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The Integration of Dual Evaluation and Minimum Spanning Tree Clustering to Support Decision-Making in Territorial Spatial Planning

Muxin Jia [1], Ang Liu [2] and Taro Narahara [1,*]

[1] Hillier College of Architecture and Design, New Jersey Institute of Technology, Newark, NJ 07102, USA; mj8@njit.edu
[2] Global Urban Studies Program, Rutgers University, Newark, NJ 07102, USA; ang.liu@rutgers.edu
* Correspondence: narahara@njit.edu

Abstract: Spatial planning, a policy instrument for creating sustainable environments that meet the needs of the current and future generations, has been implemented extensively worldwide. However, it is difficult for urban planners to thoroughly determine the spatial value of a territory and make informed decisions regarding the efficient utilization of regional resources in the real world. This study proposes a novel methodological framework for spatial pattern optimization that can guide future land use by integrating Minimum Spanning Tree (MST) clustering with a comprehensive evaluation system (dual evaluation). Furthermore, the validity of this framework is demonstrated through a case study of territorial spatial planning in Deyang, China. The findings indicate that (1) the methodological framework presented in this study offers valuable guidance for the spatial arrangement of territorial resources, especially in practical projects; and (2) the combination of dual evaluation and MST clustering can facilitate automatic regionalization to identify spatial clusters exhibiting functional similarity in terms of land use. By focusing on methodological advancements, this study concludes that the integration of dual evaluation (DE) and MST clustering not only simplifies the identification of optimal land-use patterns but also promotes a more systematic and efficient approach to support spatial planning.

Keywords: territorial spatial planning; dual evaluation; minimum spanning tree clustering; decision-making; land-use layout

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1. Introduction

With global population growth and economic development, an increasing number of people are living in urban areas. Rapid global urbanization, coupled with aggravated resource scarcity and environmental risks, has prompted policymakers to reconsider the value of long-term planning [1]. Governments worldwide have resorted to spatial planning for urban sprawl control to mitigate latent risks to ecological protection, food security, and economic growth [2].

Spatial planning is a systematic process of spatially utilizing and governing territorial resources within a specific area (a city, county, or state) [3] and is usually deemed a vital policy instrument for the public sector to become involved in future land-related activities [4]. Therefore, it is necessary for urban planners who are inseparable from regional coordination to understand the decision-making procedures for spatial planning [5].

In China, the urbanization process over the past 30 years has been temporally and spatially compressed, characterized by the rapid expansion of cities and the migration of hundreds of millions of people from rural to urban areas [6]. This compressed timeline has resulted in a series of challenges such as resource constraints, environmental degradation, and social dislocation [7]. In this context, the Chinese government founded the Ministry of

Natural Resources and established a territorial spatial planning system to effectively implement spatial planning based on unique socio-economic conditions. However, knowledge of how spatial planning works in China remains limited because of institutional disparities in the land management system compared with its Western counterparts [8].

This paper presents several key concepts, such as the dual-evaluation model, main function zoning, strategic spatial patterns, and three-zone layout, for better access to spatial planning in the Chinese institutional context. Subsequently, a novel methodological framework incorporating comprehensive evaluation and Minimum Spanning Tree clustering was adopted to automate regionalization. To verify the effectiveness of the framework, this study conducts a case study in Deyang and applies it to the practical planning scenario. Unlike previous studies, the methodological framework presented in this study innovatively provides an end-to-end approach to geospatial layout, addressing the need for a more integrated and coherent planning system. Furthermore, by automating the regionalization process using tree-based clustering, the framework reduces the subjectivity and bias that can occur during manual zoning processes, leading to more objective and data-driven planning decisions.

This study aimed to examine the effectiveness of the proposed methodological framework for decision-making, from evaluation and zoning to land-use optimization, in practical spatial planning. The results demonstrate that our methodological framework is efficient in guiding land-use optimization and promoting sustainable urban and rural development. The theoretical significance of this study lies in its contribution to enhancing the understanding of China's unique spatial planning system. Practically, this study offers insights that can inform real-world practices in China and beyond.

The structure of the remaining article is as follows:

Section 2 discusses related works and explains key concepts such as the territorial spatial planning system and the decision-making process in planning. This section provides the contextual background for this study.

Section 3 introduces the necessary research materials, including the study area and data sources.

Section 4 introduces the methodological framework and explains it in detail. This section outlines the utilization of the DE model and MST clustering techniques in the decision-making framework in spatial planning.

Section 5 presents the decision-making results of applying the framework to territorial spatial planning (TSP) in Deyang City. This section analyses the outcomes of the planning process and evaluates the effectiveness of the framework.

Section 6 provides a discussion, analyzes the practical significance and limitations of the research, and provides suggestions for future research.

Finally, Section 7 presents the conclusions, summarizes key findings, and outlines future research directions in this area.

2. Related Works

2.1. China's Territorial Spatial Planning System

The concept of 'spatial planning' was initially proposed as a technical term by the European Conference of Ministers for Regional Planning in 1983 [9] and has since been accepted worldwide. However, due to a variety of factors, such as cultural values, political systems, economic conditions, and geographic features, the legal basis and regulatory rules of spatial planning systems differ greatly by country. Many developed countries, such as the United Kingdom, Germany, France, and the Netherlands, established mature spatial planning systems in the early 20th century, although planning decisions were unpredictable and subject to frequent political changes [10]. In China, a national spatial planning system, also known as territorial spatial planning (TSP), was not established until 2019. TSP works within a hierarchical planning framework that is consistent with the organizational structure of the national government and involves multiple policy agendas,

activities, and agencies at five administrative levels: national, provincial, municipal, county, and township [11].

More importantly, studies on spatial planning are typically context-specific. Most studies have concentrated on projects in Western Europe [10,12–16] because of their prominent influence on shaping global urban planning practices. Moreover, previous research has paid more attention to the theoretical foundation, scenario-based simulation, or socioeconomic factors related to spatial planning [14,17–20], overlooking the significance of developing new technical approaches to support planning decisions.

To gain a better understanding of China's territorial spatial planning system, several novel but essential concepts associated with TSP, such as the dual-evaluation model (DE) and three-zone layout (TZL), must be explained [21]. DE is an abbreviation for the two interconnected land evaluation models: the evaluation model of resource and environmental carrying capacity (EREC) and the evaluation model of territorial development suitability (ETDS). The former is used to assess the capability of a local ecosystem to support human activities without depleting resources or causing irreversible damage to the environment, whereas the latter focuses on assessing the appropriateness and feasibility of development activities within a specific geographical area [22,23]. DE is commonly recognized as a holistic and integrated approach to analyzing land resources, which requires collaboration among experts from multiple fields, including urban planning, environmental science, economics, and social sciences [24]. It is noteworthy that the evaluation criteria, indicators, measurement methods, rating thresholds, and other technical details of the DE model are based on the official technical guidelines released by the Ministry of Natural Resources of China.

The concept of TZL refers to the ideal layout of land-use patterns within a target area, originally proposed by the Chinese central government as the regulatory basis for TSP, aimed at coordinating the existing land-use layout and resolving spatial conflicts between different land functions [21,25]. According to the corresponding standards, the territory can be ideally categorized into three different areas—ecological, agricultural, or urban zones—based on the main functions of land use identified through land evaluation. Ecological zones play an important role in maintaining biodiversity and providing ecosystem services. The agricultural zones pertain to areas that are conducive to crop cultivation, livestock farming, and other agricultural activities. Urban zones refer to areas marked by cities and towns with a concentration of residential, commercial, and industrial activities [26,27].

2.2. Decision-Making Process in TSP

Decision-making in spatial planning is always a complex process fraught with uncertainty, encompassing numerous stakeholders, conflicting objectives, and unforeseeable repercussions. Therefore, it typically entails the collective efforts of government agencies, business elites, and professional specialists [28,29].

In recent years, China's central government has developed a comprehensive TSP decision-making process based on a top-down planning logic and launched several planning initiatives across the country [30]. Goal setting is usually the first step in the decision-making process of TSP, with a priority on protecting ecological resources and ensuring food security because economic growth driven by real estate investment is no longer the primary objective for local communities. Then, an integrated land assessment technique (i.e., the DE model) was used to identify regions with potential spatial risks and determine if these places should be preserved. After the evaluation, planners proceed by drawing a strategic spatial pattern (SSP), which outlines an overall vision of future development and management. This step is crucial in the decision-making process because SSPs can visually provide a conceptual overview of planning structures, even without specifying detailed boundaries. Finally, the TZL map is delineated in the direction of the SSP to ensure that the spatial arrangement aligns with the initial planning goals and strategies [31–33].

Most planners have embraced the seemingly perfect logic of planning steps, especially with endorsements from technocrats and academics [34]. However, the rationale behind

these analytical methods and the related theories remains controversial. Most studies or guidelines explaining how choices are made are either hypothetical or based on broad general principles. Furthermore, little attention has been paid to the technical details of the spatial planning decision-making process [30]. Although some researchers have explored various approaches to facilitate the process of evaluating zoning, such as multiple attribute models [35], weighting assignment methods [36], discriminant analysis [37], and ecosystem service evaluation [38], the planning cases provided are often based on specific domain indicators rather than integrated evaluation and regionalization for spatial planning.

To fill this research gap, this study focuses on providing a methodological framework encompassing systematic evaluation and automated regionalization methods to support land-use optimization decisions.

3. Research Materials

3.1. Study Area

Deyang, on the border with Chengdu, is a municipal-level city in Sichuan Province, China. The administrative area of Deyang spans approximately 5954 km^2 and includes 6 counties (Jingyang, Luojiang, Guangan, Mianzhu, Shifang, and Zhongjiang) and 84 townships. Geographically, the region comprises three prominent landforms: mountains, plains, and hills. As shown in Figure 1, the northwest of the city is a highly mountainous area, the central and eastern areas are mainly hilly regions, and the remainder is the Chengdu Plain. The terrain slopes from the northwest to the southeast. As of 2022, Deyang has a population of 3.46 million, an urbanization rate of 57.6 percent, and a gross domestic product (GDP) of CNY 281.687 trillion (USD 39.53 trillion). Deyang not only serves as a significant industrial center but also holds a pivotal position in food supply and ecological preservation, owing to its abundant natural resources. In recent years, the influx of immigrants from neighboring provinces has triggered a notable surge in demand for both housing and infrastructure development, leading to an acceleration in urban sprawl within the expansive Chengdu–Deyang metropolitan area. Despite its positive effects on the local economy, the rapid population increase has resulted in serious problems such as pollution, less arable land, and more land-use disputes [39]. Therefore, it is imperative to propose proactive approaches that can effectively address emerging land-use conflicts and achieve the harmonious coexistence of environmental preservation and economic growth. As many researchers have pointed out, one potential approach to attaining this intricate equilibrium is to implement spatial planning [40]. Therefore, this study considers Deyang City as the research area for demonstrating the decision-making process of TSP.

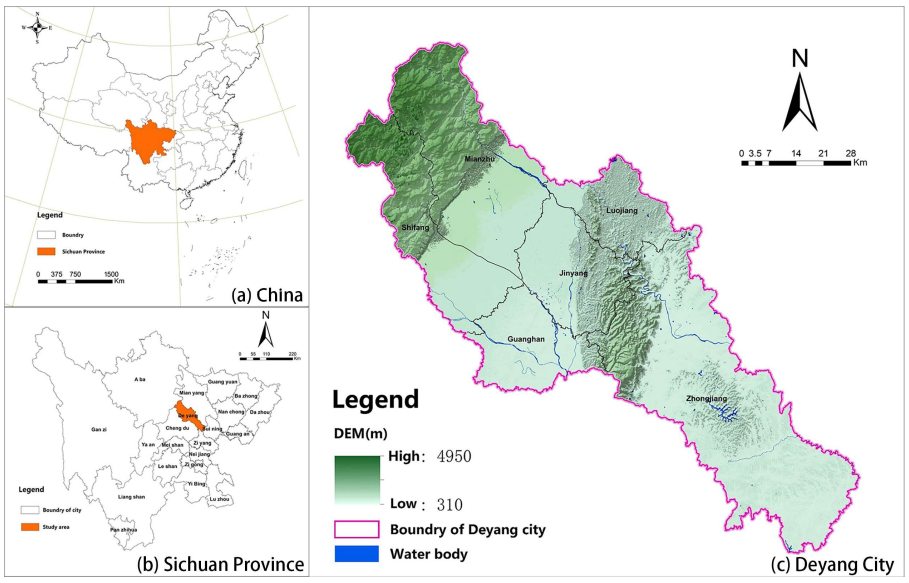


Figure 1. 'Dual Evaluation' Results of Territorial Spatial Planning in Deyang, China.

3.2. Data Source

Before the experiment, this study followed the dual-evaluation technical guidelines issued by the Ministry of Natural Resources of China and collected multi-sourced datasets that met official standards, covering seven evaluation aspects: ecology, land resources, water resources, environment, climate, geography, and disasters. Vegetation coverage (NDVI) was obtained from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/. Accessed on 12 May 2023); land-use data were sourced from the Sichuan Province's 2019 third land resource survey database; soil type and erosion data were provided by the Chinese Academy of Sciences' Resource and Environmental Science Data Center (https://www.resdc.cn/. Accessed on 12 May 2023); digital elevation model (DEM) and remote sensing image data were obtained from the 2019 Geographic Spatial Data Cloud with a resolution of 30 m (https://www.gscloud.cn/. Accessed on 12 May 2023); water resource data, including precipitation and evaporation, primarily stem from long-term observations at meteorological stations within the research area and its surroundings; environmental data related to soil pollution, water source contamination, and air pollution, were derived from field survey reports conducted by environmental protection authorities; climate data such as temperature, humidity, and wind speed were sourced from monitoring data at meteorological stations within the research area and its surroundings; and various disaster monitoring data, including earthquakes, floods, and geological hazards, were obtained from the Sichuan Province's geographical conditions survey data. After preprocessing all the aforementioned vector and raster data, a spatial information database of Deyang City based on a unified 30 m × 30 m grid was established for subsequent analysis.

4. Methodology

4.1. Methodological Framework

As shown in Figure 2, the research framework consists of three parts: dual evaluation, MST clustering, and decision-making. It was established to elucidate the specific decision-making processes associated with the effective allocation and utilization of geographic space in TSP practices. The steps of this process are as follows: (1) Establish a quantitative evaluation model, also known as DE model, according to official guidelines; (2) Employ the DE model to assess the land-use conditions of Deyang in terms of ecological protection, agricultural production, and urban construction; (3) Calculate the ratios of the area for very important ecological regions, suitable agricultural regions, and suitable construction regions, respectively, to the total area of each town, for use as the main functional metrics; (4) Convert the township boundary to a contiguity graph, with nodes representing each town and edges representing their connections; (5) Combine the contiguity graph with scaled values of main functional metrics to calculate edge costs based on the statistical distance between each node, and obtain a weighted contiguity graph; (6) Generate the minimal spanning tree using Prim's algorithm; (7) Determine the optimal clustering threshold using the F-test and obtain a town-scale main function zoning map; (8) Depict the strategic spatial pattern for the future based on the town-scale main function zoning map; and (9) Create a 'Three zones' layout under the direction of the strategic spatial pattern from Step 8.

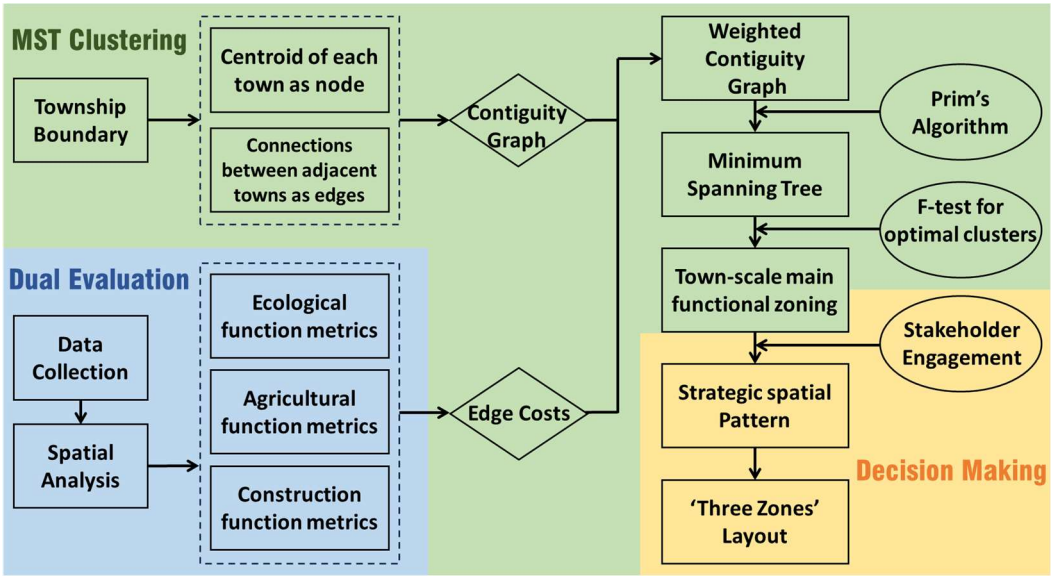


Figure 2. Diagram of the methodological framework.

4.2. Evaluation Indicator System

It is noteworthy that the indicator system has a three-level hierarchical structure, relating to seven aspects: water resources, soil resources, environment, ecology, climate, disasters, and location. The results of the evaluation categorized the land function in each raster cell based on its importance to ecology, farming efficiency, and building suitability [30,41].

According to the official guidelines of the DE model, the evaluation of resource and environmental carrying capacity (EREC) focuses on analyzing ecological importance, mainly covering two aspects (Table 1): ecosystem services (Fe1), with four third-level indicators, and ecological sensitivity (Fe2), with three third-level indicators. Each third-level indicator is calculated using a matching formula based on previous studies. Indicators e1–e4 characterize the capacity of the land to offer diverse ecosystem services, whereas indicators e5–e7 denote the vulnerability and responsiveness of ecosystems to soil erosion, desertification, and stony desertification, respectively.

The evaluation of the suitability of territorial development (ETDS) involves the assessment of both agricultural production and urban construction. Each third-level indicator was measured using a numerical rating scale with a corresponding weight. As shown in Table 2, seven third-level indicators were used to assess the suitability of agricultural production. Among them, a1 and a2 characterize the availability of land resources for agricultural production; a3 and a4 represent the availability of regional water resources for agricultural production; a5 denotes the significant impact of climate on agricultural cultivation; a6 indicates the degree to which meteorological disasters affect agricultural cultivation; and a7 denotes the influence of soil texture and salinization on agricultural cultivation. Regarding the suitability of urban construction, eight third-level indicators were selected for evaluation (Table 3): c1 and c2 denote the availability of land resources for urban construction; c3 represents the availability of regional water resources for urban construction; c4 characterizes climate conditions including humidity and temperature, which significantly impact the living comfort of human beings; c5 and c6 reflect the support capacity of ecological environmental factors represented by air and water for urban living; and c7 and c8 denote the impact of earthquakes, geological disasters, and other factors on urban safety.

Table 1. Evaluation indicators for the importance of ecological protection.

First-Grade Indicator	Second-Level Indicator	Third-Level Indicator	Calculation Formula	Explanation
Importance of ecological protection (Fe)	Ecosystem services (Fe1)	Biodiversity conservation (e1)	$e_1 = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt})$	NPP_{mean} = Net primary productivity of vegetation; F_{pre} = Perennial average precipitation; F_{tem} = Perennial average temperature; F_{alt} = Altitude factor
		Water conservation (e2)	$e_2 = NPP_{mean} \times F_{soi} \times F_{pre} \times \left(1 - F_{slp}\right)$	NPP_{mean} = Net primary productivity of vegetation; F_{soi} = Soil seepage factor; F_{pre} = Perennial average precipitation; F_{slp} = Slope factor
		Soil and water conservation (e3)	$e_3 = NPP_{mean} \times \left(1 - F_{slp}\right) \times (1 - K_i)$	NPP_{mean} = Net primary productivity of vegetation; F_{slp} = Slope factor; K_i = Soil erodibility factor
		Windbreak and sand fixation (e4)	$e_4 = NPP_{mean} \times K_i \times F_{cle}$	NPP_{mean} = Net primary productivity of vegetation; K_i = Soil erodibility factor; F_{cle} = Average annual climatic erosivity
	Ecological sensitivity (Fe2)	Soil and water loss sensitivity (e5)	$e_5 = \sqrt[4]{R_i \times K_i \times S_i \times C_i}$	R_i = Erosivity of rainfall; K_i = Soil erodibility factor; S_i = Terrain fluctuation factor; C_i = Vegetation cover factor
		Stony desertification sensitivity (e6)	$e_6 = \sqrt[3]{D_i \times F_{slp} \times C_i}$	D_i = Sensitivity indicator of stony desertification; F_{slp} = Slope factor; C_i = Vegetation cover factor
		Desertification sensitivity (e7)	$e_7 = \sqrt[4]{I_i \times W_i \times K_i \times C_i}$	I_i = Regional dryness indicator; W_i = Days of blowing sand; K_i = Soil erodibility factor; C_i = Vegetation cover factor

Source: Dual-Evaluation Technical Guideline issued by Ministry of Natural Resources of China.

Table 2. Evaluation Indicators for the suitability of agricultural production.

First-Grade Indicator	Second-Level Indicator	Third-Level Indicator	Rating Scale					Weight
			0	1	3	5	7	
Suitability of agricultural production (Fa)	Land resources factors	Slope (°) (a1)	≥25	15–25	6–15	2–6	<2	0.15
		Silt content (%) (a2)	≥80	60–80	40–60	20–40	<20	0.1
	Water resources factors	Volume of water resources (10^4 m^3/km^2) (a3)	<3	3–8	8–13	13–25	≥25	0.15
		Precipitation (mm) (a4)	<200	200–400	400–800	800–1200	≥1200	0.18
	Climate factors	Photothermal condition (10^3 °C) (a5)	<1.5	1.5–4	4–5.8	5.8–7.6	≥7.6	0.18
	Disaster factors	Annual frequency of meteorological disasters (%) (a6)	≥80	60–80	40–60	20–40	<20	0.14
	Ecological factors	Salinization sensitivity degree (a7)	1.0–3.0	3.1–5.0	5.1–6.0	6.1–7.0	>7.0	0.1

Source: Dual-Evaluation Technical Guideline issued by Ministry of Natural Resources of China.

The DE was built on the China Geodetic Coordinate System 2000 and the Krüger projection. The results are presented on a 30 m × 30 m grid map, which is compatible with the spatial scale of the database established at the beginning of the study.

Table 3. Evaluation indicators for the suitability of urban construction.

First-Grade Indicator	Second-Level Indicator	Third-Level Indicator	Rating Scale					Weight
			0	1	3	5	7	
Suitability of urban construction (Fc)	Land resources factors	Slope (°) (c1)	≥25	15–25	8–15	3–8	<3	0.1
		Altitude (m) (c2)	≥50	30–50	20–30	10–20	<10	0.1
	Water resources factors	Volume of water resources (10^4 m^3/km^2) (c3)	<5	5–10	10–20	20–50	≥50	0.08
	Climate factors	Climatic comfort degree (c4)	<32 or >90	32–41 or 82–90	41–51 or 73–82	51–60 or 65–73	60–65	0.12
	Environmental factors	Atmospheric environmental capacity degree (c5)	≤0.2	0.2–0.4	0.4–0.6	0.6–0.8	>0.8	0.09
		Water environmental capacity degree (c6)	<0.04	0.04–0.14	0.14–0.39	0.39–0.96	≥0.96	0.09
	Disaster factors	Distance from seismic fault zone (m) (c7)	<30	30–100	100–200	200–400	≥400	0.18
		Cumulative land subsidence (mm) (c8)	>2400	1600–2400	800–1600	200–800	<200	0.12
	Locational factors	Traffic distance from the central city (Km)	≥240	160–240	120–160	40–120	<40	0.12

Source: Dual-Evaluation Technical Guideline issued by Ministry of Natural Resources of China.

4.3. Evaluation Method

After obtaining the scores of the three-level indicators in ArcGIS Pro, a hierarchical aggregation was performed from the third to the first levels to obtain the overall outcome. The aggregation follows the 'law of the barrel,' which highlights that the outcome is limited by the lowest-scoring component [42]. Given that the third-level indicators in ERECC and ETDS were measured differently, the aggregation procedures also differed.

In the ERECC, the areas with the highest values of e1, e2, e3, and e4 were aggregated into the most essential for ecosystem services (i.e., F_{e1}), and the areas with the highest values of e5, e6, and e7 were aggregated into F_{e2}, which was the most environmentally sensitive. Then, the areas with the highest values of F_{e1} and F_{e2} were aggregated into very important areas of ecological importance, whereas the rest were classified into important and general areas through natural breaks. The aggregation procedure can be expressed as follows:

$$\begin{aligned} F_{e1} &= \max(e_1, e_2, e_3, e_4) \\ F_{e2} &= \max(e_5, e_6, e_7) \\ F_e &= \max(F_{e1}, F_{e2}) \end{aligned} \quad (1)$$

For the ETDS, the third-level indicators were measured using Likert scales, and the indicator weights were determined using the analytic hierarchy process (AHP) based on expert recommendations. Therefore, the aggregation process can be described mathematically as follows:

$$F_i = \begin{cases} 0 & (X_{ij} = 0) \\ \sum_{j=1}^{n} w_j \times X_{ij} & (i = 1, 2, 3 \ldots m) \end{cases} \quad (2)$$

where F_i represents the functional suitability of agricultural production or urban construction in raster cell i; w_j is the weight of indicator j; X_{ij} is the rating score of indicator j in raster cell I; N is the number of third-level indicators; and m is the number of raster cells in the study area. When $F_i = 0$, it indicates that raster cell i is unsuitable for agricultural production or urban construction; when $F_i \neq 0$, a natural breaks classification is employed

to segment the scores. Raster cells with higher values were considered suitable, and those with lower values were generally regarded as suitable.

This study then statistically analyzed the values of raster cells across the city using the raster statistics tool in ArcGIS and calculated the proportions of very important ecological areas, suitable agricultural production areas, and suitable urban construction areas within each town's administrative boundaries. The three ratios—ecological function value, agricultural function value, and living function value—were viewed as new indices to characterize the main functions of land use for subsequent statistical distance calculations.

4.4. Minimum Spanning Tree-Based Clustering

Graph-based clustering is an algorithm used in data analysis to group similar data points together based on interpoint distances within a graph [43]. In the family of graph-based algorithms, MST clustering uses the concept of a Minimum Spanning Tree to partition data points into clusters. Since the method takes into account not only statistical similarity but also spatial adjacency between distinct research objects, it is more suitable for graph partitioning in regionalization studies such as transportation planning, disaster management, and land-use zoning [44–46].

This is how MST clustering in this study works: (1) Extract the centroid of each town polygon and links based on spatial adjacency; (2) Construct a weighted undirected graph G = (V, E, D), where V is the set of nodes representing each town, E is the set of spatial connections between adjacent nodes, and D is the set of weights representing distance or similarity between the nodes, also known as an edge costs set; (3) Employ Prim's algorithm to find MST, a subset of graph G, by connecting all nodes while minimizing the total edge cost; (4) Sort the edges of the MST by their weights and find the best threshold for tree segmentation using an F-test; (5) Remove edges with weights above the threshold, splitting MST into disconnected subtrees; and (6) The subtrees obtained after edge removal correspond to clusters of the zone that share similar characteristics in spatial planning.

It is important to note that graphs G and E are described by the queen adjacency matrix. This implies that if two polygons share at least one edge or corner, the corresponding matrix elements are marked as 1; otherwise, they are marked as 0. D is described by a fuzzy similarity matrix, where each element in the matrix contains a value between 0 and 1, representing the degree of similarity between the corresponding pair of elements [46]. The value was computed using the Euclidean distance in this study (Equation (3)), where smaller distances correspond to higher similarity and vice versa.

$$D(W_{ij}) = d_{ij} = \sqrt{\sum_{k=1}^{m} \left(X_{ik} - X_{jk}\right)^2} \quad (3)$$

where $D(W_{ij})$ is the element value in the matrix, d_{ij} is the Euclidean distance between nodes, X_{ik} is the kth index value representing the main function of land use in town i, X_{jk} is the kth index value representing the main function of land use in town j, and m is the number of indices.

Prim's algorithm was named after American computer scientist Robert C. Prim, who developed it to find the MST of a connected, undirected graph. It is a popular greedy algorithm that grows the MST edges simultaneously by always selecting the minimum weight edge [47]. This process ensures that the MST remains connected and has the minimum total edge weight.

Furthermore, because MST clustering is a dynamic process that produces a hierarchy of clusters as the edge threshold varies, selecting an appropriate edge threshold is crucial. In this study, the F-test was used to obtain the optimal threshold by assessing whether the variability within different groups was statistically significant. An F-test was performed as follows:

Suppose $U = \{X_1, X_2, X_3, \cdots, X_n\}$ is the total sample set. Each sample has m features, i.e., $X_i = (X_{i1}, X_{i2}, X_{i3}, \cdots, X_{im})$, thus initializing the data matrix.

Let $\overline{X} = \left(\overline{X}_1, \overline{X}_2, \cdots \overline{X}_k \cdots, \overline{X}_m\right)$, which is the center vector of the population, where $\overline{X}_k = \frac{1}{n}\sum_{i=1}^{n} X_{ik} (k = 1, 2, \cdots, m)$.

Suppose the threshold λ corresponds to the cluster number S.

n_j is the number of samples in cluster j, so each sample can be written as: $X_1^{(j)}, X_2^{(j)}, X_3^{(j)}, \cdots, X_{n_j}^{(j)}$.

Let $\overline{X}^{(j)} = \left(\overline{X}_1^{(j)}, \overline{X}_2^{(j)}, \cdots \overline{X}_k^{(j)}, \cdots, \overline{X}_m^{(j)}\right)$, which is the center vector of cluster j, where $\overline{X}_k^{(j)} = \frac{1}{n_j}\sum_{i=1}^{n_j} X_{ik}^{(j)} (k = 1, 2, \cdots, m)$.

The F-value is set following an F-distribution with degrees of freedom for S-1 and n_j-S:

$$F = \frac{\sum_{j=1}^{S} n_j \left\| \overline{X}^{(j)} - \overline{X} \right\|^2 / (S-1)}{\sum_{j=1}^{S} \sum_{i=1}^{n_j} \left\| X_i^{(j)} - \overline{X}^{(j)} \right\|^2 / (n_j - S)} \quad (4)$$

where the denominator and numerator are the distances between the clusters.

A larger F-value indicates that the variance between clusters is much larger than that within clusters [48]. When F reaches its maximum value, the corresponding edge cost is the optimal threshold. It is worth noting that the calculated F must be statistically significant at a certain level of significance at the same time.

5. Results

5.1. 'Dual-Evaluation' Results

The DE results for Deyang are presented in Figure 3, which depicts the distribution of ecologically important, suitable farming, and construction areas. Based on the IEP assessment, the study area was divided into three categories: very important, important, and general, which constituted 49.46%, 48.44%, and 2.10% of the total area, respectively. The most important region for ecological protection covers an area of 546.56 square kilometers and is mostly located in the northwestern mountains. Although the ecological environment in this area is very fragile due to frequent geological disasters, such as earthquakes, landslides, and debris flows, it still plays an irreplaceable role in biodiversity protection, water conservation, and soil conservation.

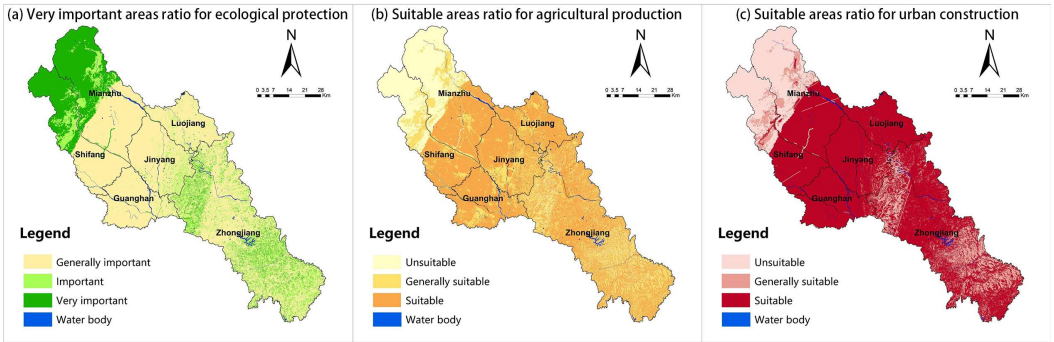


Figure 3. 'Dual Evaluation' Results of TSP in Deyang, China.

The evaluation results of the SAP showed that the proportions of suitable, generally suitable, and unsuitable areas accounted for 49.46%, 48.44%, and 2.10% of the total area, respectively. Among them, the suitable region for agricultural production is around 4317.4 square kilometers and primarily consists of plains and low hills. This region is ideal for the development of high-productivity agriculture because of its relatively low terrain, ample sunlight, water resources, and concentrated arable land.

As for the evaluation results of SUC, the proportions of suitable urban construction areas, generally suitable areas, and unsuitable areas accounted for 49.46%, 48.44%, and 2.10% of the entire study area, respectively. The suitable urban construction region covers

an area of 3302.47 square kilometers, mainly concentrated in the central plain. This region is free of geological hazards and spatially overlaps with existing town centers, making it a potential area for future high-density urban development.

In general, DE results are mapped with raster data made up of a matrix of pixels because they can easily integrate multiple layers of information, such as land cover, elevation, climate, and ecology. However, when applying raster-based evaluation outcomes to real-world practice, it is necessary to consider the planning jurisdiction within which the government or planning agency has the authority to shape and regulate physical development. In this study, planning practices in Deyang City are at the county level in China's top-down TSP system, where the township government, responsible for the allocation of financial resources, is the core actor in specific planning policies. Therefore, using township administrative districts as the evaluation unit of the land-use function facilitates the implementation of planning policies under the purview of the local administrative authority. As shown in Figure 4, choropleth maps were used to visualize the ecological, agricultural, and living function values across the city. In the process of data classification, numerical values were divided into five grades from high to low according to Jenk's natural breaks to clearly show the differences among towns.

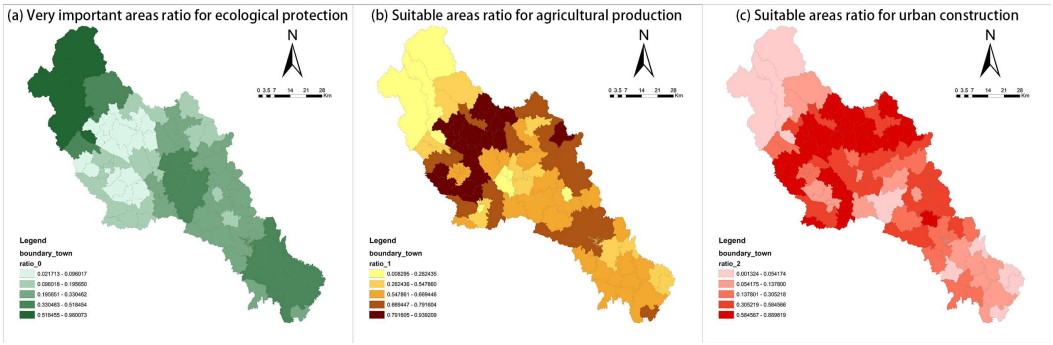


Figure 4. Choropleth map of land-use functional indicator by township.

5.2. Town-Scale Main Functional Zoning

This section provides a thorough explanation of the application of MST clustering to the main town-scale functional zones of the study area. As shown in Figure 5, there are 84 towns under the jurisdiction of Deyang City. First, a 2D data array is initiated with 84 rows and 3 columns, where each row represents a town and the 3 columns correspond to the ecological, agricultural, and living function values of each town. Given that the numeric value of the index obtained through comprehensive evaluation and raster statistics is a ratio between 0 and 1, data normalization is not required. In addition, all the polygons were transformed into an undirected connected graph according to geographical adjacency. Then, Prim's algorithm was applied to build an MST (Figure 6), covering 84 nodes and 83 edges.

To achieve the best clustering effect, the F-test was the best choice because it can assess whether there are significant differences in the variances between clusters. In the F-test, all edge weights of the MST were arranged in ascending order, where the minimum and maximum values were 0.0076 and 0.7769, respectively. These values, from small to large, were regarded as cut-offs, or thresholds. Every time a threshold was selected, the edges whose weights were greater than the threshold were cut off to create a new unconnected graph. Simultaneously, we recursively calculated some key parameters of the F-test, such as the F-value, *p*-value, and critical value, which are shown in each graph. The process was terminated when the largest and most statistically significant F-value was found. As shown in Table 4, a threshold value of 0.4494 was the best choice for branch cutting because the F-value reached the highest value of 13.7643. In addition, the table suggests that the

test result is statistically significant because the F-value exceeds the critical value, and the *p*-value is below 0.01.

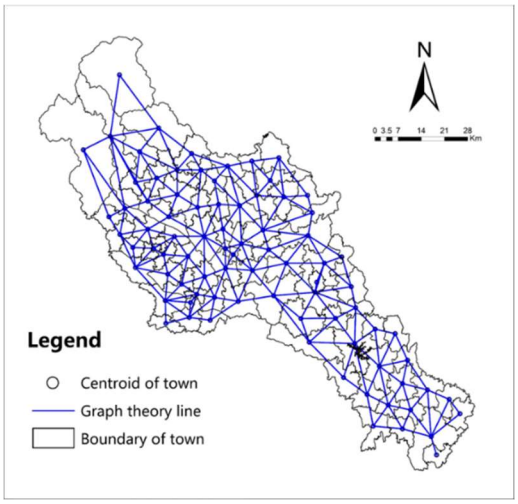


Figure 5. Township adjacency network.

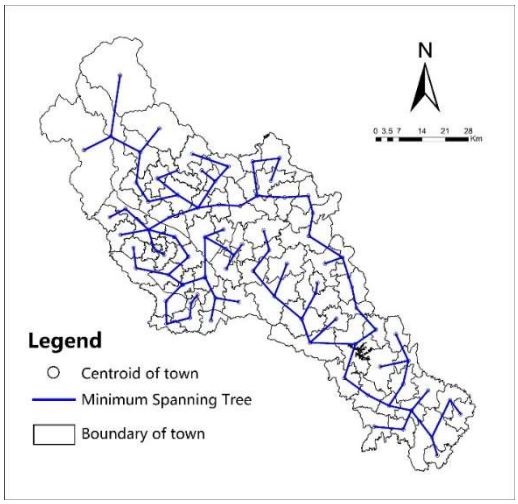


Figure 6. Minimum Spanning Tree.

Table 4. F-test result.

Threshold Value	F-Value	*p*-Value	Critical Value
0.1596	1.2900	0.2482	1.9263
0.1631	1.4230	0.1878	1.9649
0.1671	1.5764	0.1385	2.0108
0.1874	1.7732	0.0961	2.0662
0.2533	2.0924	0.0546	2.1343
0.2829	2.5488	0.0265	2.2204
0.3101	3.2337	0.0106	2.3333
0.3175	4.2760	0.0035	2.4889
0.3793	6.4745	0.0006	2.7203
0.4494	13.7643	0.0000	3.1108

After obtaining the optimal threshold, Prim's algorithm was employed to remove the edges with weights below this threshold. This process divides the Minimum Spanning Tree (MST) into six separate subgraphs (Figure 7). To apply the clustering results to spatial planning, the administrative areas that overlap with the six subgraphs are classified into ecological function, agricultural function, and living function regions according to preset

standards. Compared with zoning, which divides a municipality into different districts, this classification process, also known as Town-Scale Main Functional Zoning (TMFZ), is based on a larger geographical scale. As shown in Figure 8, the ecological function region includes ten towns, mainly distributed in the northwest mountainous and central hilly areas. The agricultural function region covers the largest territory, including 60 towns that are widely distributed in the central and southwestern plains. The living function region includes 14 towns covering the existing densely populated areas where the central cities lie. Instead of specifying the land-use function subjectively, as has been done in the past, the proposed TMFZ to some extent confirms the effective allocation of various land resources and provides strategic guidance for land-use optimization.

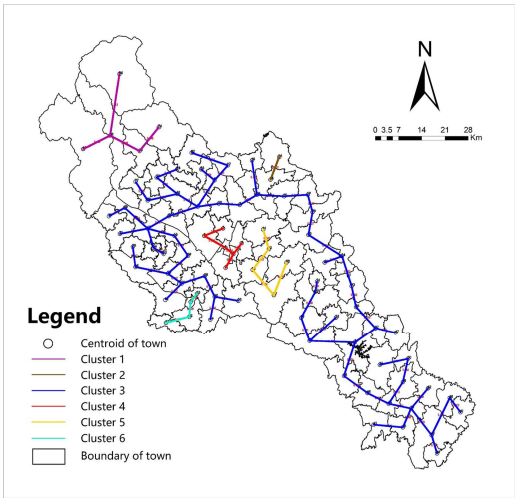


Figure 7. MST clusters.

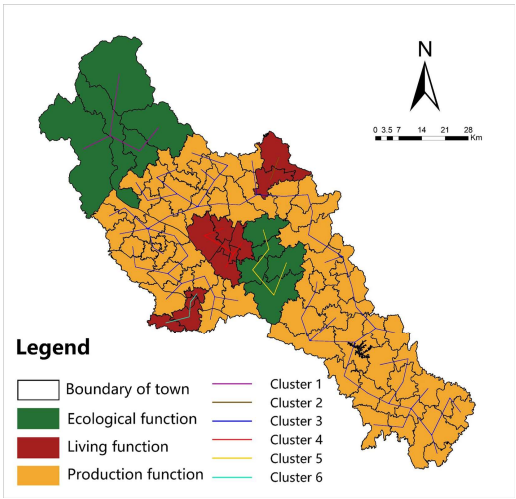


Figure 8. Main functional partition.

5.3. Strategic Spatial Pattern and Three-Zone Layout

In the context of China's TSP, the strategic spatial pattern (SSP) and three-zone layout (TZL) play crucial roles because they serve as management tools for both planners and policymakers to specify and regulate land-use functions within a region. One of the aims of this study was to visualize the SSP and TZL for future decision-making in spatial planning.

In Deyang's TSP practice, after multiple rounds of consultation with government agencies, businesses, and environmental organizations, the planning committee proposes a schematic structure of two belts, two zones, one center, and one corridor for the SSP (Figure 9). The two belts refer to the Longmen Mountain Ridge and the Longquan Mountain

Ridge. As the most significant geographical features of the study area, the two mountains are ecologically fragile because the steep and rugged terrain makes them vulnerable to soil erosion and climate change. Mountainous areas are biodiversity hotspots home to a wide variety of plant and animal species. Therefore, in spatial planning, the two corridors are designated as natural reserves and require careful management and conservation efforts to maintain their ecological integrity. 'Two zones' refers to the northwest agricultural zone and the southeast agricultural. The northwest agricultural zone is suitable for growing a wide variety of crops because the relatively open fields of the plains provide ample space for the use of large agricultural equipment such as tractors, combines, and plows. The southeastern agricultural zone is designated as a prime growing area for fruit trees and vegetables because of the soil quality and water conditions.

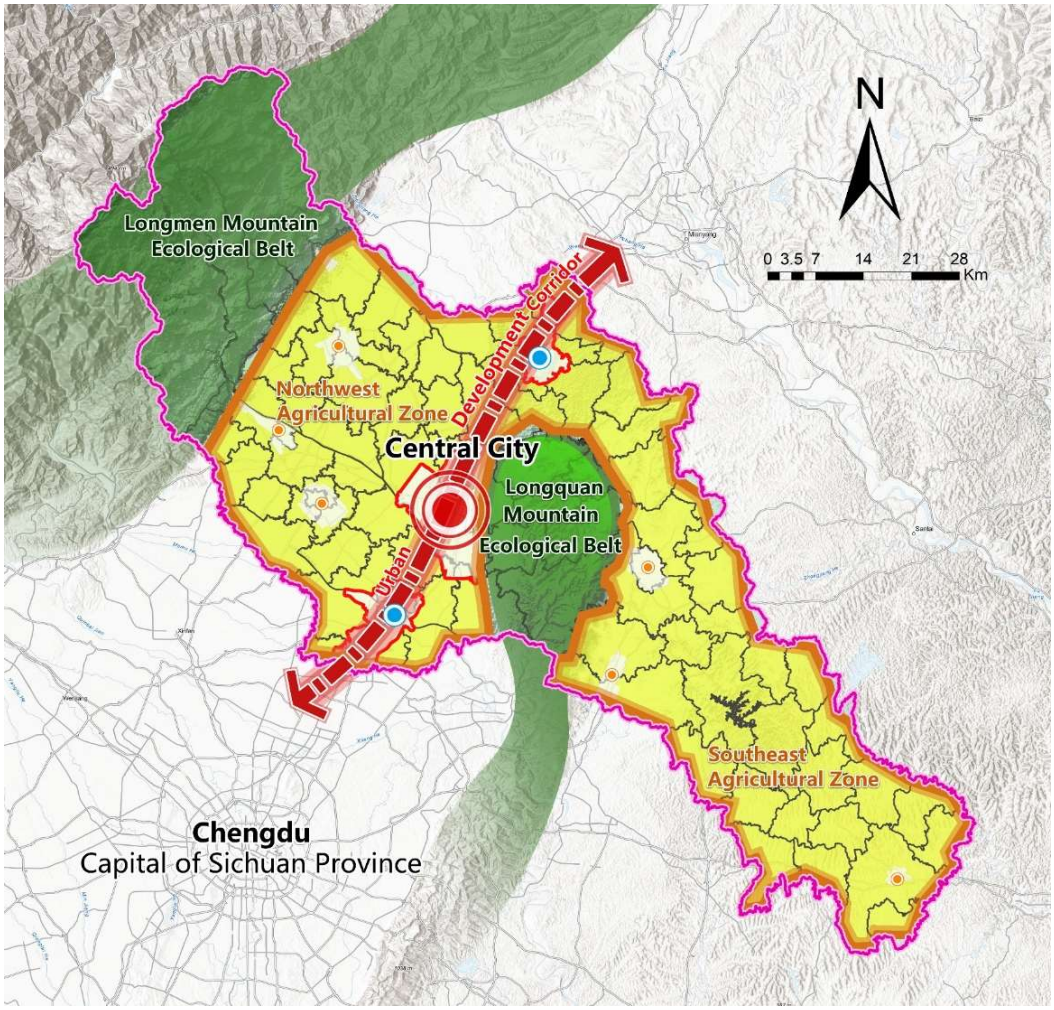


Figure 9. Strategic spatial pattern of Deyang City.

'One center' and 'One corridor' are schematic structures concerned with urban development. The former refers to the central district of Deyang. By focusing on resources and investments in urban infrastructure, transportation, and housing, the center is expected to become a growth pole, generating economic benefits that will spill over into the surrounding towns. The latter refers to a regional transportation corridor based on a newly built high-speed railway connecting major population centers, industrial zones, ports, and logistics hubs within Chengdu. It is a strategically planned route that facilitates the movement of people, goods, and services between Deyang and neighboring cities.

The TZL and SSP are highly interconnected and generally work together to shape local territorial development, provided that the TZL aligns with the broader objectives outlined

in the strategic plan. However, compared to the SSP, the TZL typically operates at a more detailed level, with the aim of guiding distinct land parcels towards prescriptive zones for ecological protection, agricultural production, and urban construction. Furthermore, the mapping of the TZL needs to consider the existing land-use patterns so that the layout of specified zones is compatible with current land uses and does not create conflicts or negative impacts.

As shown in Figure 10, the current land-use pattern of Deyang City is characterized by irregular and haphazard spatial layouts, resulting in land fragmentation, habitat degradation, and the emergence of informal settlements. Therefore, under the spatial guidance of the SSP, this study used spatial modeling technology to develop a variety of land-use scenarios, among which the final three-zone layout in Figure 11 was considered the best solution for land-use optimization. According to the statistical analysis of the TZL, the designated ecological zone covers an area of 2212.2 km^2, accounting for 37% of the city's territory. The planned agricultural zone covers 3306.3 km^2, accounting for 56% of the city's territory. The estimated urban zone covers 392.5 km^2, accounting for 7% of the city's territory. Although TZL differs from the statutory land-use plan, it provides the public with a long-term vision to guide the sustainable development of land in Deyang City.

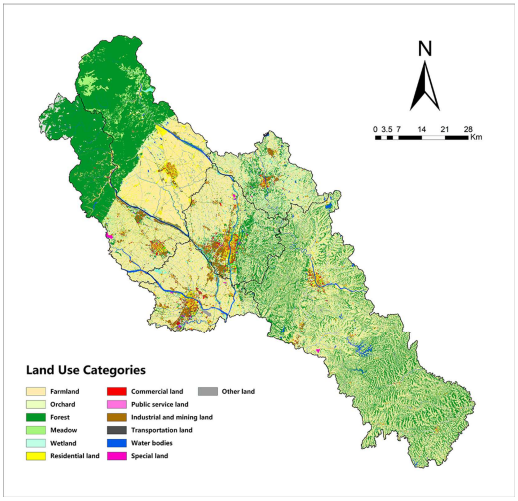


Figure 10. Current land-use pattern.

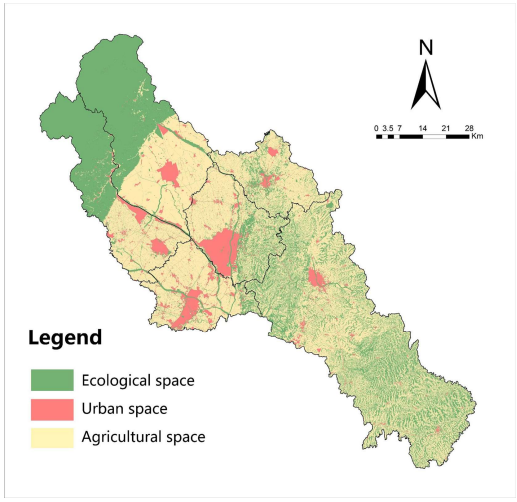


Figure 11. Three-zone layout.

Compared with the current land-use map, the TZL proposed in this study reorganizes the spatial layout, prioritizing the stability of ecological areas that are important for regional

sustainable development. This reorganization involves integrating scattered farmland and concentrating urban construction land to improve agricultural productivity and curb urban sprawl. More importantly, the TZL map serves as a comprehensive blueprint for long-term land-use planning, guiding future development in a sustainable and environmentally conscious manner.

According to the TZL map, conservation and restoration efforts involving reforestation, wetland restoration, and the creation of wildlife corridors to enhance biodiversity and ecosystem resilience would be concentrated within ecological zones. Also, much stricter regulations would be enforced to limit human activities that could degrade these sensitive areas. In agricultural zones, the consolidation of farmland would be implemented by adopting advanced agricultural practices. This may involve promoting precision farming techniques, implementing sustainable agricultural practices to enhance soil health, and introducing agroforestry systems to boost productivity while preserving ecological equilibrium. In urban zones, more restrictive actions against urban sprawl would be taken by concentrating urban construction in specific areas. This strategy includes the introduction of green infrastructure, such as parks and green roofs. Additionally, stricter zoning regulations would be implemented to encourage mixed-use development, decrease reliance on private vehicles, and promote sustainable transportation options.

6. Discussion

The territorial spatial planning (TSP) system in China is a transformative urban and regional planning reform. The current wave of nationwide planning practices places a strong emphasis on implementing rigorous regulations and controls over diverse facets of urban development, significantly bolstering government oversight of land resources. More importantly, it has put an end to the ongoing expansion of urban construction land in planning layout over the past few decades, curbing the excessive enthusiasm of local governments in pursuing urban sprawl.

Unlike previous planning models, TSP's limitation of territorial space is achieved by delineating accurate and strict boundaries (i.e., the Three Lines). Territorial space is typically viewed as a calculable field from a geographical perspective since it is inseparable from a variety of natural factors like land, water, minerals, biology, climate, oceans, and tourism, as well as various economic and social conditions. Theoretically, based on the spatial heterogeneity of various elements, the territory can be divided into a series of relatively homogeneous functional areas through spatial clustering, each of which has a unique potential for development. As a result, TSP can serve well as an important means of territorial governance for governments using planning tools such as resource and land surveys, problem assessments, regional divisions, and development priority setting. Previous research focused on the conceptual connotation and system construction of planning, especially the planning-related policy systems in developed countries.

As a prevalent issue in China's development lately, spatial planning reform has drawn a lot of interest from think tanks and academics. Prior studies concentrated on the concept connotation and system design of spatial planning, particularly industrialized countries' policy systems connected to planning. However, few studies have focused on specific technologies in spatial planning decision-making processes. This study proposes a methodological framework to elaborate on the planning process, from assessment and zoning to land-use layout, by integrating graph-based clustering with a dual-evaluation model. Additionally, based on practical work in Deyang City, the strategic spatial pattern (SSP) and three-zone layout (TZL) are presented as a roadmap to guide future spatial development. The planning results of this study suggest that (1) the officially recommended dual-evaluation (DE) model performs well in assessing regional resources and land-use potential from ecological, agricultural, and urban development perspectives; (2) MST clustering proved to be an efficient regionalization approach for identifying spatial clusters that are functionally approximate in land use; and (3) SSP and TZL, by visually mapping long-

term spatial strategies and future land-use patterns, offer an ideal vision for coordinating territorial conflicts and optimizing land-use patterns.

Although our research contributes to decision-making in the realm of spatial planning, there are several limitations in applying the methodological framework to real-world scenarios. First, it is impossible to completely understand the potential interactions of all land-related factors using geostatistical models because the dynamic mechanism of land-cover change is complex and has not been clearly explained in academia [49]. Second, the DE model, like many other spatial analytical models, depends on the quality and availability of multi-sourced input datasets, especially when the indicator system requires information from different fields [50]. As a result, the evaluation accuracy needs to be further tested, despite the thorough design of the model [51]. Third, the MST clustering method used for regionalization is fast and easy to use but does not consider the impact of zoning regulations, economic policies, and public participation on spatial planning decisions. Fourth, the ultimate precision of land-use layout in TSP is ascertained by the land-use types and minimum area division. This is because unified management is achievable at this level of precision via access and development permission restrictions, whereas flexible control on a smaller geographical scale is challenging to implement. Fifth, the formulation of territorial spatial planning is inherently a political process, as it is shaped by the diverse interests and priorities of various stakeholders, the evolving demands of development, and the varying control capabilities of different governmental departments. Therefore, the optimal land-use layout in TSP requires the integration of multiple opinions and extensive public hearings rather than rough automated zoning.

In the upcoming phase of our research, we plan to delve into cutting-edge spatial analysis and modeling methodologies, aiming to enhance the precision and effectiveness of planning decisions. This endeavor will entail the seamless integration of advanced technologies such as big data analytics, cloud computing infrastructure, and sophisticated machine learning algorithms. Through this integration, we aim to systematically identify, categorize, and analyze different zones within the urban landscape based on their unique characteristics and attributes [52–54]. Furthermore, our study will explore the incorporation of participatory mapping techniques, such as mobile mapping applications and participatory GIS tools, into spatial planning practices. These techniques will enable us to engage stakeholders directly in the data collection and analysis process, empowering them to contribute their local knowledge and insights. This participatory approach will not only enhance the transparency and inclusivity of our research but also ensure that our findings are more reflective of the needs and preferences of the communities we serve [55,56].

7. Conclusions

This study provides an innovative methodological framework that combines a systematic regional evaluation method with a tree-based regionalization technique for decision-making processes, focusing on real-world spatial planning practices in China. In addition, this study presents the indicator system and evaluation criteria of the DE model and clarifies how MST clustering works for step-by-step zoning. A blueprint for an ideal land-use layout is also presented, which serves as a visual representation of the proposed spatial planning strategy, helping stakeholders and decision-makers grasp how the proposed framework will be implemented.

The planning outcomes demonstrate that the proposed framework effectively bridges the logical gap between land assessment and spatial layout. This significantly improves the efficiency of the planning decision-making processes and contributes to more informed and sustainable spatial planning practices.

Overall, successful spatial planning not only relies on technical models but also requires the active engagement of stakeholders, including community members, developers, and public sectors, to make informed decisions for the future [14,57]. Future research in the field of spatial planning should focus on applying new techniques to geo-data analytics to support context-specific spatial planning systems [58–61]. These techniques can help

planners analyze complex urban environments more effectively, leading to more informed decision-making. Additionally, conducting comparative studies across countries could provide valuable insights into the differences and similarities in spatial planning systems. By comparing the approaches adopted by different countries, researchers can identify the best practices and areas for improvement in spatial planning policies and strategies.

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Abbreviations

The acronyms listed below are used throughout this paper.

TSP	Territorial spatial planning
DE	Dual evaluation model
EREC	Evaluation of resource and environmental carrying capacity
ETDS	Evaluation of the suitability of territorial development
IEP	Importance of ecological protection
SAP	Suitability of agricultural production
SUC	Suitability of urban construction
MST	Minimum Spanning Tree
MFZ	Main function zoning
SSP	Strategic spatial pattern
TZL	Three-zone layout

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