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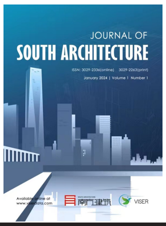

Construction and Spatial-Temporal Characteristic Analysis of the Carbon Atlas of Low-Carbon Villages in the Yangtze River Delta*

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ABSTRACT: Countryside is an integral part of China's social and economic systems. For a long time, the continuous growth of rural carbon emissions has led to a series of social, economic and ecological consequences. Carbon emission reduction has become a critical task for rural revitalization and sustainable development in China. Existing studies on low-carbon assessment mainly focus on urban areas, resulting in limited studies on rural areas. What's more, most of the planning strategies for low-carbon villages are also based on subjective evaluation and qualitative analysis, lacking support from quantitative simulation. Combining relevant theories, the concept of a rural "carbon atlas" was proposed in this study. The current rural carbon emissions and mathematics, graphics, and rationales of the temporal-spatial evolutionary characteristics were investigated using the GIS system as the technical platform for information storage and processing. The spatial domain of carbon emission units based on microscopic residential sites, factories and markets was defined and investigated. Carbon emissions of each unit were estimated according to energy consumptions for life, production and transportation. Later, carbon emissions were expressed and presented visually within the "atlas". Meanwhile, temporal and spatial distribution patterns of carbon emissions in various types of rural areas dominated by different industries were analyzed to provide resources and guidelines for building and planning low-carbon countryside and villages.

An empirical study was undertaken on four different village types dominated by different industries in the Yangtze River Delta. Results show that the rural carbon atlas has apparent characteristics of tendentious distribution, periodical changes, and typified structures: (1) Different village types have different regional tendencies of high carbon emission. This phenomenon is most evident in industrial villages, where most of the carbon emissions happen in large factories or family workshops with large homestead areas. Traditional fishing and agricultural villages are the least representative in this regard because rural industries are mainly small fishing and agricultural families, and the industrial link among families is weak. (2) Due to the industry's cyclical nature, the fluctuation of carbon emissions in different types of villages is significantly different. Since the leisure tourism industry is greatly affected by festivals and seasons, the carbon emissions in leisure tourism villages fluctuate the most. Carbon emission of professional markets is the most stable, which is attributed to their immunity to seasonal and climatic changes. (2) The rural carbon emission map has prominent typified structural characteristics, including the scattered homogeneous pattern (traditional fishing and agricultural village), the group infiltration pattern (industrial production village), the dissipative fragmentation pattern (leisure tourism village), and the kernel domain recursive pattern (professional market village). Different industrial types lead to noticeable regional differences in the temporal-spatial characteristics and trends of carbon atlas. Hence, there is an urgent need to develop an overall optimization strategy and mechanism model. The outcomes from the current study explore the method and practical application of a rural carbon emission atlas, yet more extensive research exploring various facets of the atlas are still required.

KEY WORDS: low-carbon villages; carbon atlas; spatial-temporal characteristic; the Yangtze River Delta

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Introduction

In the past few decades, China's rapid economic growth has been closely related to the growth of fossil energy consumption and carbon emissions. Statistics show that China's carbon emissions increased from 1.50 tons per capita in 1980 at the beginning of the reform and opening up to 10.12 tons in 2020[1], with an average annual growth rate of 6.58%. The rapid economic growth of nearly 10% per year came at the cost of resources and environment. China has already surpassed the United States as the world's largest carbon emitter, and there is a long way to go to achieve the Paris Agreement's goal of reducing carbon dioxide emissions by 60%-65% by 2030 compared to the figures from 2005[2].

Agriculture, farmers, and rural areas are important components of China's social and economic systems[3]. According to statistics, there are millions of villages and tens of thousands of townships in the country, with a large quantity and wide area. The resident population in rural areas accounts for 36.11% of China's total population[4], and the per capita GDP in rural areas accounts for about 1/4 of the country[5]. However, the society's acknowledgement of sustainable and low-carbon development in rural areas has always been insufficient, and investment in rural ecological protection and low-carbon development is relatively low. Increasing carbon emissions in rural areas have become an ecological issue that cannot be ignored. On the one hand, the current rural energy use model has formed a solid "carbon locking effect", and the technological locking and path dependence of energy use have led to "carbon degradation barriers". On the other hand, with the gradual infiltration, transfer, and agglomeration of urban "high energy consumption, high pollution, and high investment" industries from cities to rural areas, the total carbon emissions in rural areas have seen an "irreversible" growth [6].The continuous growth of rural carbon emissions has led to a series of social, economic, and ecological consequences, such as the deterioration of the agricultural ecological environment, the physical health of villagers being affected, and the intensification of urban-rural conflicts[7]. From this, it can be seen that rural construction in the low-carbon context is an inevitable trend and mission, and it is also an urgent demand for rural transformation and development under the "new normal". The low-carbon development of rural areas has also become an unfrivolous part of China's low-carbon process.

However, the current research on low-carbon ecological rural assessment and planning strategies mostly focus on subjective evaluation and qualitative analysis [8], lacking quantitative measurement of rural low-carbon development, and the evaluation indicators and planning strategies lack support from objective quantitative carbon emission data. At present, research on calculating greenhouse gas emissions in spatial regions using quantitative methods mainly focuses on the national, provincial, or city levels, with relatively little interest in smaller administrative units such as towns and villages[9]. The differences between urban and rural areas in China in terms of industry types, land layout, residents' lifestyles, and energy input methods make it difficult to effectively apply measures designed to measure urban carbon emission to rural evaluation, planning, and construction. Therefore, how to effectively identify the carbon emission characteristics of rural areas, construct a carbon emission evaluation model with regional suitability, and achieve a balance between sustainable development and carbon cycling is the focal point of current rural planning research and practice.

1 The current state of research on low-carbon villages and atlas studies

1.1 Theoretical research and empirical evidence of low carbon villages

From the perspective of historical development, the Danish low-carbon organization GAIA first proposed the concept of "low-carbon rural" in 1991 and clarified the three necessary conditions for low-carbon rural areas: low-carbon agricultural production supplies, advanced low-carbon planting and breeding technologies, and a diversified clean energy structure [10]. Afterwards, low-carbon rural practices were further expanded in other countries, and diverse characteristics were put forward: ① the "zero carbon emission" township communities in Beddington, UK [11]; ② The low-carbon rural construction strategy of "Green France" in France; ③ The ecological tourism development of Jeju Island's Seongeup Folk Village in South

Korea [12]; ④ The natural environment protection base in Hezhang Village, Shirakawa-go, Japan [13]. The research on low-carbon rural areas in China is still in its early stages, and there are still the drawbacks of being immature and unsystematic in the exploration of low-carbon rural areas. Representative examples include Wu Liangyong from Tsinghua University's pilot exploration of rural ecological living in Zhangjiang, Liu Jiaping from Xi'an University of Architecture and Technology's practice of rural indigenous architecture in Yunnan and other regions, and Wang Zhu from Zhejiang University's research on the traditional wisdom of green kiln dwellings on the Loess Plateau.

By consulting relevant literature, it can be found that research on low-carbon rural areas is gradually becoming a focus and hotspot in the academic community. Among them, quantitative research using mathematical methods mainly pursues the following directions: ① construction and evaluation of accounting models for rural carbon emissions [14, 15]; ② the spatio-temporal differences in and influencing factors for rural carbon emissions [16]; ③ the carbon spatial form and construction strategy of low-carbon rural areas [17]; ④ construction and practice of the evaluation index system for low-carbon rural areas [18]. The academic achievements of relevant scholars provide ideas and methodological references for research. However, existing research has paid less attention to issues at the level of individual rural areas. In fact, as the smallest administrative unit in China, the micro characteristics and spatial patterns of carbon emissions in towns and villages can serve as an important basis for formulating low-carbon control strategies. Therefore, there is an urgent need for targeted research and exploration on the micro spatial status of low-carbon rural areas and their influencing factors.

1.2 Concept of atlas and application of spatial atlas

Atlas is a systematic methodology that uses graphs, spectrum, and other methods to extract and express complex phenomena [19]. A graph is a representation of static features of an object, used to describe its current state; spectrum is a description of the dynamic laws of objects, reflecting the evolutionary process and the typified characteristics of spatiotemporal sequences. Tracing back to the source, atlas has been adopted in fields such as acupoint maps in medicine, gene maps in biology, spectra and spectroscopy in physics, all of which rely on graphs and spectra to analyze a series of complex phenomena and problems [20]. The concept of atlas was first applied to the study of spatial objects in Academician Chen Shupeng's book *Atlas Methodology for Geo-Information Science* published in 2001 [21], which used examples to reveal how to construct and apply spatial information altases with the support of spatial databases, and proposed concepts such as "hydrological atlas", "urban atlas", and "landscape atlas". Afterwards, the specific theory and application of spatial altas continued to evolve, mainly focusing on the following aspects: ① exploration of the concept and theoretical evolution of spatial atlas [22]; ② exploring the methods and expression patterns of spatial atlases [23, 24]; ③ exploring the regional practice and application strategies of spatial atlas [25].

Overall, although the theoretical system, method models, and practical applications of spatial atlas are relatively mature, they are rarely applied to the analysis of spatial patterns of rural areas or carbon emissions. On this basis, the concept of rural carbon atlas is innovatively proposed here, using geographic information systems (GIS) as a technical platform for information storage and processing. The current situation of rural carbon emissions and the characteristics of spatiotemporal evolution are explored mathematically, graphically, and causally, and reflected in spatial graphical expression, thus achieving intuitive analysis of the spatial pattern of rural carbon emissions (Figure 1).

2 Construction of carbon atlas model for low-carbon villages

2.1 Research sample selection and data sources

The Yangtze River Delta region has a large and extensive number of rural communities-over 3,100 of them-accounting for 9.4% of the total number of rural communities in China. This provides a large number of case samples for the research and practice of rural communities [26]. As a rural area with relatively complete infrastructure and industrial models, villages in the Yangtze River

Delta have significant regional characteristics such as diversified industrial models, modernization of construction technology, and urbanized lifestyles[18]. These characteristics make the trend of "high carbon" emissions in rural areas of the Yangtze River Delta increasingly obvious. Especially in recent years, the non-agricultural transformation of rural industries has led to the implantation of a large number of "high carbon emission" industries led by processing and manufacturing industries and leisure services into rural areas, resulting in a sharp increase in overall carbon emissions in rural areas and severe damage to the ecological environment.

Based on the different types of dominant industries in rural areas of the Yangtze River Delta, typical villages are selected as research samples according to theclassifications of traditional fishing and agriculture, industrial production, leisure tourism, and professional market[27]. The data sources involved in this study mainly include statistical data and field research. The statistical data mainly comes from the "Rural Energy Yearbook", environmental quality reports, online statistical databases, etc. Empirical data are collected through two methods: department visits and on-site research. Department visits refer to collecting data from the administrative departments where the villages are located. The content of on-site research can be divided into three parts: behavioral and cognitive surveys, spatial form surveys, and energy consumption surveys. (1) Behavioral and cognitive surveys record the daily production and living activities of villagers through questionnaires and interviews; (2) Patial form surveys clarify the unit boundaries of rural carbon emissions; (3) Nergy utilization and consumption survey combines a questionnaire survey with visits to administrative departments to obtain corresponding energy consumption data. The emission factor data of energy consumption data refer to the "IPCC Guidelines for National Greenhouse Gas Inventories" [28] and the "China Energy Statistical Yearbook" [29], while the electricity sector is based on the "China Regional Grid Baseline Emission Factors" [30].

2.2 Composition and calculation of carbon emissions

In rural areas, the process results of energy input, transfer, and output are ultimately reflected in the terminal composition of carbon emissions, which includes carbon emissions from domestic use (cooking, lighting, electrical appliances, heating), direct or indirect carbon emissions from industrial energy in functional spaces, and carbon emissions from transportation within and between villages [14] (Table 1).

(1) Measurement of carbon emissions from production and residential use: the 2006 IPCC National Greenhouse Gas Inventory Guidelines (referred to as the Guidelines) published by the Intergovernmental Panel on Climate Change (IPCC) established a basic framework system for carbon emission accounting [31-32].The Guide uses the product of ctivity ata and mission actors as the basic calculation formula for greenhouse gas emissions. The formula is as follows:

$$E_h = \sum_{i=0}^{n} \varepsilon_i \cdot E_i$$

Among them, E_h is the total emission of CO_2, and i is the i-th energy source, ε_i is the CO_2 emission coefficient of the i-th energy source, E_i is the consumption or usage of the i-th energy source, and n is the number of energy types.

(2) Calculation of transportation carbon emissions: mainly including internal and external transportation in villages. The calculation formula for carbon emissions of different transportation modes is:

$$E_w = \sum_{i,j} (C_{i,j} \cdot D_{i,j} \cdot P_{i,j})$$

The estimated E_w is the total carbon emissions calculated based on the distance traveled by the vehicle, where i represents the vehicle type (such as cars, motorcycles, etc.) and j represents the fuel type (such as gasoline, diesel, etc.). $C_{i,j}$ is the number of vehicles, $D_{i,j}$ is the number of kilometers traveled per year by each type of vehicle (km), $P_{i,j}$ are the average carbon emissions of the vehicle (kg/km).

In summary, the formula for calculating the total carbon emissions of rural residential units is:

$$E_t = E_h + E_w$$

2.3 Construction and generation of carbon atlas

(1) Clarifying the boundaries of carbon emission units. The units of rural carbon emissions include rural homesteads, factories, markets, etc., usually with clear spa-

tial boundaries. In addition, there is a common phenomenon in rural areas, which is the encroachment and use of public spaces in front and behind houses. Through on-site spatial morphology research, the specific usage of these semi-public spaces is clarified and incorporated into the carbon emission boundary [33] (Figure 2).

(2) Calculating unit carbon emissions. Based on the calculation method of carbon emissions, the carbon emissions of each unit was calculated, and a rural carbon emission database was established.

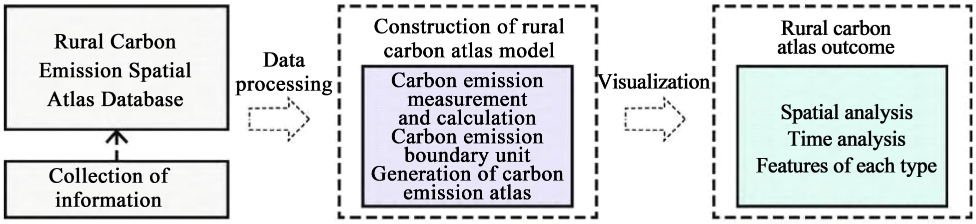

Figure 1 Schematic diagram of the generation process of rural carbon emission atlas

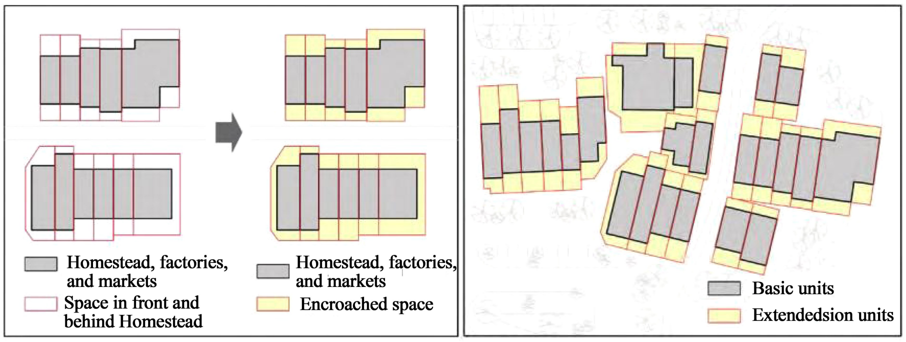

Figure 2 Schematic diagram of rural carbon emission unit boundaries

Table 1 List of energy consumption and carbon emissions in rural areas [14]

Energy usage type	Emission source	Activity level data
Daily energy consumption A	Consumption of commodity energy A_1	Electricity, heat, gas, and coalconsumption
	Consumption of straw and firewood A_2	Consumption of straw and firewood
	Biomass energy consumption such as biogas A_3	Biogas usage
Production energy consumption B	Fishing and agricultural production B_1	Electricity, diesel, and fertilizer usage
	Industrial production B_2	Electricity, heat, gas, coal, straw and firewood usage
	Tertiary industry B_3	The usage of electricity, heat, straw and firewood
Transportation energy consumption C	Private cars C_1	Gasoline and diesel usage

(3) Classification of carbon emissions data. Based on the carbon emission database, the mean and standard deviation of the data within each sample were calculated, and then a hierarchical graph distribution was performed: low carbon[min, mean standard deviation], low to medium carbon emissions (mean standard deviation, mean], medium to high carbon emissions (mean, mean + standard deviation], high carbon (mean + standard deviation, max], all mean and standard deviation are taken as integers.

(4) Carbonatlas generation. According to the classification of carbon emission data, different depth color blocks are used to calibrate rural units with different carbon emission levels [34], and ultimately form a carbon emission spatial atlas of the entire rural area (Figure 3).

3 Analysis of spatiotemporal characteristics of carbon atlas in low-carbon villages

3.1 "Tendency" distribution characteristics of carbon atlas

Relevant literature points out that industrial planning in cities and towns has a "top-down" characteristic. Generally speaking, the carbon emission spatial pattern of the secondary industry shows a significant increase from the inner circle to the outer circle, while the high carbon emission spatial pattern of the tertiary industry is mostly concentrated in the urban area. Therefore, the spatial distribution of carbon emissions in cities has a strong tendency and similarity. In comparison, the distribution of industries in rural areas often has a "bottom-up" spatial tendency, and the influencing factors of different industries in rural areas (such as rural roads, environmental resources, village patterns, etc.) differ significantly between villages, reflecting the different spatial distribution characteristics of industries in each village, as well as the different tendencies and agglomeration of carbon emission patterns. There are significant differences in the characteristics of carbon emission spatialatlas among the four types of rural areas, as follows:

Figure 3 Schematic diagram of the generation process of rural carbon emission atlas

(1) The carbonatlas of traditional agriculture and fisheries has a weak spatial "tendency" and no obvious high carbon regions. Almost every household in this type of rural areas is engaged in the fishing and agricultural industry, with similar industrial models and little impact from the location of homesteads, so the spatial differences in carbon emissions are not significant. Taking Lupu Village as an example (Figure 4-a), rural industries are mostly dominated by small fishing and agricultural households, with weak industrial links between each household. There are no large-scale production and processing factories, and therefore no obvious high carbon emission areas.

(2) The spatial "tendency" of the carbon atlas for industrial production is significant, and the morphology of high carbon emission regions is mostly clustered and blocky. There is a "industrial chain" dependency relationship between carbon emission units in this type of rural area, and some units will spontaneously form a "production alliance" that integrates manufacturing, processing, transportation and other functions [36]. Therefore, the industrial form often expands in a "imitative" manner within the cluster, and thus has a clear regional tendency. Taking Dazhuyuan Village as an example (Figure 4-b), high carbon emission areas appear near large factories or family workshops with large homesteads. At the same time, because the carbon emissions of each link in the "industrial chain" are different between high carbon emissions of rough processing in the early stage of bamboo processing and production and the relatively low carbon emissions of fine processing such as weaving in the later stage of production, the carbon emissions differences between households are also relatively significant.

(3) The carbon atlas of leisure tourism has a clear spatial "tendency", with high carbon areas concentrated near the sides of roads or landscape centers with convenient transportation. Due to the obvious dependency on tourist sources, the agglomeration effect of agricultural, fishing and foreigner-friendly resorts is significant. They are mostly distributed in areas with convenient transportation along the streets or in areas with better scenery, which can attract more tourists. Therefore, the carbon emissions of these areas are obviously higher. Units with weak accessibility and poor natural resources can only intermittently receive tourists during peak tourist seasons due to low passenger flow, resulting in lower carbon emissions. From the spatial distribution of Zhangluwan Village (Figure 4-c), the difference in carbon emissions decreases from the street to the interior of the village, and the difference between inside and outside is very obvious.

(4) The spatial "tendency" of the professional market-oriented carbonatlas is more obvious, with high carbon areas concentrated in the main streets or near the market. Commercial households are mainly distributed along the main street and both sides of the river in the settlement, and the cellular organization is characterized by linear aggregation. The large market is the "growth pole" of rural areas, which has a significant driving effect on the regional economy and living space. Taking Nanbei Lake Village

as an example (Figure 4-d), high carbon emission areas appear near main streets or markets, in the form of integrated units of shops and houses, while distant homesteads may only serve residential purposes, resulting in lower carbon emissions.

3.2 "Cyclical" variation characteristics of carbon atlas

The specific content and nature of rural industries determine the differences of periodic changes in energy consumption and carbon emissions, as well as the fluctuation of such changes:

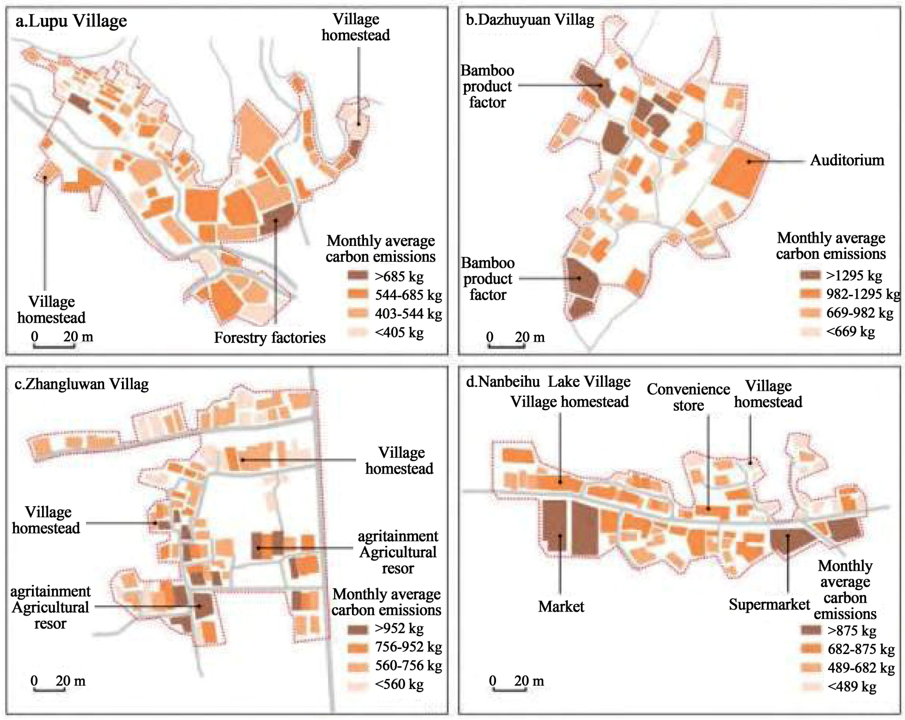

Figure 4 Carbon emission atlas of typical low-carbon villages

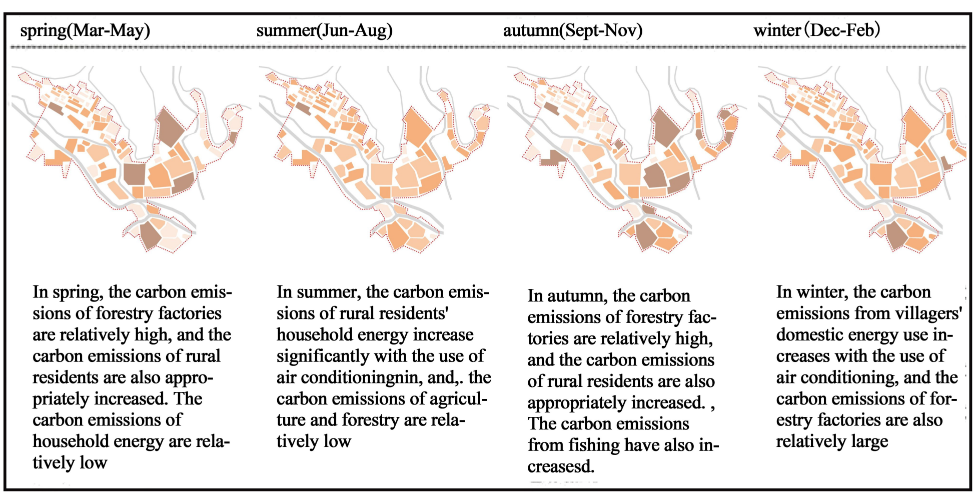

Figure 5 The "periodic" change characteristics of the carbon atlas in Lupu Village

(1) Traditional fishing and agricultural rural areas have the smallest total carbon emissions and less fluctuation. The carbon source composition of this type of rural area is mainly composed of rural residential energy, fishing and agriculture. The peak period of carbon emissions from agriculture and forestry is mainly concentrated in spring and autumn (planting and harvesting seasons), while the peak period of carbon emissions from fishing is from October to April of the following year (fishing season), and the low period is concentrated in May to September (non-fishing season). The peak period of carbon emissions from rural residential energy is concentrated in

summer and winter (Figure 5), and the overlap time of the three carbon emission peaks is short. Therefore, the overall fluctuation of carbon emissions is relatively stable, with a fluctuation range within 50% of the total. Meanwhile, due to the characteristics of the industry, its total carbon emissions are relatively low, and the carbon sink of green plants is significant, resulting in its total carbon emissions being the lowest among the four rural types.

(2) Industrial production oriented rural areas have the highest total carbon emissions and significant fluctuation. The carbon source composition of this type of rural community mainly includes industrial production, transportation energy, and domestic energy. Due to the allocation arrangement of industrial chain division of labor, there is a near-fixed pattern in the distribution of production in rural areas. In response to the increase or decrease in product demand and changes in order rhythm, production intensity will undergo certain periodic changes (Figure 6). The peak of carbon emissions is usually concentrated in summer (peak production season), while the low peak is in winter (off-season production), with fluctuations within 80% of the total. The total carbon emissions may vary significantly depending on the specific products produced and processed in different rural areas, but overall, they are still higher than other types of rural areas.

(3) The total carbon emissions of leisure tourism oriented rural areas are relatively large and have the highest fluctuation. The carbon source composition of this type of rural areas is mainly composed of service industry and transportation. Due to the significant impact of festivals and seasons on the leisure tourism industry, the fluctuation of carbon emissions is also the most significant, even reaching a fluctuation of 300%, exceeding the "critical value" that the environment can withstand. The peak is mostly concentrated in February (Chinese New Year), May (Labor Day), October (National Day), and winter and summer (Figure 7). Especially during the "Golden Week of Tourism" when lodging prices are rising, families not running agricultural, fishing and foreigner-friendly resorts make forays into these businesses. Therefore, the increase in carbon emissions will be very significant, and the carbon emissions at these two periods will even surpass those of industrial rural areas. The development of agricultural, fishing and foreigner-friendly resorts is accompanied by a large amount of high carbon emissions due to activities like cooking, barbecue, refrigeration and heating, and motor vehicle driving, resulting in a relatively large total carbon emissions in rural areas.

(4) The total carbon emissions of professional market oriented rural areas are relatively low and have the least fluctuation. The carbon source composition of this type of rural area is mainly composed of domestic energy and service industries. The periodic changes in carbon emissions of professional market-oriented enterprises are not significant, and the differences in production and operation conditions throughout the year are relatively small (Figure 8). However, there are also large-scale "trade fairs" and other activities that will sharply increase rural carbon emissions in the short term, with fluctuations ranging from 50% to 100%. For e-commerce villages such as Taobao Village, the stability of carbon emissions is higher and is basically unaffected by climate and season. Moreover, due to the fact that this type of rural areas mainly uses electricity, thermal energy, and transportation energy, its carbon emissions are not high, and the total amount is only about 1.3 to 1.5 times that of traditional fishing and agricultural rural areas.

3.3 "Typological" structural characteristics of the carbon atlas

Using GIS software for spatial data integration analysis of carbonatlas can more intuitively discover the spatial typological structural characteristics of their carbon emissions:

(1) Cluster-based infiltration pattern: industrial production-oriented rural areas can reduce commuting consumption and improve the efficiency of public supporting facilities and services through moderate concentration, infiltration, and scaling of production and operation.

From an empirical perspective, a large number of industrial "small production" clusters rely on transportation and river economic lines, forming a concentrated and dense clustered spatial form. When reflected in the carbon spatialatlas (Figure 9-A), there are obvious carbon emission centers in rural areas, gathering a large number of high carbon emission units. At the same time, high carbon emission areas have a trend of infiltration and expansion along secondary transportation lines.

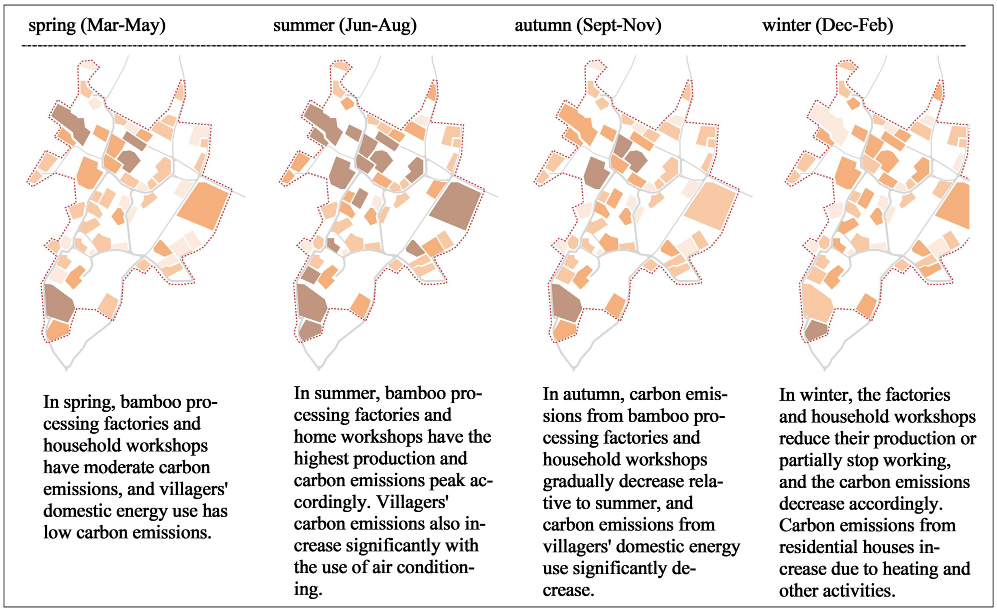

Figure 6 The "periodic" change characteristics of carbon atlas in Dazhuyuan Village

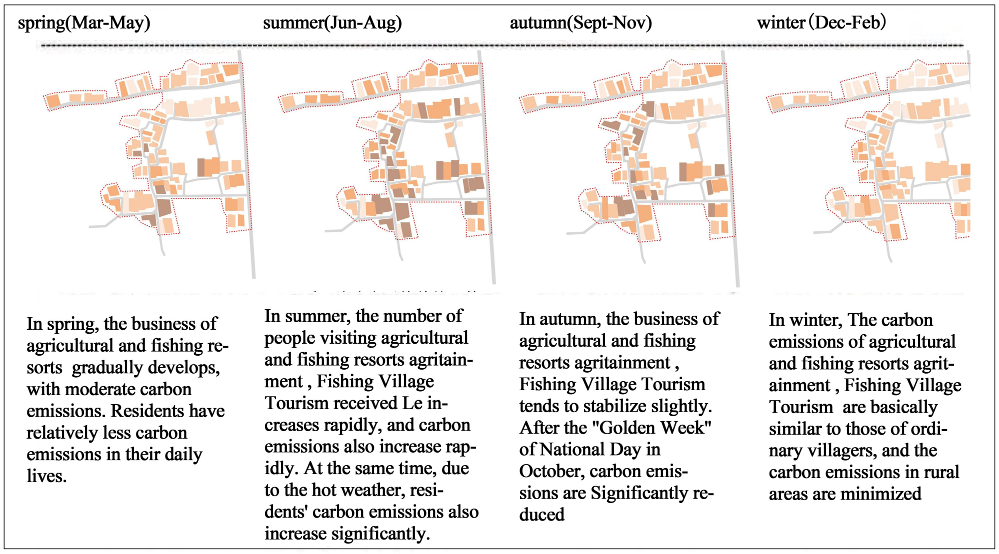

Figure 7 The "periodic" change characteristics of carbon atlas in Zhangluwan Village

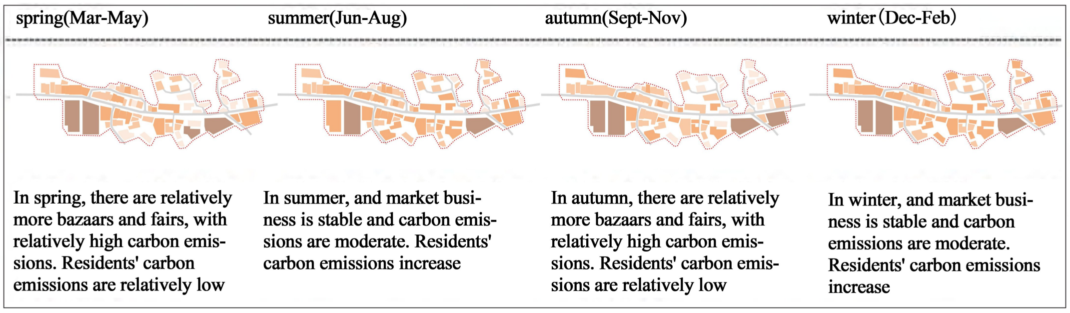

Figure 8 The "periodic" change characteristics of carbon atlas in Zhangluwan Village

(2) Dissipative fragmentated pattern: Due to the high spatial distribution of "transportation dependence" among agricultural, fishing and foreigner-friendly resorts, the carbon atlas structure characteristics of leisure tourism orien-

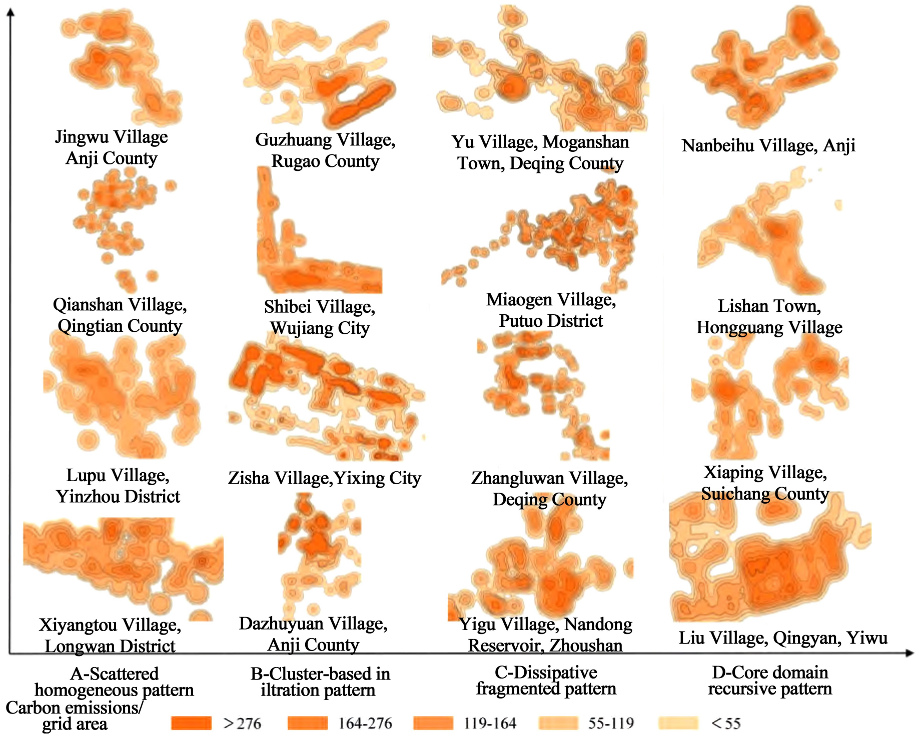

Figure 9 The "typified" structural characteristics of rural carbon atlas

ted rural areas are obvious. According to Figure 9-B, the peak carbon emission areas of this type of rural areas are mostly concentrated at the intersection of "road network" and "river network", and there is a trend of outward extension and expansion [37]. However, due to the fact that most of the business owners of agricultural, fishing and foreigner-friendly resorts are self-built or renovated by villagers without clear spatial planning, they are mainly distributed in rural areas in a scattered and dissipative manner. Therefore, the high carbon emission concentration areas of the carbon emission atlas also exhibit a pattern of being "small, scattered, and fragmented".

(3) Core domain recursive pattern: in professional market-oriented rural areas, large commercial markets are often used as the core domain to coordinate surrounding commercial and residential villages. The core new area formed by industrial alliances and transaction clusters is based on a single or several economic centers, with outward divergent growth and recursive dissemination (Figure 9-C). Analysis shows that high carbon emission cells are concentrated near the comprehensive market and transportation main roads and form a "core domain" of high carbon emissions within a range of 2-5km. The farther away from the "nucleus domain", the lower the carbon emissions of the village, and the overall rural area features a "radial" carbon emission spatial structure.

Conclusion

The construction of low-carbon rural areas is an important component of green and sustainable development in society and economy. Establishing a spatial pattern method that can quantitatively evaluate rural carbon emissions can help government decision-makers, designers, and even the public strike the balance point between low-carbon emissions and life and production. It is an important basis for rural planning, improvement, and revitalization based on the low-carbon premise. The study provides a technical method that takes small and micro rural units as the research subject, takes carbon emissions generated by energy consumption in daily life and production as the research object, uses geographic information system platforms as research support, and uses carbon emission atlas as research tools. Finally, through the practical application of four different industrial types of rural areas in the Yangtze River Delta, the spatiotemporal characteristics of the carbon atlas were obtained: ① different types of rural areas have different tendencies towards high carbon emissions, with industrial production rural areas being the most significant and traditional fishing and agriculture rural areas being the least significant; ② due to periodic changes in industries, there are significant differences in the fluctuation of carbon emissions among different types of rural areas. Leisure tourism-oriented rural areas have the highest fluctuation, while professional market-oriented rural areas have the lowest fluctuation. The carbon emission atlas of rural areas has obvious structural characteristics of "typification", including scattered homogeneous pattern in agricultural and fishing areas, cluster-based infiltration pattern in industrial areas, dissipative fragmented pattern in leisure tourism areas and core domain recursive pattern in professional market-oriented areas.

The study only provides a preliminary exploration of the methods and practical applications of rural carbon emission atlas, and there are still many research directions that can be extended [38, 39]: ① multiple dimensions of the carbon atlas (spatial, temporal, and spatiotemporal combinations); ② multiple types of carbon atlas (symptoms, diagnosis, implementation); ③multi-level hierarchy of carbon atlas (macro-, meso-, and microscope). In addition, the study may also focus on the characteristics of per capita carbon emissions, ground average carbon emissions, and time average carbon emissions in rural areas, and pay attention to the efficiency analysis of "time-space-individual" carbon emissions as a development and extension of the study. Of course, this requires a long-term accumulation and will be the focus of future research. Due to space limitations, various details and data in the study cannot be fully elaborated. This study is only used as an academic starting point to provide ideas and references for other scholars' related research.

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Figure and table sources

The figures and tables in the text were all drawn by the author.

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