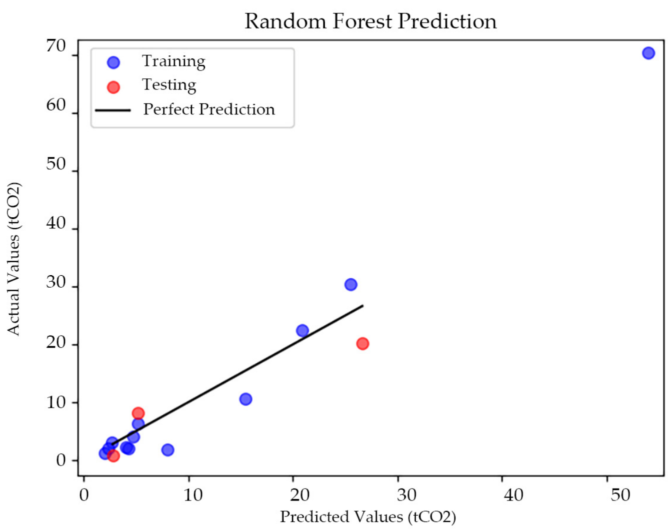


Figure 8. The effect of fitting the full dataset of carbon emission and spatial form of public land.

Table 9. Public land use model evaluation results.

	R2 Score	Mean Squared Error	Mean Absolute Error
Training	0.9181	0.3093	0.3453
Testing	0.7248	0.1775	0.3787

The results of the correlation coefficient used to rank the characteristics of influencing factors are shown in Figure 9. The indicators with a greater influence on carbon emission from public land mainly include the building area, building shape coefficient, and floor area ratio, which are the same as the results of the Pearson correlation test.

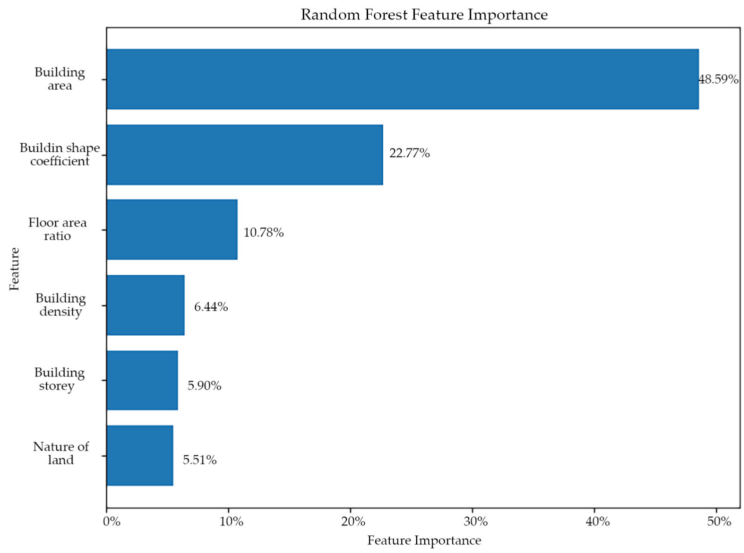


Figure 9. Importance of the spatial form characteristics in public land.

4. Discussion

4.1. Analysis of Research Findings

From the above correlation, impact analysis, and random forest regression results, we can draw several meaningful conclusions about the relationship between spatial form and carbon emissions from town construction land.

The spatial form elements of the building area and building storeys are closely related to carbon emissions from residential land. The spatial form elements of the building area, building shape coefficient, and floor area ratio are closely related to carbon emissions from public land.

The spatial morphological elements that are significantly correlated with carbon emissions from the town construction land were also analyzed.

- Regarding the nature of the land, no energy consumption, such as gas or biomass (firewood), is involved. Urban residential land produces lower carbon emissions than rural residential land, and public land, commercial service land, administrative office land, municipal utilities land, and medical land have higher carbon emissions. In comparison, educational land and cultural land have lower carbon emissions [57].
- When the floor area ratio is more significant than 1.01, the carbon emissions of residential land are correspondingly lower; when the floor area ratio is(0, 0.38) and (1.18, 1.6), the carbon emissions of public land are lower. The analysis shows that the impact of the floor area ratio on carbon emissions is mainly due to building height. A higher floor area ratio allows for a higher building height and a wider surface area, which makes it easier to obtain more light [58], thus reducing energy consumption for lighting and heating.

- In line with other academic studies, we found that the higher the building density, the lower the carbon emissions [59]. When the building density is more significant than 0.40, the carbon emissions of residential land are correspondingly lower; at a building density (0, 0.14) and (0.29, 0.35), the carbon emissions of public land are lower. The analysis shows that building density affects the wind–heat cycle within a specific geographical area. Firstly, a high building density will make it difficult to dissipate heat inside urban settlements, thus aggravating the local heat island effect and increasing the cooling energy demand in summer; secondly, a lower building density is conducive to the formation of more ventilation corridors between buildings, thus facilitating natural indoor ventilation and reducing ventilation and cooling energy consumption.
- An increase in population density can be effective in reducing carbon emissions. This study argues that when population density increases, it creates a spatial sharing of resources and increases the efficiency of energy use, thus reducing carbon emissions [60].
- A reduction in building shape coefficient can reduce carbon emissions from the town construction land. Analysis shows that the smaller the building bulk factor, the higher the thermal storage capacity of the house and the lower the carbon emissions caused by energy consumption. A more exposed surface area, i.e., a more significant building bulk factor, will likely result in higher residential energy use [61].
- When the number of building storey is greater than 10, the carbon emissions from residential land decrease accordingly, while a decrease in the number of building storeys reduces the carbon emissions from public land. This study concludes that as the average number of building storeys in a residential area increases, the neighborhood's building shape coefficient decreases, which reduces the heat dissipated by the building envelope [62].
- When the orientation of the building is more significant than 0.2645, the carbon emissions of the residential land are reduced accordingly. The analysis shows that the south façade receives the most solar radiation, and the energy consumption of the south-facing households is lower than that of the other households. Therefore, the carbon emissions decrease with the increase in the building orientation when the building orientation reaches a specific value [63]. However, the increasing trend of carbon emissions in this study, which increases and then decreases with the orientation of the building, differs from that of other scholars.
- Similar to other scholarly studies, we found that building area has a strong correlation with energy consumption [64]. A reduction in building area can significantly reduce carbon emissions from town construction land; a high building area also means a high cooling or heating demand, and a high building area also has an impact on the light, heat radiation, and airflow of the site; for example, a high building area increases the building surface area of the site to absorb solar radiation, which, in turn, affects the cooling or heating energy consumption of the site by influencing the regional microclimate [65].
- When the age of the building was completed after 2010, the carbon emissions from residential land were significantly reduced. This study concluded that the building envelope, building materials, HVAC system, and the form of the building are important influencing factors for building energy consumption and further affect the carbon emissions of town construction land [66]. Older dwellings were largely unconsidered for building energy efficiency due to the conditions at the time, with more significant heat transfer coefficients in walls and windows and a higher overall building energy consumption.

4.2. Subsection

The towns targeted in this study are located in Bengbu City, which constrains the generalizability of some of the findings and conclusions of the analysis. In future studies, it will be necessary to study more cases from different regions to draw more generalized conclusions and recommendations.

Secondly, when classifying and screening town construction land, this study only focused on residential and public town construction land. Considering the small sample size of the current industrial and mining land in Macheng town, this makes it difficult to draw valid conclusions.

5. Conclusions and Suggestions

5.1. Conclusions

In response to global climate change, increasing attention has been paid to the impact of spatial form on carbon emissions. However, an accurate and systematic quantification of the impact of spatial form elements on carbon emissions from town construction land still needs to be explored. Therefore, this study used building energy consumption to characterize and account for the carbon emissions from town construction land and used 3D theory to screen and quantify spatial form indicators and investigate the relationship between spatial form and carbon emissions. The following conclusions can be drawn from the analysis results:

(1) Through correlation analysis, nine indicators significantly related to carbon emissions from residential land, and six indicators significantly related to carbon emissions from public land, were screened out. Building area and building storey were closely related to carbon emissions from residential land, and building area, building shape coefficients and floor area ratio were closely related to carbon emissions from public land;

(2) At the residential site level, carbon emissions are effectively reduced when the plot ratio is more significant than 1.01, the building density is more significant than 0.4, the number of storeys is higher than 10, and the orientation of the building is more significant than 0.15, increasing the population density and reducing the building shape coefficient;

(3) At the public land level, carbon emissions can be effectively reduced by increasing the floor area ratio and building density, reducing the building shape coefficient, building storeys and building area, and prioritizing educational and cultural buildings.

5.2. Optimization Suggestions

Based on the above analysis, this study proposes the following suggestions for optimizing the spatial form to reduce the carbon emissions from urban construction land.

Firstly, moderate–high-intensity development should be carried out while ensuring residential comfort. An increase in plot ratio means an increase in building height, which helps to improve the microclimate and reduce carbon emissions. If the floor area ratio is determined, a reduction in the level of carbon emissions in residential areas can also be achieved by designing compact house types and increasing the population capacity. The planning process is about more than just increasing the intensity of development. However, it should be tailored to the site's needs while ensuring quality of life and avoiding large vacancies due to unreasonable allocation.

Secondly, the building shape coefficient should be controlled, and the building storeys should be appropriately increased. The number of storeys used for residential sites should be increased to 10 or more, considering other factors such as development intensity. Based on this increase in building storeys, the building shape should be adjusted to reduce the convexity of the façade, reduce the building shape coefficient and enhance the energy-saving effects.

Thirdly, the reasonable allocation of various types of construction land should be ensured. It is recommended that the proportion and layout of each type of construction land should be reasonably determined in conjunction with the functional positioning of the town's development, especially the proportion and layout of high-carbon-emission commercial service land, administrative office land, and other town construction land, to reduce the carbon emissions of the planning scheme.

Fourthly, as most of China's towns are located north of the Tropic of Cancer, the solar altitude angle is smaller in winter and larger in summer; setting the buildings to mainly face the south will allow for more oblique solar rays to enter the building in winter, thus increasing the indoor temperature, while avoiding too much sunlight being radiated in summer. This will reduce the indoor temperature and overall carbon emissions.

In conclusion, during town planning and construction, the comprehensive impact of all spatial form elements should be fully considered to reduce carbon dioxide emissions and promote the sustainable development of towns.

Author Contributions: Conceptualization, Y.X., L.S. and X.G.; data curation, Y.X. and B.W.; formal analysis, L.S. and S.D.; funding acquisition, L.S.; investigation, S.D. and S.C.; methodology, Y.X., B.W. and S.C.; project administration, L.S.; resources, L.S.; software, Y.X., B.W., X.G. and S.D.; supervision, L.S., X.G. and S.D.; visualization, Y.X. and B.W.; writing—original draft, Y.X.; writing—review and editing, Y.X. and B.W. All authors have read and agreed to the published version of the manuscript.

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

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