

Article

An Empirical Study on the Relationship Between Spatial Layout Patterns of Rural Residential Communities and Carbon Emissions: A Case Study of Northern Jiangsu

Limei Song and Jiang Chang *

School of Architecture and Design Arts, China University of Mining and Technology, Xuzhou 221116, China; tbh328@cumt.edu.cn

* Correspondence: changjiang@cumt.edu.cn; Tel.: +86-159-5210-3091

Abstract

Under the ‘dual carbon’ goals, low-carbon planning in rural areas has become a key priority. To elucidate the mechanisms through which the spatial form of rural communities influences carbon emissions, this paper examines three types of rural residential communities in the Northern Jiangsu Plain—newly concentrated, largely dispersed with small clusters, and contiguous clusters—analysing their relationship with carbon emissions from daily living and transport across two dimensions: residential layout and road transport patterns. The results indicate that the overall scale of the community is the dominant factor influencing carbon emissions. Spatial compactness has not yet surpassed the scale threshold, and a positive correlation remains evident, whereby a larger scale correlates with higher carbon emissions. The carbon emission characteristics of the three community types differ significantly: large-scale dispersed communities and small-scale clustered communities, characterised by low-rise, dispersed layouts; mixed-use development; and diverse energy sources, exhibit low domestic carbon emissions and high transport carbon emissions, resulting in the lowest total emissions. Newly developed concentrated communities, characterised by high-rise, high-density, urban-like forms, exhibit high domestic carbon emissions and low transport emissions, resulting in the highest total emissions, though these are still lower than those of comparable urban communities. Contiguous concentrated communities, meanwhile, exhibit moderate emissions. The study concludes that low-carbon development in rural areas must be based on a morphological foundation of low-rise buildings, integrated industry and residential areas, and concentrated facilities while avoiding blind expansion and simple replication of urban-style concentrated residential forms.

Keywords: rural areas; residential communities; spatial layout patterns; carbon emissions



Academic Editor: Li Yang

Received: 4 June 2026

Revised: 26 June 2026

Accepted: 7 July 2026

Published: 10 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The deep integration of the dual carbon goals and the rural revitalisation strategy means that villages, as integral components of county-level territorial space, have seen low-carbon development emerge as a pivotal element within the national carbon governance framework. Currently, county administrations are promoting carbon balance through spatial coordination. Rural communities are the main living and activity spaces for rural populations, and their carbon emissions account for a significant proportion of the carbon impact associated with territorial space utilisation. Furthermore, the sustained

upward trend in the total volume and intensity of energy-related carbon emissions in rural areas has been substantiated [1–4]. As the core settlements for agricultural populations, rural residential communities exhibit morphological characteristics—such as spatial layout and homestead distribution—that directly influence rural residents’ energy consumption, making them crucial for policy implementation [5]. In practice, the spatial form of rural residential communities is undergoing a rapid transformation. Comprehensive initiatives, including the revitalisation of depopulated villages, the reactivation of homesteads, concentrated resettlement and infrastructure upgrades, are advancing urgently and require low-carbon-oriented morphological optimisation schemes [6,7]. Rural areas are characterised by dispersed homesteads, courtyard economies and agricultural production spaces. Their carbon emission sources and carbon sink functions differ significantly from those in urban areas, making it difficult to apply existing theoretical frameworks directly. This results in a lack of effective theoretical support for practical morphological transformation and low-carbon objectives, creating a situation where ‘practice precedes theory’. Therefore, investigating the intrinsic relationship between the spatial form of rural residential communities and carbon emissions is an essential response to national strategic demands and a vital step towards resolving the current disconnect between theory and practice.

From a regional and policy perspective, the Northern Jiangsu Plain, a traditional agricultural region and a prime example of densely populated rural China, is experiencing a significant transformation of its rural landscape. Consequently, controlling carbon emissions and transforming its spatial form are matters of the utmost urgency and significance. According to statistics, carbon emissions at the county level account for around 30 per cent of China’s total emissions, with those arising from daily life in rural residential communities, small-scale agricultural production, and supporting infrastructure showing a sustained upward trend. Against the policy backdrop of Jiangsu Province’s Rural Revitalisation Plan and the initiative to ‘comprehensively advance rural revitalisation’, the transformation of rural residential communities in northern Jiangsu—represented by three categories: ‘consolidation and upgrading’, ‘relocation and amalgamation’, and ‘suburban integration’—is proceeding at a remarkable pace [8]. A typical county in Northern Jiangsu has undergone significant change in recent years through the revitalisation of depopulated villages and centralised resettlement, involving the relocation of over 10,000 farming households annually. This has resulted in a rapid transformation of the spatial form of rural residential communities, changing them from traditional, dispersed homestead sites to compact, urban-like communities within a very short period. This dramatic change has directly impacted rural residents’ energy consumption patterns, travel behaviours, and the micro-circulation of their courtyard economies. However, a systematic understanding of the spatial response patterns of carbon emissions during the rapid transformation of these three community types remains lacking. Therefore, focusing on these three types of rural communities in the Northern Jiangsu Plain provides direct evidence for optimising rural spaces in high-density agricultural areas and addresses the urgent need to reconcile the contradiction between the rapid pace of rural development and stringent low-carbon requirements.

2. Literature Review

2.1. Research on the Impact of Urban Spatial Form on Carbon Emissions

The relationship between urban spatial form and carbon emissions has long been a focal point of research for scholars both domestically and internationally. Existing studies primarily examine the impact of urban spatial form on carbon emissions through dimensions such as density, morphological structure, functional layout and transport systems. Regarding density, the idea that compact, high-density urban forms help to achieve low-carbon goals is widely accepted, as shown by research from both China and other coun-

tries [9,10]. However, some studies suggest that the negative correlation between density and carbon emissions is not absolute, instead revealing a pattern of ‘optimal moderate density’ [11]. Regarding morphological structure, research has explored the emission-reduction effects of both ‘monocentric’ and ‘polycentric’ models [12–17], emphasising that ‘structural optimisation requires alignment with transport support and functional mixing’. Research has also examined the geometric regularity of urban spaces [18] (e.g., boundary complexity and extent of sprawl), concluding that ‘greater irregularity and sprawl correlate with higher carbon emissions’. Regarding functional layout, studies have focused on the spatial combinations of residential, employment, commercial and public service zones. Core findings have centred on ‘land use mix’ [19,20], ‘work-residence spatial relationships’ [15,21] and ‘facility layout patterns’ [22], underscoring the critical role of ‘functional synergy and spatial alignment’ in reducing carbon emissions. The relationship between transport systems and carbon emissions manifests primarily through three pathways: urban spatial form (e.g., compactness and work-residence structure), road network configuration and transport mode choice. These pathways have been validated by numerous empirical studies [23,24]. In summary, key characteristics of low-carbon urban forms include moderately compact urban structures, mixed-use development with balanced work-residence distribution, high-density interconnected road networks, and efficient facility layouts at the neighbourhood/block scale.

Research into the relationship between residential spatial patterns and carbon emissions suggests that ‘compact, mixed-use, intensive and adaptive’ configurations of residential spaces can help to reduce carbon emissions. For example, moderate high-density development decreases per capita resource consumption and optimises infrastructure sharing, thereby reducing carbon emissions [25]. However, studies in specific climate zones also indicate that excessive high-density development can increase heating energy consumption due to building shading effects [26]. This necessitates the synergistic optimisation of microclimate and carbon emissions through ‘compact layout + staggered arrangement’. Functionally mixed community layouts, compact facility arrangements (15-min neighbourhoods), and micro-optimised three-dimensional residential designs can reduce household energy consumption and transport-related carbon emissions by shortening travel distances, optimising energy usage, and encouraging low-carbon behaviours [27,28].

2.2. The Evolution of Residential Community Forms in County and Rural Areas and Low-Carbon Strategies

Research at the county level primarily focuses on ‘the impact of spatial form evolution during urbanisation on carbon emissions’ and ‘pathways for optimising carbon balance’. Liu Xianzhao et al. [29] studied counties in the Chang-Zhu-Tan region, demonstrating that compact urbanisation through concentrated, contiguous township development reduces carbon emission growth rates by 30% compared to sprawling patterns. Similarly, research by Yuan et al. [30] indicates that highly compact counties, such as those with coordinated township-county urban development, exhibit higher carbon emission efficiency than loosely structured counties. This primarily influences economic efficiency of carbon emissions through the transport sector, aligning with urban-level findings. Guo Rong et al. [31] demonstrate that compact urban spatial patterns promote carbon emissions while enhancing economic benefits, confirming the applicability of compact development to county-level urban spaces. However, existing county-level research primarily focuses on ‘county towns and built-up areas of townships’, paying insufficient attention to the impact of rural spatial forms, such as village layouts and homestead distribution, on carbon emissions.

Rural areas are characterised primarily by residential plots, agricultural land and ecological spaces. They differ significantly from urban areas in terms of morphological

factors such as ‘compactness’ and ‘road network density’. Their primary source of carbon emissions is energy consumption in rural households, which differs from that in urban areas. Song et al. [32] indicate that spatial changes in peri-urban integrated rural communities lead to increased carbon emissions to varying degrees. On the one hand, this stems from carbon emissions during the construction phase of buildings and infrastructure as part of spatial production practices. On the other hand, it results from energy wastage and increased building-related carbon emissions during the operational phase caused by a lack of planning, design, and management in these spatial production practices. Within neighbourhood clusters, the smaller the spacing between buildings and the higher the density, the more pronounced the impact of the cluster’s layout on energy consumption. Under the current ‘centralised resettlement’ policy in rural areas, indiscriminate clustering of buildings can lead to a rapid increase in carbon emissions per unit area. Feng Xu et al. [5] demonstrate that existing low-carbon construction strategies in rural areas focus on the application of low-carbon technologies, including ‘low-carbon building technologies’, ‘low-carbon planning and layout’ and ‘low-carbon energy utilisation’, whilst also emphasising the protection of the ecosystem and local character. From a planning perspective, current low-carbon strategies primarily focus on improving road transport, adjusting industrial structures, and utilising clean energy.

2.3. Methods for Measuring Carbon Emissions in Rural Communities

In terms of quantifying carbon emissions in rural communities, scholars in China and elsewhere have primarily adopted two approaches: top-down accounting based on macro-level statistical data and bottom-up measurement of micro-level household behaviour.

(1) Direct measurement and conversion of energy consumption: Limei Song et al. [33] obtained first-hand data on household energy consumption through methods such as household visits, installing smart electricity meters on the grid and maintaining records of liquefied petroleum gas (LPG) and biomass energy consumption. They then used IPCC carbon emission factors to perform precise calculations. These studies reveal that the form of residential buildings significantly influences carbon emissions in rural communities due to the lack of centralised heating and cooling systems.

(2) Measurement of transport and daily behavioural trajectories: With the development of GPS tracking and mobile big data, Xiaojiang Li et al. [34] have begun to directly measure the daily travel behaviour of villagers. Studies indicate that, following rural resettlement in concentrated settlements, villagers’ non-motorised travel shifts towards motorised transport due to an expanded farming radius or centralised public service facilities. This leads to an increase in transport-related carbon emissions.

In summary, although direct measurement techniques at the micro-level are becoming increasingly sophisticated, existing literature tends to focus on the socio-economic attributes of rural carbon emissions. Few studies have established a direct quantitative spatial coupling between ‘directly measured micro-level carbon emission data’ and ‘detailed spatial morphological parameters of rural residential communities’. The mechanisms through which spatial morphological transformations in rural communities—such as centralisation and urbanisation—affect carbon emissions remain unclear.

Research into the relationship between the spatial form of rural residential communities and carbon emissions is vital for supplementing the urban-rural integration low-carbon theoretical framework and resolving practical challenges in rural low-carbon development. This study aims to develop a theoretical analytical framework applicable to rural areas that links spatial form, behavioural patterns and carbon emissions. Through case-based empirical research, the study aims to reveal the carbon emission mechanisms specific to the spatial form elements of rural residential communities. The objective is to provide

technical support for low-carbon planning in rural residential communities, thereby facilitating the coordinated achievement of county-level dual carbon goals and the rural revitalisation strategy.

3. Theoretical Framework

3.1. The ‘Space–Behaviour–Carbon Emissions’ Theoretical Framework and Transmission Pathways

The key elements of residential communities are primarily housing and road networks. The spatial forms of these include volumetric configurations, the overall layout of residential clusters (regular or sprawling), the arrangement of residential buildings (clustered or dispersed) and road configurations (connectivity). The impact of the spatial layout of residential communities on carbon emissions is primarily exerted through the influence of spatial forms on human behaviour, which in turn affects energy consumption patterns and indirectly influences carbon emissions. Based on this, this study proposes a theoretical analytical framework of ‘spatial form–behavioural patterns–carbon emissions’, as illustrated in Figure 1 below.

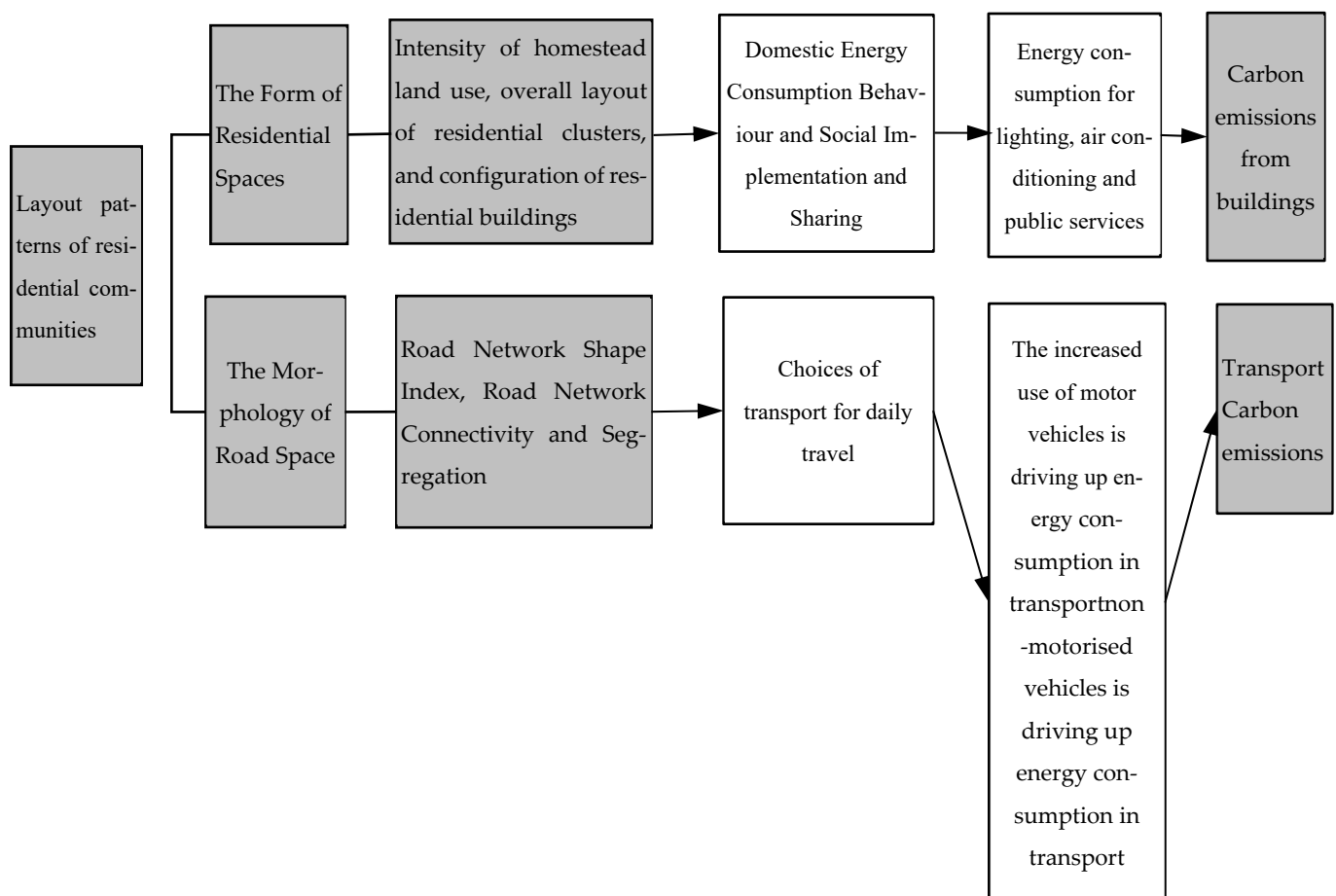


Figure 1. Theoretical framework of ‘space–behaviour–carbon emissions’ in residential communities.

Research on the carbon emissions of rural areas in the north of China: the relationship between residential community layout and carbon emissions.

(1) Transmission mechanism of residential layout on domestic carbon emissions: Firstly, residents in high-density communities are more likely to use centralised heating and shared hot water systems, improving energy efficiency. In contrast, a dispersed layout leads to higher costs for grid and water supply network coverage, as well as increased energy transmission losses. Secondly, the configuration, density and number of storeys of

residential buildings directly influence the community's microclimate and transmission losses in utility networks through their physical attributes. Moreover, they shape residents' lifestyle patterns at a deeper level.

(2) Transmission mechanism of road transport on transport-related carbon emissions: The connectivity of the road network and the degree of functional integration between 'work' and 'residential' areas directly determine residents' daily travel distances and transport choices. Spatial arrangements that integrate commercial and residential functions, coupled with good road connectivity, can effectively reduce daily travel distances and encourage the use of low-carbon modes of transport, such as walking or cycling. Conversely, separating commercial and residential functions and spatial dispersion increases commuting costs, forcing residents to rely on motorised transport and leading to an increase in transport-related carbon emissions.

3.2. Spatial Layout Indicator System for Residential Communities

Taking into account the core characteristics of rural residential communities—namely, 'scattered dwellings, frequent social interaction, and the intertwining of production and living spaces'—this study adopts a spatial hierarchy comprising 'macro-level overall layout, meso-level building clusters, and micro-level transport networks' to construct an indicator system for the spatial form of rural residential communities.

(1) Overall layout and morphology dimension: This primarily reflects the degree of regularity in the spatial arrangement of residential communities and the fragmentation of land parcels. Fragmented, irregular rural land parcels often entail increased energy consumption for the extension and maintenance of infrastructure networks, such as sanitation, water supply, and centralised waste treatment. The study uses the number of patches (X1), patch density (X2), overall shape index (X3) and perimeter-to-area ratio index (X4) to characterise this dimension. Limei Song et al. [33] indicate that there is a significant positive correlation between the geometric regularity of rural landscape patches and the low-carbon operational efficiency of infrastructure.

(2) Building agglomeration dimension: This primarily reflects the intensive utilisation efficiency of residential buildings against the backdrop of revitalising residential land, as well as its impact on residents' energy consumption. The study quantifies the compactness and spatial proximity of villagers' dwellings by introducing building agglomeration (X5), building connectivity (X6), patch cohesion (X7), patch separation (X8) and patch dispersion index (X9) from landscape ecology. A compact and continuous building layout can effectively form a microclimatic defence barrier for the community, reducing seasonal energy consumption for heating or cooling and facilitating the synergistic and efficient use of centralised and distributed energy sources (e.g., rooftop photovoltaic systems) (Xiaojiang Li et al. [34]).

(3) Road network morphology and structure dimension: This dimension primarily reflects the accessibility and connectivity of internal village transport. This directly determines the extent of villagers' daily production, social interactions, and agricultural machinery travel, as well as the associated energy consumption. Based on road network shape, adjacency and connectivity, the study selected seven indicators: the number of road network patches (X10); the road network shape index (X11); the road patch adjacency index (X12); the road network connectivity (X13); the road patch cohesion (X14); the road separation (X15); and the road dispersion index (X16). A highly connected, regular road network can effectively reduce the distance travelled by motorised transport and lower transport-related carbon emissions.

In summary, this study has developed a system of indicators for the spatial layout patterns of rural residential communities, comprising three major dimensions, five criteria

levels and 16 specific indicators (see Table 1). It should be noted that, while this study has drawn on some of the measurement methods used in traditional urban spatial morphology, such as density and connectivity, the concept of compactness in rural areas does not refer to a forest of high-rise buildings, but rather to the clustering of homesteads.

Table 1. Spatial Form Indicator System for Residential Communities.

		Policy Layer	Specific Indicators	Explanation of Indicators
Rural Housing Communities	Elements of layout design	Quantitative Form	X1 Number of patches	Area of all building patches
			X2 Patch density	Proportion of building patch area relative to the total area of the neighbourhood
		Regularity of Form	X3 Overall landscape shape index	The higher the value, the less regular the shape
			X4 Perimeter-to-area ratio (PAFRAC)	The complexity of the spatial form; the higher the value above 1, the further the shape deviates from regular geometric forms
		Residential compactness	X5 Architectural aggregation (AI)	When the degree of fragmentation of settlements is at its maximum, AI equals 0; when they are aggregated into a single entity, AI equals 100.
			X6 Architectural connectivity (CONNECT)	The connectivity is 0 when there is only one patch or when there are no connections between patches; it is 100 when the patch is connected to every other patch.
		Residential connectivity	X7 Patch cohesion (COHESION)	As patches become more fragmented, connectivity decreases and the value approaches 0.
			X8 Patch division (DIVISION)	When there is only one patch, DIVISION = 0; when the landscape is fragmented to the greatest extent, DIVISION reaches its maximum value.
			X9 Patch dispersion index (SPLIT)	When there is only one patch, SPLIT = 1; as the landscape becomes fragmented into smaller patches, the indicator value gradually increases.
		Road network configuration	X10 Number of road network patches	Area index of all road network landscape patches
			X11 Road Network Shape Index	Morphological complexity; values greater than 1 indicate a departure from regular geometric shapes, with shapes becoming increasingly complex
			X12 Road Block Contiguity Index (CONTIG)	Proximity between road patches; higher values indicate better connectivity
			X13 Road Network Connectivity (CONNECT)	The connectivity of patches, ranging from 0 to 100; connectivity decreases as patches become more fragmented
			X14 Road Block Cohesion	The connectivity of patches, ranging from 0 to 100
			X15 Road Division Index	The value reaches its maximum when the landscape is fragmented to the greatest extent
			X16 Road Dispersion Index	As the landscape becomes fragmented into smaller patches, the index value gradually increases

3.3. Model Selection and Construction

This study analyses the relationship between the spatial layout of rural communities and their carbon emissions. It should be noted that the sample villages are geographically dispersed, with no spatial adjacency between them, and the individual samples remain independent of one another. Consequently, the study does not consider the spillover effects

of geographical proximity and uses a multiple linear regression model with principal components (OLS), with multicollinearity eliminated, for empirical analysis. This choice was primarily based on the following rationale: (1) Rural community carbon emissions are influenced by multiple dimensions, including spatial layout characteristics (e.g., compactness and fragmentation) and infrastructure configuration (e.g., road density and energy facility distribution). This model enables the precise quantification of the independent and combined effects of multiple independent variables on the dependent variable, thereby identifying the key spatial drivers of carbon emissions.

(2) The core research objective is to reveal the quantitative relationship between spatial layout patterns and carbon emissions, providing actionable guidance for optimising low-carbon rural spaces. The regression coefficients generated by the model directly reflect the magnitude of carbon emission change per unit variation in a spatial indicator, yielding intuitive results with practical implications.

The model formula is set as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \quad (1)$$

In the equation, Y represents the carbon emission level of rural communities, measured as total community carbon emissions (t) and calculated by combining energy consumption statistics with carbon emission conversion factors. The constant term β_0 represents the baseline level of rural community carbon emissions when all the independent variables are set to zero. The regression coefficient β_1 – β_n reflects the magnitude and direction of each variable's impact on carbon emissions. A positive coefficient indicates that an increase in that indicator promotes carbon emissions, while a negative coefficient indicates that it inhibits them. X_1 – X_n denotes the independent variables, i.e., the core indicators of rural community spatial layout patterns. ε denotes the random error term representing other minor influencing factors not incorporated into the model, such as short-term climate fluctuations or temporary changes in residents' energy usage. This follows a normal distribution with a mean of zero and constant variance.

4. Study Area and Data Sources

4.1. Overview of the Study Area

The layout of residential communities significantly influences building energy consumption, being affected by climatic zones and topography [26,35]. This study focuses on rural areas within the climatic and topographical conditions of the Northern Jiangsu Plain. In terms of sample selection, the research team adopted a method combining stratified random sampling with the analysis of typical case studies, based on the principles of 'typicality', 'representativeness' and 'spatial heterogeneity'. Ultimately, a total of 28 typical rural residential communities in the Northern Jiangsu Plain were selected as the research sample. Field research on the study subjects revealed that the spatial layout patterns of rural residential communities in Northern Jiangsu can be categorised into three types: 'widely dispersed with small clusters', 'new-style community clusters' and 'concentrated contiguous areas', as shown in Table 2 below. The distribution of the sample across these three community types was as follows: 12 'widely dispersed with small clusters', 8 'new-style community clusters' and 8 'concentrated contiguous areas'. This distribution took into account both the pace of spatial restructuring and the gradation of population size. This is in stark contrast to the free-form layouts characteristic of hilly regions such as Hunan [32].

Furthermore, as energy consumption in rural residential settings is influenced by both the climate and indoor design standards, this study establishes physical and policy benchmarks for empirical research. In terms of climatic characteristics, the Northern

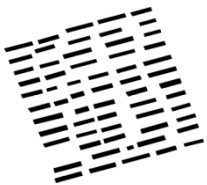
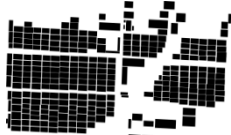
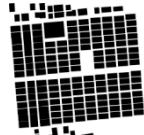
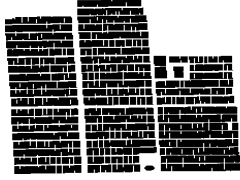
Jiangsu Plain is a typical cold climate zone bordering the northern boundary of the ‘hot summers, cold winters’ region, with distinct seasons characterised by cold winters and hot summers. In recent years, the annual average temperature has ranged from 13.2 °C to 14.8 °C, the annual average rainfall has ranged from 850 mm to 1000 mm, and the annual average relative humidity has ranged from 71% to 76%. In accordance with current national regulations, such as the ‘Energy-Efficient Design Standards for Rural Residential Buildings’ (GB/T 50824-2013) [36] and the ‘Jiangsu Provincial Energy-Efficient Design Standards for Rural Residential Buildings’ (DB32/4066-2021) [37], this study sets the indoor design comfort temperature for summer at 26 °C with a relative humidity of 40–65%, and the indoor design comfort temperature for winter at 14–16 °C with a relative humidity of 30–60%. This winter standard takes into account the specific energy consumption habits of rural China and the baseline requirements for low-carbon energy conservation. These meteorological benchmarks and industry regulations collectively constitute the boundary conditions for analysing how spatial forms, such as residential clusters and building-induced microclimates, affect residents’ heating and cooling energy consumption and carbon impact.

Large-scale dispersion and small-scale concentration: This pattern perpetuates the traditional village layout of the North Jiangsu plains. Residential buildings predominantly feature courtyard-style arrangements, clustered along main village thoroughfares or natural boundaries (such as ditches and field ridges). Each cluster comprises a small number of households (5–10 per group), forming a loosely structured yet internally ordered pattern. Building types are primarily one or two storeys in height.

Table 2. Case Studies of Residential Communities in the Northern Jiangsu Plain.

Type	Residential Community			
Widespread but localised				
	Anzhuang	Dizhuang	Ganzhuang Village	Kongzhuang Village
				
	Mengdian Village	Xuyuan Community	Jiuyaoqiao Community	Nanzhongshan Village
				
	Songzhuang Village	Menglou Village	Qianwuyan Village	Luwan Village

Table 2. *Cont.*

Type	Residential Community			
Clustered layout for new residential communities				
	Hanrun Garden	Kangzhuang Garden	Zijin Garden	Sunwa Resettlement Estate
				
	Wangzhuang	Shenjiang New Village	Guanhu Residential	Area Yangtun Community
Clustered layout				
	Dongyangqiao Community	Xiyangqiao Community	Xuwangzhuang Community	Shangzhuang
				
	Zhangjie Community	Kongzhuang New Village	Pengguantun Village	Zhou Tian Village

New Community Cluster Layout: Breaking from the traditional village layout, this approach uses unified planning to create large-scale, high-density residential clusters. Road networks adopt grid or chessboard patterns and feature centralised public facilities. Building types predominantly feature six storeys. **Clustered contiguous layout:** This approach is organised around the ‘community’ unit and integrates multiple residential clusters with public service facilities to form a hierarchical structure of ‘large community–small cluster’. This approach balances centralised and modular management, with predominantly one- to two-storey building types.

4.2. Data Sources

(1) Scope of carbon emissions accounting and underlying assumptions

Assumption of scope consistency: The scope of carbon emissions accounting for rural communities is limited to energy consumption associated with residents’ daily lives within the physical boundaries of the residential community. This includes energy consumption

arising from daily interactions and agricultural machinery travel derived from the community's structure. However, it excludes non-community-based carbon emissions resulting from field crop production, such as the use of pesticides and chemical fertilisers.

Assumption regarding the attribution of transport carbon footprints: Given the extremely high penetration rates of electric bicycles and new energy vehicles in rural northern Jiangsu, transport-related carbon emissions generated by villagers' daily travel (by car, electric bicycle, or short-distance walking) are internalised within the electricity consumption data of the local power supply office, provided the travel is powered by electricity. Emissions from motor vehicles fuelled by petrol or diesel are estimated via a sample questionnaire.

Spatial consistency assumption: It is assumed that energy availability for all households within the sample community is entirely consistent with the climate baseline and that differences in carbon emissions are driven solely by spatial patterns, which are then mediated by behavioural patterns.

(2) Formulas for calculating carbon emissions and sources of parameters

The spatial layout of the case study community was mapped based on field research and satellite imagery. A community's total carbon emissions are determined by the sum of the products of its consumption of the three main energy sources—electricity, liquefied petroleum gas (LPG) and petrol—and their corresponding carbon emission factors. As household energy consumption in the case communities is predominantly electricity-based, this study exclusively accounts for electricity-related carbon emissions. Electricity usage data represents total residential consumption within the communities and was obtained through direct interviews with the local power supply office serving the case villages. The electricity carbon emission factor references the 2022 electricity carbon dioxide emission factor published by EcoData, specifically the Jiangsu Province grid average emission factor of 0.5978 kg/kWh. The calculation formula is as follows:

$$C = E_e \times EM_i \quad (2)$$

In the formula, C denotes the carbon emissions generated by residential electricity consumption; E_e represents the total electricity consumption of the residential community; and EM_i signifies the carbon emission factor of the grid in the city's region.

5. Results

5.1. Carbon Emission Calculation for Case Study Communities

The results of the carbon emission calculations for domestic energy use in the case study communities (see Table 3) reveal distinct emission characteristics among the three types of rural residential communities in northern Jiangsu, as shown in Figure 2. Large-scale dispersed communities exhibit 'low-carbon living coupled with high transport emissions'; new-style communities display 'high-carbon living with low transport emissions' under high-density conditions; and contiguous clustered communities demonstrate 'moderate carbon emissions'. Of the three types of rural communities, dispersed, low-density communities exhibit the lowest carbon emissions due to their 'low-rise dispersion + mixed-use residential-commercial + diverse energy sources' model. Compact, contiguous communities follow with the next lowest emissions. Newly developed, concentrated communities have the highest emissions due to their 'urban-like form', but these remain lower than those of comparable urban communities.

Table 3. Total Domestic Carbon Emissions for Case Study Rural Communities.

Community Name	Yangtun Community	Hanrun Garden	Kangzhuang Garden	Zijing Garden	Shenjiang New Village	Sunwa Resettlement Estate	Guanhu
Carbon emissions	4685.84	4369.83	622.96	1997.93	1556.52	1237.38	100.73

Community Name	Wangzhuang	Dongyaoqiao Community	Xiyaoqiao Community	Xuwan Zhuang Community	Zhangjie Community	Shangzhuang	Kongzhuang New Village
Carbon emissions	448.10	688.44	1454.65	349.62	1602.17	114.22	321.88

Community Name	Pengguantun Village	Zhou Tian Village	Nanzhongshan Village	Menglou	Songzhuang Village	Luwan	Dizhuang
Carbon emissions	1012.20	826.56	952.49	930.39	788.15	2828.27	566.92

Community Name	Ganzhuang Village	Anzhuang	Xuyuan	Qianwuyan	Mengdian Village	Kongzhuang Village	Jiuyaoqiao Community
Carbon emissions	477.25	467.65	364.62	326.92	105.89	1256.69	1791.09

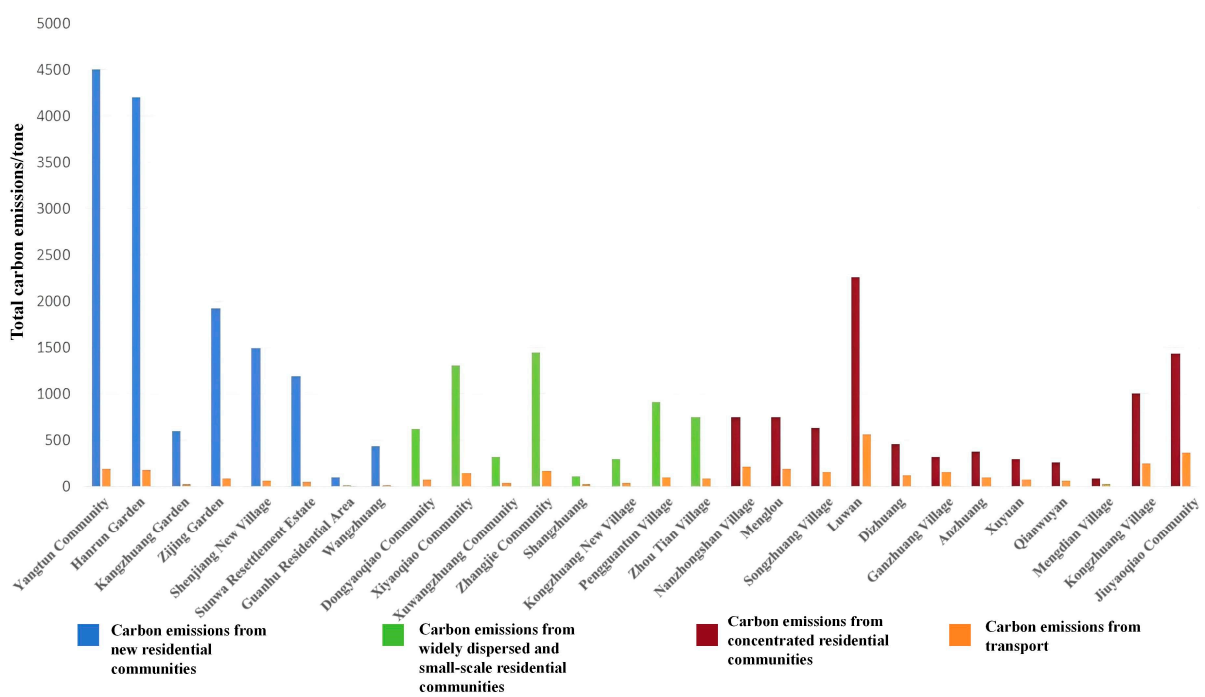


Figure 2. Comparison of carbon emissions in the case study community.

5.1.1. Large-Scale Dispersed, Small-Scale Concentrated Layout

Residential communities of this type have lower carbon emissions from domestic electricity consumption, but higher emissions from transport. These predominantly traditional communities retain conventional living practices, such as courtyard gardening and wood-burning stoves, thereby reducing electricity usage for air conditioning and lighting. However, the dispersed layout of these communities necessitates an extensive road network, resulting in average daily travel distances of 1–3 km. This increases reliance on electric tricycles and private vehicles, leading to higher carbon emissions from transport electricity consumption.

5.1.2. New Community Cluster Layout Type

Carbon emissions from residential electricity in new communities are significantly higher than in other areas. This is primarily due to building designs and lifestyles that

are more similar to those of urban dwellers, coupled with generally higher economic conditions among residents. The demand for air conditioning and lighting surges, resulting in electricity consumption that is 30–50% higher than in traditional layouts. However, these communities exhibit low transport-related carbon emissions. Field research indicates that such developments feature centrally located supermarkets and community centres, with average travel distances of 0.5–1 km. Daily needs can be met through walking or short-distance cycling, which significantly reduces transport-related electricity consumption.

5.1.3. Compact Clustered Layout Type

Residential communities of this type have medium levels of carbon emissions from domestic electricity consumption. This is primarily because they retain one or two storeys of traditional building forms, which preserve the advantages of natural ventilation and daylighting. This results in lower electricity consumption for air conditioning and lighting than in newer communities. Additionally, residents' lifestyles blend traditional and modern practices, leading to more carbon-efficient electricity usage patterns than in newer communities. Modular management of 'small clusters' ensures that public service facilities are evenly distributed across each cluster, thereby reducing residents' travel-related carbon emissions.

5.2. Analysis of Spatial Form and Carbon Emissions Correlation

(1) Partial Correlation Analysis

Using 16 candidate form indicators (X1–X16) as variables, alongside community per capita income level and community scale (X17, X18) as control variables, Pearson's correlation analysis examined the relationship between X1–X16 and community carbon emissions. Results are presented in Table 4 below. It can be observed that X2, X4, X5, X13, X14, and X16 exhibit relatively weak correlations with community carbon emissions. X9 shares similar connotations with X8 but demonstrates an even lower correlation. Consequently, the seven indicators with comparatively weaker correlations were excluded, and regression analysis was conducted using the remaining nine indicators.

Table 4. Results of Partial Correlation Analysis.

	LNX1	LNX2	LNX3	LNX4	LNX5	LNX6	LNX7	LNX8
Correlation	0.192	0.134	0.88	0.19	−0.092	−0.191	−0.252	0.784
Significance	0.347	0.515	0	0.354	0.654	0.351	0.213	0
	LNX9	LNX10	LNX11	LNX12	LNX13	LNX14	LNX15	LNX16
Correlation	0.319	0.481	0.788	−0.248	0.204	−0.107	0.751	0.152
Significance	0.112	0.013	0	0.223	0.318	0.601	0	0.457

To further examine whether multicollinearity existed among the remaining nine spatial morphological indicators, this study conducted variance inflation factor (VIF) and tolerance tests on these nine variables. The diagnostic results (as shown in Table 5) indicate that the VIF values for the nine spatial form indicators range from 1.35 to 13.98, with X1 and X3 having VIF values greater than 10 and tolerance values close to 0. This confirms the presence of multicollinearity among the rural residential community form indicators. As these two core indicators are crucial for characterising rural morphology, this study subsequently employed principal component analysis (PCA) to perform dimensionality reduction and information extraction on these nine indicators, thereby eliminating the interference caused by multicollinearity.

Table 5. Results of the Multicollinearity Analysis of the Variables.

	LNx1	LNx3	LNx6	LNx7	LNx8	LNx10	LNx11	LNx12	LNx15
Tolerance	0.075	0.072	0.737	0.601	0.326	0.41	0.54	0.462	0.474
VIF	13.32	13.98	1.357	1.663	3.071	2.437	1.852	2.162	2.111

(2) Principal Component Analysis

Log-transformed data were input into SPSS 22 for standardisation, a principal component analysis was performed on the driving factors after the effects of multicollinearity had been removed. The correlation matrix and results from analysing the nine related factors. The KMO value of 0.567 indicates acceptable information overlap between variables, principal component analysis is suitable for addressing the problem of multicollinearity. Through principal component analysis, four composite variables with the strongest explanatory power for the logarithmically transformed original variables were extracted, denoted as F1, F2, F3, and F4. These composite variables explain 83.84% of the variance in the original variables. The Sig value from the *t*-test was 0.000, indicating excellent model fit. From the component score matrix, the relationships between composite variables F1, F2, F3, F4 and the original variables are as follows:

$$F_1 = 0.059LNx_1 + 0.235LNx_3 - 0.018LNx_6 - 0.062LNx_7 + 0.237LNx_8 + 0.134LNx_{10} + 0.23LNx_{11} - 0.135LNx_{12} + 0.206LNx_{15} \quad (3)$$

$$F_2 = -0.199LNx_1 + 0.081LNx_3 - 0.484LNx_6 + 0.533LNx_7 - 0.001LNx_8 + 0.263LNx_{10} + 0.009LNx_{11} + 0.228LNx_{12} + 0.053LNx_{15} \quad (4)$$

$$F_3 = 0.019LNx_1 - 0.209LNx_3 + 0.478LNx_6 + 0.372LNx_7 - 0.104LNx_8 + 0.541LNx_{10} - 0.19LNx_{11} - 0.405LNx_{12} + 0.103LNx_{15} \quad (5)$$

$$F_4 = 0.891LNx_1 - 0.021LNx_3 - 0.112LNx_6 - 0.016LNx_7 - 0.034LNx_8 + 0.267LNx_{10} - 0.096LNx_{11} + 0.297LNx_{12} - 0.079LNx_{15} \quad (6)$$

The four composite factors extracted in this study represent different core dimensions of the spatial morphology of rural residential communities, as indicated by the distribution of scores in the principal component load matrix. Their substantive interpretations are as follows:

F1: spatial boundary regularity and fragmentation factors, whose core driving indicators include the overall shape index (X3), patch separation index (X8), road network shape index (X11), and road separation index (X15). Within the composition of F1, X3 and X11—which reflect the geometric complexity of patches and road networks—and X8 and X15—which reflect the degree of spatial fragmentation—all exhibit significant positive loadings. This indicates that this factor primarily characterises the ‘degree of disorderly sprawl and geometric irregularity’ in rural residential communities at both the macro and micro levels. In the Northern Jiangsu Plain region, a higher score for this factor implies that the spatial boundaries of villages are more fragmented and the road network is more disjointed. This directly leads to a substantial increase in the extension costs and energy consumption associated with the transmission and distribution of low-carbon infrastructure, such as water supply and sanitation networks.

F2, the residential spatial heterogeneity combination factor, is driven primarily by patch cohesion (X7, positive) and building connectivity (X6, negative). F2 exhibits a distinctive spatial dichotomy: patch cohesion (X7) exerts a strong positive pull, while building connectivity (X6) exerts a strong negative constraint. This accurately captures the heterogeneous spatial configuration of rural dwellings, characterised by ‘high internal cohesion and low external connectivity’. This reflects the typical ‘traditional dispersed’ or ‘clustered’ village patterns found on the Northern Jiangsu Plain, where individual residential clusters possess internal cohesion but the buildings are not as closely interconnected as those in

urban neighbourhoods. This configuration directly influences the microclimatic resilience of farmhouses and their heating energy consumption.

F3: The community micro-accessibility and functional mix factor comprises core driving indicators such as the number of road network patches (X10), building connectivity (X6) and the road patch proximity index (X12, negative). F3 is strongly influenced by the degree of internal road network segmentation (X10) and building connectivity (X6) while being negatively affected by the road proximity index (X12). From a planning perspective, this reflects the accessibility of the neighbourhood's internal capillary road network and the connectivity of residential public interfaces. A high score for this factor indicates an interconnected internal road network and good micro-accessibility. However, in the absence of appropriate spatial guidance, high accessibility may result in slow, circuitous vehicle movements, thereby exerting complex effects on residents' daily interactions and transport-related carbon emissions.

F4: The community scale and volume threshold factor, whose core driver is the number of patches (X1). This factor's composition is extremely straightforward, with the number of patches (X1) in the original indicators occupying an absolutely dominant position and carrying a weighting coefficient of 0.891. This indicates that F4 is a pure 'scale threshold variable', intuitively characterising the built-up area of rural residential communities and the basic scale of population concentration. In the empirical analysis, this factor will serve as the core basis for determining whether carbon emissions in rural northern Jiangsu are still dominated by absolute scale factors, such as 'energy-consuming population' and 'building stock'.

(3) Regression fitting

Ordinary least squares (OLS) multiple regression analysis was performed using SPSS, with carbon emissions ($\ln Y$) as the dependent variable and the four orthogonal composite variables F1, F2, F3 and F4—derived from principal component analysis with multicollinearity fully eliminated—as independent variables. The model's R^2 value is 0.837, the F-test value is 29.583 and the Sig. (p -value) is less than 0.01, indicating that the model fits well and the regression equation is statistically significant. Based on the model coefficients in the table, the composite variables F1, F2, F3 and F4 are statistically significant, with Sig. (p -value) below 0.01, indicating a satisfactory model fit and the statistical significance of the regression equation. The equations relating the composite variables F1, F2, F3 and F4 to the dependent variable are:

$$\begin{aligned} \ln Y = & 13.459 \ln X_1 + 13.782 \ln X_3 + 13.361 \ln X_6 + 13.459 \ln X_7 + 13.754 \ln X_8 \\ & + 13.537 \ln X_{10} + 13.772 \ln X_{11} + 13.484 \ln X_{12} + 13.696 \ln X_{15} \end{aligned} \quad (7)$$

According to the regression equation, X3, X8, X11 and X15 are highly correlated with total community carbon emissions (see Figure 3). It can be seen that both the X3 landscape shape index and the X8 landscape separation index are indicators of community building patch regularity. Higher values for these indices signify a more irregular overall community morphology and a larger land area. The X11 road network shape index and the X15 landscape dispersion index represent the shape and dispersion characteristics of the road network respectively. Higher values indicate more irregular and fragmented patterns in the road network. Consequently, for rural communities, the overall scale of the community exerts a more significant influence on carbon emissions. The compactness of the spatial layout has no effect on carbon emissions beyond the scale threshold, remaining within the positive correlation phase where a larger community scale correlates with higher carbon emissions.

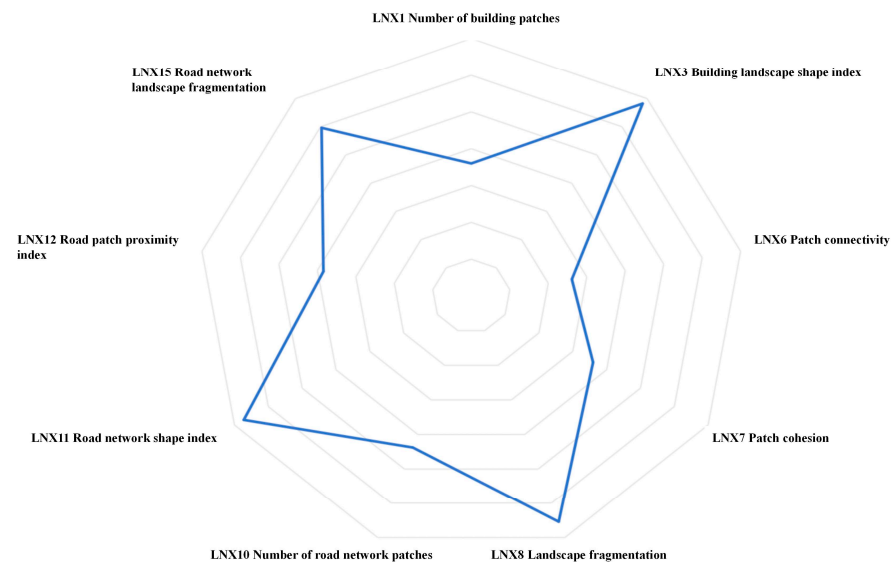


Figure 3. Radar Chart of Residential Community Carbon Emission Impact Factors.

5.3. Mechanism Analysis

5.3.1. Synergies Between Spatial Expansion and High-Carbon Behavioural Patterns

The positive impact of community size on carbon emissions is driven by the combined effects of spatial expansion, the use of high-carbon materials, and modern lifestyles. New, high-density community forms, while accommodating more residents, have profoundly altered existing energy consumption behaviours among villagers. The traditional rural community's mixed-energy model, characterised by wood-burning stoves and a limited number of electrical appliances, has been replaced by a purely electricity-based consumption model heavily reliant on modern household appliances during the process of spatial centralisation. This shift in energy consumption behaviour, triggered by the transformation of the physical environment, has significantly amplified the multiplier effect of carbon emissions resulting from spatial expansion.

5.3.2. Differentiation in Carbon Emission Mechanisms Across Different Types of Rural Communities

Significant heterogeneity in the carbon emission responses triggered by spatial expansion is evident across different types of rural communities, manifesting in three specific aspects:

(1) Strong positive coupling in newly formed concentrated communities: These communities consist of large-scale residential clusters developed under unified planning. They predominantly comprise lift-served residential buildings of six storeys or more, with plot ratios ranging from 1.5 to 2.0. The residents are predominantly non-agricultural, with a clear separation between production and living spaces. This urban-like physical form leads to residents' behaviour being highly dependent on commercial energy and motorised transport. The expansion of their physical scale is strongly coupled with modern, high-carbon behavioural patterns, resulting in a significant positive trend in total carbon emissions as the scale increases. In addition to the configuration of the internal road network within villages, connectivity with external urban-rural networks (such as neighbouring villages, towns and county centres) also profoundly impacts transport-related carbon emissions. Although the road networks within the villages of new communities generally adopted a 'consolidating and relocating scattered villages' model and are highly organised, leading to low internal transport emissions, the average radius over which villagers travel to their fields has increased by 1.5–3.0 km. Furthermore, the distance travelled to reach town centres and access public services has increased significantly, forcing villagers to switch

from walking or using electric bicycles to motor vehicles for their daily journeys. This spatial mismatch, characterised by ‘optimised internal connectivity but reduced external accessibility’, is a latent factor contributing to the rise in transport-related carbon emissions in new communities.

(2) Low-carbon resilience in highly dispersed and small-scale, concentrated communities

These communities consist of small clusters of five to ten households, predominantly located along field ridges or ditches. The buildings are mostly one- or two-storey courtyard-style dwellings. As the layout retains the spatial redundancy associated with agricultural production, residents are able to continue traditional practices such as courtyard gardening and cooking over wood-fired stoves. This results in an energy consumption structure that combines electricity and biomass energy. At the same time, the close integration of production and living spaces keeps daily transport needs to a minimum. Empirical evidence shows that when the number of households doubles, total carbon emissions increase by only 50–70%, demonstrating clear low-carbon resilience.

(3) Physical Scale Dominance in Concentrated, Contiguous Communities

These communities are formed by the integration of multiple natural villages. Although their geographical scale has expanded, they still retain the spatial foundation of traditional one- or two-storey dwellings. The residents remain predominantly agricultural, with relatively traditional lifestyles. As the energy-saving attributes of low-rise buildings, such as excellent natural lighting and ventilation, have not fundamentally changed, growth in their overall carbon emissions is primarily determined by the physical accumulation of buildings rather than a shift towards high-carbon lifestyles resulting from spatial transformation.

6. Conclusions and Discussion

6.1. Conclusions

This research investigated the relationship between the spatial forms and carbon emissions of three types of rural residential communities in the Northern Jiangsu Plain: newly developed concentrated communities; communities characterised by a mix of large-scale dispersion and small-scale concentration; and contiguous concentrated communities. The main conclusions of the study are as follows:

Firstly, the physical scale of the community is the dominant factor influencing carbon emissions. The overall scale of rural residential communities, such as the number of households and population density, has a significantly greater impact on carbon emissions than the compactness of their spatial layout. At the current stage of development, rural areas still exhibit a positive correlation where a larger scale leads to higher carbon emissions, and the mitigating effect of spatial compactness on carbon emissions has not yet surpassed the scale threshold.

Secondly, there is a clear difference in carbon emission characteristics between different types of rural community. Large dispersed communities and small concentrated communities exhibit low-carbon living patterns coupled with high transport emissions. Due to their extremely low carbon emissions from domestic energy use, their overall emissions are the lowest of the three community types. Newly developed concentrated communities exhibit high-carbon living patterns coupled with low transport emissions. Influenced by their urban form, their total carbon emissions are the highest, though still lower than those of comparable urban communities. The overall carbon emissions of contiguous concentrated communities fall between these two extremes, exhibiting moderate carbon emission characteristics.

Thirdly, developing low-carbon rural forms requires balancing traditional strengths with the integration of modern technology. Traditional low-rise cluster layouts have inher-

ent advantages in terms of low-carbon domestic energy consumption. However, local infrastructure integration is required to reduce energy transmission losses and transport-related carbon emissions resulting from spatially dispersed layouts. While modern, high-density residential models improve land use efficiency, their high energy consumption requires active offsetting through green, low-carbon technologies, such as building-integrated photovoltaics and smart grids.

6.2. Discussion

Understanding the mechanisms of rural carbon emissions requires an appreciation of the urban-rural disparities arising from structural transformation. The study found that rural communities experience a surge in carbon emissions driven by scale expansion, and that the low-carbon benefits of compactness have not yet been realised. This is in stark contrast to the mainstream academic conclusion that urban communities reduce transport-related carbon emissions through compact layouts. The core reason for this lies in the fundamental differences between urban and rural communities in terms of their morphological foundations and behavioural patterns. Rural communities, with their low-rise buildings and mixed-use development, have naturally cultivated unique low-carbon characteristics through long-term evolution, such as inherent energy efficiency in housing, short-distance travel and the use of biomass energy. In contrast, urban communities, constrained by high-rise, high-density development and strict functional zoning, are trapped in a high-carbon cycle characterised by high energy consumption and long-distance commuting. However, when rural areas transition to concentrated residential communities and replicate urban high-rise housing, the adoption of modern household appliances and severing of ties with traditional ways of life will cause the high-carbon lock-in effect to outweigh the energy-saving benefits of compact layouts. Consequently, low-carbon planning at county level must abandon the mindset of simply replicating urban compactness. It must respect and protect the unique spatial foundations of rural areas and avoid the loss of rural low-carbon characteristics resulting from residential concentration.

Based on the above analysis of these mechanisms, future low-carbon planning for rural areas must strike a balance between maintaining the continuity of the built environment and centralising facilities, while also adopting categorised, differentiated planning strategies.

(1) For villages characterised by a ‘highly dispersed, small-scale concentrated’ pattern, planners must avoid large-scale demolition and reconstruction when drawing up village plans. The focus should be on ‘slight boundary adjustments and enclosure by tree belts’, utilising the village’s existing greenery and courtyards to form windbreaks in winter. This will reduce the spatial shape index and enhance the intensity of infrastructure whilst preserving the traditional character.

(2) For villages comprising new community clusters: As such communities are prone to a sharp rise in transport-related carbon emissions due to ‘internal high density coupled with external agricultural isolation’, planners should define a reasonable 3-km farming radius and provide centralised parking areas for agricultural machinery and tool storage modules at the community periphery. They should also avoid extreme grid-pattern dead-end roads and establish a ‘highly connected micro-circulation’ capillary road network to minimise vehicle detours.

(3) For contiguous rural communities: Given the large scale of such communities, the key to carbon control lies in ‘functional clustering and integration’. Planners should strictly control their physical scale and tendency towards unchecked sprawl by adopting a hierarchical ‘large community–small cluster’ structure. Public service facilities (such as rural community centres and charging points) should be situated at core nodes within a 10-min walking radius to offset the increase in energy consumption resulting from expansion.

This study focuses on the Northern Jiangsu Plain. While it has revealed distinct inter-relationships within rural communities compared to urban areas and provided guidance on low-carbon planning in rural agricultural areas, the regional applicability of its conclusions still needs to be verified in rural communities situated in other geographical environments, such as mountainous and hilly regions. Future research could explore three areas in depth: the precise mechanisms by which micro-spatial factors influence residents' energy consumption and travel behaviour; the dynamic evolution of community form and carbon emissions; and the technical translation of planning practices. This would further refine the theoretical framework for low-carbon rural areas and inform the development of tailored planning strategies.

Author Contributions: Conceptualization, L.S.; Methodology, L.S.; Software, L.S.; Validation, L.S.; Formal analysis, L.S.; Investigation, L.S.; Resources, L.S.; Data curation, L.S. and J.C.; Writing—original draft, L.S.; Writing—review & editing, L.S. and J.C.; Visualization, L.S. and J.C.; Supervision, L.S. and J.C.; Project administration, J.C.; Funding acquisition, J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by “The Fundamental Research Funds for the Central Universities” (2024QN11085); Jiangsu Provincial Philosophy and Social Sciences Project (2025SJYB0789); Jiangsu Provincial Social Sciences Applied Research Excellence Program—Social Education (Social Sciences Popularization) Special Project (25SJC-13).

Institutional Review Board Statement: The present study involved the conduct of interviews with human participants. However, the data collected were anonymised, and no identifiable personal information was recorded. As stated in Chapter 3, Article 32 of the Measures for the Ethical Review of Life Science and Medical Research Involving Humans (National Health Commission of the PRC, 2023), this category of research, which employs anonymised information data, is not subject to ethical review. Consequently, ethical approval was not sought for this study.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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

References

1. Li, B.; Lu, Y.; Xia, R.; Zheng, J. Analysis of Trends in Carbon Emissions from Rural Energy Use in China and Key Influencing Factors. *Environ. Sci.* **2026**, *47*, 36–46. [[CrossRef](#)] [[PubMed](#)]
2. Lin, Y.; Chen, L.; Yang, X.; Wang, X.; Sang, Y.; Pan, Y. Spatiotemporal Variation in Carbon Effects of Village Land-Use Changes and Analysis of Influencing Factors: A Case Study of Jiangsu Province. *J. Ecol. Rural Environ.* **2026**, *42*, 41–55. [[CrossRef](#)]
3. Wang, X.R.; Chen, S.Q. Urban-rural carbon footprint disparity across China from essential household expenditure: Survey-based analysis, 2010–2014. *J. Environ. Manag.* **2020**, *267*, 110570. [[CrossRef](#)]
4. Song, L.; Chang, J.; Luo, P. Research Progress and Influencing Factors of Carbon Emissions from Rural Land Use. In *Chinese Society for Urban Planning, Hefei Municipal People's Government. Beautiful China: Co-Building, Co-Governing, Co-Sharing—Proceedings of the 2024 China Urban Planning Annual Conference (20 Rural Planning)*; China University of Mining and Technology: Beijing, China, 2024; pp. 168–180. [[CrossRef](#)]
5. Xu, F.; Yang, Q. A Review of Spatial Carbon Reduction Strategies for Rural Communities from a Multidimensional Perspective. *J. West. Hum. Settl.* **2024**, *39*, 129–136. [[CrossRef](#)]
6. Long, H.; Chen, K. Transformation of Rural Residential Forms and Spatial Governance in China's New Urbanisation Process. *Econ. Geogr.* **2024**, *44*, 12–21. [[CrossRef](#)]
7. Song, L.; Xu, F.; Sun, L.; Ang, M. Spatial Form Changes and Spatial Development Strategies in a Typical Suburban-Rural Integrated Community in Hunan Province. *Mod. Urban Res.* **2023**, *2*, 91–100.
8. Huang, Q.; Li, C.; Shen, S. Industrial Types and Spatial Layout of Characteristic Rural Villages in Northern Jiangsu. *J. Jiangsu Norm. Univ. (Nat. Sci. Ed.)* **2023**, *41*, 1–6. [[CrossRef](#)]

9. Yi, Y.C.; Ma, S.S.; Guan, W.J. Is a compact city low-carbon? *Urban Plan.* **2018**, *42*, 31–38+86.
10. Cheng, L.H.; Yang, X.M.; Wu, X.Y. Impact of urban compactness on carbon emission performance in the Yellow River Basin. *Arid. Land Geogr.* **2025**, *48*, 838–853.
11. Yue, W.; Zhang, L.; Qin, Y.; Wang, Y.; Liu, X. Nonlinear Driving Mechanism of Urban Spatial Form on Residential Energy Consumption Carbon Emissions in the Yellow River Basin. *Acta Ecol. Sin.* **2025**, *45*, 7052–7064. [[CrossRef](#)]
12. Bao, L.; Liu, Y. Spatiotemporal Evolution of Beijing's Urban Form under the 'Dual Carbon' Goals and Its Impact on Carbon Emissions. *Acta Ecol. Sin.* **2024**, *44*, 7507–7519. [[CrossRef](#)]
13. Yang, H.; Lu, X.; Kuang, B.; Hou, J. Spatiotemporal Interaction and Driving Factors of Urban Compactness and Carbon Emission Intensity: A Case Study of the Changzhutan Urban Agglomeration. *Resour. Environ. Yangtze Basin* **2021**, *30*, 2618–2629.
14. Tian, D.; Yang, S.; Guan, C.; Li, Y. Exploring the Correlation Between Urban Spatial Agglomeration and Residents' Living Carbon Emissions: An Analysis Based on Data from 110 Cities Nationwide. *Urban Plan.* **2023**, *47*, 76–85.
15. Teng, F.; Wang, Y.; Wang, M.; Li, S.; Lin, Y.; Cai, H. Spatiotemporal Coupling Relationship Between Urban Spatial Form and Carbon Budget in the Yangtze River Delta Urban Agglomeration. *Acta Ecol. Sin.* **2022**, *42*, 9636–9650. [[CrossRef](#)]
16. Sun, W.; Dai, J.; Liu, X.; Jie, W.; Cheng, W.; Li, X. Research on Commuting Carbon Emissions from the Perspective of Spatial Structure Patterns: A Case Study of the Guangdong-Hong Kong-Macao Greater Bay Area. *J. Urban Plan.* **2022**, *51*, 18–27. [[CrossRef](#)]
17. Xu, K.; Zhan, B.; Jiang, C.; Bao, H.; Su, J.; He, M. Optimising Urban Spatial Patterns Under Carbon Emission Constraints: Theoretical Framework, Indicator System and Practical Pathways. *Acta Natrum. Resur. Sin.* **2024**, *39*, 682–696. [[CrossRef](#)]
18. Niu, T.; Cui, X.; Liu, Y.; Zhen, T.; He, X. Optimization of County-Level Territorial Spatial Carbon Balance Zoning Based on the Evolution of Urban Spatial Morphology. *Environ. Sci.* **2026**, *47*, 3166–3177. [[CrossRef](#)] [[PubMed](#)]
19. Yang, L.; Li, G.; Lin, Y. Spatial Form Factors Influencing Urban Residents' Carbon Emissions. *Res. Urban Dev.* **2012**, *19*, 26–31.
20. Chen, S.; Cheng, L.; Wang, Z. Multi-scale Urban Form Optimisation Based on Low-carbon Ecological Principles: A Case Study of Shanghai's Beixinjing District. *Archit. Sci.* **2025**, *41*, 19–29+99. [[CrossRef](#)]
21. Feng, X.; Li, Y.; Wang, S.; Yu, E.; Yang, J.; Wu, N. Impact of Urban Form on Carbon Emissions under the 'Dual Carbon' Goals: A Case Study of the Yangtze River Economic Belt. *Environ. Sci.* **2024**, *45*, 3389–3401. [[CrossRef](#)] [[PubMed](#)]
22. Zhang, X.; Yang, H. Low-carbon renewal models for urban community living circles: An exploration based on facility layout typologies. *Urban Plan.* **2025**, *49*, 43–51+60.
23. Hu, S.; Wang, Z.; Xing, H.; Liu, K.; Liu, Y.; Li, J.; Zhang, G. Research on the Relationship and Influencing Mechanisms between Urban Road Network Form and Transport Carbon Emissions in China. *J. Geoinf. Sci.* **2025**, *27*, 1687–1703.
24. Qin, B.; Tian, H. Community Spatial Form Types and Resident Carbon Emissions: A Questionnaire Survey Based on Beijing. *Res. Urban Dev.* **2014**, *21*, 15–20.
25. Wang, W.; Li, J. A Study on the Correlation between Residential Density and Household Energy Consumption Carbon Emissions: The Case of Caoyang New Village in Shanghai. *Urban Plan.* **2017**, *41*, 83–91.
26. Li, S.; Hou, K.; Zhou, S.; Sun, J. Research on the Synergistic Optimisation of Residential Spatial Form and Carbon Emission Effects under Cold-Climate Microclimate Influences. *Shanghai Urban Plan.* **2024**, *4*, 31–39.
27. Guo, H.; Shu, P. Research Progress on Optimised Carbon Reduction Design for Micro-Living Spaces under the Dual Carbon Context. *Archit. Sci.* **2025**, *41*, 1–10+18. [[CrossRef](#)]
28. Wang, J.; Zhang, L.; Li, Y.; Cai, Z.; Wen, H.; Guo, Y.; Zhang, Z. Mechanism of Three-dimensional Spatial Form of Urban Blocks on Carbon Emissions. *Environ. Sci.* **2025**, *46*, 2921–2933. [[CrossRef](#)] [[PubMed](#)]
29. Liu, Z.; Li, Y. Relationship between Urbanisation and Carbon Emissions in the Changzhutan Region at County Scale. *Environ. Sci.* **2023**, *44*, 6664–6679. [[CrossRef](#)] [[PubMed](#)]
30. Yuan, Q.; Guo, R.; Leng, H.; Song, S. Study on the Impact of Spatial Form of Small and Medium-sized Cities in County-level Areas of the Yangtze River Delta on Carbon Emission Efficiency. *J. West. Hum. Settl.* **2021**, *36*, 8–15. [[CrossRef](#)]
31. Guo, R.; Wu, X.; Rui, F. Research on the Impact of Urban Spatial Compactness on Carbon Emissions: A Case Study of Changxing County. *J. West. Hum. Settl.* **2023**, *38*, 122–128. [[CrossRef](#)]
32. Song, L.; Xu, F.; Sheng, M.; Wen, B. The Relationship between Rural Spatial Form and Carbon Emission—A Case Study of Suburban Integrated Villages in Hunan Province, China. *Land* **2023**, *12*, 1585. [[CrossRef](#)]
33. Song, L.; Chang, J.; Yi, J. A Bottom-Up Carbon Emission Assessment Model for Carbon Emission Control at the Level of Rural Detailed Planning. *Land* **2024**, *13*, 1023. [[CrossRef](#)]
34. Li, X.; Lyu, X.; Shao, L. 'Community Carbon Reduction': Measurement Methods, Emission Characteristics and Implementation Pathways. *J. Urban Plan.* **2024**, *5*, 40–46. [[CrossRef](#)]
35. Liu, X.; Wang, L.; Zhu, S. Does Urban Sprawl Increase Household Residential Carbon Emissions? Evidence from Panel Data of Southern Chinese Cities. *J. Southeast Univ. (Philos. Soc. Sci. Ed.)* **2016**, *18*, 101–108+148. [[CrossRef](#)]

36. GB/T 50824-2013; Energy Efficiency Design Standards for Rural Residential Buildings. China Architecture & Building Press: Beijing, China, 2013.
37. DB32/4066-2021; Design Standards for Thermal Environment and Energy Conservation in Residential Buildings. Phoenix Publishing House: Nanjing, China, 2021.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.