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The Relationship between Rural Spatial Form and Carbon Emission—A Case Study of Suburban Integrated Villages in Hunan Province, China

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Abstract: With the implementation of China's rural revitalization strategy, the societies and economies of villages have been comprehensively developed, but the carbon emissions in rural areas have also been increasing year by year. Therefore, low-carbon control of the rural spatial form has become an important element of rural revitalization. This paper takes 18 suburban integrated villages in the plain terrain within Hunan Province, China, as the research object, quantifies the spatial morphology indicators of the overall rural community and the neighborhood building groups, and investigates the relationship between rural spatial form and carbon emissions in plain terrain, aiming to clarify the content of low-carbon control in rural spatial planning. The main conclusions are as follows. (1) The correlation between spatial form and carbon emissions at different levels of suburban integrated villages is "total volume form > neighborhood building groups combination form > overall layout form > neighborhood connection form". When the scale of the villages is fixed, the spatial layout of the neighborhood building groups has a more direct influence on the carbon emissions of the residents. (2) The building density in the overall spatial form of the village has the greatest influence on the carbon emissions of the suburban integrated villages, and it is positively correlated. (3) There is a negative correlation between the form of neighborhood building groups and carbon emissions within a certain range. When the distance between the front and back of a building is 8–12 m, the carbon emissions of the building decrease with the increase in the degree of aggregation on the building, but when the distance between the front and back of a building reaches 12 m or more, the influence of the group layout form on the carbon emissions of the building is weakened. (4) Finally, based on the principle of "macro-control quantity and meso-control shape", this paper proposes new control content and indicators for Hunan's rural territorial space planning, which can provide a reference for low-carbon control in rural space form planning with suburban integration.

Keywords: rural spatial form; carbon emissions; suburban integrated villages

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1. Introduction

China has proposed the goal of "striving to reach the peak of carbon dioxide emissions before 2030 and striving to achieve carbon neutrality before 2060", which reflects its responsibility as a major country to actively address the global climate issue and also shows its determination to promote the construction of an ecological civilization and achieve high-quality development [1]. In 2019, China's Ministry of Agriculture and Rural Development (MOAR) released the "Highlights of Green Development in Agriculture and Rural Areas" to promote green development in rural areas. The report of the Conference of the Twenty emphasized the need to optimize the standard system for green and low-carbon development and to shift to a "dual control" system for total carbon emissions and intensity. In the new development stage of urban–rural integration, the spatial production phenomenon is more typical among the four types of villages in the rapidly developing suburban integration areas near the cities, which rely on the spillover industrial functions of the cities [2]. The transformation of rural industries promotes and activates the production of a material space, in which the unreasonable spatial layout not only causes inefficient land use but also indirectly increases the spatial carbon emissions of land use [3]. Therefore, it is important to focus on the carbon emissions associated with changes in the spatial form of rural areas and to explore low-carbon spatial form patterns in suburban integrated villages, both academically and in terms of rural development policy formulation. In this context, the goal of "carbon attainment and carbon neutrality" (hereafter referred to as "double carbon") has placed new demands on the spatial form of China's rural–urban integration. The relationship between spatial form and carbon emissions has become an important issue both in the world and in China in the new era. In recent years, studies on the relationship between spatial form and carbon emissions have mainly focused on spatial expansion (sprawl), spatial structure (concentration), and spatial patterns (compactness, fragmentation, irregularity). As early as 2012, the impact of urban sprawl on transportation energy consumption was investigated using some urban areas in the US as case studies, and a significant relationship was found between urban sprawl and transportation energy consumption and the carbon footprint [4]. In terms of spatial structure, Meen C. J et al. [5] studied 130 large cities in the US using urban night time data and found that the more urban centers there are, the higher the carbon emissions (composition dimension), and the wider the spatial distribution of urban centers, the lower the carbon emissions (configuration dimension). Research on spatial patterns suggests that compact, sprawling, mixed-use cities are more conducive to the reduction of carbon emissions. R. Van der Borgh et al. [6] studied the relationship between urban sprawl and carbon emissions in 635 cities in seven Latin American countries and found that compact sprawl patterns were associated with smaller increases in urban carbon emissions. Maged Zagow's study of US cities showed that a mixed-use density is negatively correlated with carbon dioxide emissions, and low-density metropolitan areas have lower carbon dioxide emissions [7]. Kai Zhu [8], Wei Sha [9], and others also showed that multi-center and more compact urban development is conducive to CO_2 emission efficiency, but there is no significant relationship between the number of urban centers and CO_2 emission efficiency. Many studies have discussed the impact of urban spatial planning on the carbon emission intensity of energy consumption, especially the urban functional form, which is an important consideration for urban planning. For example, the latest study, based on data from 178 Chinese cities, show that the functional compactness index (FCI) reduces carbon emissions most effectively in plain and single-center cities [10]. Planning and form control are more important in hilly and mountainous cities, multi-center cities, and highly industrialized cities. The studies by S. Zuo [11] and others showed that in urban planning, the fragmentation of industrial land will reduce the carbon emissions of the space, while the fragmentation of residential land will increase the carbon emissions of the space. However, while some empirical studies have shown that more compact cities tend to be associated with lower carbon emissions [12], others have found that the effect of urban compactness on carbon emissions is relatively modest [13]. Compact development and the planning of urban transport systems are believed to be the sources of the declining per capita carbon dioxide emissions [14]. At the same time, it has also been shown that there is a certain threshold range for the effect of urban form compactness (UFC) on carbon emissions, i.e., for small and medium-sized cities, compactness is more effective in reducing carbon emissions [15].

The studies that have been carried out on the relationship between spatial form and carbon emissions have mainly been focused on urban areas. According to previous studies, up to 50% of the carbon emissions in cities can be attributed to the choice of urban spatial form. For example, changes in urban spatial form can affect the energy demands of urban buildings by up to 2.5 times and the performance of urban energy systems by up to two times [16]. Urban growth, complexity, and compactness are the most commonly used indicators of urban spatial form. Based on temporal data from 15 cities in Iran, Falahatkar et al. empirically found that urban growth was positively associated with complexity and carbon emissions. On the contrary, urban compactness was negatively correlated with carbon emissions and the correlation was stronger [17]. Makido et al. [18] used the landscape pattern index to measure urban compactness and complexity in 15 cities in Japan and showed that compact cities with less fragmentation had lower CO_2 emissions than disordered cities. A sensible urban form is conducive to reducing energy consumption from human activities. Urban form can also affect carbon emissions by influencing regional meteorological factors, such as the urban heat island effect, which directly or indirectly affects energy consumption [19]. Qin Bo et al. [20–23] examined the impact of the urban residential community form on carbon emissions in terms of community density, accessibility, and compactness; many scholars agree that good accessibility [24], a degree of mixing [25], and intensive land use [26,27] have positive effects in terms of reducing carbon emissions. However, some studies have also shown that the socio-economic level, the distance between work and home, and the level of public transport have a stronger influence on carbon emissions than the neighborhood spatial form [28].

Academics have paid less attention to the relationship between space and carbon emissions in rural areas, and the only studies that have been conducted have focused mainly on urban–rural areas. For example, Stefano P et al. [29] studied the role of spatial planning between urban and rural areas in the metabolism of urban carbon emissions, and they proposed an optimization framework for the planning of low-carbon urban–rural ecosystems that integrates transport and land use planning and addresses urban metabolism, including urban mobility, food transport, and the energy supply. Zhu X. Q. et al. [30] analyzed the spatial pattern and driving factors of carbon emissions in mixed-use communities on the urban–rural fringe, and they showed that the carbon emissions of mixed-use communities were characterized by features such as planning structure decisiveness, road directionality, infrastructure directionality, and industrial linkages. There have also been some studies focusing on the impact of spatial patterns at the rural building scale on building carbon emissions, suggesting that spontaneous spatial modifications of buildings by villagers are conducive to reducing rural building carbon emissions [31,32]. For the rural areas in China, Wang Zhu et al. focused on low-carbon spatial planning and low-carbon construction in rural areas in the developed Zhejiang Province [33–35]; Shi Bin [36] explored the low-carbon construction systems of rural communities with different industrial types, taking the suburban integrated villages in Zhejiang Province as an example. From the perspective of research content, the existing spatial low-carbon studies in rural areas are mostly based on the scale and structure of land use, but it is difficult to implement the guidance in the spatial layout of land use, and the research on the optimization of the spatial pattern of national land under the goal of carbon reduction needs to be further deepened and strengthened. In terms of the research scope, there are more studies on low carbon in rural areas in China's developed eastern regions and less developed western regions, while there is a lack of studies on low carbon in rural areas in China's central regions. At the same time, the spatial levels examined in the studies on the relationship between rural space and carbon emissions have been dominated by correlation analysis between spatial patterns and carbon emissions at a single scale, and there is a lack of comparative analyses of the effects of spatial forms at different scales on carbon emissions.

In view of the above research deficiencies, this paper takes the suburban integrated villages of Hunan as the research object and adopts field research and principal component analysis methods to investigate the relationship between rural spatial form and carbon emissions in 18 suburban integrated villages in Hunan in the plain terrain. The results identify the main influencing elements of rural carbon emissions and clarify the content of low-carbon control in rural spatial planning, which can help to propose low-carbon construction strategies in the process of the spatial optimization of the suburban integrated countryside and provide a reference for rural low-carbon construction.

2. Relevant Theoretical Background

2.1. Hierarchy of Spatial Form and Indicators

L. Y. Wu [37] believed that the rural spatial form of the countryside in a broad sense can be understood as the distribution state and morphological characteristics of the countryside. This study takes the rural spatial form as the research object and conducts the research at two spatial levels: the overall rural community and the neighborhood building groups. The spatial form indicators are based on the statutory indicators of national spatial planning and the spatial indicators of the urban design guidelines, such as the layout of settlements and roads [38,39]. The spatial form indicators of the overall rural community include the scale, density, complexity, and form index; the spatial form of the neighborhood building groups mainly focuses on the state of building clustering and scattering, as well as the road morphology, including the degree of aggregation and connectivity. The spatial form hierarchy and index data collection methods are shown in Table 1 below.

Table 1. The spatial form indicators and data collection methods.

Scale	Morphology	Tier 1 Indicators	Secondary Indicators	Data Collection Method
The overall rural community scale	Volume form	Size indicators	X_1 Total land area (ha)	Land use data
			X_2 Construction land area (ha)	Land use data
		Compactness of land use	X_3 Building density	Calculation
	Layout form	Shape complexity	X_4 Perimeter area fractional dimension index (PAFRAC)	Fragstats
		Layout pattern	X_5 Overall landscape shape index (OLSI)	Fragstats
Neighborhood building groups scale	Combination form	Settlement Aggregation	X_6 Aggregation (AI)	Fragstats
		Settlement Connectivity	X_7 Connectivity index (CONNECT)	Fragstats
	Connection Form	Road shape index	X_8 Road network shape index (RLSI)	Fragstats
		Connectivity index	X_9 Road patch proximity index (CONTIG)	Fragstats
		Public space Accessibility	X_{10} Average distance to public space	Field research

X_1 is the total land area of the rural community and X_2 is the area of built-up land in the countryside, both of which can be obtained from the rural land area data. X_3 or building density is the ratio of the built-up area to the total area of the community. X_4 is the perimeter area fractional dimension index, where values between 1 and 2, or greater than 1, mean that it has deviated from a simple geometry; the higher the value, the more complex the shape. X_5 is the overall landscape shape index, which is a simple description of the degree of morphological aggregation; the larger the value, the more irregular it is. If it is equal to 1, it is closer to a square, becoming progressively larger as the patch type becomes more discrete, and the smaller the value, the more aggregated it is. X_6 is an indicator of aggregation (AI). AI is equal to 0 when settlements are most fragmented, and it is equal to 100 when they are clustered together as a whole. X_7 is the connectivity index (CONNECT); when there is no connection between patches, the connectivity is 0, and when the patch is connected to every other patch, the connectivity is 100. X_8 is the road network shape index (RNSI), which is a measure of the degree of aggregation and disaggregation of the landscape. If it is equal to 1, it is a square; the larger the value, the more irregular it is, and the smaller the value, the more regular and compact it is. X_9 is the road patch proximity index (CONTIG), reflecting the connectivity or proximity of rasters within road landscape patches, with better connectivity reflected by values closer to 1. X_{10} is the average distance to public space for each village group.

2.2. Correlation between Spatial Form and Carbon Emissions

The influence of spatial form on carbon emissions occurs mainly through the influence of the spatial form on human activity and behavior, acting indirectly on carbon emissions. The influence process of spatial form elements on carbon emissions can be summarized in the following aspects, as shown in Figure 1.

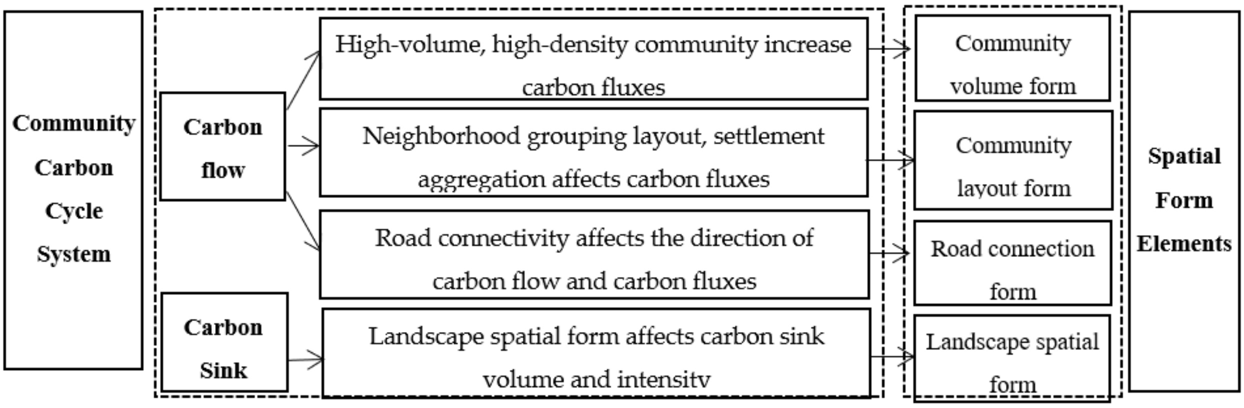


Figure 1. Correlations between spatial form elements and the carbon cycle system.

(1) The overall spacial form of rural communities, such as the total community area, building land area, building density, and other elements, affects the overall level of community carbon emissions in terms of total amount, increasing carbon fluxes [40].
(2) Secondly, the spatial morphology of neighborhood building groups, such as the aggregation and connectivity of settlements, affects the carbon fluxes of the building system [26].
(3) The spatial morphology of roads affects transport carbon input/output fluxes and carbon circulation intensity, as the distances of residences from work and public spaces significantly influences transport use and thus transport carbon fluxes [41].

In this paper, we mainly investigate the relationship between the carbon source component and the spatial form of rural communities, and the carbon sink part of the calculation is not considered.

3. Research Methods

The study includes 18 case villages with a total of 200 households in different locations in the north, west, and south of Hunan Province, mainly consisting of two types of buildings: brick buildings and wooden buildings. The main purpose of this study is to verify the correlation between carbon emissions and spatial form. The research methodology includes three parts: the measurement of carbon emissions, the quantification of spatial form indicators, and a correlation analysis between spatial patterns and carbon emissions.

3.1. Measuring Carbon Emissions of the Rural Community

Most scholars have used the IPCC carbon emission calculation method to measure carbon emissions [42]. Carbon emissions are determined by the product of the energy consumption and the carbon emission factor of the corresponding energy source, and the carbon emission calculation formula is as follows:

$$C = \sum_{i=1}^{i} \sum_{j=1}^{j} (E_{ij} \times \sigma_j \times \theta_j) \quad (1)$$

C denotes the carbon emissions in the study area, and the subscript i denotes different types of space in end-use energy consumption, such as residential space, production space, and ecological space. The subscript j denotes different energy categories; σ_j and θ_j denote the standard coal conversion factor of fossil energy and the carbon emission factor of different energy sources, respectively. The carbon emission factors mainly refer to the IPCC and existing domestic and international literature [42,43], among which the carbon emission factors of cellular coal and wood fuel refer to the Guidelines for the Preparation of Provincial Greenhouse Gas Inventory (2011), and the carbon dioxide emission factor of the power grid refers to the average carbon dioxide emission factor of 0.4987 kg/KWh of the Hunan power grid in the latest Provincial Greenhouse Gas Inventory of 2016, as shown in Table 2 below.

Table 2. Standard coal conversion factors and carbon emission factors for production energy sources.

Energy Category	Standard Coal Conversion Factor (kg Standard Coal/kg)	Carbon Emission Factor (kg/kg Standard Coal)	Energy Category	Standard Coal Conversion Factor (kg Standard Coal/kg)	Carbon Emission Factor (kg/kg Standard Coal)
Gasoline	1.4714	0.5538	Natural Gas	1.3300	0.4483
Liquefied Petroleum Gas	1.7143	0.0030	Power	0.1229 kg standard coal/kWh	0.4987 kg/KWh
Honeycomb Coal	0.6302 kgC/kg		Firewood		2.7 g/kg

Note: It is assumed that all honeycomb coal used in rural areas is Class A smokeless honeycomb coal and that a single bottle of LPG weighs 14.5 kg.

Firstly, it should be noted that the rural carbon emissions in this study mainly come from two components: building carbon emissions and transport carbon emissions. Through the preliminary research on the 18 case study villages in Hunan, it is found that the main building types in Hunan are brick buildings and wooden buildings.

The carbon emissions from buildings are calculated by measuring the energy consumption during the building construction phase and the building operation phase for typical building types in the countryside. The calculation of carbon emissions in the building construction phase is obtained form the results of the consumption of building materials during the construction phase and the corresponding energy carbon emission coefficients of the building materials, where the consumption of building materials needed for the construction of the building is obtained through interviews with local construction workers; the calculation of carbon emissions in the building use phase is obtained from the results of the consumption of energy and the corresponding energy carbon emission coefficients of the energy used during the use of the building, where the energy used during the use phase of the building is obtained through interviews with the users of the building.

Transportation carbon emissions are estimated based on the miles traveled by villagers and the energy consumed per mile. The formula for the calculation of the average household carbon emissions from transport is as follows:

$$C_T = \frac{M_T}{F} \times E \tag{2}$$

C_T denotes the carbon emissions from transport, M_T denotes the annual mileage traveled by villagers, F denotes the fuel consumption per km, and E denotes the automobile carbon emission coefficient. Villagers' mileage data are obtained by interviewing villagers about their daily destinations and frequency of travel.

Thus, this paper measures rural carbon emissions in a logical "bottom-up" relationship, as shown in Figure 2, which includes carbon emissions from buildings and transport.

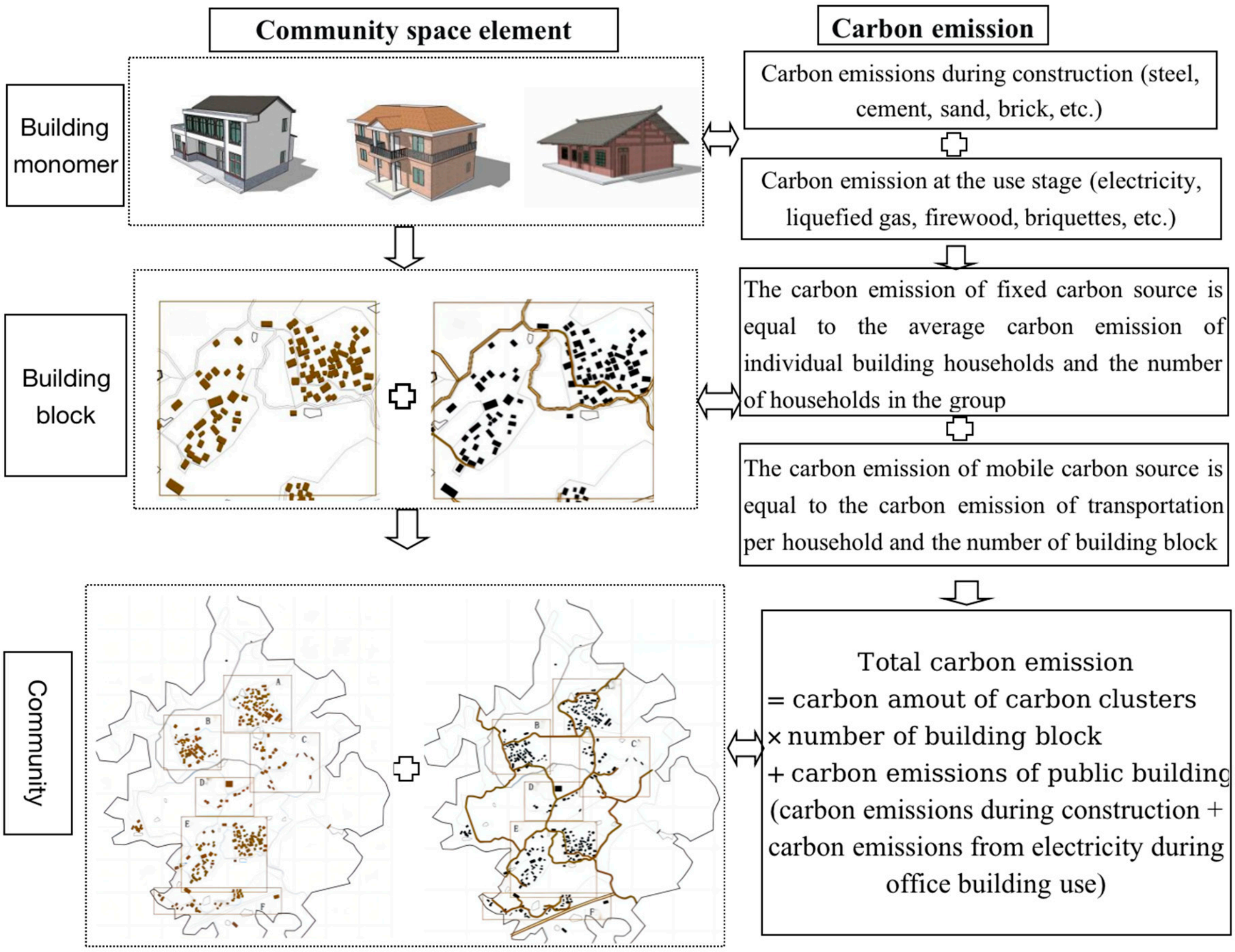


Figure 2. Carbon emission calculation model for rural communities.

The formula for the calculation of the total carbon emissions of the rural community is as follows:

$$C_{community} = N \times \left(C_{construction\ phase} \times S_{average\ household} + C_{use\ stage} + C_{traffic}\right) \quad (3)$$

where N is the number of households, $C_{construction\ phase}$ is the carbon intensity of the building in the construction phase, $S_{average\ household}$ is the average floor area of a household, $C_{use\ stage}$ is the average carbon emission intensity of the household in the building use phase, and $C_{traffic}$ is the annual transport carbon emissions per household.

3.2. Quantification of Spatial Form Indicators

Hunan Province is located in the central part of China, which includes a variety of natural terrain conditions, such as plains, hills, and mountains. However, since most of the suburban integrated villages are close to cities and the settlement locations are relatively flat, this study only focuses on the relationship between the spatial forms of rural communities and carbon emissions in the plain terrain. Through the investigation of suburban integrated villages in different areas of Hunan, we find that the villages in Northern Hunan have the form of large, scattered, and small clusters; Western Hunan has a linear layout, and Southern Hunan has a centripetal layout of traditional villages, as shown in Figure 3. The spatial forms of neighborhood building groups mainly include row, staggered, diagonal, and free styles.

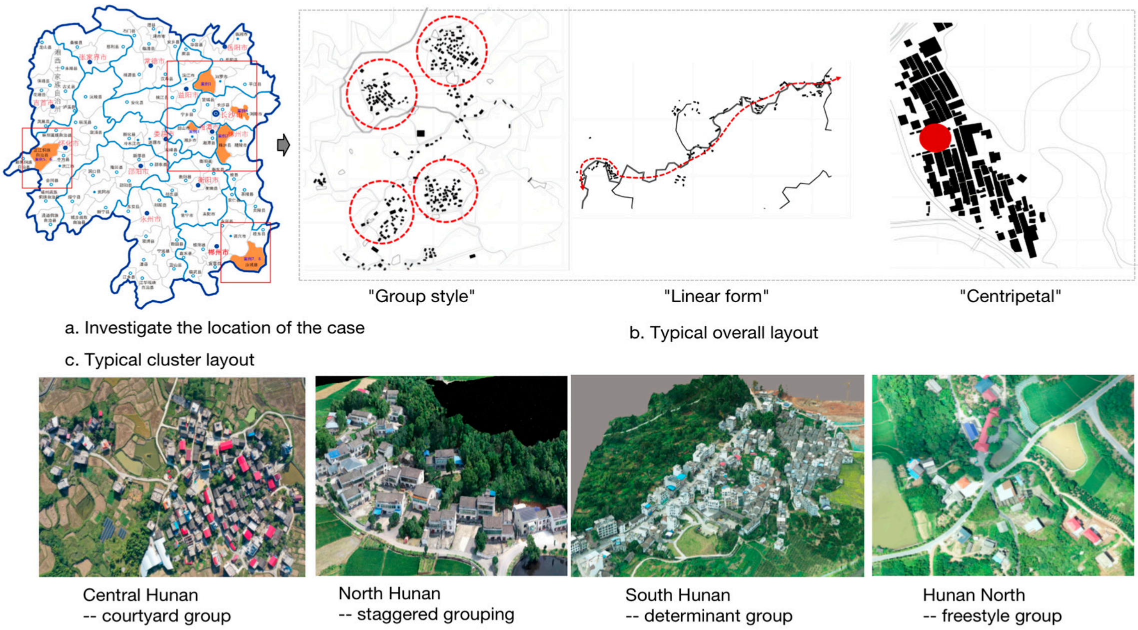


Figure 3. General spatial form of the villages of Hunan.

Image sources: Figure 3a,b are the author's own drawings; Figure 3c is the photographic material of the subject group.

As can be seen in Table 1, X_1, X_2, X_3, and X_{10} are obtained through basic research in the case villages, while the other indicators X_4–X_9 are obtained through the Fragstats software 4.2, which is operated as follows (Figure 4).

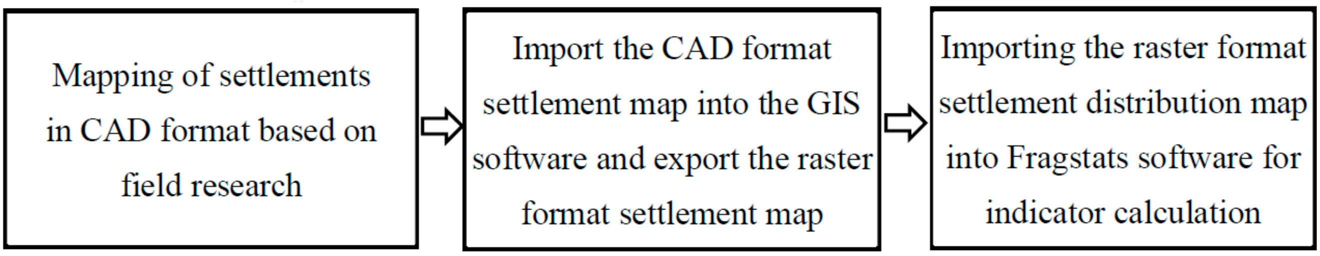


Figure 4. Methodological pathways for quantification of spatial form indicators.

3.3. Correlation Analysis

(1) Partial Correlation Analysis

Ten spatial form indicators are used as independent variables, and the average household carbon emission intensity Y_1, total carbon emissions Y_2, community building land carbon intensity Y_3, and per capita carbon emission intensity Y_4 are used as dependent variables. The SPSS 22.0 statistical software is used to conduct partial correlation analysis. X_2, X_9 and Y_1, Y_2, Y_3 among the indicators have small correlation coefficients and can be eliminated; the remaining eight indicators are selected and retained as driving factors to be applied in the regression simulation.

(2) Measuring the Contributions of Driving Factors

In order to eliminate the dimensional relationship between the driving factors, the dependent and explanatory variables in the previous step are taken as logarithms and then standardized, and then the driving factors are subjected to principal component analysis.

The results of the driving factors obtained are shown in Tables 3–5 below. It can be seen that the three composite variables with the strongest explanatory power for the original variables can be extracted through principal component analysis, which are expressed by

F_1, F_2, and F_3. The composite variables can explain 76% of the original variables, and the *t*-test Sig value is 0.000, indicating a very good fit. The relationship between the composite variables F_1, F_2, and F_3 and the original variables can be obtained from the component score matrix in Table 5 as follows.

$$F_1 = 0.137LNX_1 + 0.079LNX_3 - 0.027LNX_4 + 0.376LNX_5 + 0.294LNX_6 + 0.179LNX_7 + 0.206LNX_8 + 0.075LNX_{10} \quad (4)$$

$$F_2 = 0.259LNX_1 - 0.204LNX_3 + 0.27LNX_4 + 0.08LNX_5 + 0.087LNX_6 - 0.35LNX_7 + 0.318LNX_8 - 0.069LNX_{10} \quad (5)$$

$$F_3 = 0.359LNX_1 - 0.383LNX_3 - 0.129LNX_4 - 0.016LNX_5 - 0.32LNX_6 + 0.155LNX_7 - 0.07LNX_8 + 0.438LNX_{10} \quad (6)$$

Table 3. KMO and Bartlett's test.

The Kaiser–Meyer–Olkin Metric of Sampling Adequacy		0.465
Bartlett's sphericity test	Approximate cardinality	76.009
	df	28
	Sig.	0.000

Table 4. Total variance explained.

Ingredients	Initial Eigenvalue			Extraction of Squares and Loading		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.462	30.778	30.778	2.462	30.778	30.778
2	2.361	29.507	60.285	2.361	29.507	60.285
3	1.623	20.285	80.57	1.623	20.285	80.57
4	0.81	10.121	90.692			
5	0.405	5.068	95.76			
6	0.165	2.068	97.827			
7	0.11	1.379	99.206			
8	0.063	0.794	100			

Extraction method: principal component analysis.

Table 5. Component score coefficient matrix.

	Component		
	1	2	3
Z-score $(LNX)_1$	0.137	0.259	0.359
Z-score $(LNX)_3$	0.079	−0.204	−0.383
Z-score $(LNX)_4$	−0.27	0.27	−0.129
Z-score $(LNX)_5$	0.376	0.08	−0.016
Z-score $(LNX)_6$	0.294	0.087	−0.32
Z-score $(LNX)_7$	0.179	−0.35	0.155
Z-score $(LNX)_8$	0.206	0.318	−0.07
Z-score $(LN)_{10}$	0.075	−0.069	0.438

Extraction method: principal component analysis.

(3) Regression Fitting

With carbon emissions as the explanatory variable, the principal components from the previous step as the explanatory variables, and LNX_1–LNX_{10} as the instrumental variables, the least squares multiple regression analysis is performed using SPSS 22.0. If Sig. (*p* value) is less than 0.01, it means that the model is well fitted and the regression equation is statistically significant.

4. Results—The Case of Hunan's Suburban Integrated Villages

4.1. Indicators of Spatial Form in the Case Villages

Obtained through the research and analysis of the case villages' planning data, typical case villages are shown in Table 6 below, and the panel data of 10 indicators for the 18 case villages are shown in Table 7 below.

Table 6. Spatial forms of the neighborhood building groups in the villages of Hunan (500 m × 500 m).

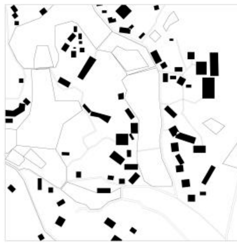
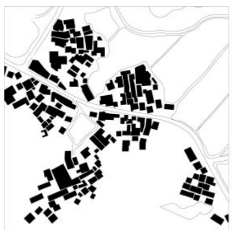
	Liaoyuan Village	**Jinhua Village**	**Wangxing Village**	**Traffic Village**
Northern Hunan Region				
	Zhushan Village	Penglang Village	Songshan Village	Hegun Village
Xiangxi Region				
	Shimen Village	Gwangyang Village	Yongfu Village	Shidu Village
Central Hunan Region				
	Hantian Village	Shazhou Village	Xiushui Village	Wazao Village
Southern Hunan Region				

Table 7. Spatial morphological index parameters of the case villages.

	Total Land Area	Construction Land Area	Building Density	PAFRAC	OLSI	AI	CONNECT	RLSI	CONTIG	Average Distance
Liaoyuan Village	811.40	45.81	0.06	1.65	20.61	99.32	2.42	67.00	0.45	308.10
Jiao Long Village	748.05	188.36	0.20	1.30	19.04	89.21	65.22	20.71	0.60	398.69
Shaoshan Village	16.83	2.70	0.16	1.26	15.42	84.29	100.00	11.49	0.66	314.72
Tianhan Village	1185.95	150.50	0.17	1.12	17.47	80.68	98.59	35.08	0.20	417.41
Qingting Village	350.00	36.36	0.10	1.25	22.77	89.04	93.49	24.45	0.50	428.51
Lutang Village	860.14	193.46	0.22	1.63	20.26	99.16	1.23	61.37	0.40	345.52
Ma Ying Tong	400.00	19.00	0.05	1.72	18.90	80.95	0.00	28.05	0.53	271.19
Zhushan Village	476.76	18.62	0.04	1.12	16.44	81.21	100.00	18.85	0.46	671.79
Penglang Village	1376.88	22.53	0.02	1.12	20.67	78.00	99.47	15.76	0.57	365.49
Little Fishing Creek	2100.00	9.00	0.00	1.72	15.14	80.64	0.00	24.13	0.53	239.13
Shuangqiao Village	1610.43	46.39	0.02	1.27	25.85	78.45	0.78	47.65	0.48	390.12
Xiuzhou Village	551.68	17.00	0.03	1.57	7.13	9.26	20.39	8.98	0.22	467.52
Shituo Village	244.57	23.42	0.10	1.09	18.75	83.20	99.63	19.13	0.66	380.85
Wushan Village	1036.55	39.80	0.04	1.09	22.87	84.50	100.00	22.06	0.60	341.71
Wazao Village	324.95	54.82	0.17	1.09	19.45	86.27	98.05	21.25	0.65	248.27
Ishizen Village	1384.53	69.17	0.05	1.09	30.33	85.18	96.94	28.11	0.54	309.60
Shazhou Village	92.62	10.77	0.12	1.60	7.21	68.17	0.00	12.65	0.60	187.78
Hongxing Village	369.29	66.77	0.18	1.08	23.94	87.99	99.77	14.96	0.64	188.51

4.2. Identifying Carbon Emissions in the Sample Villages

4.2.1. Carbon Emissions from Buildings

(1) Construction Phase Carbon Emissions

According to the research, the residential buildings in Northern and Southern Hunan are mainly brick buildings, and the wooden structure buildings in Western Hunan are mainly wooded structures. Through the calculation of the material use in the construction phase, the carbon emissions in the construction phase of brick buildings are 157,477.14 kg, as shown in Table 8 below. The carbon emissions of wood building in the construction phase are 31,431.85 kg, as shown in Table 9 below.

Table 8. Carbon emissions in the construction phase of brick buildings.

	Material Name	Use Parts	Usage	Unit	Obsolescence Rate	Carbon Emission Factor	Carbon Emissions
Brick building	Clay bricks	Exterior wall, interior wall, footer, foundation	151	m^3	5%	323.4 $kgCO_2$ e/m^3	51,275.07
	Caliber galvanized steel pipe	Roof	0.12	t	7%	2190 $kgCO_2$ e/t	281.20
	C30 concrete	Ring beam, floor slab, mat	138.7	m^3	1.5%	295 $kgCO_2$ e/m^3	44,153.21
	Ordinary silicate cement	Masonry mortar, plastering mortar	28.06	t	5%	735 $kgCO_2$ e/t	20,173.55
	Lime	Foundation bedding	6.58	t	5%	1190 $kgCO_2$ e/t	7659.44
	Steel reinforcement	Ring beam, floor slab	4.10	t	7%	2310 $kgCO_2$ e/t	10,776.61
	Gravel	Foundation bedding	25.87	t	5%	2.18 $kgCO_2$ e/t	59.22
	Sand	Foundation, mortar	112.28	t	5%	2.51 $kgCO_2$ e/t	295.91
	Aluminum–plastic co-extruded windows	Exterior Windows	76.26	m^2	0	129 $kgCO_2$ e/m^2	9837.54
	Tile	Exterior wall surface	2.6	t	5%	1.4 tCO_2 e/t	12,201.00
	Coatings	Exterior wall surface	1.29	t	5%	1.2 tCO_2 e/t	764.40
		Total carbon emissions (kg)					157,477.14

Data sources: carbon emission factor data were obtained from the engineering design list and published journal literature [44,45]. Material use data were obtained from actual research and estimated according to the sufficient amount of material during the construction process, without considering the manual errors during construction. The brick building area was 330.76 m^2 per household.

Table 9. Calculation of material use and carbon emissions for wooded structure buildings.

Type	Material Name	Use Parts	Usage	Unit	Obsolescence Rate	Carbon Emission Factor [1]	Carbon Emissions
Wood knot structure	Wood	Wall, roof frame	100	m^3	10%	283.55 $kgCO_2$ e/m^3	31,190.50
	Column cornerstone (column base)	Foundation bedding	20	m^3	5%	5.08 $kgCO_2$ e/t	1.60
	Steel nails	Wood fixing	10	kg	0	2375 $kgCO_2$ e/t	23.75
	Green tiles	Roofing	3200	Block	0	0.27 $kgCO_2$ e/kg	216
Total carbon emissions (kg)							31,431.85

Data sources: wood carbon emission factor data are obtained from engineering design inventories and published journal literature [46,47]. The average values are 329.63 $kgCO_2$ e/m^3 (calculated by referring to Dr. X. C. Zhang's thesis as 178 $kgCO_2$ e/t and cedar wood density 0.54) and 374.71 $kgCO_2$ e/m^3, and the average value of 146.3 $kgCO_2$ e/m^3 is obtained from Y. X. Gao's Master's thesis, with 283.55; the carbon emission factor of green tile is 610 $kgCO_2$ e/unit with reference to Dr. X. C. Zhang's thesis; the carbon emission factor of green tile refers to foreign literature [48]. The usage data are obtained from interviews with local carpenters in the actual research, and the construction area is 105 m^2 per household.

(2) Carbon Emissions in the Use Phase

The main types of energy used in the 18 typical rural buildings are electricity, firewood, LPG, and charcoal, and the carbon emission contribution of each energy source to the annual energy carbon emissions is shown in Figure 5 below, with electricity being the main energy type.

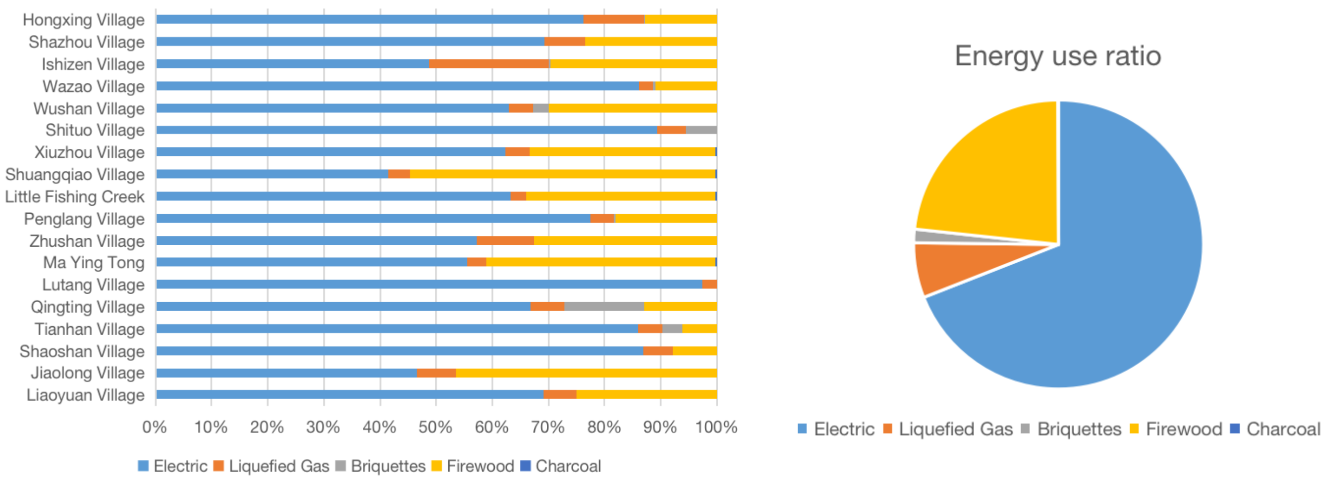


Figure 5. Share of carbon emissions from buildings.

After the comprehensive calculation of the construction and operation phases, the carbon emission intensity of the integrated brick buildings is 489.69 kg/m^2 and the carbon emission intensity of the wooden structure buildings is determined as 324.61 kg/m^2, as shown in Table 10 below.

Table 10. Carbon emission intensity of residential buildings in rural communities with suburban integration in Hunan (unit: kg).

Building Type	Construction Phase	Operation Phase/Year	Total	Carbon Emission Intensity
Brick and mortar building	157,477.14 kg	4492.17 kg	161,969.31 kg	489.69 kg/m^2
Wooden architecture	31,431.85 kg	2652.37 kg	34,084.22 kg	324.61 kg/m^2

Data note: the building area has been taken as the average area of residential buildings, the brick building area is 330.76 m^2, and the wooden structure building area is 105 m^2.

4.2.2. Transportation Carbon Emissions

According to the research, the household survey in the case villages finds that the main travel distance for residents is the distance to the township, with elderly residents traveling approximately once a week and the workers traveling daily, so that the transport carbon emissions are correlated with the distance of the community from the township/market town. The carbon emissions from transport trips in each case village are shown in Table 11 below.

Table 11. Carbon emissions from transport of rural residents in Hunan's integrated suburban areas (unit: kg/year).

	Liaoyuan Village	Jiao Long Community	Shaoshan Village	Tianhan Village	Green Pavilion Village	Lutang Village
Distance traveled/km	2880.00	2160.00	8400.20	5564.20	389.33	1945.20
Carbon emissions	1241.74	931.31	2204.42	2423.15	839.32	838.69
	Ma Ying Tong Village	Zhushan Village	Penglang Village	Little Fishery Creek Village	Shuangqiao Village	Xiuzhou Village
Distance traveled/km	432.00	8929.17	521.43	520.80	1167.36	393.60
Carbon emissions	186.26	1924.95	112.41	224.55	503.32	169.70
	Wushan Village	Wazao Village	Ishizen Village	Shazhou Village	Hongxing Village	Shituo Village
Distance traveled/km	677.76	935.10	3615.24	743.04	4505.14	1160.22
Carbon emissions	292.22	60.48	338.73	320.37	839.03	250.12

Data description: cars are uniformly calculated at 10 L/100 km, motorcycles are uniformly calculated at 3 L/100 km, and the carbon emission factor for petrol is calculated at 2.1558 kg/L. Due to the different means of transport, motorcycles have lower transport carbon emissions, even for the same mileage.

4.2.3. Total Carbon Emissions of the Rural Community

Once the average household carbon emissions from buildings and the average household carbon emissions from transport in rural areas are determined, the product of the number of households and the average household carbon emissions can be used to obtain the total carbon emissions of the rural community. The total carbon emissions are shown in Table 12 below.

Table 12. Total carbon emissions in the case villages (in tonnes).

Calculation of Carbon Emissions					Construction Phase	Operation Phase		Total Carbon Emissions/t
			Number of Households	Building Area/m^2	Carbon Emission Intensity/kg	Energy Carbon Emission/kg	Transportation Carbon Emission/kg	
Northern Hunan Region	1	Liaoyuan Village	775	168.06	489.69	2787.06	1201.67	66,871.68
	2	Jiao Long Village	765	212.31	489.69	1650.66	711.7	80,306.24
	3	Shaoshan Village	1355	283.56	489.69	4467.58	2204.42	197,191.10
	4	Tianhan Village	736	375	489.69	7145.50	2423.15	141,097.95
	5	Qingting Village	840	280	489.69	2746.43	839.32	116,820.63
	6	Lutang Village	1040	308.09	489.69	7027.94	4819.72	164,355.68
Western Hunan Region	7	Ma Ying Tong	601	164.46	324.61	2836.51	1635.13	34,524.36
	8	Zhushan Village	302	180	324.61	7844.09	1924.95	20,596.05
	9	Penglang Village	386	200.21	324.61	6368.33	112.41	27,587.77
	10	Little Fishing Creek	700	144.36	324.61	2941.28	1754.41	35,749.09
	11	Shuangqiao Village	672	150.66	324.61	2537.42	1369.39	35,305.00
	12	Xiuzhou Village	347	170	324.61	3227.43	1916.64	20,751.52

Table 12. *Cont.*

Calculation of Carbon Emissions			Construction Phase			Operation Phase		Total Carbon Emissions/t
			Number of Households	Building Area/m^2	Carbon Emission Intensity/kg	Energy Carbon Emission/kg	Transportation Carbon Emission/kg	
Central Hunan	13	Shito Village	377	179.19	489.69	2239.94	250.12	33,408.60
Southern Hunan Region	14	Wushan Village	729	179.19	489.69	3818.60	2273.09	67,951.97
	15	Wazao Village	394	304.29	489.69	6345.81	60.48	60,490.42
	16	Ishizen Village	1098	283.33	489.69	4705.72	338.73	157,879.57
	17	Shazhou Village	142	172.19	489.69	2429.67	1487.81	12,467.17
	18	Hongxing Village	585	460	489.69	9739.01	839.03	135,940.59

Data sources: the number of households and the average floor area of households in the case villages were obtained from the village committee's field research. The carbon emission intensity of buildings was obtained from the carbon emission intensity of typical buildings.

In terms of regional differences, the rural carbon emissions in Northern and Southern Hunan are higher than those in Western Hunan, as shown in Figure 6 below. This is because, firstly, the carbon emissions from wood-framed buildings in Western Hunan are much lower than those from brick-framed buildings in Northern and Southern Hunan; secondly, transport in Western Hunan is generally based on walking or motorcycling, resulting in relatively low carbon emissions from transport.

In terms of the ratio of carbon emissions from buildings to carbon emissions from transport, as shown in Figure 7 below, it can be seen that rural carbon emissions mainly come from carbon emissions generated during the use phases of buildings, as transport generates less carbon emissions. The reasons for this are, firstly, that agriculture is the main production activity in rural areas, and workplaces are relatively close to the home, so that residents travel mainly on foot; secondly, the economic development of the rural areas is relatively backward, so that fewer families use cars as their daily means of transport.

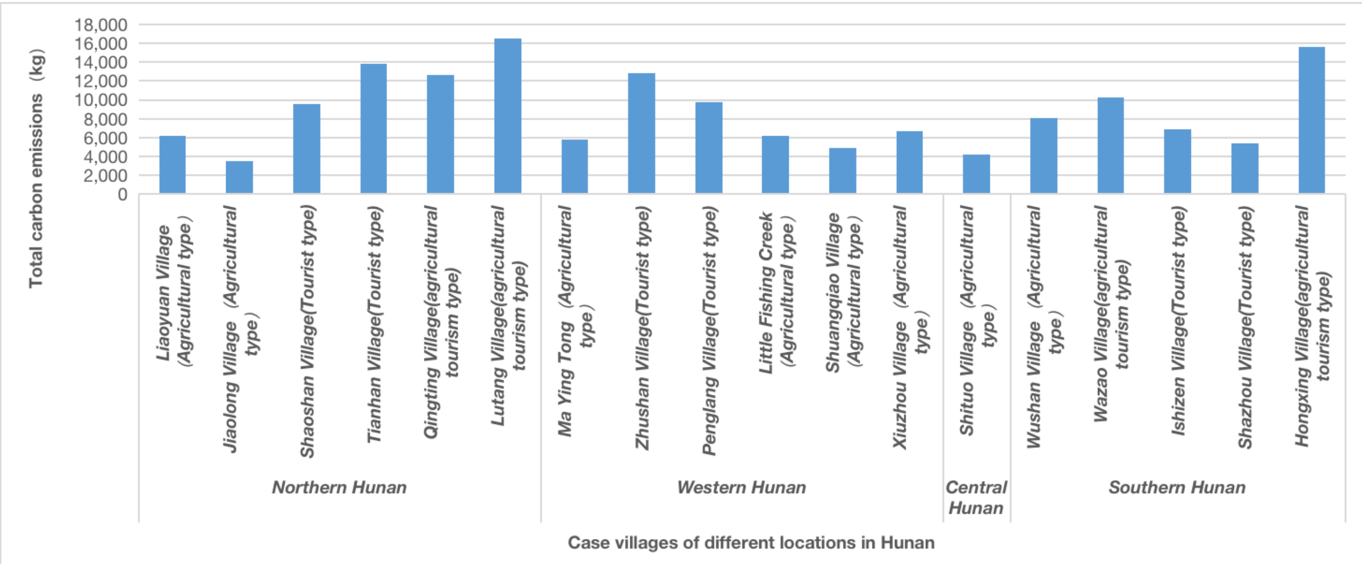


Figure 6. Comparison of rural carbon emissions in different regions of Hunan.

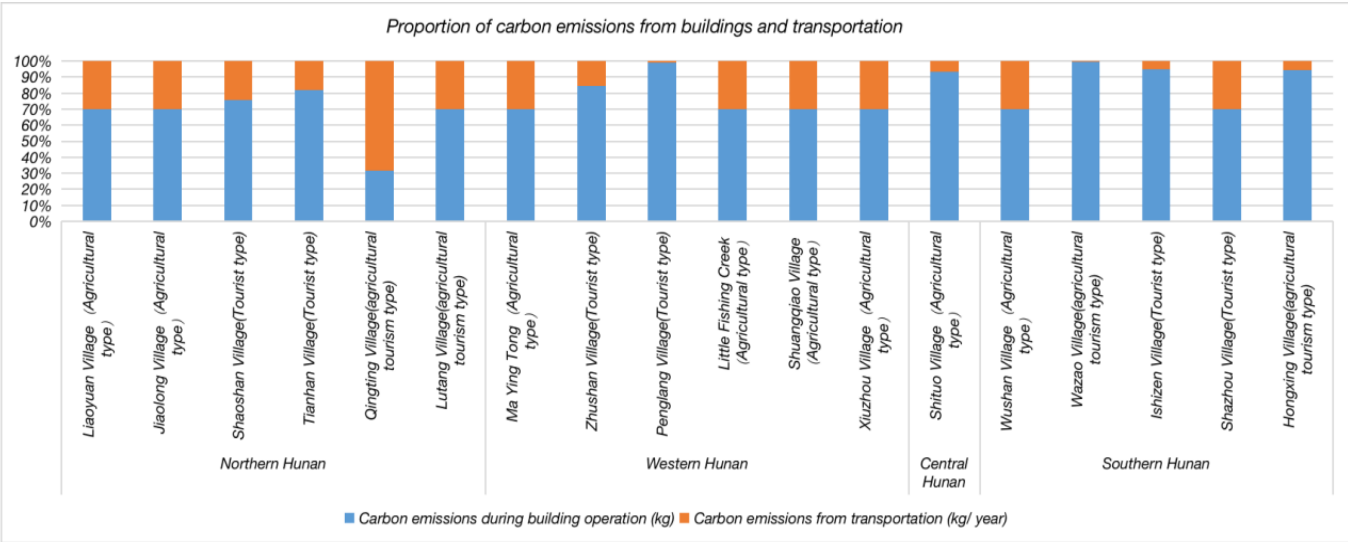


Figure 7. Comparison of carbon emissions from building use phase and transport in Hunan villages.

4.3. Correlation between Spatial Form and Carbon Emissions

4.3.1. Correlation between Overall Community Spatial Patterns and Carbon Emissions

Using LnY_1 as the explanatory variable, F_1, F_2, F_3 as the explanatory variables, and LNX_1–LNX_{10} as the instrumental variables, the least squares multiple regression analysis is performed using SPSS 22.0, and the results are shown in Table 13 below. The R^2 of the model is 0.61, the F-test value is 7.294, $p = 0.004$, and Sig. (p-value) is less than 0.01, indicating that the model fits relatively well and the regression equation has statistical significance.

Table 13. Model summary.

Equation (1)	Compound Correlation Coefficient	0.781
	R-Square	0.61
	Adjustment of R-Square	0.526
	Estimated Standard Error	0.318

The equation for the composite variables F_1, F_2, F_3 and the dependent variable LN (Y_1) can be obtained from the model coefficients in the table as

$$LNX_1 = 0.205F_1 - 0.205F_2 - 0.214F_3 + 4.596 \quad (7)$$

Substituting Equations (4)–(6) into Equation (7) yields

$$LNX_1 = 4.496LNX_1 + 4.736LNX_3 + 4.513LNX_4 + 4.66LNX_5 + 4.707LNX_6 + 4.671LNX_7 + 4.588LNX_8 + 4.532LNX_{10} \quad (8)$$

From the above Equation (8), it can be seen that the influencing factors and coefficients of carbon emissions from the largest to the smallest are the building density (4.736), aggregation (4.707), settlement connectivity (4.671), landscape shape index (4.660), road network shape index (4.588), public space accessibility (4.532), perimeter area sub-dimension index (4.513), and total land use area (4.496).

Similarly, LnY_2, LnY_3, and LnY_4 are used as explanatory variables, and F_1, F_2, and F_3 are used as explanatory variables for the regression fitting analysis. The comparison results of the correlation between the land spatial morphology index and carbon emissions are shown in Figure 8. Among them, the regression fitting equation of the carbon emission intensity of construction land and the spatial form indicators has the best fit, and the conclusion of the correlation between the carbon emission intensity of construction land and spatial form indicators has the highest credibility.

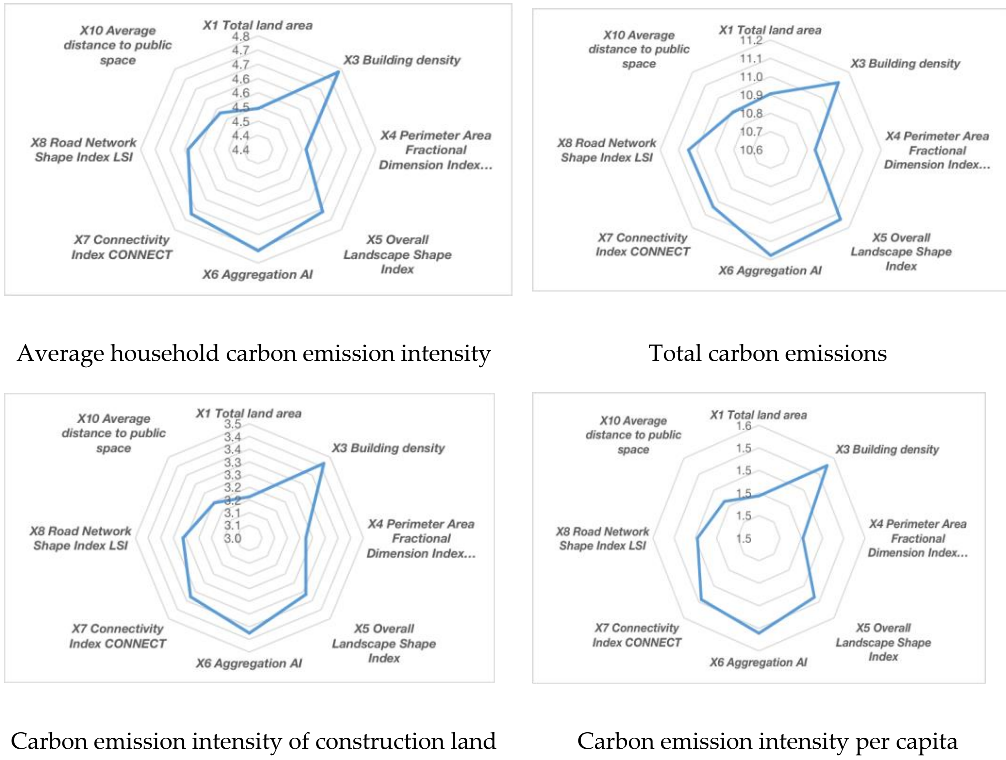


Figure 8. Radar map of spatial form index coefficients.

It can be seen that the correlation between the total carbon emissions, the carbon emission intensity of built-up areas, the carbon emission intensity per capita, and the spatial form indicators is more consistent, and that the building density, settlement aggregation, and road form index are the spatial morphological indicators that significantly affect rural carbon emissions.

4.3.2. Relationship between Rural Community Spatial Form and Carbon Emissions from Transport

Again, using the 10 spatial form indicators as explanatory variables and transport carbon emissions as the dependent variable, a partial correlation analysis is performed using the SPSS 22.0 software. Several factors with a weaker correlation with traffic carbon emissions are excluded, and the remaining seven indicators are selected as driving factors for the regression simulation. The KMO test value is 0.516, the total explained variance is 81.08%, and the regression fitting results are as follows:

$$LNY = 6.026LNX_1 + 6.605LNX_3 + 6.255LNX_5 + 6.24LNX_6 + 6.345LNX_8 + 5.953X_9 + 6.442X_{10} \quad (9)$$

From Equation (9), it can be seen that the influencing factors for the carbon emissions of transport are X_3 building density, X_{10} public space accessibility, X_8 road network shape index, X_5 overall shape index, X_6 agglomeration, and X_9 road connectivity, from the largest to the smallest. The radar diagram of the factors influencing rural transport carbon emissions is shown in Figure 9 below. It can be seen that the building density, public space accessibility, and road network shape index are the most important spatial form indicators affecting carbon emissions from transport.

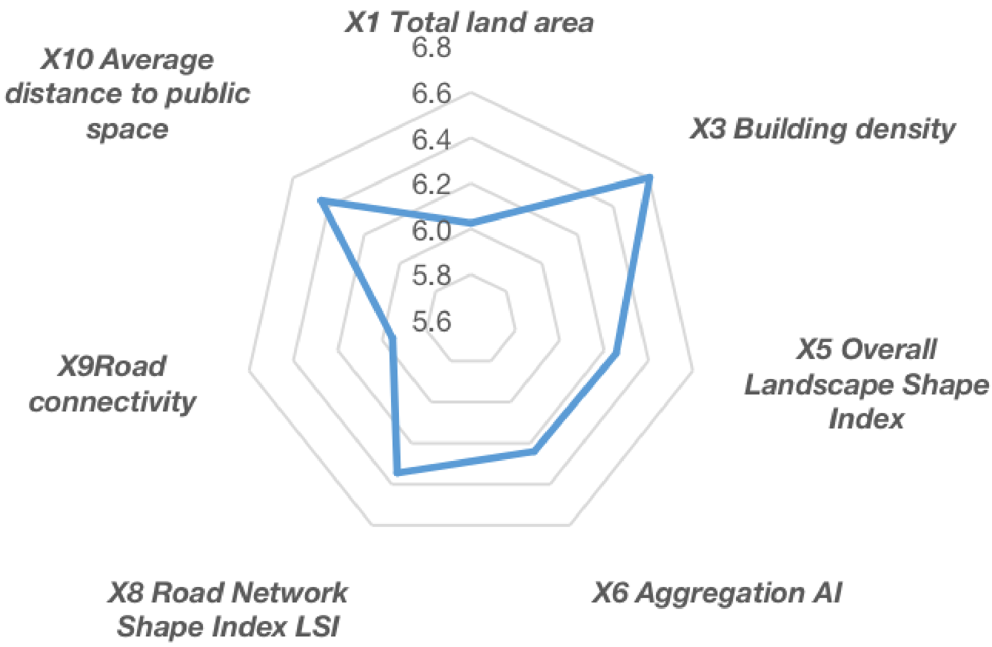
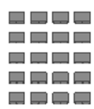


Figure 9. Radar map of transport carbon impact factors.

4.3.3. Relationship between the Spatial Form of Neighborhood Building Groups and Carbon Emissions

Having clarified that the building density and settlement aggregation are closely related to the total rural carbon emissions, the influence of the spatial form of neighborhood building groups on building carbon emissions is further verified using Design Builder. To ensure the validity of the simulation, the scale and number of households at the neighborhood group scale of rural communities are determined based on the research data. The scale of neighborhood groups is approximately 20–70 households for rural communities with a grouped layout, 10–30 households for rural neighborhood groups with a linear layout, and 10–50 households for rural communities with a centripetal layout, which are clustered as a whole. To verify the validity of the model, the carbon emissions per unit building area of the clusters with 8–24 households in the ranked layout are verified under the same building spacing, and the results are found to be less different, as shown in Table 14 below. The number of model households does not affect the accuracy of the simulation results.

Table 14. Carbon emission simulation results for different households (unit: kg).

Number of Households	8	12	16	20	24
Layout					
Carbon emissions per unit of floor space	7.8682	7.8707	7.8720	7.8732	7.8732

Source: self-drawn by the author.

(1) Controlling the Density of Building Groups

Different building density models are shown in Table 15 below, and the simulation results are shown in Figure 10. It can be seen that the building density is positively related to the total carbon emissions of the community but has less influence on the carbon emissions of neighborhood building groups. The carbon emission intensity of buildings may be the same under different densities, so the carbon emissions of buildings are more influenced by the layout patterns of surrounding buildings.

Table 15. Different density models.

Rows	4 × 2	3 × 3	4 × 3	3 × 5	4 × 4	4 × 5	5 × 5	5 × 6
Building density	8.28%	9.31%	12.41%	15.52%	16.55%	20.69%	25.86%	31.04%

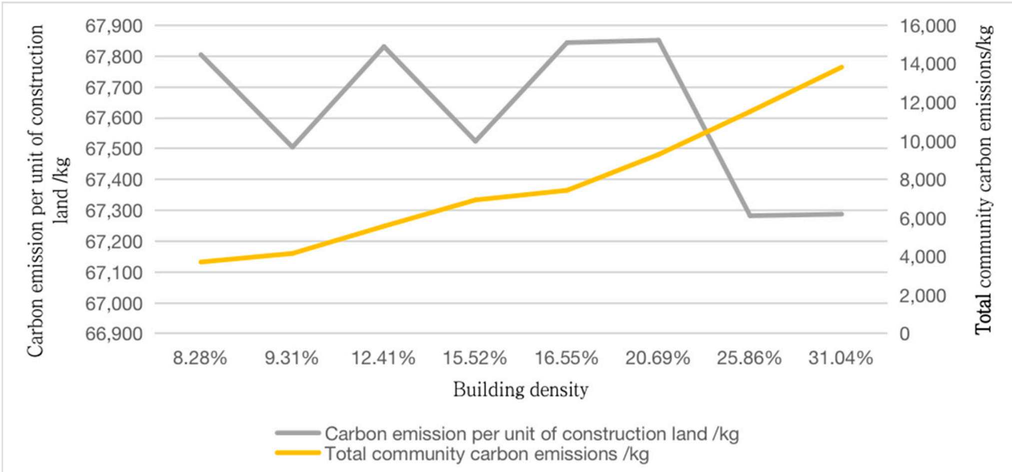
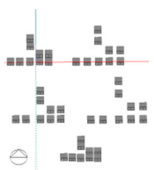
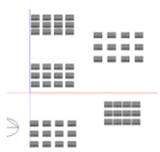
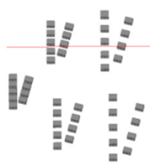
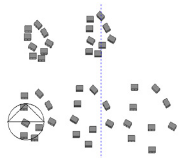


Figure 10. The effect of different building densities on carbon emissions.

(2) Controlling Building Spacing

The typical building layout form is selected in Table 16 below, and the magnitude of the aggregation degree is changed by adjusting the building spacing; the energy consumption simulation results are shown in Figure 11. It can be seen that the higher the degree of aggregation, the more obvious the effect of the layout form of the neighborhood building group on the energy consumption of the building. In the range of 8–12 m, the carbon emissions of the building increase as the degree of aggregation decreases. When the main distance between buildings reaches 12 m or more, the influence of different building layouts on the buildings diminishes. Among the different layout forms, the energy consumption of the row and diagonal layout is the lowest in the case of a positive southern orientation and 8 m primary and secondary building spacing, as shown in Figure 12.

Table 16. Different aggregation degree models.

T-Shaped	Lineage	Wrong Column	Oblique Column	Freestyle
				

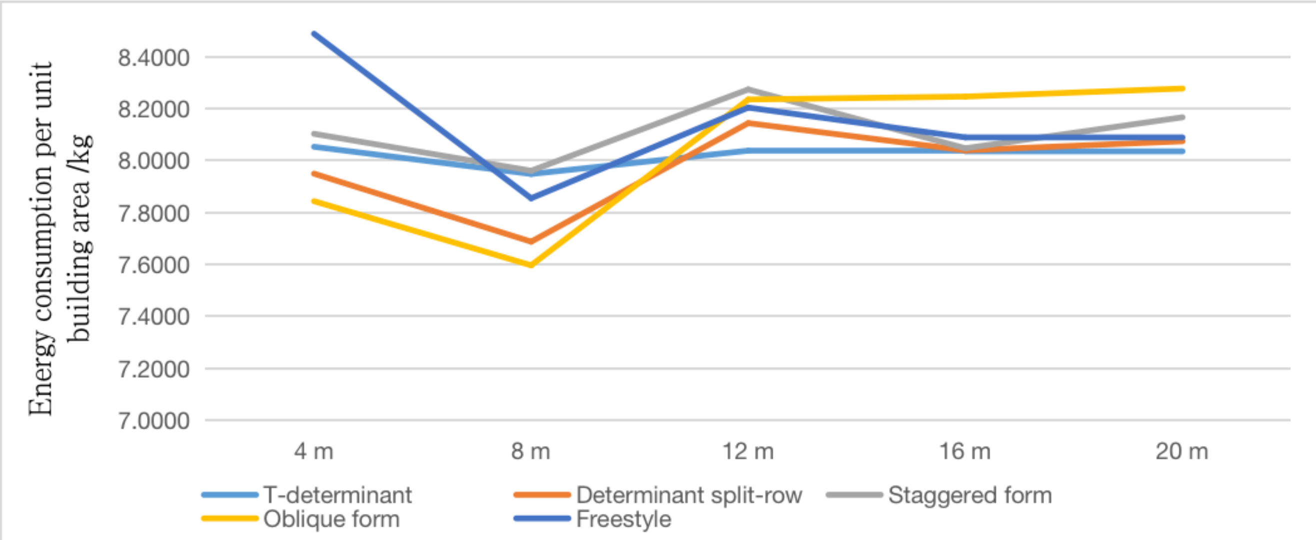


Figure 11. Effects of different aggregation degrees on building carbon emissions.

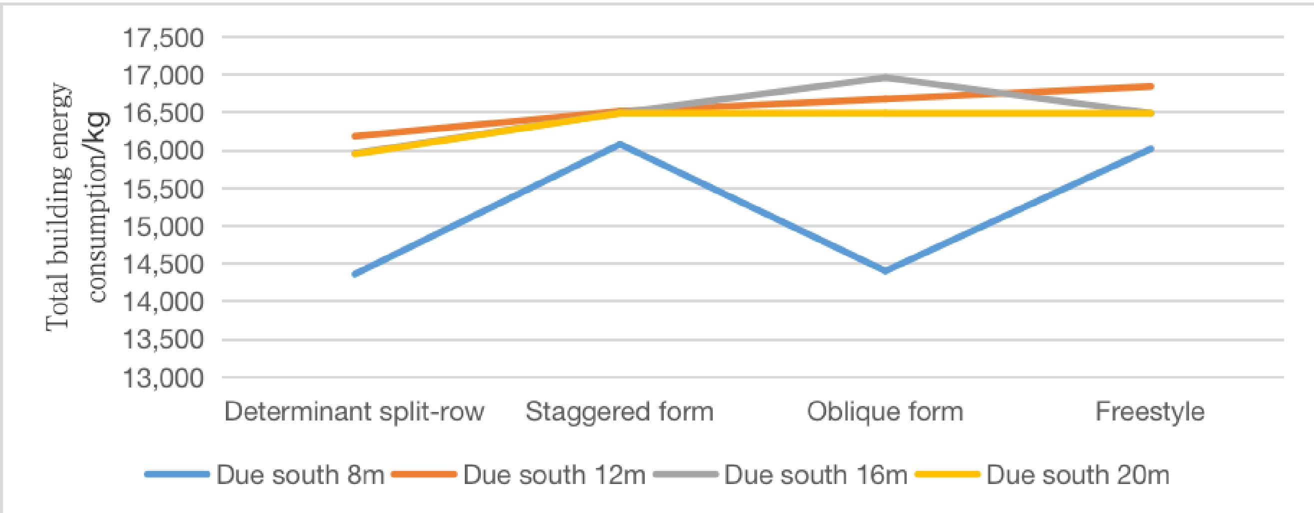


Figure 12. Effects of different layout forms on neighborhood building groups' carbon emissions.

The above correlation analysis shows the following results.

(1) The spatial layout of neighborhood buildings has a more significant impact on rural community carbon emissions when the scale of the community is certain.

From the correlation between different levels of spatial patterns and carbon emissions, "total volume form > neighborhood building groups combination form > overall layout form > neighborhood connection form". In other words, when the village scale is certain, the spatial layout morphology of the neighborhood building group has a more direct influence on the carbon emissions of residents.

(2) Building density has the greatest impact on rural carbon emissions among the spatial form indicators.

The building density in the overall spatial form of the village has a significant impact on the carbon emissions of the area. The higher the building density, the higher the rural carbon emissions in the countryside, but the impact on the carbon emissions of individual buildings is smaller. The correlation between the overall scale of the rural community and the carbon emission intensity of the countryside is smaller, indicating that the carbon emission intensity in the countryside is lower than that of the cities, and that increasing the scale of development does not significantly affect the overall carbon emission efficiency.

(3) There is a negative correlation between the form of neighborhood building groups and carbon emissions within a certain range.

The spatial form indicators that significantly affect the carbon emission intensity in the spatial form of neighborhood building groups are the degree of building aggregation and the degree of building connectivity. The higher the degree of aggregation and the higher the degree of connectivity, the closer the buildings are to each other, the higher the carbon emissions per unit area, and the more obvious the influence of the spatial form of building groups on the energy consumption of buildings. However, the influences of the degree of building aggregation and the carbon emissions per unit building area are non-linearly correlated, and the influence of the degree of aggregation on buildings is weakened when the distance between the front and back of a building is greater than 12 m.

The road network shape index is the factor with the least influence on carbon emissions among the neighborhood building spatial forms. The higher the road network shape index, the more complex the road network and the higher the carbon emissions from transport. A 1% increase in the road network shape index increases the average household carbon emissions by 4.588%.

4.4. Reference Values for Spatial Form Indicators

After clarifying that three spatial morphological indicators, namely the building density and the overall landscape shape index at the community level, and the aggregation of neighborhood building groups at the mesoscopic level, are important influencing factors for carbon emissions in rural communities, and the road shape index and the accessibility of public space are important influencing factors for transport carbon emissions, regression fitting is carried out based on the existing data, and the results are shown in Figure 13 below.

From the fitted curves above, we can see that (1) the building density of suburban integrated rural communities reaches a turning point at 0.1724, and the carbon emissions increase with the increase in building density when the building density is less than 0.1724. (2) The more discrete the overall spatial shape of the community is, the greater the carbon emissions are, and when it reaches 14.03, the growth trend slows down slightly. Overall, however, carbon emissions are positively correlated with the degree of dispersion. (3) When the degree of aggregation of neighborhood building groups is less than 25.91, the carbon emissions increase as the degree of aggregation increases. When the aggregation degree is 25.91–69.09, the carbon emissions decrease with the increase in the aggregation degree. (4) Due to the influence of the topography, the shape index of rural roads in Hunan is large. A systematic and regular road system is necessary for future transport planning. (5) Rural public space accessibility as a whole has a positive relationship with transport carbon emissions. According to Jan Gale's design theory of pedestrian spaces, the ideal range of human walking activities is within a 300 m radius [49]. The main public space in the Hunan case village is the village committee, and the number of public spaces is small and of a single type. The space should be built according to the road connectivity and the spatial preferences and living habits of the residents, so as to increase the locations of public space within 300–400 m. On the one hand, this could enrich the neighborhood interactions of the villagers, and, on the other hand, it could avoid the carbon emissions from the use of transport within the walking range of the public space.

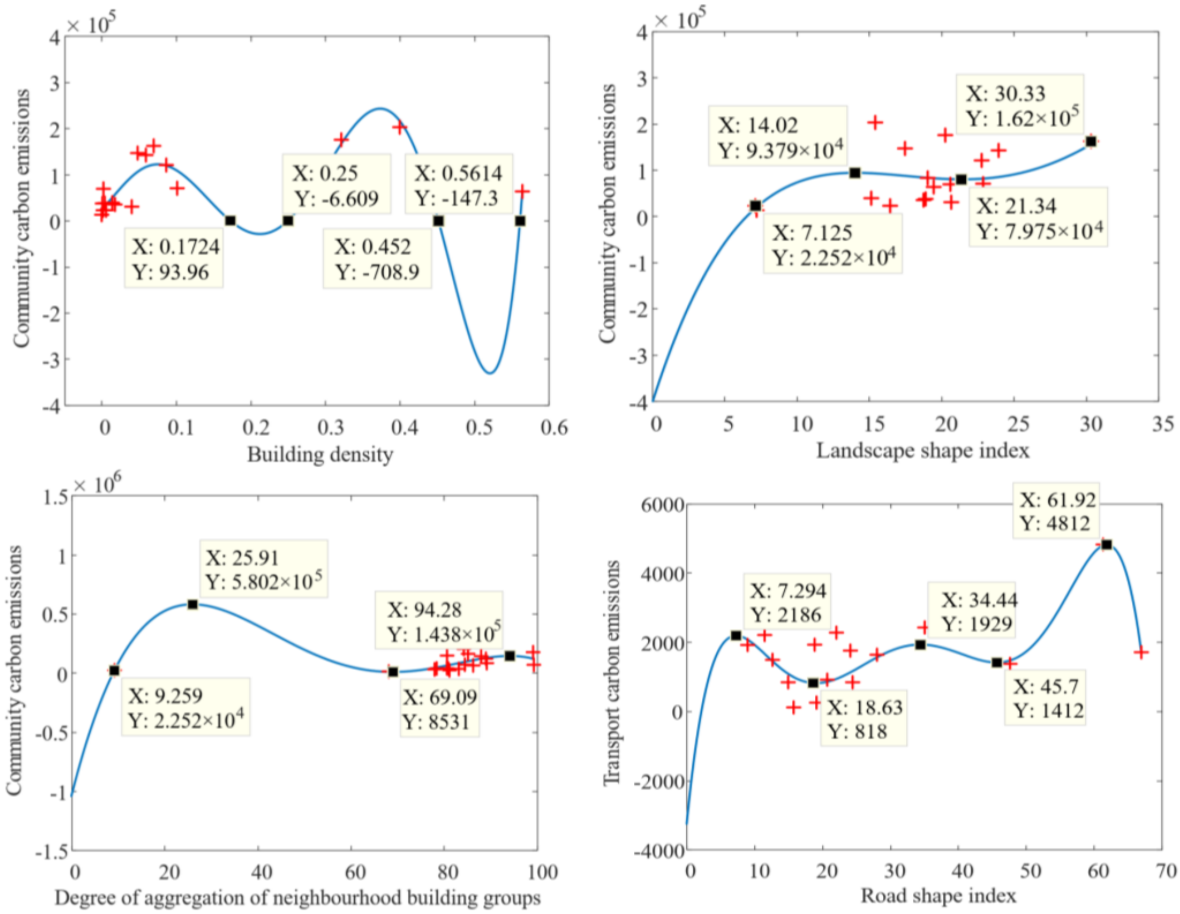


Figure 13. Spatial morphology index threshold analysis. The colored plus/asterisks is different sample cases.

5. Discussion

Taking rural villages in Hunan Province as the object of an empirical analysis, through screening and regression analysis of 10 indicators at two spatial levels, "overall community—neighborhood building groups", it is found that the building density in the overall spatial form of the rural community and the degree of aggregation in the neighborhood building groups have a strong influence on carbon emissions. The higher the building density, the higher the carbon emissions in the countryside, while the degree of aggregation of the neighborhood building groups within a certain area has a negative correlation with carbon emissions. The closer the distances between buildings, the higher the carbon emissions per unit area, and the layout form of building groups has a more obvious effect on the energy consumption of buildings. In the context of Hunan's countryside, villages with higher densities tend to be those with flatter terrain and well-developed transport, so that the population is more concentrated and the overall level of development in the countryside is better. For example, Lutang Village, Tianhan Village, and Shaoshan Village in the north of Hunan, and Hongxing Village in the south of Hunan, all of which are close to the city, have a good basis for development and a high population density, and therefore the total carbon emissions of the villages are highest, as shown in Figure 6. Thus, the conclusions of the study are in line with the actual situation of rural development in Hunan. At the same time, it is widely accepted that the energy consumption of buildings is related to the spatial arrangement of neighborhood groups of buildings, as the building layout affects the wind and light environment of the building, which in turn affects its energy consumption [50]. Related studies have also shown that mandatory targets in regulatory planning, especially the "greening ratio" and "building density", can be effective in mitigating climate change [51]. Studies for the rural areas of Guangzhou have also shown that the increase in the rural built-up area (LR) has a significant positive correlation with carbon emissions [52]. However, this study has also shown that carbon emissions have little correlation with spatial landscape patterns, and the effects of different settlements on carbon emissions in Guangdong also show apparent heterogeneity across cities. The role of the spatial forms of rural communities in influencing carbon emissions also varies according to the type of village, and, in particular, the differences in the roles of the spatial forms of villages with different types of industries on carbon emissions should be the focus of future research.

Therefore, controlling the overall building density and optimizing the spatial forms of rural neighborhood building groups are the main strategies to build low-carbon rural communities. From the above analysis, it can be seen that the low-carbon control of the rural spatial form can be approached from two aspects: "quantity" and "shape". According to the principle of "macroscopic control of quantity and macroscopic control of shape", in the detailed spatial planning of the country, firstly, the density of settlements as a whole should be strictly controlled to avoid an excessive scale; secondly, the reasonable layout of the neighborhood building groups within the community should be guided by people's travel and living behavior to reduce unnecessary carbon emissions.

Referring to the Hunan Provincial Village Planning Guideline (2019 Trial), firstly, the concepts of "low-carbon control" and low-carbon control indexes should be added to the construction space in Hunan rural spatial planning under the current double-carbon target, as shown in Figure 14 below. Second, the different "production activities" of different industrial types of rural community spaces result in different spatial needs, and the low-carbon control units and control rules of rural spaces should be analyzed according to actual cases. The models and methods of land use planning and carbon emission control applicable to different types of villages should be proposed according to the actual village's development, and the carbon emission thresholds of villages should be clarified in the early stage of planning. Then, a feasible territorial spatial planning scheme under the carbon emission target can be proposed.

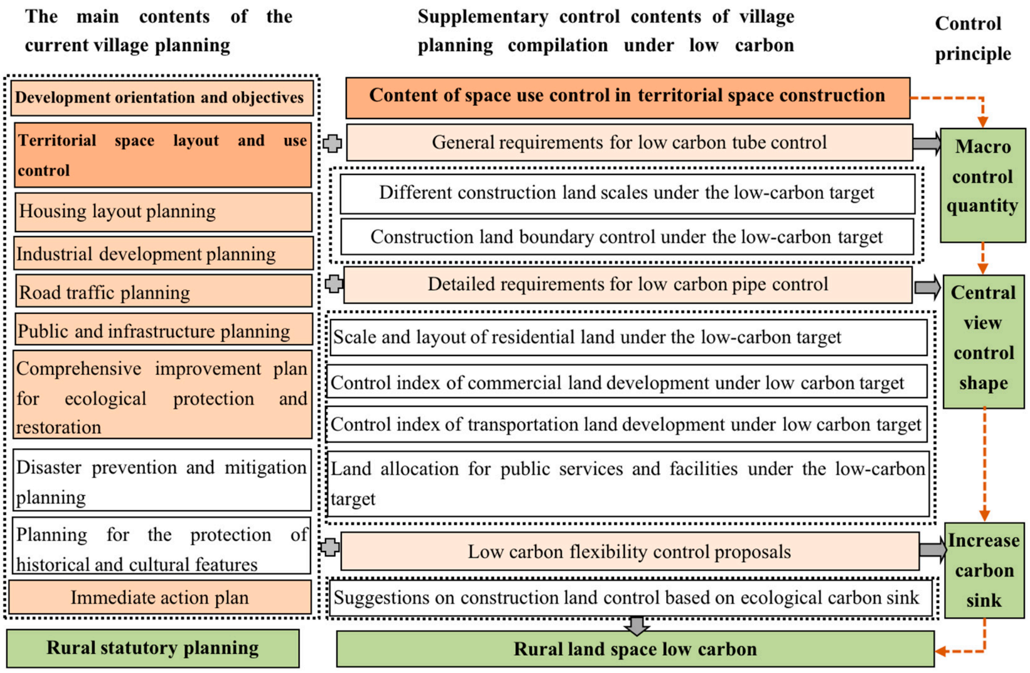


Figure 14. Schematic representation of the low-carbon content of rural territorial spatial planning.

Rural construction has brought about significant changes in the economic level, village appearance, and ecological environment in rural areas, improving people's living environments and overall quality of life. However, under the constraints of limited resources, environments, and space, Chinese villages need to follow the path of low-carbon, environmental protection and a green economy, build a natural and compact rural spatial pattern, and reduce unnecessary carbon emissions. As different regions are in different stages of rural transformation and have different problems and needs, the methods and strategies of low-carbon rural space construction cannot be generalized. The low-carbon spatial planning and construction practices of different types of villages and the construction of a low-carbon information platform for rural communities should be the focus of future research. Through the carbon emission assessment of the whole rural area, carbon emission reduction units at the regional level can be screened and established, and key technologies and core indicators for carbon emission reduction planning can be provided [53]. Referring to the existing low-carbon planning techniques for cities, such as using GIS platforms to combine land use planning models with carbon emission accounting models, it is necessary to quickly consider the carbon emission changes under different planning schemes and guide the optimization of low-carbon country rural land spatial planning schemes at different scales.

6. Conclusions

In this study, the spatial form index and the rural carbon emission index were calculated for 18 rural villages in Hunan Province, and the effects of different spatial form indexes on carbon emissions were analyzed by principal component analysis and regression analysis. The main conclusions of the study are as follows. (1) Through the screening of different land use spatial form indices, four types of rural spatial form indices were finally identified, including the "total volume form, overall layout form, neighborhood building groups combination form, and neighborhood connection form". From the correlations between different spatial form indices and carbon emission, (2) the correlation between different spatial patterns and carbon emission is as follows: "total volume form > neighborhood building groups combination form > overall layout form > neighborhood connection form". When the village is of a certain scale, the spatial layout morphology of neighborhood building groups has a more direct influence on the carbon emissions of the residents. (3) The building density in the overall rural community significantly affects the carbon emissions of the village. The greater the building density, the greater the overall carbon emissions of the village, but the effect on the carbon emissions of individual buildings is smaller. The spatial pattern indicators that significantly affect the carbon emission intensity of neighborhood building groups are the degree of building aggregation and the degree of building connectivity. However, the influence of the building aggregation degree and carbon emissions per unit building area are non-linearly correlated, and the influence of the aggregation degree on buildings is weakened when the distance between the front and back of a building is greater than 12 m. (4) Based on the above conclusions, the spatial low-carbon control of the rural spatial form can be based on both "quantity" and "shape". Following the principle of "macroscopic control of quantity and mesoscopic control of shape", the detailed spatial planning of the countryside should, on the one hand, strictly control the density of settlements as a whole to avoid an excessive scale, and, on the other hand, reduce unnecessary carbon emissions by adopting a reasonable layout form for building groups within communities.

Due to the limited data available, there were some limitations in the construction of spatial form indicators in this paper. For example, the building volume, floor area ratio, and other dimensional indicators were not included in the study, but they can be considered in future work. Meanwhile, future research can also classify villages into different industrial types and study the differences in spatial morphology with regard to carbon emissions in different types of villages; future work could also propose models and methods of spatial planning and carbon emission control applicable to different types of villages.

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Notes

[1] There are two views on the calculation of the carbon emission factor of wood: one believes that wood can fix carbon dioxide in the air during the growth process and considers the carbon emission factor of wood to be negative; the other believes that carbon sequestration during wood growth should not be considered in the system boundary of building carbon emission analysis. In this paper, we refer to the latter viewpoint and only consider the wood cutting and processing process to calculate the carbon emission coefficient of wood.

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