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# Research on the Coordination Relationship and Zoning Optimization of Territorial Spatial Functions in Southern Karst Regions Based on a Multi-Scale Fusion Model

**Ting Feng [1,2,*], Xiaodong Yu [1], Yan Zhou [1], Renling Dong [1], Dong Wu [1] and Meilin Zhang [1]**

[1] School of Public Policy and Management, Guangxi University, Nanning 530004, China; 2301301062@st.gxu.edu.cn (X.Y.); 2201301079@st.gxu.edu.cn (Y.Z.); 2301301009@st.gxu.edu.cn (R.D.); wd0703@st.gxu.edu.cn (D.W.); 2401301065@st.gxu.edu.cn (M.Z.)
[2] Research Center for Natural Resources Management and Public Policy, Guangxi University, Nanning 530004, China
* Correspondence: fting@gxu.edu.cn

**Abstract:** Territorial Space (TS) is characterized by its multifunctionality. The identification and management of Territorial Spatial Functions (TSFs) across multi-scale is crucial for achieving the SDGs. However, previous studies have primarily concentrated on the variations in TSFs within the administrative or grid units at a single scale, with multi-scale investigations remaining a challenge. This study focuses on the typical karst region of Guangxi province in China and develops a Multi-Scale Fusion model (MSF) for assessing TSFs and employs a coupling coordination degree (CCD) model to examine the TSFs relationships. Furthermore, principal component analysis (PCA) is used to classify various types of influencing factors, and the Revealed Comparative Advantage (RCA) index is employed to identify the primary types of influencing factors at the county level. The study integrates coupling coordination types and advantage factors into the zoning process. The results demonstrate: (1) Ecological function is the dominant function. At the administrative unit scale, production and living functions exhibit a spatial pattern of "high in the southeast and low in the northwest", while ecological function shows the opposite pattern. Under grid units scale and multi-scale fusion, the high and low texture characteristics of production and ecological functions are more pronounced. (2) TSFs are primarily characterized by slight and moderate disorder. Slight disorder is widely distributed, while moderate disorder is predominantly found in the northwest karst mountainous regions. In contrast, coordinated relationships are more frequently observed in urban areas. (3) The driver types of TSFs can be categorized into four categories: Terrain-Population, Agriculture Development, Location-Economy, and Non-Agriculture Development. By integrating the TSFs relationships, six zones are delineated. Based on this, precise and differentiated optimization suggestions are proposed to promote orderly utilization and sustainable development of TS.

**Keywords:** territorial spatial functions; multi-scale fusion; coupling coordination; influencing factors; southern karst region

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## 1. Introduction

Territorial Space (TS) is the comprehensive spatial layout of a country or region, encompassing natural geography, social structure, and economic activities [1]. Products and services that meet human needs through land use can be categorized into distinct functions [2]. Territorial Spatial Functions (TSFs) focus on the interactions between various

spatial elements, emphasizing development goals such as regional development, ecological balance, and resource management [3]. Currently, human exploitation and utilization of TS are approaching or surpassing the environmental carrying capacity [4]. This has led to negative impacts such as ecological damage, biodiversity loss, and landscape degradation [5,6]. This situation compels us to reevaluate the coordination of TSFs, fortify sustainable development, and mitigate environmental pressure. Consequently, how countries or regions around the world can implement effective and precise Territorial Spatial Planning and Management (TSP, TSM) measures to achieve the harmonious coexistence of humans and nature, in line with the SDGs, and maximize human well-being has become an important issue of the present day.

By the end of the 20th century, Europe and the US had already focused on the competition of TS in urban planning, landscape ecology, and land use [7–10]. They explored TS governance solutions for different stakeholders in the context of limited land situations, pursuing optimal solutions in social welfare, environmental governance, and economic services [11]. Currently, LUCC that serves humanity is increasingly becoming a research hot spot [12]. The multifunctionality of land, its dynamic evolution, complex interplay, and explorations into environmental and spatial justice have attracted extensive attention from scholars [13–16]. In the 21st century, drawing on the development experience of Europe and the US and aligning with their national policies, China has gradually shifted its TS development goals from urban development to ecological protection [17]. Research on TSFs have shifted from a two-dimensional land-based view to a three-dimensional spatial perspective [18]. Under the guidance of policy texts, the concept of the "production, living and ecological" functions in TS have gradually been applied to specific studies such as functional evolution, coupling, and zoning [19,20]. This shift now illustrates a scientific and localized understanding and application of the LUFs theory, while also emphasizing the sustainable development of land at various stages and the importance of harmonizing human-land relations [21].

On a global scale, the study of TS and TSFs are carried out in various countries and regions on a land-based structure. It focuses on the coordinated relationship between functions, exploring zoning governance modes that are local and planned to realize the harmonious coexistence of human societies and the synergistic development of society, economy, and environment [22]. Therefore, it is essential to identify and evaluate TSFs and their internal relationships scientifically and efficiently. Currently, two primary methods exist for identifying TSFs: one approach involves merging different land use types at the grid scale and assigning scores to determine the differences in functional values. While this method can finely identify the internal characteristics of TSFs, it fails to specifically express detailed socio-economic information [23]. The other approach is the comprehensive evaluation method based on constructing an index system and assigning weights, typically conducted at the administrative unit scale. While this method can macroscopically display the overall spatial pattern of TSFs, it overlooks the internal heterogeneity [24]. With the implementation of multi-scale concepts in LUCC and ESV [25,26], the multi-scale fusion model (MSF) has been increasingly used to study the spatial and temporal evolution of TSFs or LUFs [27]. The model can analyze the spatio-temporal variability of TSFs and their internal relationships in a refined "macro-micro" manner [28].

The diversity and complexity of products and services provided by land as a carrier is reflected in the relationship between different functions in human demand for land [29,30]. Scholars commonly employ Trade-offs, synergies and coupling coordination to analyze these relationships, where Trade-offs, synergies correspond to competitive or coordinated functional relationships, and coupling coordination indicates the level of functional relationships [31,32]. Current research concentrates on single or comprehensive functional di-

mension relationships. However, understanding TSFs relationships from a global to local scale requires considering multi-dimensional, multi-level interactions, which is crucial for implementing scientific and sustainable functional zoning. Zoning governance is a vital instrument for enhancing TSFs relationships. Currently, scholars typically approach zoning from a singular perspective, such as functional dominance and coordination. However, they rarely incorporate influencing factors into zoning governance strategies. The TSFs relationship is a comprehensive product under the influence of the natural geography, socio-economy, and regional policy [33]. Natural geography provides the background conditions for the transmission of spatial functions [34]. Socioeconomic and regional policies profoundly influence the TSFs relationships through the accumulation and transmission of elements [35]. Incorporating these influencing factors into functional zoning practices can yield precise regional optimization strategies, complementing the current TSP and TSM. Therefore, by identifying administrative unit grids and performing multi-scale fusion of the current status of TSFs and exploring the coordination among these functions, we can delineate zones based on the dominant types of influencing factors. Subsequently, effective optimization countermeasures can be proposed on the foundation of TSFs zoning.

Guangxi is a typical karst region in southern China, characterized by highly sensitive ecosystems [36]. In recent years, with the implementation of the Western development strategy and the construction of the new Western-to-Marine corridor, the evolution of the TS in Guangxi has been drastic. The TSFs relationships tend to be complicated [37]. Scientific and precise TSP and TSM to coordinate the relationship between ecological environment and economic development is essential to achieve SDGs and maximize human well-being. In this study, we chose Guangxi as the research area and proposed the primary goals:

(1) To analyze the TSFs pattern at the administrative unit scale, grid unit scale and multi-scale fusion;
(2) To explore the coupling coordination Relationships of TSFs;
(3) To classify the principal component types of the influencing factors;
(4) To realize the optimization of zoning by integrating the coupling coordination Relationships of TSFs and the principal component types of influencing factors.

## 2. Research Area and Data

### *2.1. Research Area*

Guangxi (104°26′ E~112°04′ E, 20°54′ N~26°24′ N) is located in the karst region of southern China. It comprises 14 prefecture-level cities and 111 districts and counties. The region had a permanent population of 50.1268 million in 2020. The total land area is 237,600 $km^2$. Mountains, hills, and basins are extensively distributed throughout the area, resulting in complex topography and geomorphology. It is characterized by the typical interlacing of mountains, seas, and land. The terrain is higher in the northwest and lower in the southeast, with an average elevation of 395 m (Figure 1). Guangxi is located in the subtropical monsoon climate zone; the type of land use is dominated by woodland, farmland, and grassland, with a forest coverage rate of 62.55%. In recent years, driven by policies, Guangxi has undergone a rapid transformation in industrialization and urbanization, leading to significant changes in the spatial evolution of the region's land. Consequently, the TSFs relationships have become increasingly complex.

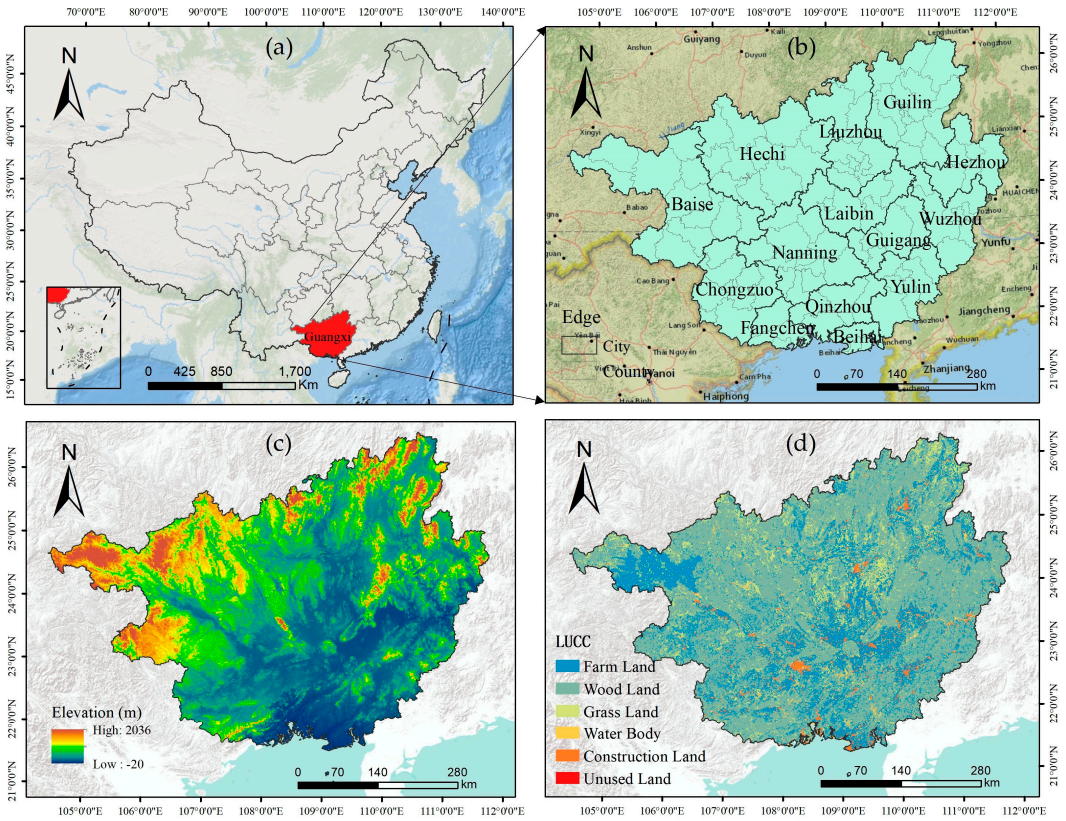



**Figure 1.** Research Area. (**a**) Location of the study area; (**b**) Cities and counties in the study area; (**c**) Elevation of the study area; (**d**) Land Use and Land Cover Change of the study area in 2020.

### *2.2. Data Sources*

This study takes 2020 as the time point, with 14 prefecture-level cities and 111 districts and counties as the main units of analysis. The socioeconomic data were obtained from the Guangxi Statistical Yearbook, the China County Statistical Yearbook, and the statistical yearbooks of each city. Among the spatial vector and raster data, administrative boundaries, land use, and Land Cover Change (LUCC), digital elevation model (DEM), population raster, net primary productivity of vegetation (NPP), and NPP-VIIRS satellite nighttime light data (NTL) were obtained from the Resource and Environment Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 12 December 2024). Carbon emission data were obtained from the China Emission Accounts and Datasets (https://www.ceads.net.cn/, accessed on 15 December 2024). The background base map for the research area is sourced from the ArcGIS Online Map (https://services.arcgisonline.com/, accessed on 4 January 2025). Policy text data were collected from the people's government website of each district and county, capturing relevant policy documents based on relevant keywords in the past three years.

## 3. Methods

### *3.1. Research Framework*

This study takes Guangxi, a southern karst region, as the research object and 2020 as the research time node. First, a multi-scale fusion (MSF) model is constructed based on administrative and grid unit scales. The administrative unit scale measures data primarily using statistical data through a weighted summation measurement method based on an index system. The grid unit scale measures data primarily using spatial data through an area-weighted summation method with a 4 km × 4 km grid. In the multi-scale fusion

phase, we specifically employed two strategies. One strategy involved extracting key features from the grid unit scale and progressively integrating them with the administrative unit scale, with the aim of preserving spatial details and overall trends. This approach is primarily used for precise "macro-micro" analysis of TSFs. The other strategy involved a comprehensive evaluation based on area-weighted summation, which is mainly used to identify the coordination of TSFs across multiple dimensions and levels. Secondly, the influencing factors are selected according to the study area's natural geographic characteristics and socio-economic status. The principal component analysis is applied to identify the comprehensive and composite types of the influencing factors. The Revealed Comparative Advantage index is adopted to identify the advantageous influencing factors of the districts and counties. Finally, according to the type of coordination, advantageous influencing factors for the TSFs zoning should be put forward, as well as scientific and precise regional optimization countermeasures. These steps are mainly completed in ArcGIS 10.7 and SPSS 26 (Figure 2).

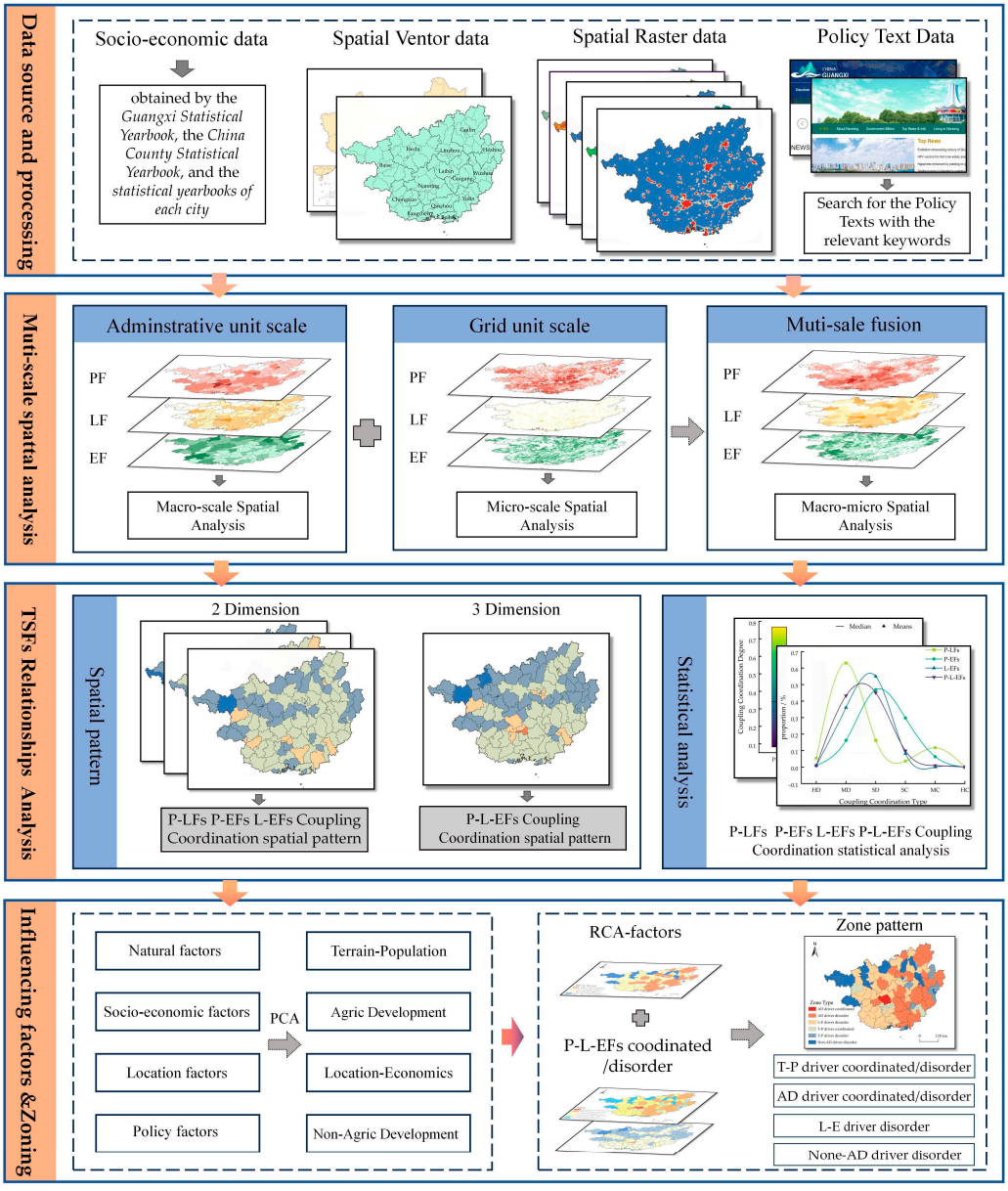



**Figure 2.** Research framework.

### *3.2. Measurement of TSFs at the Administrative Units Scale*

#### 3.2.1. Evaluation Index System and Weighting

Production function (PF) is to provide social production and services [38]. This study divides the PF into agricultural production, which embodies the agricultural inputs and outputs; non-agricultural production, which embodies the development of secondary and tertiary industries; and sustainable production, which embodies the sustainable development of economic production. The 9 indicators are selected for characterization (Table 1).

**Table 1.** Evaluation index system of administrative unit scale.

| Destination Layer | Criterion Layer | Index Level | Index Description | Index Weight | Property |
|---|---|---|---|---|---|
| PF | Agriculture froduction Functions | Food productivity | Food crop production/Food crop area | 0.024 | + |
| | | Non-food productivity | Non-food crop production/Non-food crop area | 0.061 | + |
| | | The proportion of primary production | Output value of primary production/GDP (%) | 0.055 | + |
| | Non-agriculture production functions | Large-scale industrial enterprises | Number of large-scale industrial enterprises | 0.090 | + |
| | | Density of secondary and tertiary Industries | Output value of secondary and tertiary production/and area | 0.264 | + |
| | | The proportion of secondary and tertiary industries | Output value of secondary and tertiary/GDP | 0.017 | + |
| | Sustainable production | Patent grant | Number of patents granted for the year | 0.185 | + |
| | | Output value of large-scale industrial | Output value of large-scale industrial enterprises | 0.128 | + |
| | | External trade dependence | Total exports/GDP | 0.177 | + |
| LF | Living standard | Per capita GDP | GDP/Regional population | 0.125 | + |
| | | Per capita total retail sales of consumer goods | Total retail sales of consumer goods/land area | 0.297 | + |
| | Space support | Road network density | Road mileage/Land area | 0.062 | + |
| | | Per capita built-up area | built-up area of towns and rural/population | 0.115 | + |
| | Social service | Sports and recreation level | Number of gymnasiums/Population | 0.236 | + |
| | | Education level | Number of primary and secondary schools/population | 0.076 | + |
| | | Medical level | Number of medical beds/Population | 0.089 | + |

**Table 1.** *Cont.*

| Destination Layer | Criterion Layer | Index Level | Index Description | Index Weight | Property |
|---|---|---|---|---|---|
| EF | Ecological maintenance | The proportion of nature reserves area | Nature reserves area/Land area | 0.395 | + |
| | | Waste disposal level | Number of refuse disposal stations/population | 0.261 | + |
| | | Forest cover | Woodland area/Land area | 0.044 | + |
| | Ecological pressure | Carbon emissions | Reflecting industry carbon efficiency | 0.148 | - |
| | | Agricultural plastic film pollution | Agricultural plastic film area/Farmland area | 0.102 | - |
| | | Farmland surface pollution | Pesticide and fertilizer application/farmland area | 0.050 | - |

Living Function (LF) mainly carries and protects people's livelihoods, reflecting the ability to have economic security, spatial security, social security, etc. [39]. In this study, the LF is divided into 3 criterion layers: living standards, spatial support, and social services. These layers cover the aspects of residents' income and consumption, transportation, public services, etc. The 7 indexes are selected to characterize the LF (Table 1).

Ecological Function (EF), as a natural condition to maintain human survival, is a necessary precondition for the realization of production and living functions [40]. EF reflects the important concepts of ecological civilization construction and sustainable development. It is characterized by the two criterion layers of ecological maintenance reflecting the basic conditions of ecosystems and ecological pressure reflecting the limitations of ecological equilibrium. The 6 indicators are selected (Table 1).

Considering that there are different indexes of positive and negative attributes in the TSFs, the original indexes are standardized by the method of extreme difference [41]. The entropy weight method and coefficient of variation method are used to determine the single weight and then take the average value to determine the comprehensive weight of the indexes [42,43]. This weighting method can avoid the stochastic errors associated with a single weighting approach, thereby enhancing the scientific validity and rationality of the evaluation results (Table 1).

#### 3.2.2. Weighted Summation Measurement Model

The weighted summation measurement model (WSM) obtains the comprehensive evaluation value by multiplying the weight of each indicator [44]. WSM was used to calculate the TSF levels at the administrative unit scale. The formula is as follows:

$$S_{\mathrm{p}} = \sum_{a=1}^{n} u_a \times p_a,\ S_{\mathrm{l}} = \sum_{b=1}^{n} u_b \times l_b,\ S_e = \sum_{c=1}^{n} u_c \times e_c \quad (1)$$

where $S_{\mathrm{p}}$, $S_{\mathrm{l}}$, and $S_{\mathrm{e}}$ are the evaluation values of the TSFs at the administrative unit scale; $p_{\mathrm{a}}$, $l_{\mathrm{b}}$, and $e_{\mathrm{c}}$ are the standardized values of the indexes in the TSFs; $u_{\mathrm{a}}$, $u_{\mathrm{b}}$, and $u_{\mathrm{c}}$ are the weights of the indexes for each function, and $a$, $b$, and $c$ are the number of indexes for each function.

### *3.3. Measurement of TSFs at the Grid Unit Scale*

#### 3.3.1. Measurement of Production Function at the Grid Unit Scale

PF is the role of providing social production and services, which can be divided into agricultural production function (APF) and non-agricultural production function (Non-APF), corresponding to agricultural production space and urban production space [45]. NPP index refers to the amount of organic matter accumulated by surface vegetation per unit area and time, which directly reflects the production capacity of vegetation under natural environmental conditions. APF can be characterized as the ability to provide agricultural products in agricultural space. Related studies show that the ability to provide agricultural products in the agricultural space has a significant positive correlation with the biological productivity of land [46]. So, the average value of the NPP index of farmland within the grid can be measured to characterize the APF at the grid unit scale. Non-APF can characterize the ability to provide industrial products and services in the urban production space. Related studies have shown that the NTL can reflect the intensity of economic activities per unit area and time, and there is a strong correlation with the urban construction land. Therefore, the mean value of the NTL index of construction land in the grid was measured to characterize the Non-APF at the grid unit scale.

Considering that the ratio of primary production to secondary and tertiary production in Guangxi is 16:84, the weights of APF and Non-APF in this study were 0.16 and 0.84, respectively, when calculating the PF at the 4 km × 4 km grid scale.

#### 3.3.2. Measurement of Living Function at the Grid Unit Scale

Population Density (PD) refers to the number of people living in a unit area, which is an important index of population pattern in a region. It reflects the degree of population congestion, resource allocation, urban planning, etc. [47]. The higher the PD is in a unit area, the stronger the capacity of land bearing and security, and the higher the value of the LF accordingly. Therefore, the grid unit scale LF was characterized by measuring the PD index at the 4 km × 4 km grid scale.

#### 3.3.3. Measurement of Ecological Function at the Grid Unit Scale

EF provides basic resources and environmental capacity for human social production and living activities. Ecological Index (EI) is a method of calculating the ecological environment index of a region by scoring the ecological function and environmental quality of different land categories [48]. It also can intuitively reflect the ecological environment status of a region. Generally, there is a significant correlation between EF and EI, so the grid unit scale EI was characterized by measuring the mean value of the EI at the 4 km × 4 km grid scale.

### *3.4. Multi-Scale Fusion Model*

Using the iterative method to construct the spatial connection between the administrative and grid unit scales. Constructing the mathematical model for the MSF of the TSFs based on the scores and weights of the evaluation index at each scale [27]. We can not only make the evaluation results reflect the macroscopic background of the TSFs of the administrative unit but also characterize the texture characteristics of the grid unit within the administrative unit. The formula is as follows:

$$F_{\mathrm{p,l,e}} = (1-\alpha) \times A_{\mathrm{p,l,}e} + \alpha \sum_{i=1}^{n} A_i \times \beta \quad (2)$$

where $F_{\mathrm{p,l,e}}$ is the comprehensive evaluation value of TSFs under multi-scale fusion; $\alpha$ is the weight occupied by administrative unit scale; $A_{\mathrm{p,l,e}}$ represents the evaluation index

value of TSFs at grid scale; $A_i$ and $\beta$ are the corresponding index weights of the TSFs at the administrative unit scale, respectively.

To precisely measure the TSFs relationships in Guangxi, this paper adopts the area-weighted summation method to obtain the multi-scale fusion map based on the administrative unit. Considering the equal importance of evaluation values at both the administrative and grid unit scales, the weights are assigned as 0.5 for each.

### *3.5. Measurement of Coupling Coordination Degree*

Although the traditional coupling degree model (CD) can judge the synergistic degree of the TSFs, there is a situation where the TSFs have a low level of development but show a high degree of coupling. Moreover, the higher the level of development of the TSFs, the closer the symbiotic relationship of the functions tends to be, and the conflicts and contradictions arising from the interaction of the functions can be resolved [49,50]. Therefore, this study introduces the coupling coordination degree (CCD) model to measure the relationships of the TSFs in Guangxi. The formula is as follows:

$$C_{p,l,e} = 3 \times \left\{ \frac{F_p \times F_l \times F_e}{(F_p + F_l + F_e)^3} \right\}^{1/3} \tag{3}$$

$$T_{p,l,e} = \alpha \times S_p + \beta \times S_l + \gamma \times S_e \tag{4}$$

$$D_{p,l,e} = \sqrt{C \times T} \tag{5}$$

where $C_{p,l,e}$ is the CD among the TSFs, the value range is [0, 1]; $F_p$, $F_l$, and $F_e$ are the multi-scale fusion evaluation value of the TSFs; $T_{p,l,e}$ is the comprehensive development degree among the TSFs, the value range is [0, 1]; $D_{p,l,e}$ is the CCD among the TSFs. The pending coefficient is determined as $\alpha = \beta = \gamma = 1/3$. To further analyze the coordination status within the TSFs, the CCD model can be evolved as follows:

$$C_{p,l} = 2 \times \left\{ \frac{F_p \times F_l}{(F_p + F_l)^2} \right\}^{1/2}, \; C_{p,e} = 2 \times \left\{ \frac{F_p \times F_e}{(F_p + F_e)^2} \right\}^{1/2}, \; C_{l,e} = 2 \times \left\{ \frac{F_l \times F_e}{(F_l + F_e)^2} \right\}^{1/2} \tag{6}$$

$$T_{p,l} = \delta \times F_p + \varepsilon \times F_l, \; T_{p,e} = \varphi \times F_p + \phi \times F_e, \; T_{l,e} = \gamma \times F_l + \eta \times F_e \tag{7}$$

$$D_{p,l} = \sqrt{C_{p,l} \times T_{p,l}}, \; D_{p,e} = \sqrt{C_{p,e} \times T_{p,e}}, \; D_{l,e} = \sqrt{C_{l,e} \times T_{l,e}}, \tag{8}$$

where $C_{p,l}$, $C_{p,e}$, and $C_{l,e}$ is the CD between the TSFs, the value range is [0, 1]; $T_{p,l}$, $T_{p,e}$, and $T_{l,e}$ are the comprehensive development degrees between the TSFs, the value range is [0, 1]; $\delta$, $\varepsilon$, $\varphi$, $\psi$, $\gamma$, and $\eta$ are the pending coefficients between the TSFs, and it is determined that the pending coefficients are $\delta = \varepsilon = 1/2$, $\varphi = \psi = 1/2$, $\gamma = \eta = 1/2$. By referring to relevant studies, consulting experts [41,51] and based on the development level and actual situation of the TSFs in the study area, the coupling coordination types are divided into the six major categories (Table 2).

**Table 2.** Classification of coupling coordination degrees of TSFs.

| Type | CCD | Characteristic |
| --- | --- | --- |
| Height Disorder (HD) | [0.0, 0.2) | In TSFs, one or two functions are at a low level, and the relationships between TSFs are disorderly and highly conflicting. |
| Moderate Disorder (MD) | [0.2, 0.4) | In TSFs, one or two functions lag behind, resulting in a competitive effect among functional relationships. |

**Table 2.** *Cont.*

| Type | CCD | Characteristic |
|---|---|---|
| Slight Disorder (SD) | [0.4, 0.5) | TSFs are developing towards a medium level, with functional relationships progressing towards slight coordination. |
| Slight Coordination (SC) | [0.5, 0.6) | TSFs exhibit medium-level development, but due to the lagging of certain functions, functional relationships only manifest as slight coordination. |
| Moderate Coordination (MC) | [0.6, 0.8) | TSFs have been elevated to a higher level, with functional relationships gradually improving and becoming more coordinated. |
| High Coordination (HC) | [0.8, 0.1] | TSFs exhibit a high-level state, with functional relationships entering a stage of sustained orderliness and coordination. |

### *3.6. Influencing Factors and Zoning of TSFs*

#### 3.6.1. Selection of Influencing Factors

Based on the four dimensions—natural endowment, socio-economics, location, and policy—the indexes are selected to construct the influence factors of the TSFs relationship. The higher the altitude and the larger the slope, the more limited the development and utilization of production and living space, which is not conducive to the landing of PF and LF [51], so the above 2 indexes are chosen as the factors of natural endowment (Table 2). The industrial development and per capita income can characterize the overall development of the regional economy. The resident population, agricultural labor force, and investment in fixed assets provide the basic impetus for socio-economic development. They mutually promote the development of PF and LF. Therefore, the above 8 indexes are chosen as the factors of socio-economics (Table 2). Since 2019, Guangxi has launched a series of policies to support the implementation of the strong capital city strategy. Therefore, the central city of Nanning, the capital city, has become an area where regional production and living factors are highly aggregated [52]. Districts or counties closer to the capital city are conducive to the mobility of PF and LF, so the distance to the provincial capital is selected as a factor to measure the locational conditions (Table 2). Guangxi, as a traditional agricultural province, is an important production area for national grain crops. The arable farmland protection policy can guarantee food security, maintain agroecology, and promote the sustainable development of the agricultural economy [51], so the farmland protection intensity is chosen as a factor to measure the regional policy (Table 3).

**Table 3.** Index system of influencing factors.

| Index | Index description | Property |
|---|---|---|
| Elevation X1 | Average elevation of districts and counties | - |
| Slope X2 | Average slope of the districts and counties | - |
| Resident population X3 | Urban and rural resident population in the district and county during the study period | + |
| Agricultural labor X4 | Number of people working in rural agriculture | + |
| Output value of primary production X5 | Total value of primary industries in the districts and counties during the study period | + |
| Output value of secondary production X6 | Total value of secondary industries in the districts and counties during the study period | + |

**Table 3.** *Cont.*

| Index | Index description | Property |
| --- | --- | --- |
| Output value of tertiary production X7 | Total value of tertiary industries in the districts and counties during the study period | + |
| Growth rate of investment in social fixed assets X8 | Growth rate of total social asset investment over the study period in the districts and counties | + |
| Per capita income of urban residents X9 | Primary distribution and redistribution of the total income of urban and rural residents after deducting various corresponding expenditures | + |
| Per capita income of rural residents X10 | | + |
| Distance to provincial capital X11 | Euclidean Distance of districts and counties from provincial capital | + |
| Farmland protection intensity X12 | Frequency of policy texts with keywords "耕地保护 (Farmland protection)", "耕地红线 (Farmland red line)" and "基本农田 (Basic farmland)" in each district and county of the study area | + |

#### 3.6.2. Classification of Influencing Factor Types and Comprehensive Zoning

Principal component analysis (PCA) reduces dimensionality by transforming multiple factors into one or several composite factors, capturing the characteristic information present in the original data [53]. In this study, PCA was used to extract the composite types of the influencing factors. The Revealed Comparative Advantage Index (RCA) was used to identify composite types of district and county advantages [54]. Finally, we combined the composite types with coupling coordination types to achieve zoning. The formula of RCA is as follows:

$$RCA = \frac{(X_{ij}/Y_i)}{(X_{wj}/Y_w)} \quad (9)$$

where $X_{ij}$ represents the principal component score of the $j$-th major impact type in districts or counties $i$; $Y_i$ represents the sum of the principal component scores of all major impact types in district i; $X_{\mathrm{wj}}$ represents the sum of the principal component scores of the j-th major impact type in all districts and counties; and $Y_{\mathrm{w}}$ represents the sum of the principal component scores of all major impact types in all districts.

## 4. Results

### *4.1. Spatial Pattern of TSFs*

#### 4.1.1. Administrative Unit Scale

Using the administrative unit scale evaluation model to measure the TSF value of Guangxi districts and counties, Figure 3a,d,g illustrates the spatial pattern characteristics. The average values of PF, LF, and EF are 0.183, 0.151, and 0.384, respectively; the EF is the advantageous function in Guangxi. The spatial pattern of PF and LF as a whole was a "high in the south and low in the north". In terms of PF, Nanning, Liuzhou, and Guilin urban areas show a continuous distribution of high values, Yulin and coastal Beihai urban areas show sporadic distribution of high values; the medium value areas are mainly distributed in the areas adjacent to the central urban area and the middle of the Laibin, Guigang, and the main agricultural production areas; the lower value areas are continuously distributed in the north and sporadically distributed in the south. In terms of LF, the high value areas are continuously distributed in urban areas of Nanning, Liuzhou, and Guilin, sporadically distributed in urban areas of Yulin, Wuzhou, Beihai, and Baise; the medium value areas are mainly distributed in southern suburban counties, and low value areas are continuously distributed in northern and western counties. The spatial pattern of EF is opposite

to PF and LF, with an overall pattern of "high in the northwest and low in the southeast". High value and medium value areas mainly distributed in the northern and western karst mountainous counties; low value areas are mainly distributed in the central part.

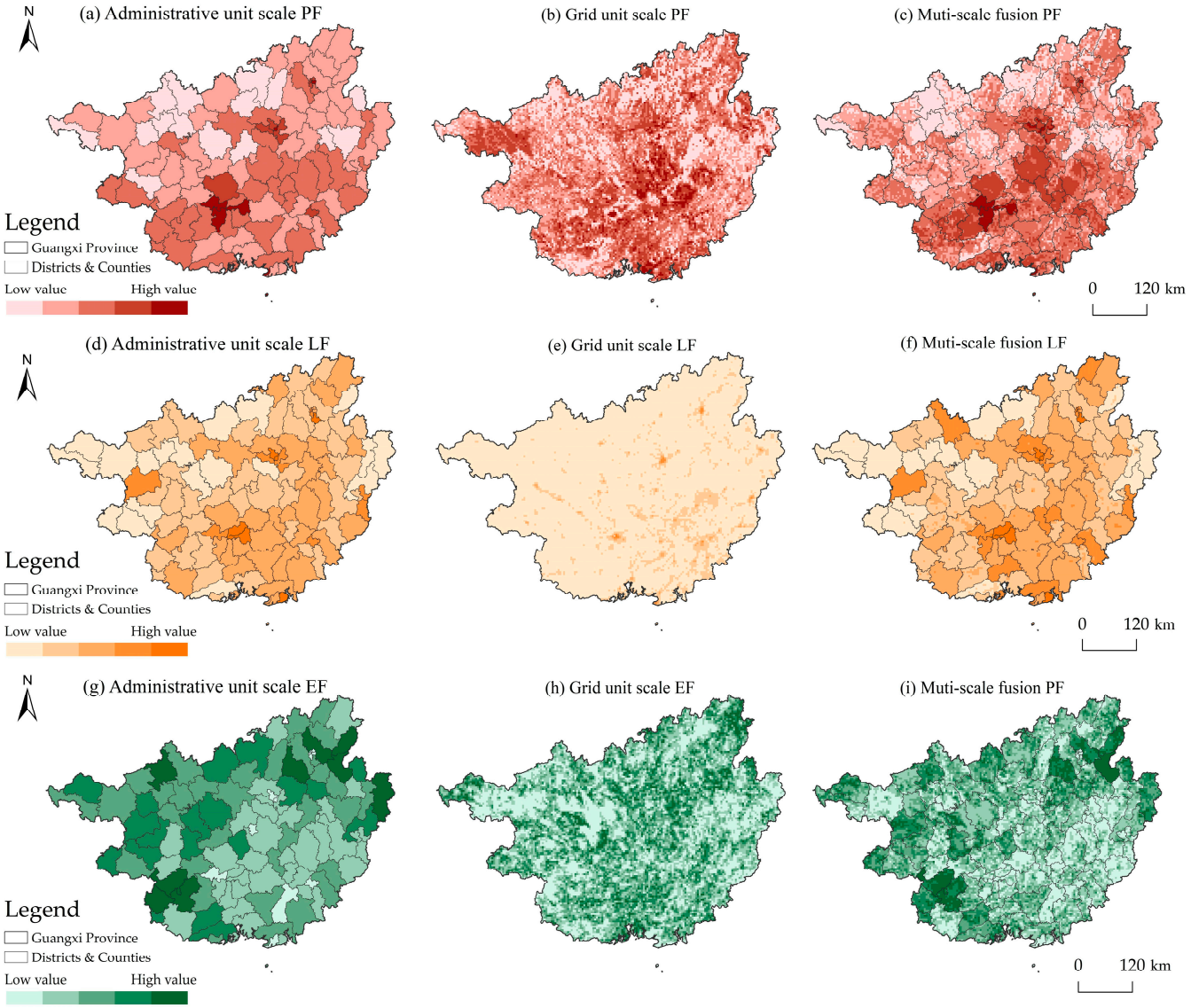



**Figure 3.** Spatial pattern of TSFs (PF, LF, EF). (**a**,**d**,**g**) Spatial pattern of TSFs at administrative unit scale; (**b**,**e**,**h**) Spatial pattern of TSFs at grid unit scale; (**c**,**f**,**i**) Spatial pattern of TSFs at multi-scale fusion.

#### 4.1.2. Grid Unit Scale

Using the grid unit scale evaluation model to measure the TSF value of Guangxi on the 4 km × 4 km grid, Figure 3b,e,h illustrates the spatial distribution characteristics. The spatial pattern of the PF is more homogeneous than the administrative unit scale, while the LF, on the contrary, shows more significant spatial differentiation characteristics; the PF shows two types of high value distribution characteristics, one type is the Non-APF area in the central cities represented by Nanning, Liuzhou, and Guilin, and the other type is the APF high value area in the counties represented by Laibin, Guigang, Hechi, and Baise. The grid LF strengthens the spatial differentiation of "high-low value" between the central urban areas and the counties. The spatial differentiation is more significant in Nanning, Liuzhou, Guilin, and Yulin areas. Because the EF is the dominant TSF in Guangxi, the performance of the grid EF is more homogeneous, and the high value areas are widely

distributed in the study area. However, due to the inherent fragility of the ecological environment in karst regions, the high value distribution of EF is relatively fragmented in areas such as Hechi, Baise, and Chongzuo.

#### 4.1.3. Fusion of Administrative and Grid Unit Scales

Using the MSF model to quantitatively analyze the TSFs of Guangxi, Figure 3c,f,i illustrates the spatial pattern characteristics of multi-scale fusion. The spatial differentiation of PF and EF under multi-scale fusion is obvious, and the spatial differentiation of LF is general, but based on maintaining the spatial differentiation of macro-administrative units, it also expands the internal micro-texture differences. Specifically, the PF and EF maintain this "macro-micro" spatial differentiation as a whole. Because the grid PF distinguished between plots at the non-agricultural and agricultural levels, the non-agricultural production advantageous areas in the center of the urban areas are significantly different from the agricultural production advantageous areas in the counties. Concurrently, in karst mountainous counties that exhibit high levels of EF at the administrative unit scale, the internal texture features are more pronounced. Because the LF is more homogeneous at the grid scale, it maintains the spatial differentiation at the macro-administrative scale but is less obvious than the PF and EF at the micro-texture.

### *4.2. Coupling Coordination Analysis of TSFs*

Based on the evaluation results of TSFs in Guangxi districts and counties in 2020, the TSF's relationships were measured with the help of the CCD model. The mean values of Production-Living Functions (P-LFs), Production-Ecologic Functions (P-EFs), Living-Ecologic Functions (L-EFs), and Production-Living-Ecologic Functions (P-L-EFs) coupling coordination degrees are 0.371, 0.47, 0.42, and 0.41; the whole is in a slight disorder state, in which the P-EFs coordination relationship is stronger, and the P-LFs coordination relationship is weaker (Table 4, Figure 4).

**Table 4.** Statistical analysis of TSFs relationships.

| Groups | Ranges | Means | Proportion of Coupling Coordination Types (%) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | HD | MD | SD | SC | MC | HC |
| P-LFs | [0.08–0.77] | 0.37 | 5.41% | 63.06% | 16.22% | 3.60% | 11.71% | - |
| P-EFs | [0.15–0.66] | 0.47 | 0.90% | 16.22% | 46.85% | 29.73% | 6.30% | - |
| E-LFs | [0.14–0.58] | 0.42 | 0.90% | 36.04% | 54.95% | 8.11% | - | - |
| P-L-EFs | [0.18–0.60] | 0.41 | 0.92% | 43.24% | 45.05% | 9.91% | 0.90% | - |

Figure 5a–d illustrates the spatial pattern characteristics of TSF relationships. In the P-LFs relationship, the proportion of moderate disorder is the highest, 63.06%, and widely distributed in the whole study area; High Disorder is distributed in the mountainous counties of Baise in the northwestern part of Guangxi; moderate disorder and slight disorder are mainly distributed in the central and southern parts of Guangxi around the central urban areas; slight and moderate coordination is mainly distributed in the urban areas of Guilin, Liuzhou, and Nanning. In the P-EFs relationship, slight disorder accounts for the highest proportion of 46.86% and is widely distributed with slight coordination in the counties around the central urban areas; high disorder and moderate disorder are sporadically distributed in the northern karst mountainous counties and the central urban areas of Guilin, Liuzhou, Yulin, and Beihai; moderate coordination is mainly distributed in the central urban areas of Nanning, Baise, Laibin, Qinzhou, and Fangcheng. In the L-EFs relationship, the proportion of slight disorder is the highest, 54.95%, and is widely distributed in Guangxi; slight coordination is mainly distributed in the urban areas of Nanning, Guilin,

and Baise, as well as in some of the counties of Chongzuo, Qinzhou, and Baise. In the P-L-EFs relationship, slight disorder accounts for a higher proportion of 45.05% and is distributed in the central and southern regions in clusters; high disorder and moderate disorder are similar to the spatial pattern of L-EFs and show an expanding trend; slight coordination and high coordination are mainly distributed in the central urban areas of Nanning, Liuzhou, Guilin, Yulin, Beihai, and Hechi.

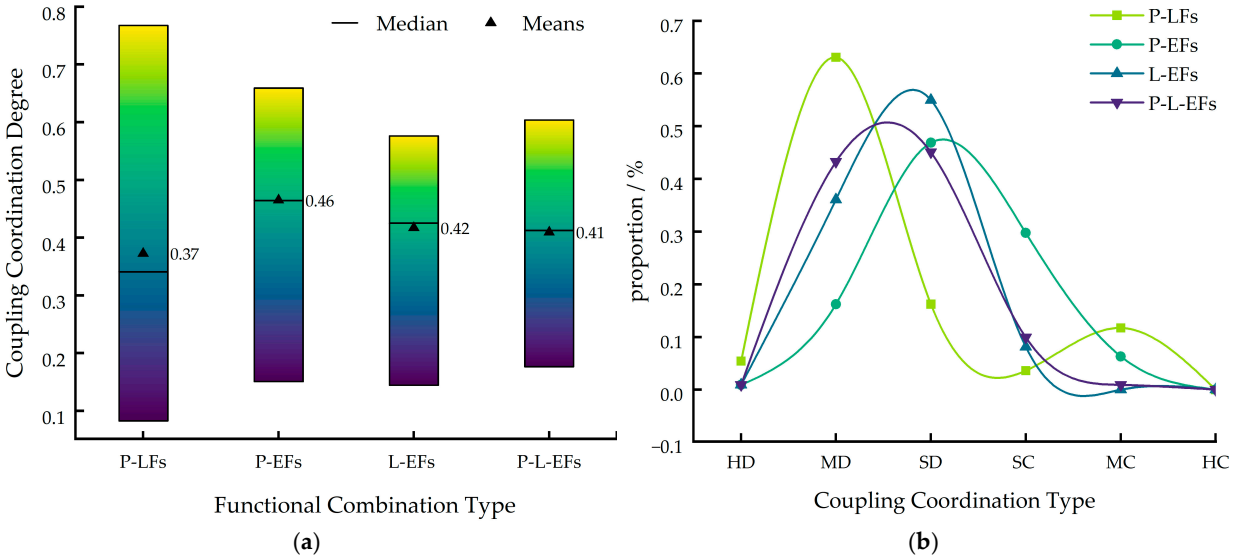



**Figure 4.** (**a**) The distribution interval, median line, and mean value of the coupling coordination degree for functional combinations; (**b**) The evolution curve of coupling coordination type proportions for functional combinations.

### *4.3. Influencing Factors Analysis of TSFs*

PCA was used to extract the principal components of the indexes to determine the main factors affecting the TSFs relationships. The KMO value obtained from the principal component analysis was 0.69, which passed the significance test, indicating that the PCA was feasible. The eigenvalues of the first four principal components are 4.42, 2.37, 1.16, and 1.03, respectively, accounting for a cumulative contribution rate of 74.83% of the total variance (Table 5). This indicates that the first four principal components can capture the information contained in the 12 indicators. Therefore, the first four principal components were chosen as the basis for classifying the driver types of TSF relationships.

**Table 5.** Eigenvalues and contribution rates of principal components.

| Component | Initial Eigenvalue | | |
|---|---|---|---|
| | **Total** | **Percentage of Variance/%** | **Cumulative/%** |
| PCR 1 | 4.419 | 36.823 | 36.823 |
| PCR 2 | 2.365 | 19.71 | 56.533 |
| PCR 3 | 1.159 | 9.655 | 66.188 |
| PCR 4 | 1.036 | 8.637 | 74.825 |

The component matrix (Table 6) shows that PCR1 has a large loading and positive correlation on the factors of elevation, slope, and resident population. This principal component can thus be categorized as a Terrain-Population factor; PCR2 has a large loading and positive correlation on agricultural labor, the output value of primary production, and land protection intensity. This principal component can thus be categorized as an agricultural development factor: PCR3 has a large loading on the distance to the provincial

capital, slope, and per capita income of residents and is positively correlated except for slope. This principal component can thus be categorized as a Location-Economy factor; PCR4 has a larger load and is positively correlated with the growth rate of investment in social fixed assets, the output value of secondary production, and the output value of tertiary production. Therefore, this principal component is categorized as a non-agricultural development factor.

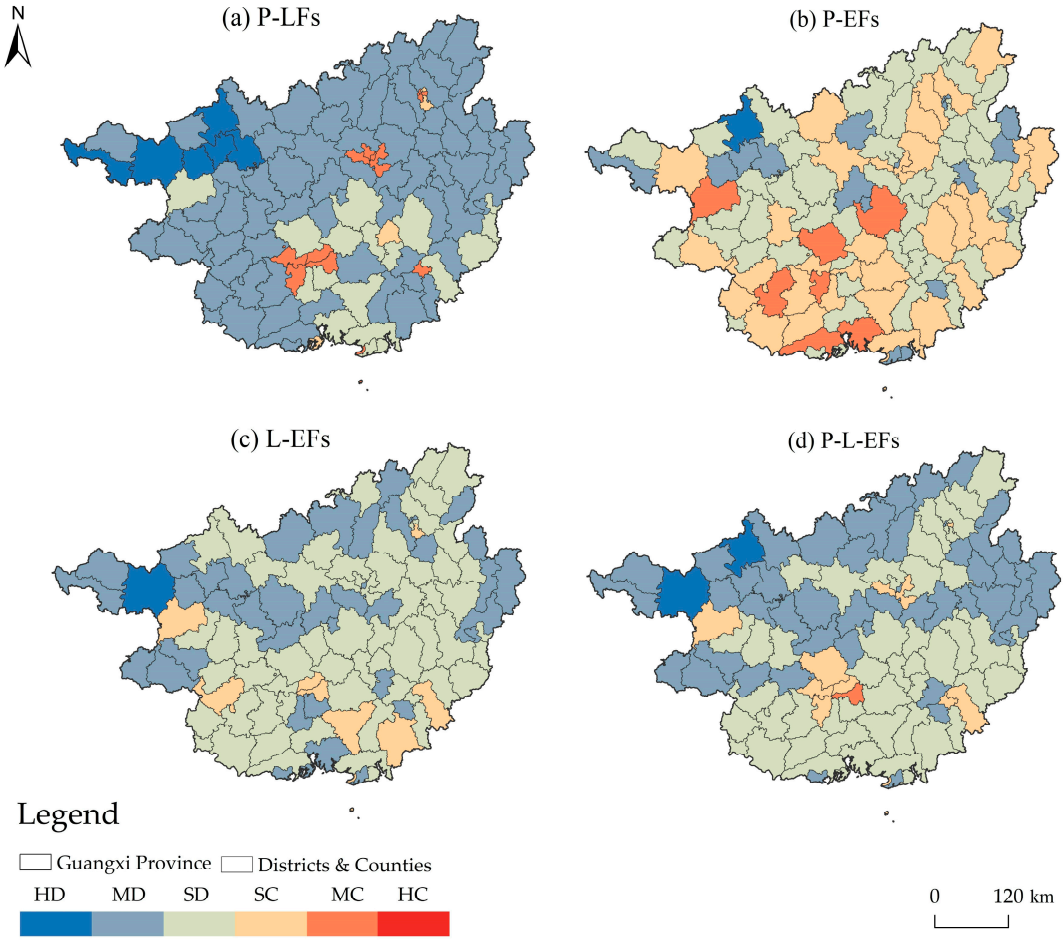



**Figure 5.** (**a**) Spatial pattern of P-LFs relationship; (**b**) Spatial pattern of P-EFs relationship; (**c**) Spatial pattern of L-EFs relationship; (**d**) Spatial pattern of P-L-EFs relationship.

**Table 6.** Component matrix.

| Influence Factor | PCR 1 | PCR 2 | PCR 3 | PCR 4 |
|---|---|---|---|---|
| Elevation X1 | 0.810 | −0.095 | −0.293 | −0.246 |
| Slope X2 | 0.784 | −0.117 | −0.493 | −0.071 |
| Resident population X3 | 0.769 | 0.417 | 0.22 | 0.143 |
| Agricultural labor X4 | 0.431 | 0.766 | 0.162 | −0.13 |
| Output value of primary production X5 | 0.503 | 0.676 | 0.234 | −0.127 |
| Output value of secondary production X6 | 0.646 | −0.391 | 0.08 | 0.285 |
| Output value of tertiary production X7 | 0.672 | −0.261 | 0.126 | 0.322 |
| Growth rate of investment in social fixed assets X8 | −0.232 | 0.209 | −0.085 | 0.839 |
| Per capita income of urban residents X9 | 0.585 | −0.546 | 0.389 | −0.073 |
| Per capita income of rural residents X10 | 0.651 | −0.399 | 0.36 | 0.014 |
| Distance to provincial capital X11 | −0.61 | −0.14 | 0.616 | −0.11 |
| farmland protection intensity X12 | 0.239 | 0.618 | 0.105 | 0.104 |

### *4.4. Zoning in Relation to TSFs Relationships and PCA Types of Influencing Factors*

The RAC index was used to identify the composite types of advantageous influencing factors in different districts or counties, and at the same time, superimposed coupling coordination types for zoning. The zoning aligns with Guangxi's most recent TSP, particularly in agriculturally dominant functional areas and the metropolitan area centered around Nanning. Figure 6 illustrates the spatial pattern of the advantageous influencing factors and zoning, which presents an interactive distribution of "urban areas-counties" and "east-central-west".

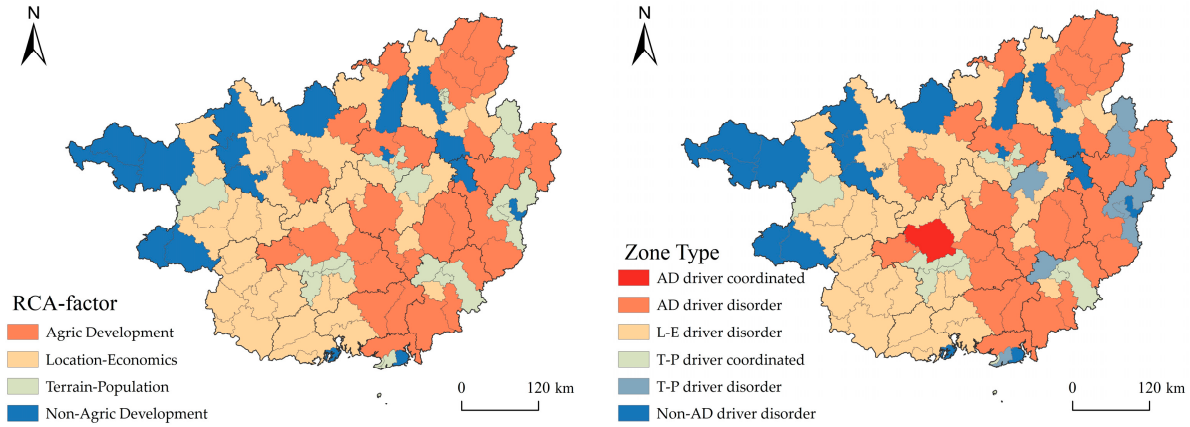



**Figure 6.** RCA factors and zone type.

(1) Terrain-Population (T-P) driver coordinated zone: this type accounts for 9.91%, mostly located in Nanning, Liuzhou, and other central urban areas. The region has superior terrain conditions and a large population base, with good production and living function development of the background conditions.

(2) Agricultural Development (AD) driver coordinated zone: this type has only one district, Nanning's new district of Wuming. Wuming is the demonstration area of characteristic agriculture in Guangxi, agricultural inputs, and outputs to occupy the advantage.

(3) Terrain-Population (T-P) driver disorder zone: this type accounts for 10.81% and is sporadically distributed in the central and western Guilin, Hezhou, Wuzhou, and other centers of urban areas. The region also has superior terrain conditions, but the advantage of the resident population is limited, and the performance for the outflow is poor.

(4) Agricultural Development (AD) driver disorder zone: this type accounts for 27.03%, located in the central and eastern Nanning, Yulin, Laibin, Guilin, and other districts or counties. These counties are mostly located in relatively flat plains and hilly areas, with small zoning located in the karst mountains. Their agricultural labor and the output value of primary production occupy an advantage, and farmland protection intensity is higher under the policy orientation.

(5) Location-Economy (L-E) driver disorder zone: this type accounts for 36.04%, mostly located in the western Chongzuo, Baise, and Hechi, which are not as good as the central and eastern areas in terms of the basic conditions of agricultural production. However, because most of them are close to the capital of Nanning, the radiation effects of the PF and EF elements are strong.

(6) Non-Agricultural Development (Non-AD) driver disorder zone: the type accounts for 15.32% and is sporadically distributed in the karst mountainous counties along the western and central boundaries, as well as in some central urban areas. The terrain

conditions in the karst mountainous areas are generally moderate. In recent years, under the policy guidance of rural revitalization, large-scale infrastructure investment has flowed into the region, promoting the development of non-agricultural production functions. In contrast, the central urban areas have an advantage in the secondary and tertiary industries.

### *4.5. TSFs Relationship Influences Driving Mechanisms in Zones*

(1) T-P driver coordinated zones have the advantages in administrative unit scale indexes such as the density of secondary and tertiary industries, the proportion of secondary and tertiary industries, patent grants, etc. At the grid scale, construction land is widely distributed and has strong nighttime light intensity. The PF in terms of non-agricultural production and production sustainability, as well as the living functions, is strong. There is a significant trend towards slight and moderate coordination in the development of TSFs.

(2) AD driver coordinated zones have a large number of agricultural laborers. At the administrative unit scale, the added value of the primary industry and grain production capacity is dominant. At the grid scale, the NPP index of agricultural land is high, indicating a strong APF. Additionally, due to the relatively large proportion of nature reserve areas, the EF is high, and the coordination relationship is characterized as slightly coordinated.

(3) T-P driver disorder zones are similar to coordinated zones in terms of advantages and disadvantages. However, they have limited advantages in permanent population and often exhibit a population outflow status. At both the administrative and grid unit scales, compared to the coordinated areas, they have weaker advantages in PF and LF, and the coordination relationship is mostly characterized as slight disorder.

(4) AD driver disorder zones have the advantages in agricultural labor and output value of primary industry. Under policy guidance, the farmland protection intensity is high. The forest coverage rate and the proportion of nature reserve areas are also high, with low per capita carbon emissions. These areas have advantages in APF and EF but show weaknesses in non-agricultural production functions. Additionally, due to generally low levels of per capita retail sales of consumer goods and medical and educational public services, the LF is also weak. The TSFs relationships Showed slight or moderate disorder.

(5) L-D driver disorder zones are mostly adjacent to the provincial capital, Nanning. Although the capital has a strong radiating effect on PF and LF: it also exhibits a suction effect on population and economy. The LF and EF in these areas are similar to those in the AD driver disorder zones. However, due to lower proportions of the primary industry and grain production capacity compared to the AD driver disorder zones, the overall PF is weaker, with a larger proportion of moderate disorder.

(6) The karst mountain counties in the non-AD driver disorder zone have a higher EI on the grid scale and a strong EF due to their superiority in the area of nature reserves and forest coverage. In recent years, the large-scale inflow of infrastructure investment under the policy orientation has promoted the development of Non-APF in the area. However, under the premise of large-scale population outflow, labor resources are relatively insufficient, and they do not have an advantage in terms of location and economy. So the PF and LF are still relatively weak, and the TSFs relationships mostly showed moderate or high disorder. The urban areas, due to economic transformation and upgrading, transportation, logistics, and other infrastructure construction, accelerated, and the fixed asset investment growth rate accelerated. PF and LF

have certain advantages; the TSFs relationships are better than the karst mountainous counties, which mostly showed slight disorder.

## 5. Discussion

### *5.1. Countermeasures to Optimize the Zones*

Countermeasures to optimize the zones should first examine the coupling-coordinated relationships, deeply understand the current status of the TSFs, and comprehensively assess the baseline conditions and potential for regional coordinated development. On this basis, further analysis should be conducted on the key factors affecting regional development. By integrating the current use and functional status of TS resources in each zone, adaptive functional enhancement measures can be proposed to promote the coordinated development of TSF relationships. Based on this idea, the following countermeasures are proposed (Table 7):

**Table 7.** Countermeasures for zones.

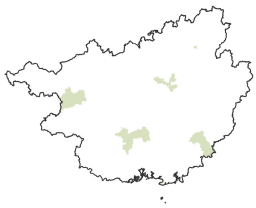
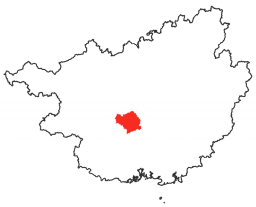
| Zones | Countermeasures |
| --- | --- |
|  T-P driver coordinated zone | (1) Leveraging the advantages of relatively flat terrain and population agglomeration, implement preferential policies in land use and taxation to attract high-end industries, financial trade, and regionally advantageous industries, including new energy vehicles, intelligent manufacturing, and green mining.<br>(2) Enhance the radiation effect of the central urban area on surrounding regions by optimizing the transportation network and improving the level of public services.<br>(3) Optimize the urban land use structure, establish a strict land use supervision mechanism, continuously advance urban renewal policies, and tap into the potential of existing land resources within the urban area.<br>(4) Control the illegal encroachment of ecological land by the expansion of production and living spaces, ensure the integrity and stability of ecological space, increase urban parks and green corridors, and enhance ecological supply. |
|  AD driver coordinated zone | (1) It is essential to continue leveraging agricultural production advantages, enhance the capacity for characteristic agriculture and grain production, and ensure food security and stable supply of agricultural products.<br>(2) Through agricultural policy support and technological investment, modern agricultural technologies and management methods, such as smart agricultural equipment, precision agricultural technology, and green agricultural models. The use of chemical fertilizers and pesticides should be reduced to improve the sustainability of agriculture.<br>(3) Leveraging the advantages of being adjacent to Nanning's urban center, improving living facilities while maintaining a favorable ecological base and effective environmental governance, to enhance residents' quality of life. |

**Table 7.** *Cont.*

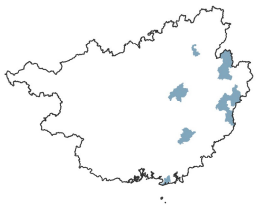
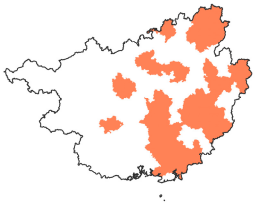
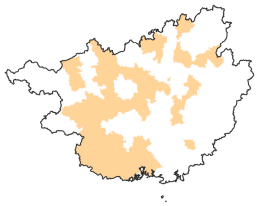
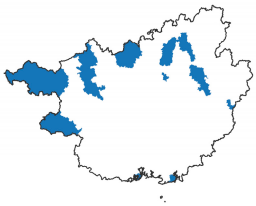
| Zones | Countermeasures |
| --- | --- |
|  T-P driver disorder zone | (1) Industrial supporting facilities should be optimized. Through policy guidance and financial support, high-tech, low-pollution industries, such as biomedicine and electronic information, should be prioritized for development. Comprehensive measures should be taken to enhance land use efficiency and promote the transformation of land resources towards intensive and orderly use.<br>(2) Districts or counties adjacent to coordinated areas can leverage their locational advantages to optimize transportation networks and enhance public service levels, thereby attracting employment populations. This can drive the clustering development of industries with potential, upgrade local production and supporting capabilities, and build a modern industrial system with strong competitiveness.<br>(3) Given the ecological vulnerabilities, sustainable development must be adhered to. It is necessary to construct green production and lifestyle models as well as urban construction and operation modes. Meanwhile, enterprises should be encouraged to adopt green production technologies to reduce pollutant emissions and enhance the environmental friendliness of industries. |
|  AD driver disorder zone | (1) Utilize the advantages of agricultural production conditions to develop competitive agricultural products under the support of relevant policies, thereby achieving a sustainable agricultural economy. Promote ecological and organic agriculture to enhance the quality and market competitiveness of agricultural products and increase farmers' income.<br>(2) Strengthen rural infrastructure construction to enhance living and production conditions in rural areas. For example, improve the rural transportation network, enhance the quality of village roads, advance rural informatization, and, through agricultural economic growth, promote the convenience of rural living facilities.<br>(3) On the basis of agricultural economic growth, in combination with TSP, optimize the layout of public service facilities and enhance the utilization efficiency of these facilities. By scientifically and rationally planning public service facilities such as education, healthcare, and elderly care, promote the improvement of living facilities. |
|  L-E driver disorder zone | (1) Districts or counties adjacent to economic centers should continue to strengthen the construction of industrial and transportation infrastructure. By undertaking the supporting industries of the Nanning urban center, they should promote the integrated development of county and urban economies<br>(2) Northern karst counties can develop characteristic "ecology+" additional industries based on local forestry. They should continue to create green and sustainable non-ferrous metal mining. Relying on the advantages of geographical and cultural landscapes, they can develop a tourism industry that combines ethnic cultural charm with karst scenery. This will create more local employment opportunities for residents and increase their per capita disposable income.<br>(3) Southwestern border counties can seize the opportunity of border trade to extend the local characteristic sugar production and refining industry chain. By leveraging industrial development and trade benefits, they can improve residents' income, comprehensively address the weaknesses in production and living functions, and promote coordinated development of functional relationships. |

**Table 7.** *Cont.*

| Zones | Countermeasures |
| --- | --- |
|  Non-AD driver disorder zone | (1) Coastal urban areas should accelerate economic transformation and upgrading and continue to develop low-carbon, sustainable port-related industries. These include intelligent port logistics, new energy power generation, and marine biomedicine.<br>(2) Inland urban areas and their surroundings should quicken the optimization of industrial structure, moderately engage in industrial park construction, and take on new material and digital creative industries. This will enhance the sustainability of production and living functions and comprehensively improve the currently widespread imbalance in the zoning.<br>(3) Northwestern karst mountain counties should leverage their fixed asset investment advantages to extend traditional industrial chains, achieve green industry support, and perfect the value mechanism of ecological products. Through policy support and scientific ecological compensation, the protection and trade of ecological products should be promoted. Meanwhile, social capital should be encouraged to participate in ecological protection and restoration. |

### *5.2. Comparison with Relevant Studies*

The results show that TSFs exhibit significant spatial differentiation in both single-scale, multi-scale, and complex coupling coordination relationships in the TSFs. The coupling coordination types vary with the differences in socio-economic development or resource endowment corresponding to each region at the functional level. This pattern is similar to the findings in studies of southern China's karst regions, including Guangxi, Yunnan, and Guizhou. Areas with high values in PF, LF, or its suitability differ from ecological functions. Under the influence of relatively superior ecological environments, EF often emerge as dominant functions. However, due to the long-term lag in PF and LF, functional relationships often exhibit disorder or conflict. In terms of influencing factors, we find that economic factors have a profound impact on functional levels, while natural factors are the most fundamental in shaping functional relationships. This conclusion is drawn from comparative studies of the Guangxi Beibu Gulf Economic Zone and Guizhou Province (Table 8).

In contrast to non-typical karst regions such as the Central Yunnan Urban Agglomeration and the Yellow River Basin, we find that the functional levels or functional spaces exhibit spatial consistency. However, in terms of functional or spatial relationships, this region has a broader and higher proportion of coordinated or synergistic functional relationships. This is attributed to the fact that large river basins have long been economic growth poles for the region, providing ample support for production and living elements. Additionally, we find that the Yellow River Basin, such as typical karst regions, is ecologically fragile. Natural factors are similarly the most fundamental and important influencing factors in functional or spatial relationships. Future development must focus on the limitations of regional natural resource conditions and emphasize the sustainability of the ecological environment (Table 8).

**Table 8.** Comparison of relevant studies.

| Region | Year | Study Results | | |
|---|---|---|---|---|
| | | **Spatial Pattern** | **Relationship** | **Influencing Factor** |
| Guangxi Province [55] | 2009 2012 2015 2018 | (1) The spatial pattern of PF and LF is similar. (2) EF are generally high | The spatial pattern of functional coupling coordination shows an "east high, west low" | — |
| Guizhou Province [56] | 2000 2006 2012 2018 | (1) High value areas for PF and LF are located in the western and northern regions. (2) High value zones of EF are mainly located in the eastern regions | — | The single factor with the strongest explanatory power for functional levels is primarily an economic factor. |
| Central Yunnan Urban Agglomeration [57] | 2020 | The spatial distribution of production space suitability is distinct from that of ecological space. | In 2020, the majority of land faced potential conflicts in land use. | The occurrence of PLE potential spatial conflicts is significantly influenced by both natural environmental factors and human activities. |
| Guangxi Beibu Gulf Economic Zone [51] | 2010 2015 2020 | The spatial patterns of PF and LF are distinct from those of EF. | In 2020, disorder was mainly distributed in the western mountainous counties | Terrain is the main factor in the formation of the CCD spatial pattern of the PLE functions. |
| Middle Reaches of the Yangtze River Urban Agglomerations [58] | 2008 2012 2015 2018 | (1) The spatial patterns of the high value areas of PF and LF differ from EF. (2) The EF is superior to the PF and LF. | In 2018, in most cities, there were synergistic effects in the PLE functions, with fewer trade-off effects. | Socioeconomic factors have a more prominent and crucial impact on the relationships of PLE functions than natural factors, especially the degree of land use. |
| Jiangsu Province [59] | 2010 2015 2020 | (1) The PF shows higher values in the central area and lower values in the north and south. (2) The scores of the LF and EF decrease from south to north. | In 2020, the CCD was generally high, and the coordinated zones were widely distributed in space. | — |
| Yellow River Basin [50] | 1995 2000 2005 2010 2015 | The ecological space has been squeezed by production and living spaces in most years. | The proportion of disorder counties is relatively large. The functional relationships are in a non-benign development state. | More natural factors, such as altitude, slope, temperature, etc., have a significant impact on the coordinated relationships. |

### *5.3. Contributions and Limitations*

By constructing an MSF model, combining the measurement of CCD with the classification of influencing factor types, this study carries out a targeted TSF zoning to provide guiding policy support for TSP and SDGs. The study finds that TSFs are relatively balanced at the administrative unit scale. Grid unit scale can further uncover the differences and texture features of TSFs within districts and counties. The MSF model can synthesize

information from administrative units and grid units across multiple scales, providing a more comprehensive evaluation of regional TSFs. This approach not only reflects the functional trends at the administrative unit scale but also fully captures the textural differences of functions within the district and county. Additionally, this paper selects Guangxi as the study area, where the main influencing factors on the TSFs relationships are terrain and agricultural development. As a karst mountainous area in southern China, the terrain determines the pattern of TSP. Intermontane basins and valley plains often facilitate the agglomeration of production and living spaces, enhancing PF and LF, thereby improving the coordination of TSFs. Unlike the past study of zoning based on LUFs at a single scale, this paper revealed the spatial pattern of TSFs at multi-scale fusion and identified driver zoning based on the types of TSF relationships and advantageous influencing factors. The zoning results closely align with Guangxi's new round of TSP at the macro level and can achieve more precise and region-specific zoning optimization at the county and district scale. This study provides a new perspective for understanding the TSFs and emphasizes the importance of integrated assessment at different scales for more precise and SDG management of TS.

However, due to limitations in data accessibility and the spatialization of indexes, this study only calculated static cross-sectional data for 2020, lacking socio-economic data for rural areas. In the future, the temporal scale and comprehensiveness of data can be further enhanced based on the integration of multi-scale data to reveal the dynamic evolution of regional TSFs and coordination relationships. This could provide a strong decision-making basis for multi-level TSFs zoning. This dynamic, multi-scale analysis method will help to accurately reveal the complexity of TSFs and provide support for TSP to be more scientific and rational.

## 6. Conclusions

(1) The TSFs in Guangxi present significant spatial differentiation at different scales, with EF as the dominant function of the region. Under the administrative unit scale, the PF and LF are distributed "high in the south and low in the north", while the EFs are distributed "high in the northwest and low in the southeast". At the grid unit scale, the distribution of PF and EF is more homogeneous, while the LF shows more significant spatial differentiation. The multi-scale fusion analysis reveals the "macro-micro" spatial differentiation of PF and EF, while the micro-level differentiation of LF is not as obvious as that of PF and EF.

(2) The mean values of P-LFs, P-EFs, L-EFs, and P-L-EFs, coupling coordination degree, are 0.371, 0.47, 0.42, and 0.41, respectively, which are in a state of slight disorder. Among them, the P-EFs relationship is stronger, while the P-LFs coordination relationship is weaker. The spatial pattern characteristics show that moderate disorder accounts for the highest proportion in the P-LFs relationship and is widely distributed; the P-EFs relationship is dominated by slight disorder and is widely distributed around the central urban area; slight disorder accounts for the highest proportion in the L-EFs relationship; high and moderate disorder is distributed contiguously in a specific area; and slight disorder accounts for a high proportion of the P-LFs relationship and presents a cluster distribution.

(3) The type of influence factors TSFs in Guangxi can be divided into four major types: Terrain-Population, Agricultural Development, Location-Economy, and Non-Agricultural Development. Combining the coupling coordination types and advantages, influence factors can be divided into T-P driver coordinated zone, AD driver coordinated zone, T-P driver disorder zone, AD driver disorder zone, L-E driver disorder zone, and non-AD driver disorder zone. The spatial pattern presents an in-

teractive distribution of "urban areas-counties" and "east-central-west". Based on the advantageous influencing factors, the regional socio-economic and resource endowments, and precise decision-making suggestions for sustainable and coordinated development of TSFs are put forward.

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