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Article

The nonlinear relationship between rural territorial functions and regional economic development—A case study of Yangtze River Delta, China

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Abstract: This study investigates the nonlinear relationship between rural territorial functions—encompassing production, living, and ecological dimensions—and economic development in China's Yangtze River Delta (YRD) from 2000 to 2020, employing entropy weight and Kuznets curve analyses. Findings reveal pronounced regional disparities: economically advanced areas achieve balanced multifunctionality, whereas underdeveloped regions remain production-centric. Economic growth exhibits an inverted U-shaped relationship with rural functions, peaking at approximately 13,000 yuan per capita GDP, initially enhancing functions but leading to imbalances beyond this threshold. The production function follows a W-shaped trajectory, reflecting structural economic shifts, while living and ecological functions peak at intermediate development stages before stabilizing or declining. These insights underscore the necessity for tailored policies to harmonize rural functions, mitigate disparities, and balance economic growth with sustainability.

Keywords: rural territorial functions; Kuznets curve; Yangtze River Delta; economic development; spatial disparities; multifunctionality

1. Introduction

Rural areas, foundational to socio-economic systems, confront significant challenges in the 21st century. The 2023 Global Multidimensional Poverty Index (MPI) reports that 1.1 billion people globally live in poverty, with 84% residing in rural regions [1]. These statistics highlight rural vulnerabilities persisting despite economic and technological advancements. Consequently, rural revitalization has become a pivotal global priority to alleviate poverty, reduce inequalities, and promote sustainable development [2]. However, effective revitalization extends beyond mere economic growth; it demands a nuanced understanding of rural areas' multifaceted roles within socio-economic and ecological frameworks [3].

Rural territorial functions—integrating production, living, and ecological dimensions—offer a comprehensive perspective for analyzing rural evolution [4]. These functions encapsulate the socio-economic and environmental transformations of rural spaces [5]. Production functions underpin economic vitality through agriculture, industry, and emerging sectors like rural tourism and e-commerce [6]. Living functions embody quality-of-life aspects, including infrastructure, public services, and social welfare [7], while ecological functions emphasize sustainability via optimized land use, resource conservation, and environmental stewardship [8]. Far from static traits, these functions dynamically evolve as outcomes of socio-economic pressures and critical drivers of sustainable rural development, both shaping and being shaped by regional economic growth in a reciprocal relationship [9]. Yet, their study remains limited in rapidly urbanizing, economically advanced regions like metropolitan rural areas.

This research gap is particularly stark in the Yangtze River Delta (YRD), where rural landscapes are profoundly reshaped by swift economic development, urban-rural integration, and evolving policy priorities [10]. While prior studies have elucidated rural territorial functions in traditional agrarian contexts, their dynamic evolution in metropolitan settings is underexplored. The mechanisms driving these shifts—especially the influence of socio-economic factors—remain insufficiently understood. Addressing this gap not only deepens insight into rural transformation amid urbanization but also provides actionable scientific guidance for optimizing revitalization strategies and fostering sustainable development.

To achieve these objectives, this study constructs a systematic framework to examine the dynamic evolution of rural territorial functions in metropolitan rural areas, focusing on the Yangtze River Delta as a case study. By integrating spatiotemporal analysis with socio-economic influence factors, it seeks to address critical gaps in understanding rural transformations under rapid urbanization. This approach not only enhances theoretical insights into rural multifunctionality but also provides practical strategies for sustainable development in fast-developing regions.

2. Literature review

Rural territorial functions provide an essential framework for analyzing the diverse roles of rural areas within socio-economic and ecological systems [11]. Commonly delineated into production, living, and ecological dimensions, these functions reflect dynamic rural processes. Production functions drive economic transitions through agriculture, industry, and emerging sectors such as tourism and e-commerce [12]. Living functions gauge quality of life through public services and infrastructure, facilitating rural integration into urban systems [13]. Ecological functions prioritize sustainable land use and conservation [14]. Early research often examined these functions in isolation [15], neglecting their interdependence—for instance, production gains may compromise ecological integrity, while living enhancements bolster human capital for production. Theoretically, rural territorial functions emerge as both consequences of rural existence and prerequisites for sustainable development in rapidly transforming regions like the YRD, adapting dynamically to economic, technological, and social pressures in a reciprocal, nonlinear relationship [16].

Despite advances, capturing these complex, nonlinear interactions remains challenging, with many studies relying on linear models that oversimplify adaptive trade-offs [17]. Economic drivers (e.g., industrial restructuring), technological innovations (e.g., smart agriculture), policy initiatives (e.g., urban-rural integration), and social factors (e.g., demographic shifts) collectively shape these functions [18–20]. The Entropy Weight Method (EWM) offers an objective quantification approach [21], yet gaps persist in understanding context-specific, dynamic evolution, necessitating a more integrated theoretical framework.

These shortcomings underscore the need for a comprehensive model to elucidate rural territorial functions' dynamic transformations across diverse developmental contexts. This study integrates their multidimensional nature with influencing factors, building on prior work to advance the field. Focusing on the YRD—a region of rapid socio-economic change—It provides a detailed analysis of functional shift mechanisms, contributing to both theoretical progress and practical solutions for metropolitan rural revitalization.

3. Study area, research methods, and data sources

3.1. Study area

The Yangtze River Delta (YRD), spanning Jiangsu, Zhejiang, Anhui provinces, and Shanghai Municipality, covers approximately 211,700 km^2, or 2.2% of China's land area. A powerhouse of economic dynamism and urbanization, the YRD generates over 24% of China's GDP, spearheading national industrialization and urban growth. Shanghai, a global financial hub, anchors regional development, while Jiangsu and Zhejiang excel in advanced manufacturing and services. Anhui, through industrial relocation and transformation, accelerates its economic ascent.

National policies and robust infrastructure bolster this progress. Since 2002, China has championed urban-rural coordination, modernizing agriculture and enhancing rural livelihoods to build a moderately prosperous society. The 2010 urban-rural integration push furthered rural urbanization and infrastructure upgrades. In 2018, the YRD Integration Strategy became a national priority, advancing connectivity and high-quality development. The Rural Revitalization Strategy, emphasizing ecological sustainability, has optimized rural functions, supported by extensive investments in high-speed rail and transportation networks, strengthening urban-rural ties.

The YRD's industrial structure diversifies toward high-value sectors, with traditional agriculture yielding to modern practices, rural tourism, and e-commerce—key drivers of economic transformation [22]. Green industries and ecological chains further enhance sustainability [23]. However, disparities endure: coastal cities like Shanghai exhibit robust rural vitality, while inland Anhui lags in production and living functions, requiring targeted interventions.

The YRD's rural evolution reflects a nexus of economic growth, policy support, and geographic advantages, offering a critical case for studying urban-rural integration and sustainable revitalization with broader implications.

3.2. Classification and quantitative measurement of rural territorial functions

This study adopts the "Production-Living-Ecological Space Theory" to evaluate rural territorial functions across three dimensions: production, living, and ecological functions. A tailored indicator system for the Yangtze River Delta (YRD) was developed to measure these functions, incorporating both explicit indicators, which directly reflect functional intensity through variables like land use and population size, and implicit indicators, which assess comprehensive functional benefits through relative weights and numerical evaluations (see **Table 1**).

Table 1. Index System of rural regional function measurement.

Target Layer	**Indicator Layer**				**Data Source**
	Explicit Indicators	**Weight**	**Implicit Indicators**	**Weight**	
Production Function	Grain Crops Sown Area	0.22	Proportion of Primary Industry in GDP	0.21	China Urban Statistical Yearbook
	Rural Per Capita GDP	0.30	Grain Output	0.26	Statistical Yearbooks of Zhejiang, Shanghai, Jiangsu, and Anhui
Living Function	Rural Residential Area	0.26	Total Rural Electricity Consumption	0.20	Yangtze River Delta Statistical Yearbook
	Rural Per Capita Net Income	0.29	Population Density	0.25	sourced from Statistical Yearbooks of Zhejiang, Shanghai, Jiangsu, and Anhui
Ecological Function	Rural Green Space Area	0.27	Rural Domestic Sewage Treatment Rate	0.23	China Urban Statistical Yearbook
	Urban Land Area Ratio	0.21	Usage of Agricultural Fertilizer	0.29	Yangtze River Delta Statistical Yearbook

3.2.1. Indicator system and weight assignment for rural territorial functions

In the Yangtze River Delta (YRD), explicit indicators for the rural production function include grain-sown area and grain yield, while implicit indicators include per capita GDP and the proportion of primary industry in GDP. For the rural living function, explicit indicators are residential area and per capita net income, with implicit indicators being annual electricity consumption and population density. The rural ecological function uses explicit indicators such as green area, greening coverage, and urban land use proportion, and implicit indicators like sewage treatment rate and fertilizer usage.

This study adopts the Entropy Weight Method (EWM), as described in Section 2, to determine indicator weights, yielding weights of 0.25, 0.35, and 0.40 for production, living, and ecological functions, respectively. The specific calculation steps are as follows:

Normalization: For an indicator matrix $X = x_{ij}$ (where i is the region and j is the indicator), normalize the data:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}.$$

Entropy Calculation: Compute the entropy for each indicator:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}),$$

where $k = \frac{1}{\ln(m)}$ and m is the number of regions.

Weight Determination: Calculate the weight:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)},$$

where n is the number of indicators.

EWM ensures objectivity by weighting variable indicators higher, though it assumes independence (e.g., ignoring GDP-income correlations) and may amplify outliers in small datasets. Its suitability for the YRD's diverse data justifies its use.

3.2.2. Functional assessment and regional comparison

To systematically quantify the evolution of rural territorial functions across different municipal regions, this study employs SPSS software for data standardization, ensuring comparability across indicators with varying units and scales. This study employs min-max normalization rather than the standard *Z*-score approach because it scales data to a 0–1 range, preserving relative differences and aligning with the Entropy Weight Method's (EWM) emphasis on variability. *Z*-score normalization, while effective for normally distributed data, may distort EWM weights by assuming a mean-centered distribution, which is less suitable for the heterogeneous YRD dataset. The standardization formulas used are as follows:

For positive indicators:

$$x'_{ij} = \frac{x_{ij} - min\{x_{ij}, \cdots, x_{nj}\}}{max\{x_{1j}, \cdots, x_{nj}\} - min\{x_{ij}, \cdots, x_{nj}\}}.$$

For negative indicators:

$$x'_{ij} = \frac{max\{x_{1j}, \cdots, x_{nj}\} - x_{ij}}{max\{x_{1j}, \cdots, x_{nj}\} - min\{x_{ij}, \cdots, x_{nj}\}},$$

where x_{ij} represents the raw value of the *j*-th indicator in the *i*-th region, and x'_{ij} is the standardized value. min and max denote the minimum and maximum values of the indicator across all regions, respectively.

The standardized values are then combined with the corresponding weights derived from the entropy weight method to calculate the functional index for each region:

$$F_i = \sum_{j=1}^{n} W_j \times T'_{ij},$$

where F_i is the composite functional index for the i *i*-th region, W_j represents the weight of the *j*-th indicator, and T'_{ij} is the standardized value of the indicator in the region.

To evaluate the overall functional level of rural territories, the study calculates a comprehensive functional index that integrates production, living, and ecological functions:

$$F = F_1 * 0.25 + F_2 * 0.35 + F_3 * 0.40,$$

where *F*1, *F*2, *F*3 are the functional indices for rural production, living, and ecological dimensions, respectively. The weights (0.25, 0.35, and 0.40) reflect the relative importance of these functions in the context of rural development.

3.3. Kuznets curve of rural territorial functions

Using 2000–2020 data from 26 YRD units, SPSS constructs Kuznets Curves (**Figure 1**) to model rural function-economic development relationships, revealing temporal trends. ArcGIS maps spatial variations, integrating both dimensions for a holistic analysis, informing sustainable rural policy.

To complement the temporal analysis, ArcGIS software is utilized to conduct spatial analyses, mapping regional variations in rural territorial functions and their interplay with economic development. This dual approach—integrating temporal and spatial dimensions—allows for a comprehensive investigation of the dynamic relationships between these two domains.

The findings provide valuable empirical evidence on the spatial and temporal linkages between rural territorial functions and economic development. Such insights are critical for informing policy strategies aimed at rural revitalization and sustainable development. By identifying areas where economic growth either enhances or inhibits rural functions, this research offers practical recommendations to optimize the interplay between economic growth and the evolving roles of rural territories.

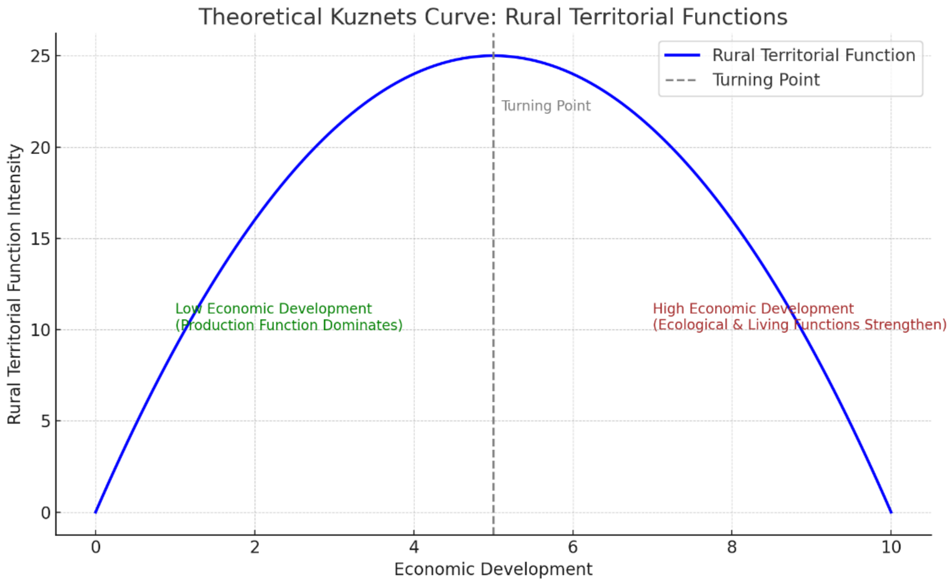

Figure 1. Environmental Kuznets curve.

3.4. Data sources and processing

Data are sourced from Yangtze River Delta Statistical Yearbook (2000–2020), China Urban Statistical Yearbook, and provincial yearbooks (Zhejiang, Jiangsu, Anhui, Shanghai). Linear interpolation addresses missing values, and economic indicators are adjusted to 2000 prices for consistency.

To address missing data, a linear interpolation method was employed to ensure data completeness. Additionally, all economic indicators—including GDP, the proportion of the primary sector in GDP, per capita GDP, and rural residents' disposable income—were adjusted to constant 2000 prices to account for inflation and ensure data comparability over time. This preprocessing ensures consistency in the dataset, allowing for robust longitudinal analysis and facilitating meaningful cross-regional comparisons.

4. Results and analysis

4.1. The spatiotemporal evolution of rural regional functions

Using the entropy weight method, this study assesses the comprehensive and PLE function indices in the YRD from 2000 to 2020.

4.1.1. The overall trends in the evolution of rural regional functions in the Yangtze River Delta

Function trajectories (**Figure 2**) show an upward trend in comprehensive, production, living, and ecological indices, stabilizing post-2013. Ecologically, indices remain highest, production disparities widen, and living functions converge, minimally impacting the comprehensive index, unlike the more volatile production and ecological functions.

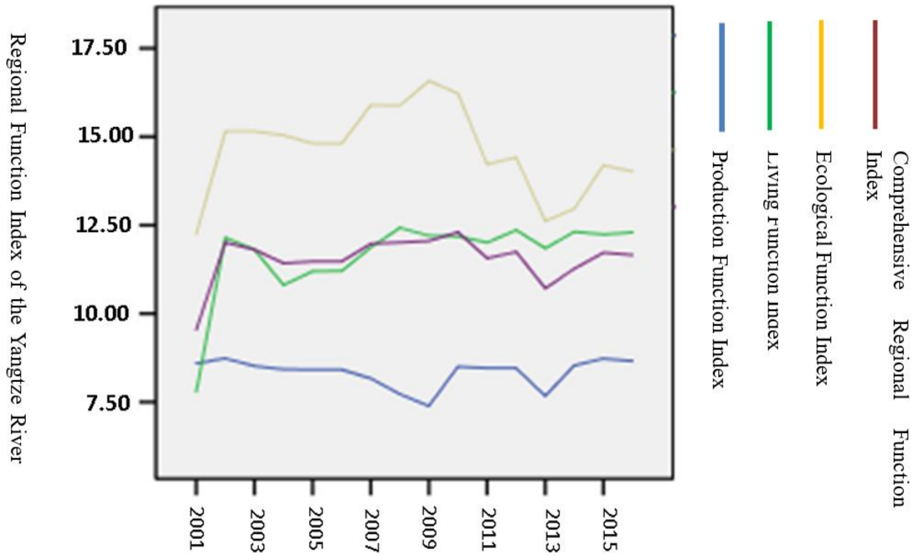

Figure 2. Changes of different rural territorial functions in the Yangtze River Delta from 2000 to 2020.

From a functional perspective, the ecological function index consistently exhibited the highest values, while the production function index demonstrated an expansion trend, and the living function index exhibited a convergence pattern. This suggests that disparities in production function have gradually widened, whereas variations in living and comprehensive functions have diminished and reached a stable equilibrium. The living function index displayed minimal fluctuations and exerted a relatively weak impact on overall comprehensive function performance, indicating its stability. In contrast, the ecological and production functions experienced greater fluctuations, exerting a more pronounced influence on the comprehensive function index, although both ultimately exhibited a stabilizing tendency.

4.1.2. Regional disparities in the evolution of rural regional functions in the Yangtze River Delta

Although the rural territorial functions in the Yangtze River Delta (YRD) follow certain spatiotemporal evolution patterns, pronounced regional disparities persist, shaping the spatial dynamics of rural development and influencing resource allocation and policy strategies across the region. To better understand these variations, this study analyzes PLE function indices across different municipalities and employs the Jenks Natural Breaks Classification Method to categorize them into four levels. The Jenks

Natural Breaks Classification Method is applied to categorize PLE function indices into four levels, minimizing within-group variance while maximizing between-group differences based on natural data breaks. Unlike Fisher's Discriminant Analysis, which assumes predefined groups and linear separability, Jenks is non-parametric and excels at identifying inherent patterns in spatial data with unknown distributions, making it advantageous for capturing the YRD's regional disparities. This classification not only highlights key trends in the evolution of rural territorial functions but also provides valuable insights for guiding regional policy adjustments and promoting balanced rural development.

(1) Spatial Differentiation of Rural Territorial Production Function Index

In the YRD, high-value production function areas are primarily located in the economically developed core city zones and parts of the central region. These areas are marked by a shift towards modern agriculture, which integrates agricultural technologies and services, leading to enhanced production efficiency and value-added agriculture (**Figure 3**).

High-Value Areas (Core City Zones and Central Region): In regions like Wuxi, Changzhou, Hangzhou, Shanghai, Jinhua, and Nanjing, rural production functions are strong. These areas have significantly improved their agricultural efficiency and productivity through modern agriculture, green farming, and smart agriculture practices. The integration of agriculture with service industries, particularly in Wuxi and Hangzhou, has contributed to a sustained improvement in rural production functions.

Low-Value Areas (Traditional Agricultural Zones and Smaller Cities): In regions such as Hefei, Wuhu, Anqing, Quzhou, Shaoxing, and Jiaxing, agricultural production remains limited by slower industrial development and infrastructure deficiencies. Traditional agricultural structures and slower transitions towards modern farming practices have hindered improvements in production functions, particularly in Shaoxing and Quzhou, where agricultural technology and land resource constraints have slowed progress.

High-value production areas are concentrated in regions with a strong economic base and advanced urbanization, where modern agriculture and industry integration drive the enhancement of production functions. In contrast, low-value areas, especially in traditional agricultural zones, struggle with slow agricultural modernization and limited infrastructure development, facing challenges in transforming their production functions.

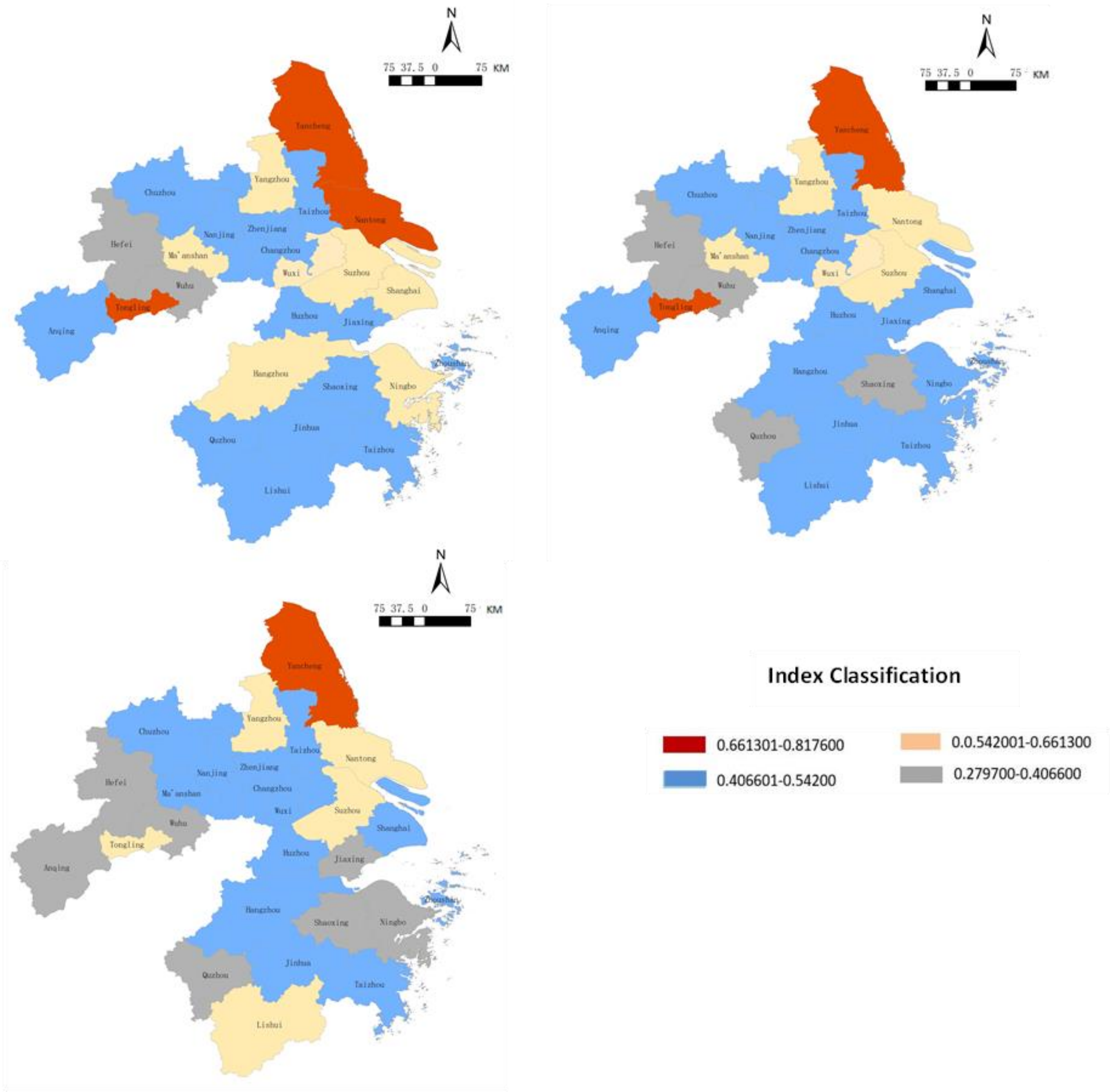

Figure 3. Spatial differentiation of the proportion of rural territorial production function index in the Yangtze River Delta. 2000–2020.

(2) Spatial Differentiation of Rural Territorial Living Function

The spatial disparities in rural living functions are also distinct, with high-value areas generally located in rapidly urbanizing regions that benefit from improved infrastructure, public services, and a higher quality of life (**Figure 4**).

High-Value Areas (Core City Zones and Southern and Central Regions): Regions like Yancheng, Taizhou, Suzhou, and Hangzhou exhibit strong rural living functions, with consistent improvements over time. Urbanization has led to notable advancements in infrastructure and public services, particularly in housing, transportation, healthcare, and education, significantly raising rural living standards.

Low-Value Areas (Chuzhou, Ma’anshan, Wuhu, Tongling, Anqing, Taizhou): These areas have lower living function indices, primarily due to slow urbanization and insufficient infrastructure development. For example, Chuzhou, Ma’anshan, and

Wuhu are still lagging in urban development, and their rural living conditions have not improved significantly.

High-value living function areas tend to be located in regions with advanced urbanization and infrastructure development, leading to improved public services and living standards. On the other hand, low-value living function areas are concentrated in regions with slower urbanization and less developed infrastructure, which hampers the improvement of living conditions.

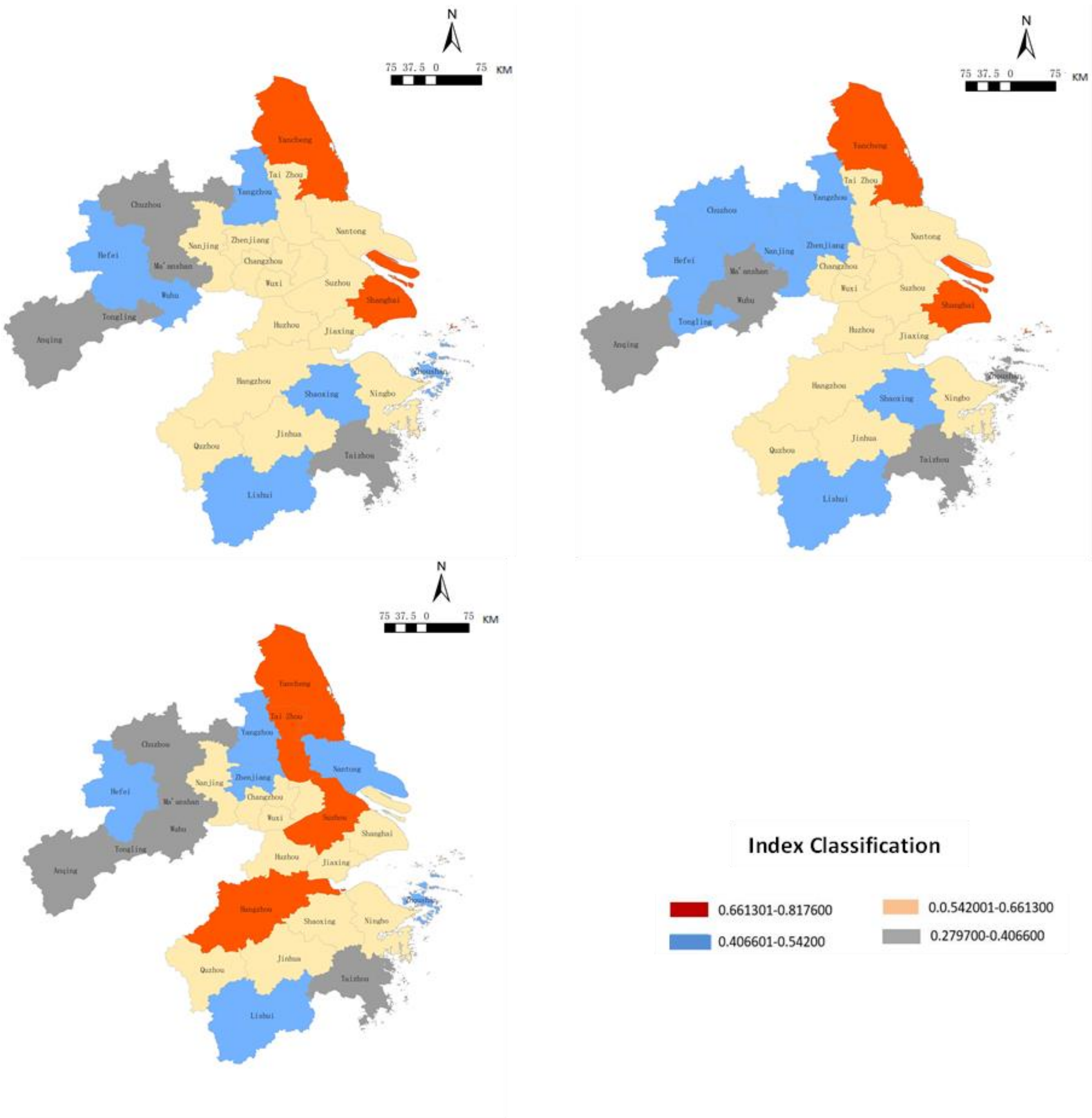

Figure 4. Spatial differentiation of the proportion of rural territorial living function index in the Yangtze River Delta. 2000–2020.

(3) Spatial Differentiation of Rural Territorial Ecological Function

The distribution of rural ecological functions in the YRD also shows clear regional differences. High-value areas are often found in economically developed core city zones and central/southern regions, where ecological protection measures are actively implemented alongside agricultural modernization efforts (**Figure 5**).

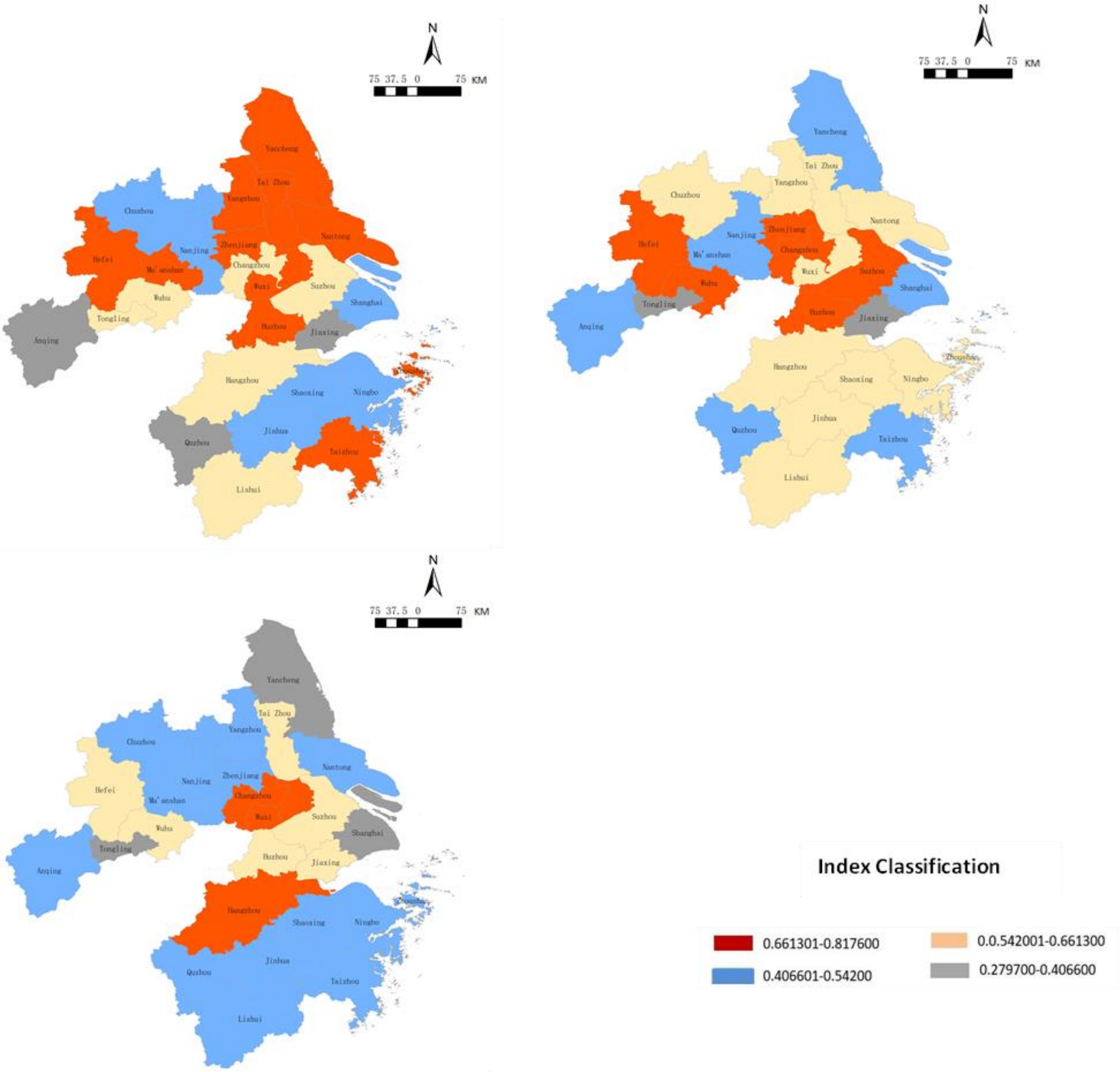

Figure 5. Spatial differentiation of the proportion of rural territorial ecological function index in the Yangtze River Delta. 2000–2020.

High-Value Areas (Core City Zones and Central and Southern Regions): Areas such as Changzhou, Wuxi, Hangzhou, Yangzhou, Zhenjiang, and Suzhou exhibit strong rural ecological functions. These regions have actively promoted modern and green agricultural practices, significantly improving their ecological environments. Efforts in ecological protection and sustainable farming practices have been key to enhancing rural ecological functions in these areas.

Low-Value Areas (Yancheng, Shanghai, Tongling, Quzhou, Lishui): Yancheng, Shanghai, and Tongling are regions where rural ecological functions remain weak. These areas face ecological challenges due to rapid urbanization and industrialization, which have led to the conversion of agricultural land to non-agricultural uses, impairing ecological sustainability. Lishui and Quzhou also face limitations due to their mountainous terrain and reliance on traditional farming methods, slowing improvements in ecological functions.

High-value ecological function areas are typically located in regions with strong economic development, urbanization, and advanced ecological policies. These areas benefit from modern agriculture and ecological restoration efforts that enhance environmental quality. Conversely, low-value ecological function areas are characterized by rapid industrialization, land-use changes, and limited ecological.

(4) Interaction Between Production, Living, and Ecological Functions

The three functions—production, living, and ecology—are deeply interconnected and influence one another. Urbanization, industrialization, and infrastructure development have different effects on these functions, and these effects can interact in various ways:

Interaction Between Production and Ecological Functions: In high-value areas, the modernization of agriculture and the development of green farming not only boost agricultural productivity but also enhance environmental quality. However, rapid industrialization and urban expansion can lead to agricultural land being converted to non-agricultural uses, which negatively impacts ecological functions.

Interaction Between Living and Production Functions: In economically developed regions, improvements in living functions, such as infrastructure and public services, often go hand in hand with improvements in production functions. Better living conditions and infrastructure attract more investment and skilled labor, which in turn boosts productivity.

Interaction Between Ecological and Living Functions: Strong ecological protection can enhance the quality of life by improving the environment. Green agriculture and ecological restoration initiatives provide cleaner air, water, and better land, improving living conditions. Conversely, environmental degradation can deteriorate living standards, especially in areas where industrialization has outpaced ecological protection.

4.2. Nonlinear relationship between rural territorial functions and economic development

In the Yangtze River Delta, although the economy has continued to grow, the evolution of rural territorial functions has shown different trends. From the analysis in Section 4.1, we can observe that with economic development, not all rural functions have continuously improved, and in some regions, certain functions have either not improved significantly or have declined to varying degrees. This phenomenon reflects that the relationship between rural territorial functions and economic development is not a simple linear one. To explore this nonlinear relationship and the underlying mechanisms, this study further constructs the Environmental Kuznets Curve (EKC) and uses this model to examine the relationship between rural territorial functions and economic development.

Overall, the continuous economic development has not directly driven a one-way improvement in rural territorial functions. Instead, at certain economic levels, some functions have experienced "regressions" or "plateaus". These nonlinear relationships reflect the adaptive transformation process of rural territorial functions, where production, living, and ecological functions evolve along different trajectories at various stages of development (**Figure 6**).

While this study focuses on economic development (measured via per capita GDP) due to its central role in the YRD and data availability, rural territorial functions are also influenced by technological, policy, and social drivers [16]. These factors, though not quantitatively analyzed here due to data constraints, are implicitly reflected in economic trends—e.g., policy-driven infrastructure growth or technology-enabled agricultural shifts—and merit further exploration in future research.

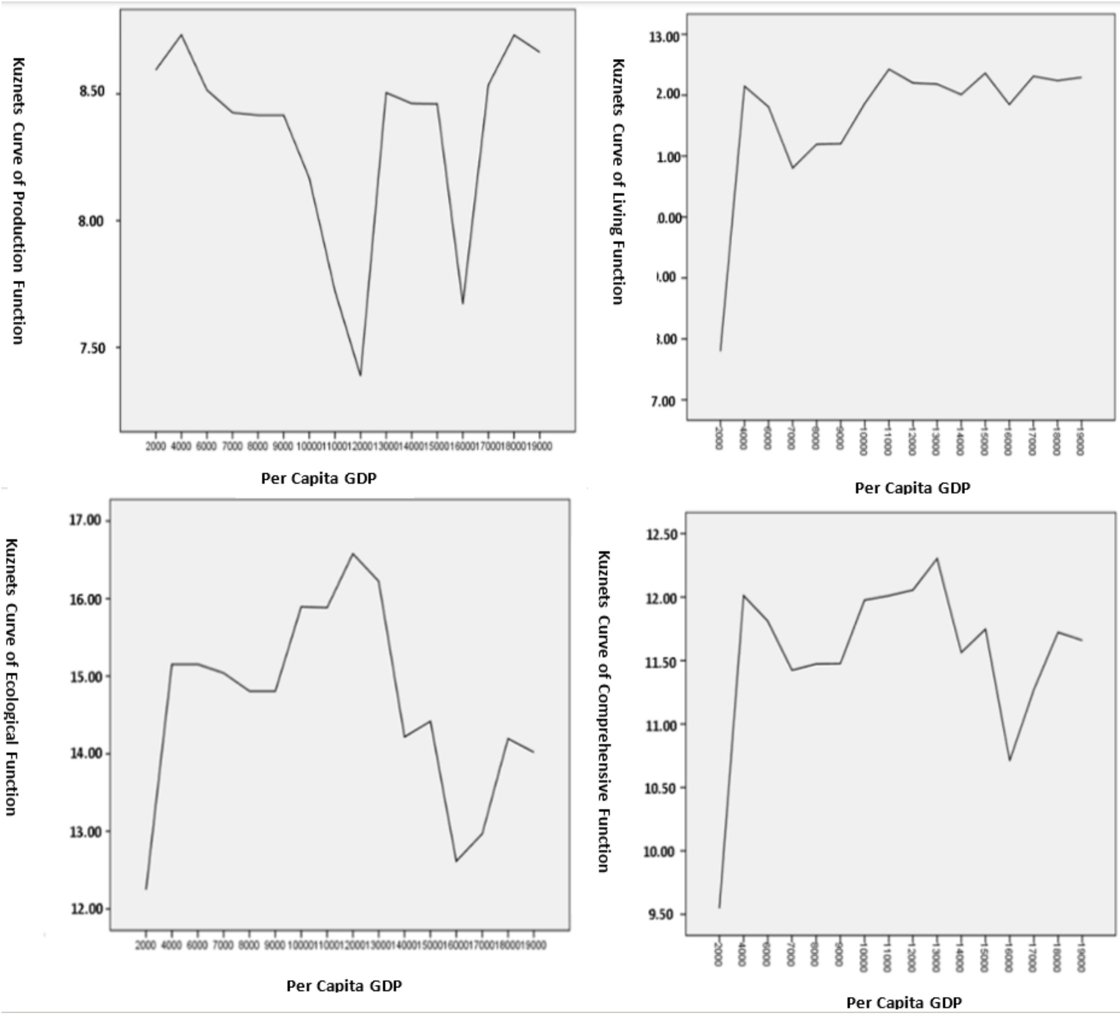

Figure 6. Kuznets curve of rural regional functions.

4.2.1. Impact of economic development on rural territorial functions

Based on the fitted results, we can further understand the nonlinear relationship between economic development and rural territorial functions. For the production function, a W-shaped relationship emerges. During the early stages of economic growth, particularly when per capita GDP is between 2000 and 12,000 yuan, the production function shows a declining trend, reflecting the pressures of transitioning from a traditional agricultural system to a more diversified rural economy. However, when per capita GDP enters the range of 12,000 to 13,000 yuan, there is a short-term recovery, indicating that emerging industrial and agricultural practices help drive rural economic transformation. Beyond 17,000 yuan, the production function stabilizes, marking a shift toward higher value-added industries and a balanced industrial structure.

For the living function, an inverted U-shaped relationship is observed. The living function improves significantly during the early stages of economic development, particularly when per capita GDP is between 2000 and 6000 yuan, driven by investments in infrastructure, public services, and rising household incomes. However, when per capita GDP reaches around 11,000 yuan, the improvement in living conditions begins to plateau, indicating diminishing returns from further economic growth in terms of enhancing rural living standards.

The ecological function also follows an inverted U-shaped curve. Between 2000 and 12,000 yuan, ecological function steadily improves due to increased environmental awareness and investments in ecological conservation. However, after 12,000 yuan, the ecological function declines, largely due to the pressures of industrialization and urbanization. This reflects the trade-off between economic growth and environmental sustainability, particularly in regions where industrial activities intensify.

For the comprehensive rural function, an inverted U-shaped relationship emerges as well. At approximately 13,000 yuan per capita GDP, the comprehensive function reaches its peak, representing the optimal balance between production, living, and ecological priorities. However, as economic growth exceeds this threshold, the competing demands among these functions lead to a decline in overall functionality. These findings highlight the presence of economic thresholds, where early-stage growth helps diversify and enhance rural functions, but when economic development exceeds key thresholds, conflicts among these functions increase, necessitating policy interventions to mitigate the trade-offs and maintain balanced development.

4.2.2. Classification of territorial function types in the Yangtze River Delta

After exploring the nonlinear relationship between rural territorial functions and economic development in the Yangtze River Delta, further classification analysis enhances our understanding of functional characteristics across regions at varying economic development levels. This classification provides a theoretical foundation for research and practical guidance for regional policy formulation. Based on the spatiotemporal evolution of PLE indices in Section 4.1, rural territorial functions in the Yangtze River Delta can be categorized into leading development zones, upgrading development zones, and lagging development zones, each with distinct functional traits (**Table 2**).

These classifications are qualitatively derived from the relative performance of PLE indices and economic development levels, reflecting the degree of functional coordination rather than fixed thresholds, given significant regional variability and data constraints. As shown in Section 4.1.2, leading development zones (e.g., Shanghai, Nanjing, Hangzhou) typically exhibit higher comprehensive indices, indicating coordinated development of production, living, and ecological functions, particularly in economically advanced core areas. In contrast, lagging development zones (e.g., Tongling, Xuancheng) show lower indices, with less balanced functional development, often in regions with weaker economies and infrastructure. Section 4.2.1 further reveals that the comprehensive function peaks at approximately 13,000 yuan per capita GDP, with leading zones generally beyond this stage and lagging zones yet to reach it. Future studies could establish quantitative thresholds with more granular data.

Leading development zones typically display mature rural territorial functions. For instance, agricultural production areas like Hefei and Yancheng sustain high productivity through modern agriculture and rural-industrial integration; ecological dominance areas like Zhoushan and Taizhou prioritize ecological protection, with strong ecological functions; residential living areas such as Nanjing, Hangzhou, Ningbo, and Wuxi benefit from urbanization-driven improvements in living standards and infrastructure; and non-agricultural production areas like Shanghai focus on high-tech industries and services, fostering economic diversification.

Upgrading development zones represents regions in transition with evolving functions. For example, agriculture-living composite areas like Ma'anshan and Wuhu integrate agricultural innovation with welfare enhancements; agriculture-ecology composite areas like Chizhou and Anqing balance sustainable agriculture with ecological protection; living-non-agricultural composite areas like Jinhua, Huzhou, Jiaxing, and Nantong promote industrial diversification and employment; ecology-living composite areas like Shaoxing and Suzhou enhance green infrastructure and environmental governance; and ecology-non-agricultural composite zones like Zhenjiang and Changzhou emphasize eco-industrial development.

Lagging development zones, such as Tongling, Xuancheng, and Chizhou, exhibit weaker rural territorial functions, facing greater challenges in coordinating production, living, and ecological roles, necessitating targeted interventions to bridge development gaps.

These classifications highlight variations in economic development levels and functional characteristics across the Yangtze River Delta, underscoring differing degrees of PLE function coordination in each region.

Table 2. Classification of territorial function types in the Yangtze River Delta.

	Classification	**Prefecture-Level Cities**
Leading Development Zones	Agricultural Production Type	Hefei, Yancheng
	Ecological Dominance Type	Zhoushan, Taizhou
	Residential Living Type	Nanjing, Hangzhou, Ningbo, Wuxi
	Non-Agricultural Production Type	Shanghai
Upgrading Development Zones	Agriculture-Living Composite Type	Ma anshan, Wuhu
	Agriculture-Ecology Composite Type	Chizhou, Anqing
	Living-Non-Agricultural Composite Type	Jinhua, Huzhou, Jiaxing, Nantong
	Ecology-Living Composite Type	Shaoxing, Suzhou
	Ecology-Non-Agricultural Composite Type	Zhenjiang, Changzhou
Lagging Development Zones		Tongling, Xuan cheng, Chizhou

5. Conclusion and policy recommendations

This study examines the spatial and temporal evolution of rural territorial functions and their nonlinear relationship with economic development. The findings highlight the transition from single-function dominance to multifunctional coordination, the existence of threshold effects, and significant regional disparities. Based on these insights, targeted policy recommendations are proposed to support sustainable rural development.

5.1. Shift to multifunctional coordination

Rural areas are evolving from production-dominated functions to a more balanced integration of production, living, and ecological roles. However, this transition varies across regions, with economically advanced areas achieving better coordination, while underdeveloped regions remain production-focused.

To promote multifunctional rural development, policies should support industrial upgrading, infrastructure enhancement, and environmental protection. In production-dominant areas, modern agricultural technologies and industrial integration should be prioritized. In peri-urban rural areas, diversified industries such as rural tourism and ecological conservation should be emphasized to ensure sustainable growth.

5.2. Nonlinear dynamics

This study reveals that rural territorial functions in the Yangtze River Delta vary widely over time and space, showing a nonlinear link with economic development. Production follows a W-shaped pattern, while living and ecological functions trace inverted U-shapes, tied to distinct growth stages. The comprehensive function peaks at 13,000 yuan per capita GDP, after which trade-offs between functions increase, signaling a need for targeted strategies to maintain balanced rural progress.

To address these dynamics, rural policies should adopt a stage-specific approach. Underdeveloped regions require targeted investments in agriculture, infrastructure, and public services. In contrast, developed areas should focus on industrial restructuring, preventing rural hollowing-out, and strengthening environmental governance to ensure long-term sustainability.

5.3. Policy recommendations

Drawing on the spatiotemporal evolution (Section 4.1) and nonlinear dynamics (Section 4.2) of rural territorial functions, this study offers targeted guidance for regional planning in the Yangtze River Delta (YRD) to enhance coordination of production, living, and ecological functions.

Leading Development Zones: In southeastern coastal areas (e.g., Shanghai, Nanjing), where functions are well-coordinated (Section 4.1.2), yet face ecological strain and talent loss, planning should bolster production through green industries like eco-tourism or high-tech agriculture, mitigating burdens noted beyond the 13,000 yuan GDP threshold (Section 4.2.1). Strengthening farmland protection policies can curb excessive land conversion, ensuring ecological sustainability. Cultural revitalization, such as branding local traditions, can foster community cohesion and attract talent, enriching regional planning efforts.

Upgrading Development Zones: In central and northern YRD (e.g., Ma'anshan, Nantong), amid functional transitions (Section 4.2.2), planning should enhance urban-rural linkages and industrial integration. Leveraging proximity to economic cores, industrial belts linking rural production to urban markets can balance agriculture and industry. Improved transport and infrastructure can boost connectivity with metropolitan areas, supporting employment and living functions. Encouraging innovation clusters can draw skilled talent and diversify economies, aiding planning for functional upgrades.

Lagging Development Zones: In western and northern YRD (e.g., Tongling, Chizhou), where functions lag (Section 4.1.2), planning should prioritize infrastructure and agricultural modernization. Building on production potential (Section 4.1.1), specialized agricultural bases can optimize water-soil resources to boost efficiency. Upgrading rural housing and public services can improve living conditions, while digital tools (e.g., "Internet+" models) can bridge industrial gaps, integrating rural areas into regional networks and laying a foundation for planning.

Tailored to YRD's regional disparities and functional traits, these recommendations guide planners in harmonizing production, living, and ecological functions for sustainable growth. While centered on per capita GDP, the nonlinear trends and classifications from Section 4 reveal technology (e.g., Shanghai's modern agriculture), policy (e.g., Tongling's infrastructure needs), and social influences, supported by literature, offering a comprehensive planning framework.

5.4. Areas for further research

This study provides a robust foundation for understanding rural territorial functions, yet several areas warrant further exploration. First, while focused on economic development via per capita GDP, future research could quantitatively assess technological advancements (e.g., smart agriculture), policy interventions (e.g., rural revitalization programs), and social drivers (e.g., demographic changes) to capture their direct impacts. Second, the static 2000–2020 dataset limits predictive capacity; dynamic modeling could enable forecasting of PLE function trends. Third, establishing quantitative thresholds for zone classifications (e.g., leading vs. lagging zones) would refine the qualitative framework presented here. These directions could enhance the understanding and management of rural transformation in the YRD and beyond.

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