

Research on Typology Identification for Low-Carbon Development of Rural Settlements Based on the “Morphology-Size-Function” Framework: A case study of Longxi County

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ABSTRACT

Exploring the spatial configuration of rural settlements for low-carbon development is of great significance for addressing global climate change and promoting sustainable urban-rural transitions. It also constitutes a critical component in achieving China's "Dual Carbon" goals. Existing studies predominantly focus on the singular dimensions of morphology, size, or function, which limits their capacity to address the complex demands of systemic decarbonization in rural areas. Taking Longxi County, a typical loess hilly-gully region on the Loess Plateau, as a case study, this research constructs a three-dimensional analytical framework integrating "Morphology, Size, and Function". By employing spatial analysis, K-means clustering, this paper examines the evolution of rural settlements from 2000 to 2020. The results indicated a trend of agglomerative restructuring in settlement morphology, evolving from scattered points to clustered patches. Settlement sizes were characterized by polarization towards large villages and decline of small ones, while functions transitioned from production-dominated to diversified. Both total carbon emissions and emission intensity increased significantly, forming "high-carbon corridors" along transportation arteries and "high-carbon poles" in valley areas. $M_2-S_1-F_4$ and $M_3-S_1-F_4$ types demonstrated relatively superior low-carbon performance, whereas $M_2-S_1-F_2$ and large-scale settlements exhibited higher emissions.

KEYWORDS

"Morphology-Size-Function"; Rural settlements; Low-carbon development; Typology

1. INTRODUCTION

Global climate change represents a common challenge confronting human society, and advancing the low-carbon transition has emerged as both an international consensus and a core policy priority (UNFCCC, 2015). From the Paris Agreement to the United Nations Sustainable Development Goals (SDGs), and the scientific warnings articulated in Intergovernmental Panel on Climate Change (IPCC) reports, a series of international conventions and initiatives have consistently emphasized the imperative of integrating climate mitigation and adaptation fully into local development practices (United Nations, 2015). This underscores the urgency of accelerating low-carbon governance worldwide. Within this context, rural areas have become a focal point of international academic inquiry and policy attention, given their dual role as significant sources of carbon emissions and reservoirs of substantial carbon sink capacity and renewable energy potential (Ministry of Agriculture and Rural Affairs, 2023).

International research on rural low-carbon development generally focuses on the intersection of global climate change mitigation and sustainable rural development, concentrating predominantly on energy transitions (Piwowar and Dzikuc, 2019), industrial restructuring (Liu et al., 2025), community participation (Tang et al., 2022), and policy innovation (Wang et al., 2025b). Studies have addressed topics including economic assessments of distributed renewable energy (Furmankiewicz et al., 2021), diffusion of low-carbon agricultural technologies (Singh-Peterson et al., 2025), and community-based carbon emission management mechanisms (Saah et al., 2014). Research on settlement spatial characteristics typically adopts perspectives from geography, planning, and ecology, examining how spatial attributes such as settlement morphology, size expansion, and land use influence transportation energy consumption, building energy efficiency, and ecosystem carbon sinks (Stefano and Manzini, 2019; Creutzig et al., 2015; Gaur et al., 2024; Chen et al., 2022b). Nevertheless, systematic investigations into the relationships between rural settlement spatial patterns and carbon emissions remain relatively limited. Existing contributions predominantly concentrate on specific regions such as urban-rural fringes (Stefano and Manzini, 2019; Wen et al., 2023), and a universally applicable analytical framework has yet to emerge.

Domestic research closely aligns with China's "Dual Carbon" goals and the national rural revitalization strategy. Within the domain of pollution and carbon reduction synergies, studies have established theoretical frameworks, technical systems, and implementation pathways for territorial spatial planning oriented toward synergistic effectiveness (Zeng et al., 2025), while also revealing the mechanisms through which digital rural construction enables agricultural carbon emission reduction (Ren et al., 2025). Concerning the realization of ecological product value, researchers have measured spatiotemporal evolution characteristics of coupling coordination among rural "ecological-economic-social" systems in Zhejiang Province (Wang et al., 2025a). Green finance research has not only validated theoretical mechanisms and policy effectiveness in supporting rural revitalization (Wu et al., 2023) but also explored construction models for "carbon neutrality-new rural villages" utilizing distributed photovoltaic systems (Ye et al., 2021). Low-carbon rural spatial design has generated design strategies and evaluation methods encompassing the Yangtze River Delta region (Fan, 2017; Wu, 2016; Bin, 2020) and Northwest China (Liu, 2016; Fan et al., 2023; Zhao, 2019). Research on settlement spatial characteristics has progressively revealed spatiotemporal evolution patterns of rural settlements (Song and Li, 2020), proposed spatial optimization models for settlements in ecologically fragile areas (Yin et al., 2023), elucidated contributions of settlement consolidation to sustainable development (Yanbo et al., 2021), and identified spatial reconstruction pathways based on livability considerations (Ma et al., 2022). These achievements signify that research has advanced from thematic enumeration toward mechanism revelation, model construction, and spatial optimization.

2. MATERIALS AND METHODS

2.1. Study Area

Longxi County is situated in the southwestern Loess Plateau (104°18'–104°54' E, 34°50'–35°23'N), representing a typical loess hill and gully landscape region (Fig.1). The terrain is characterized by fragmented topography with undulating variations, averaging approximately 2000 meters above sea level, which substantially constrains the spatial expansion and morphological evolution of rural settlements. Covering a total area of approximately 2408 km² and administering 10 towns and 7 townships, Longxi County exemplifies traditional rural settlements influenced by Qin-Long culture. Through long-term human-land co-evolution, this area has developed rural settlement spatial patterns with distinctive regional characteristics. Constrained by natural conditions, relatively peripheral geographical location, and lagging development policies, rural settlements collectively confront challenges of insufficient vitality and sluggish growth.

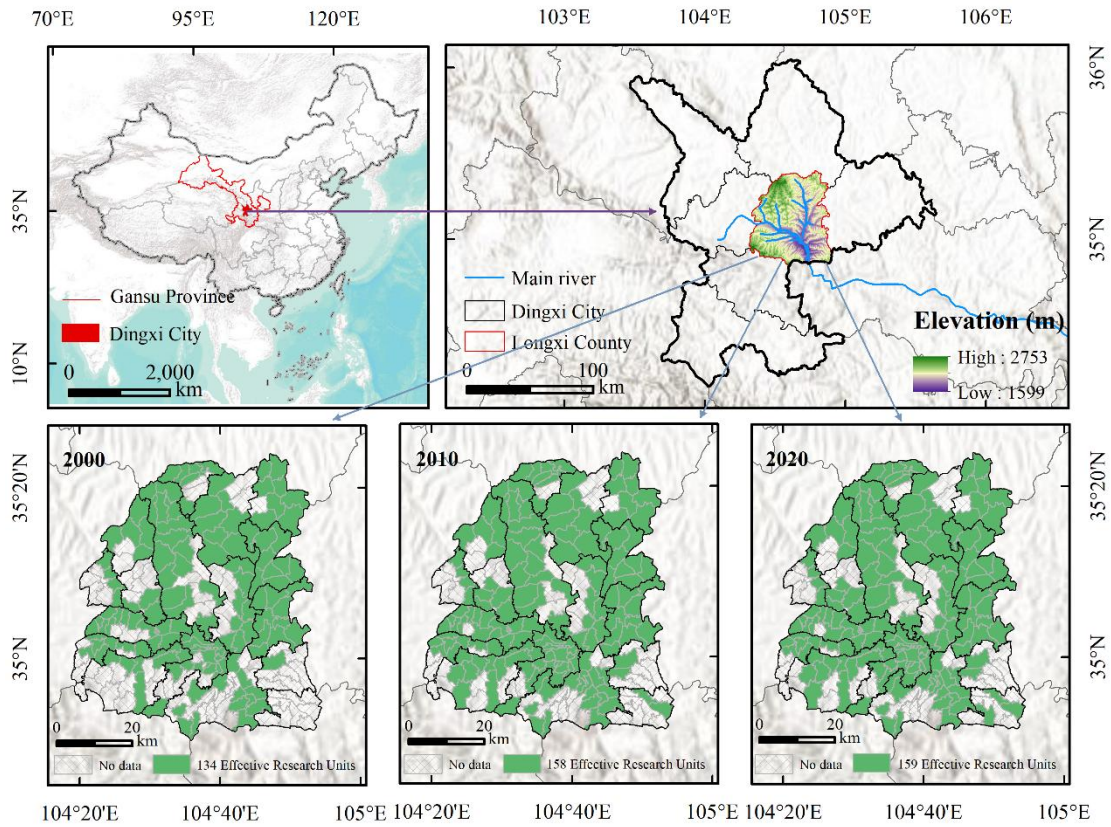


Figure 1. Location map of the study area and valid analysis units of rural settlements

2.2. Data Sources and Processing

The data utilized in this study encompass geospatial data, remote sensing imagery data, socioeconomic data, and carbon emission data (Table 1).

Table 1. Description of data used in this study

Data Category	Data Type	Source	Temporal Coverage
Geospatial data	Rivers	Geospatial Data Cloud Platform (http://www.gscloud.cn/)	2020
	Administrative boundaries at various levels	Resource and Environmental Science Data Platform, Chinese Academy of Sciences (http://www.resdc.cn)	2000, 2010, 2020
Remote sensing imagery data	Land use	Resource and Environmental Science Data Platform, Chinese Academy of Sciences (http://www.resdc.cn)	2000, 2010, 2020
	Digital Elevation Model	Geospatial Data Cloud Platform (http://www.gscloud.cn/)	2020
Socioeconomic data	Population	Resource and Environmental Science Data Platform, Chinese Academy of Sciences (http://www.resdc.cn)	2000, 2010, 2020
	GDP	Resource and Environmental Science Data Platform, Chinese Academy of Sciences (http://www.resdc.cn)	2000, 2010, 2020
Carbon emission data	China carbon emission data	RStudio Data Center (https://tidyfriday.cn/rsdb2/)	2000, 2010, 2020

2.3. Research Method

2.3.1. Indicator System Construction

Based on the “Morphology-Size-Function” analytical framework, this study selected nine primary indicators and fifteen secondary indicators across the three dimensions to construct a comprehensive evaluation system for rural settlements. (Table 2-4).

Table 2. Indicator system for rural settlement morphology

Target Layer	Indicator Layer	Indicator Description	Calculation Formula
Morphology	LSI	Measures the complexity of settlement patch shapes	$LSI = \frac{E}{4\sqrt{A}}$
	MPI	Measures the spatial aggregation degree of settlement patches	$MPI = \frac{\sum_{i=1}^n \left(\frac{a_{ij}}{h_{ij}^2} \right)}{N}$
	PD	Measures the fragmentation degree of settlement spatial distribution	$PD = \frac{N}{A}$

Table 3. Indicator system for rural settlement size

Target Layer	Criterion Layer	Indicator Layer	Indicator Description	Calculation Method
Size	Land size	CA	Reflects the spatial scale of settlements	Calculated using FRAGSTATS
	Population size	VTP	Reflects the degree of population aggregation	Extracted from 100 m × 100 m population raster data of China using village boundary vectors
	Economic size	VGDP/A	Reflects economic activity intensity	Extracted from 1 km × 1 km GDP raster data of China using village boundary vectors

Table 4. Indicator system for rural settlement function

Target Layer	Criterion Layer	Indicator Layer	Indicator Description	Indicator Attribute	Weight		
					2000	2010	2020
Function	Production function	CI	Cultivated land area within village / Total village area	+	0.130	0.125	0.120
		CLPC	Cultivated land area within village / Total village population	+	0.120	0.115	0.110
		GEO-V	Extracted from 1 km × 1 km GDP raster data of China using village boundary vectors	+	0.135	0.145	0.150
	Living function	TA	Straight-line distance from each administrative village to the nearest main road	-	0.090	0.100	0.110
		VPD	Total village population / Total village area	+	0.100	0.105	0.110
		RRAPC	Rural settlement area within village / Total village population	+	0.095	0.100	0.105
	Ecological function	GCR	Forest and grassland area within village / Total village area	+	0.110	0.120	0.130
		WSR	Water area within village / Total village area	+	0.080	0.075	0.070
		EV	Maximum elevation within region - Minimum elevation within region	-	0.140	0.115	0.095

2.3.2. Functional Evaluation Method

(1) Functional index. All evaluation indicators were normalized using the extremum method, indicator weights were determined using the CRITIC weighting method, and the functional values of each village were calculated through weighted summation (Yang et al., 2021). The formula is as follows:

$$S_i = \sum_{j=1}^m X'_{ij} W_j \quad (1)$$

Where: S_i represents the functional index of the i -th administrative village, with values ranging from 0 to 1 (higher values indicate stronger functionality); X'_{ij} represents the standardized value of the j -th evaluation indicator for the i -th administrative village; m represents the number of indicators; and W_j represents the weight of the j -th indicator.

(2) Dominance. Based on the relationship between each functional value of the research unit and the mean value of that function category, whether the function constitutes a dominant function was determined. The formula is as follows:

$$C_j = d_{ij} - \frac{d_j}{n} \quad (2)$$

Where: C_j represents the difference between the j -th functional value of each administrative village and the mean value of that function. If $C_j > 0$, then this function is identified as a dominant function; if $C_j \leq 0$, then this function is identified as a non-dominant function.

(3) Classification of dominant function types. Based on the identification results of dominant functions, each rural unit was classified into dominant function types as follows: units with only one dominant function were defined as single-function dominant type; units with two or more dominant functions were defined as comprehensive development type; units with no dominant functions were defined as balanced development type.

2.3.3. K-means

The K-means clustering algorithm (Wang and Bai, 2016) was employed to identify comprehensive MSF types of rural settlements. The objective function minimizes the Sum of Squared Errors (SSE) within clusters:

$$J = \sum_{k=1}^k \sum_{x_i \in C_k} \|x_i - \mu_k\|^2 \quad (3)$$

Where: k represents the pre-determined number of clusters; C_k denotes the set of samples belonging to the k -th cluster; μ_k represents the centroid of the k -th cluster, namely the mean vector of all sample features within that cluster; and $\|x_i - \mu_k\|$ typically refers to the Euclidean distance, measuring the dissimilarity between sample x_i and its cluster centroid μ_k .

2.3.4. Kruskal-Wallis H test

To examine whether significant differences exist in the distribution of carbon emission ranks among rural settlements of different comprehensive MSF types, this study employed the Kruskal-Wallis H test (Bhattacharyya, 2014). This non-parametric method is suitable for comparing medians across three or more independent groups and does not require the data to satisfy normality assumptions.

H_0 : The distribution of carbon emission ranks is identical across all comprehensive types.

H_1 : At least one type has a different distribution of carbon emission ranks.

3. RESULTS AND ANALYSIS

3.1. Spatiotemporal Evolution and Clustering Types of Multidimensional Characteristics of Rural Settlements

3.1.1. Morphology

During 2000-2020, the morphology of rural settlements in Longxi County underwent significant stage-based evolution, exhibiting an overall spatial restructuring characterized by a transition from dispersion to agglomeration (Fig. 2). In 2000, rural settlements were predominantly characterized by scattered morphology, widely and sporadically distributed across the loess hill and gully region. By 2010, settlement morphology had undergone a marked transformation, with strip-shaped settlements expanding rapidly along river valleys and major transportation arteries, forming longitudinal spatial

corridors connecting urban and rural areas. By 2020, clumped settlements had emerged as a significant morphological type, with their proportion increasing substantially and forming high-density clusters in the Weihe River valley plain and surrounding areas of the county seat and key towns.

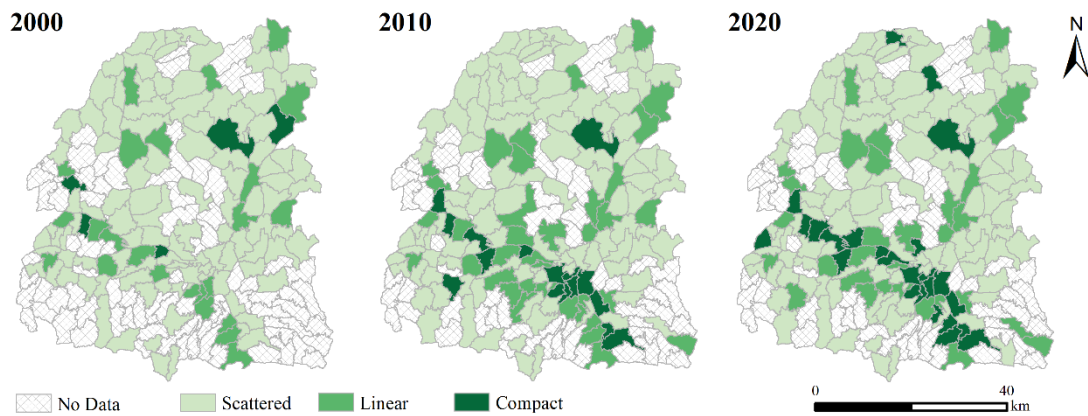


Figure 2. Spatiotemporal evolution of rural settlement morphology

3.1.2. Size

During 2000-2020, the size system of rural settlements in Longxi County exhibited significant spatiotemporal differentiation and polarization trends across the three dimensions of land, population, and economy (Fig. 3). Regarding land size, high-value areas transitioned from scattered distribution in 2000 to gradual agglomeration in the convergence zone of the Weihe and Xianhe Rivers, ultimately forming a distinct valley cluster pattern by 2020. The spatial pattern of population size evolved from a relatively dispersed state in the early period to a “dual-nucleus agglomeration” pattern centered on the 10-kilometer peri-urban ring, with population growth hotspots markedly concentrating around towns. The high-value areas of economic size expanded substantially, with their proportion increasing from 12% in 2000 to 39% in 2020. Spatially, a “traditional Chinese medicine industry corridor” formed along transportation arteries, with economic strongholds emerging at major transportation nodes, while low-value areas progressively retreated to peripheral regions with inconvenient transportation. Comprehensive size type analysis indicates that, during the study period, the number of large-scale settlements increased and were predominantly distributed in a pattern along river valleys and transportation axes, whereas the proportion of small-scale settlements correspondingly declined. These overall exhibits a polarized development trajectory characterized by the agglomeration of development elements toward large villages with advantageous location and resource conditions, accompanied by the systemic decline of peripheral small villages.

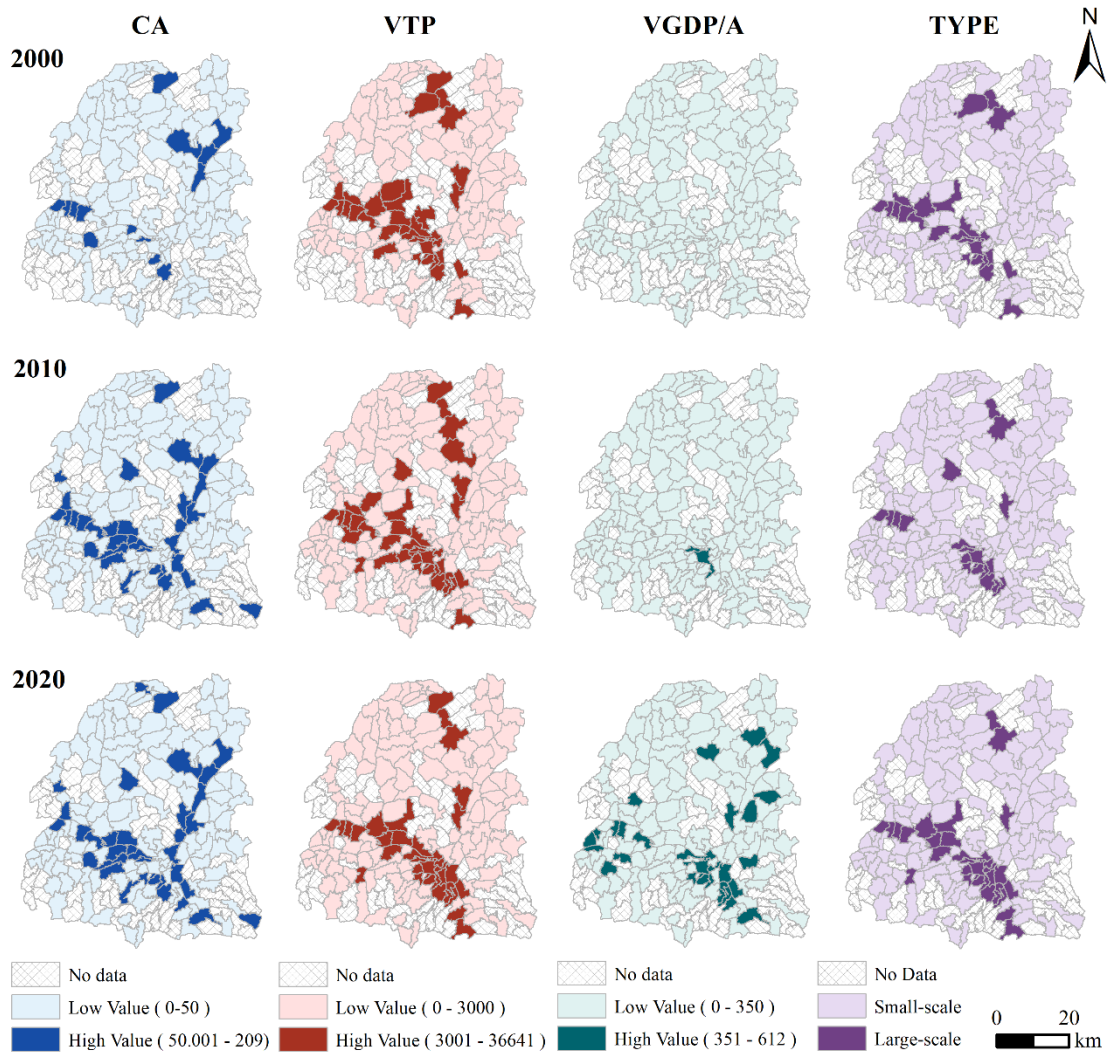


Figure 3. Spatiotemporal evolution of rural settlement size

3.1.3. Function

During 2000-2020, the production, living, and ecological functions of rural settlements in Longxi County exhibited pronounced spatiotemporal differentiation and transitional characteristics (Fig. 4). Examining the evolution of dominant function types, production-dominated villages predominated in 2000. Subsequently, the number of comprehensive development and balanced development villages increased significantly. By 2020, the proportion of ecologically dominated villages had risen markedly, with dominant functions exhibiting a diversified development trend. Spatially, functional differentiation has formed an echelon evolution and belt-like differentiation pattern characterized by “eastern production, central living, western ecology,” reflecting the combined shaping effects of natural background, locational conditions, and development policies on the spatial differentiation of rural functions.

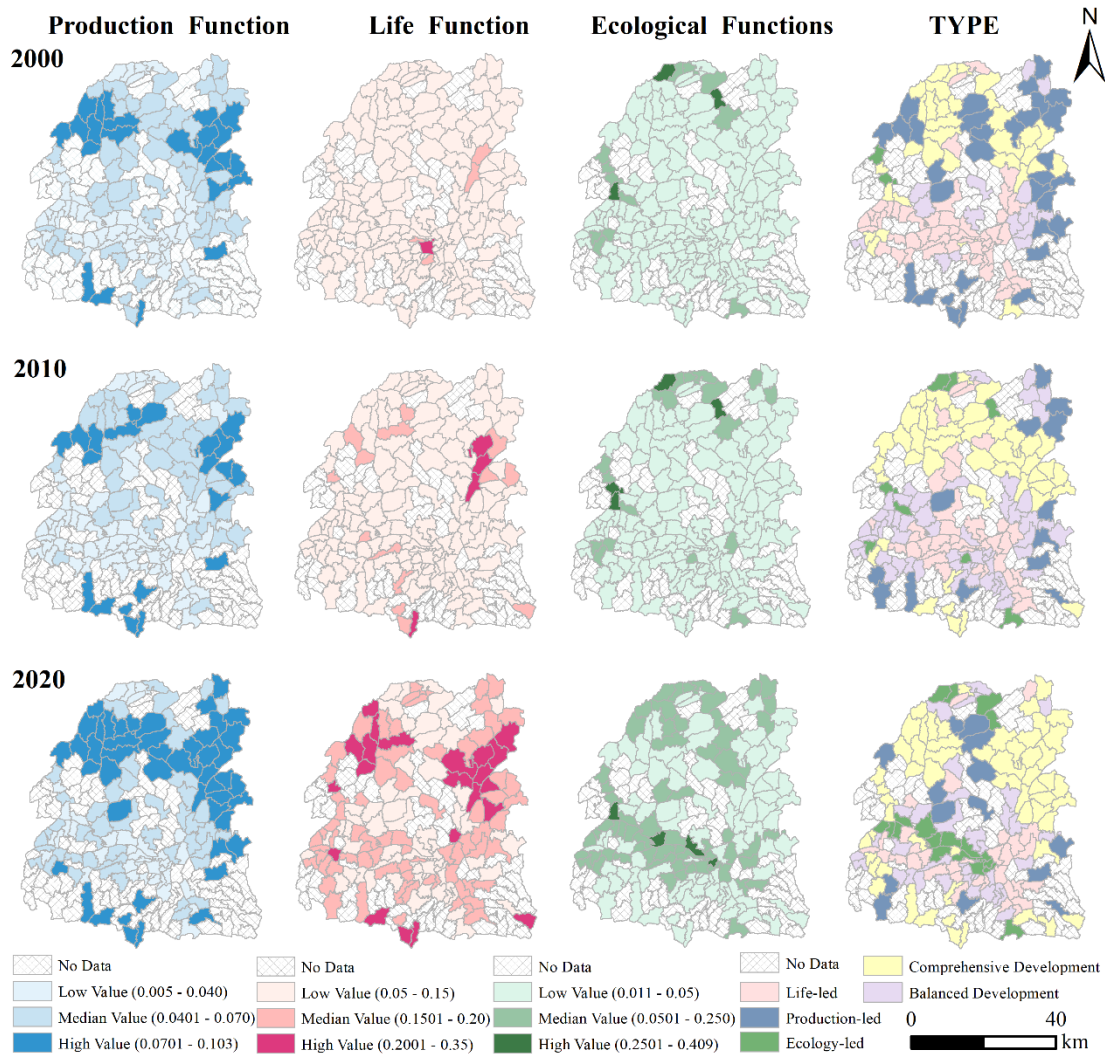


Figure 4. Spatiotemporal evolution of rural settlement functions

3.1.4. Identification of Comprehensive MSF Types

Figure 5 reveal that eight major types were identified for each year, collectively covering over 75% of the effective administrative villages in each period, indicating that the classification results possess good representativeness. Regarding overall composition, combination types based on scattered morphology and small scale consistently predominated, among which M₃-S₁-F₄, M₃-S₁-F₂, and M₃-S₁-F₅ constituted the core types persisting throughout the study period with the highest frequencies. This reflects that, under the topographical constraints of the Loess Plateau hilly-gully region, small-scale, dispersed settlements remain the background spatial form.

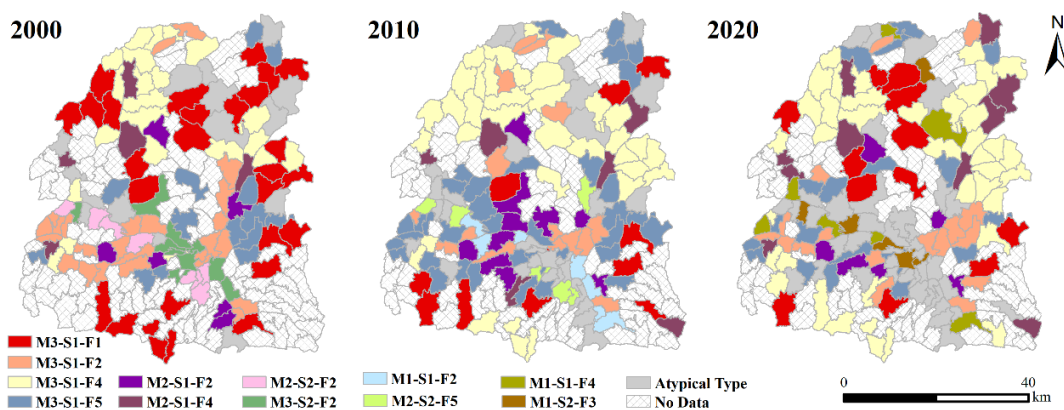


Figure 5. Spatiotemporal evolution of typical comprehensive MSF types of rural settlements

Note: In the morphology representation, 1 = clumped, 2 = strip-shaped, 3 = scattered. In the size representation, 1 = small-scale, 2 = large-scale. In the function representation, 1 = production function, 2 = living function, 3 = ecological function, 4 = comprehensive development type, 5 = balanced development type. Additionally, "\ " indicates that no rural settlements of this type existed in that year.

3.2. Spatiotemporal Differentiation Patterns of Carbon Emissions From Rural Settlements

3.2.1. Total carbon emissions

During 2000-2020, the Total Carbon Emissions (TCE) from rural settlements in Longxi County exhibited a stepped upward trend (Fig. 6), with high-value areas continuously expanding. By 2020, the maximum TCE value reached 45,818 tons, representing an over 100-fold increase compared to 2000. The spatial pattern of TCE evolved from a relatively dispersed distribution in the early period to a "T-shaped" structure expanding axially along main roads and river corridors. By 2020, this pattern further polarized, forming high-carbon emission core clusters in the Weihe River valley and at intersections of major transportation arteries, while the northern mountainous areas maintained relatively low emission levels.

3.2.2. Carbon emission intensity

During the same period, carbon emissions per unit area of rural settlements also underwent a pronounced structural shift (Fig. 6). Carbon Emission Intensity (CEI) evolved from an early-stage homogeneous pattern dominated by low values to a progressively distinct gradient structure. By 2020, a multi-ring pattern had formed, characterized by high-intensity circles centered on transportation nodes and river valleys, medium-intensity transitional zones extending outward, and low-intensity peripheral areas.

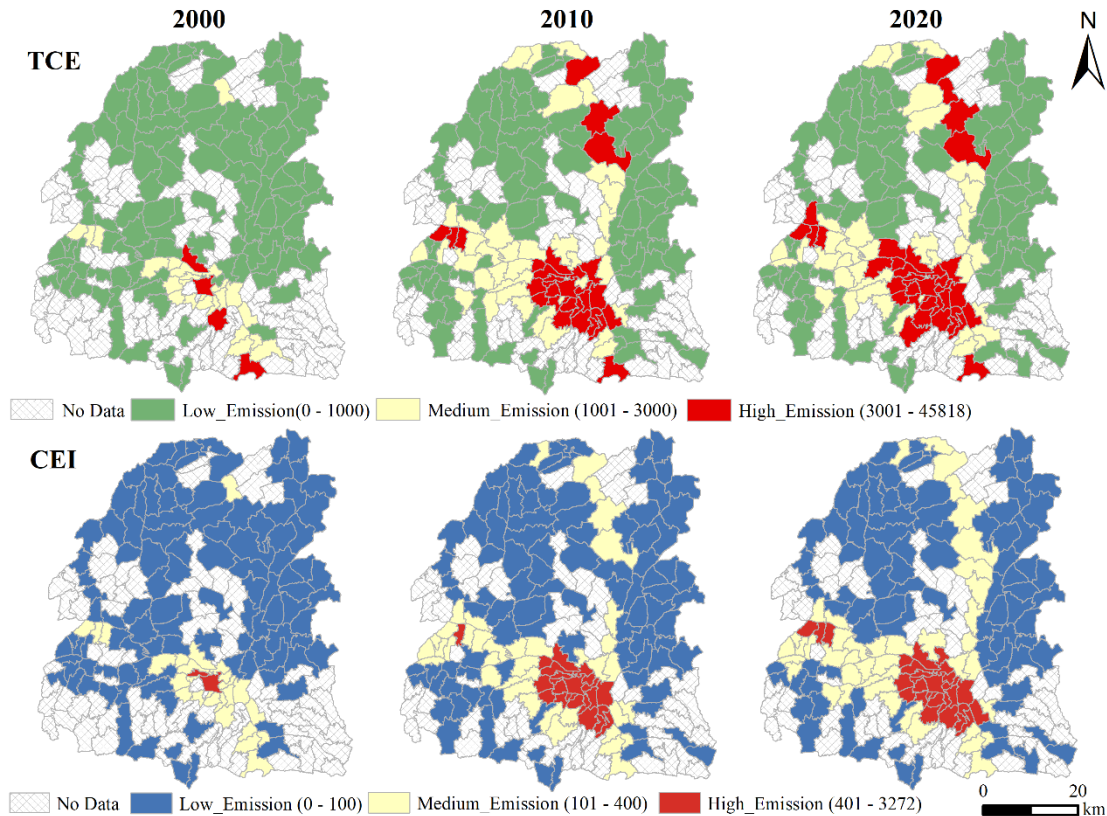


Figure 6. Spatiotemporal evolution of CO₂ emissions from rural settlements

3.3. Analysis of Carbon Emission Differences Among Different MSF Types

Statistical analyses based on the Kruskal-Wallis's test (Tables 5-7) reveal that, during 2000-2020, significant statistical differences existed in both TCE and CEI among different MSF types of rural settlements in Longxi County. This result confirms that a stable association exists between the spatial attribute combinations of rural settlements and their carbon emission performance.

Specifically, settlement types with lower carbon emissions exhibited a certain persistence across the three study years. In 2000, the M₃-S₁-F₂, M₂-S₁-F₄, and M₃-S₁-F₄ types ranked lowest in carbon emissions. By 2010 and 2020, the M₂-S₁-F₄, M₃-S₁-F₄, and M₃-S₁-F₁ types consistently maintained relatively low carbon emission levels and can thus be regarded as low-carbon advantageous types within the region. Types with higher carbon emissions exhibited dynamic evolutionary characteristics. The type with the highest carbon emissions in 2000 was M₃-S₂-F₂, which shifted to M₂-S₂-F₅ in 2010, and to M₁-S₂-F₃ in 2020. Additionally, the M₂-S₁-F₂ type consistently exhibited relatively high carbon emissions throughout the entire study period.

Table 5. Kruskal-Wallis H test results for carbon emission ranks of different rural settlement types in 2000

	MSF type (Median)								H	p
	M ₂ -S ₁ -F ₂ (n=6)	M ₂ -S ₁ -F ₄ (n=5)	M ₂ -S ₂ -F ₂ (n=8)	M ₃ -S ₁ -F ₁ (n=28)	M ₃ -S ₁ -F ₂ (n=25)	M ₃ -S ₁ -F ₄ (n=23)	M ₃ -S ₁ -F ₅ (n=14)	M ₃ -S ₂ -F ₂ (n=10)		
TCE	105	43	119	70	22	51	74.5	126.5	38.538	0.000**
CEI	103	43	117.5	70	22	51	74.5	123.5	35.280	0.000**

Note: * p<0.05 ** p<0.01

Table 6. Kruskal-Wallis H test results for carbon emission ranks of different rural settlement types in 2010

	MSF type (Median)								H	p
	M ₁ -S ₁ -F ₂ (n=7)	M ₂ -S ₁ -F ₂ (n=10)	M ₂ -S ₁ -F ₄ (n=6)	M ₂ -S ₂ -F ₅ (n=6)	M ₃ -S ₁ -F ₁ (n=11)	M ₃ -S ₁ -F ₂ (n=15)	M ₃ -S ₁ -F ₄ (n=35)	M ₃ -S ₁ -F ₅ (n=37)		
TCE	102	106.5	33	132.5	41	85	37	78	43.709	0.000**
CEI	114	101.5	33	139	41	85	37	80	46.125	0.000**

Note: * p<0.05 ** p<0.01

Table 7. Kruskal-Wallis H test results for carbon emission ranks of different rural settlement types in 2020

	MSF type (Median)								H	p
	M ₁ -S ₁ -F ₄ (n=7)	M ₁ -S ₂ -F ₃ (n=6)	M ₂ -S ₁ -F ₂ (n=6)	M ₂ -S ₁ -F ₄ (n=10)	M ₃ -S ₁ -F ₁ (n=12)	M ₃ -S ₁ -F ₂ (n=17)	M ₃ -S ₁ -F ₄ (n=39)	M ₃ -S ₁ -F ₅ (n=21)		
TCE	103	137.5	102.5	33	33.5	86	48	84	49.239	0.000**
CEI	105	139.5	105	33	33.5	83	48	88	49.734	0.000**

Note: * p<0.05 ** p<0.01

4. DISCUSSION

4.1. Interpretation of Research Findings

The study reveals that in the ecologically fragile Loess Plateau hilly-gully region, small-scale, functionally comprehensive settlements with scattered or strip-shaped morphology (M₃-S₁-F₄ and M₂-S₁-F₄) demonstrate superior low-carbon performance. Longxi County, situated in the Loess Plateau hilly-gully region, is characterized by fragmented terrain and significant ecological constraints. In such areas, blindly pursuing highly compact morphology may increase the extension and construction costs of infrastructure such as roads and pipe networks, while exacerbating disturbances to fragile ecosystems (Chen et al., 2022b; Yin et al., 2023). Consequently, a development pathway characterized by "moderate small-scale" that is more aligned with local resource and environmental carrying capacity proves more conducive to reducing overall systemic carbon emission pressure while meeting basic production and living needs.

4.2. Innovations and Limitations of This Study

The main innovations are as follows: A three-dimensional analytical framework of "morphology-size-function" was constructed, conceptualizing rural settlements as complex systems shaped by the synergistic interactions among morphology, size, and function, thereby transcending the limitations of traditional single-dimension studies.

Study systematically investigated the linking rural settlement "morphology-size-function" types with carbon emissions. However, further research is warranted in the following two aspects:(1) Regarding data, carbon emission accounting relied on 1 km grid data. While suitable for pattern analysis at the county scale, this data cannot finely capture the spatial heterogeneity of distributed emission sources within settlements. (2) Regarding methodology, this study primarily conducted type classification and mechanism diagnosis based on cross-sectional data at three time nodes, constituting a static and comparative static analysis.

5. CONCLUSION

The main conclusions are as follows:

(1) From 2000 to 2020: the rural settlements in Longxi County were mainly scattered and experienced the spatial and temporal evolution from dispersion to agglomeration. The size of rural settlements in Longxi County showed polarized spatial characteristics. The function of rural settlements in Longxi County showed a phased evolution.

(2) A stable and significant spatial differentiation pattern exists between the "morphology-size-function" characteristics of rural settlements and their carbon emission performance. Settlement types characterized by strip-shaped or scattered morphology, small scale, and comprehensive functional development exhibit superior low-carbon performance, whereas types dominated by strip-shaped small-scale living functions and various large-scale settlements generally face higher carbon emission pressure. This empirically reveals the low-carbon potential of specific spatial combinations.

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