Land-Use Dynamic Change Mapping and Ecological Network Construction from Multi-Temporal Remote Sensing Imagery

Qinglie Yuan[a*]

[a] School of Civil and Architecture Engineering, Panzhihua University, Panzhihua 617000, China-*yuanqinglie@pzhu.edu.cn

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Abstract

Regional economic growth drives significant land-use changes, impacting urban development, resource allocation, and ecological networks. Challenges such as climate change, ecological degradation, and land-use-ecology conflicts threaten human habitats, elevating the importance of biodiversity conservation. This study investigates the spatio-temporal evolution of land use (1990–2020) in Meishan City, China, using multi-temporal Landsat imageries, and assesses its impact on ecological security using land-use dynamic index model. Research found that Cultivated land remained dominant but decreased over the study period, while forest and construction land expanded. Construction land primarily developed along rivers, forest land concentrated in Hongya County, and cultivated land prevailed in Renshou County. Utilizing resistance factors, this study identified ecological sources, constructed resistance surfaces, and delineated ecological corridors. Ecological sources covered 18.85% of the study area, with corridors totaling 461.77 km, predominantly located in the central region. Three key ecological pinch points were identified. Optimizing land-use patterns and the ecological network structure are recommended, prioritizing ecological restoration in Dongpo and Pengshan Districts. This research provides a scientific basis for sustainable land-resource utilization in Meishan and offers valuable insights for similar regions.

1. Introduction

Land use transformation, a key element in worldwide environmental shifts, exerts a deep influence on ecosystem functions, climatic systems, and human social and economic behaviors. In the past few years, as urbanization and industrialization have advanced at a fast pace across the globe, the issue of how to make sensible use of land assets while effectively safeguarding the ecological surroundings has grown into a major topic of international attention (An et al., 2021). Multi-temporal remote sensing imagery, with its advantages of broad coverage, long time series, and objective data acquisition, has become the core technical support for land-use dynamic change mapping, enabling quantitative analysis of spatiotemporal evolution patterns of land cover and providing a scientific basis for ecological management decisions.

Land-use dynamic change mapping focuses on capturing the type, extent, and trend of land cover transitions over a specific period, which is essential for revealing the interaction between human activities and the natural environment (Ding et al., 2024). With the continuous advancement of remote sensing technology, from Landsat series to Sentinel satellites, multi-source and multi-resolution remote sensing data have been widely applied in land-use classification and dynamic monitoring. Traditional mapping methods mainly rely on single-temporal imagery and manual interpretation, which are inefficient and subjective. In contrast, modern techniques integrating machine learning algorithms such as, random forest, support vector machine, with multi-temporal spectral, texture, and phenological features significantly improve the accuracy and efficiency of land-use mapping, especially in complex regions with diverse land cover types.

Global biodiversity loss and habitat fragmentation, driven by urban sprawl, agricultural expansion, and infrastructure construction, have become critical ecological crises threatening ecosystem stability. Fragmented habitats disrupt species migration, gene flow, and energy cycling, leading to the degradation of ecological functions and an increased risk of local extinction for endangered species. As a core ecological restoration tool, ecological corridors aim to connect isolated habitat patches, optimize landscape connectivity, and provide migration routes and survival spaces for wildlife, which is recognized as an effective measure to mitigate habitat fragmentation.

The research on ecological corridor construction is of profound theoretical and practical significance. Theoretically, it enriches the theories of landscape ecology and conservation biology, clarifying the mechanism of corridors in regulating ecological processes at multiple scales. Practically, it provides scientific basis for regional ecological security pattern construction, guides the rational planning of ecological corridors in urban and rural areas, and balances the contradiction between economic development and ecological protection. Moreover, it contributes to enhancing ecosystem resilience, coping with climate change, and realizing the sustainable development of human-land relations, which is crucial for achieving global biodiversity conservation goals and ecological civilization construction.

Against the backdrop of intensified land-use transformation, ecological network construction has emerged as a critical approach to mitigate ecological degradation and maintain regional ecological security. An ecological network consists of ecological patches (core habitats), ecological corridors (connecting pathways), and ecological nodes, which together enhance the connectivity and stability of ecosystems. Land-use changes, such as urban sprawl, agricultural expansion, and industrial land occupation, often lead to the fragmentation of ecological patches and the interruption of ecological corridors, thereby reducing ecosystem resilience. Thus, integrating land-use dynamic change mapping with ecological network

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construction is crucial for understanding the impact of land-use transitions on ecological processes and formulating targeted ecological protection strategies.

Existing studies have explored the coupling relationship between land-use change and ecological networks, but there are still obvious gaps. Most research focuses on static analysis of a single period, lacking in-depth exploration of the spatiotemporal response of ecological networks to long-term land-use dynamic changes (Cao et al., 2024). Moreover, in fast-urbanizing regions in the Yangtze River Basin, the interaction mechanism between intensive human activities-driven land-use transformation and ecological network evolution remains unclear. Additionally, few studies have fully utilized the advantages of multi-temporal remote sensing data to dynamically adjust ecological network construction schemes based on real-time land-use change information, resulting in a disconnect between research results and practical ecological management needs.

The expansion of urban areas, the growth of industrial sectors, and shifts in farming practices have been continuously altering the land utilization framework in Meishan, China. These changes are having an impact on both the quality of the local ecological environment and the ecological equilibrium within the Yangtze River basin. This research has important implications for the local and surrounding ecological security and sustainable development. In-depth analysis can grasp the trend of ecological environment change in Meishan City, assess the impact of human activities, and put forward scientific strategies. This research is capable of underpinning the sustainable exploitation of land resources, boosting ecological security and sustainable progress in Meishan City as well as the Yangtze River Basin, and offering a scientific foundation for land administration and ecological conservation.

2. Research Method

2.1 Land use change modelling

The land-use dynamic index model (LUDI) serves as a crucial metric for gauging the pace of land use transformation (Cao et al., 2024; Jalkanen et al., 2020; Nie et al., 2022), enabling it to capture variations in the area of different land use categories over a defined time frame. By computing the rate of area alteration, this model can present the speed at land cover changes occur.

LUDI is categorized into the single LUDI as K_{lu} and the comprehensive LUDI as M_{lu}. The calculation equation for the single land use dynamic degree is as Equation (1).

$$K_{lu} = \frac{(u_b - u_a)}{u_a} \times \frac{1}{T} \times 100\% \tag{1}$$

where K_{lu} represents the rate of change for a specific type of land use within a given period;
u_a and u_b represent the land use area in the initial and final stages, respectively;
T refers to the length of the study period.

M_{lu} is defined in Equation (2).

$$M_{lu} = \frac{\sum_{i=1}^{n} \Delta U_{i-j}}{2\sum_{i=1}^{n} \Delta U_i} \times \frac{1}{T} \times 100\% \tag{2}$$

where M_{lu} is the comprehensive dynamic degree of land use;
ΔU_i is the area of the i-th type of land use in initial stage;
ΔU_{i-j} is change area from the i-th land cover category into j-th non-land category;
T denotes the duration.

The land use transfer matrix incorporates the Markov model (Wang et al., 2023) into the study of land use changes. It quantifies the conversion relationships between various land use types over a specific time scale by spatial analysis methods like overlay analysis in ArcGIS, as illustrated in Equation (3).

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \tag{3}$$

where S_{ij} is conversion factor and n is dimension of transfer matrix.

2.2 Ecological Network Modelling

Ecological source areas constitute the core of ecological security in Meishan and also serve as a vital factor influencing regional ecological security. This paper employs Morphological Spatial Pattern Analysis (MSPA) to identify the ecological sources within the region (Yang et al., 2020). By taking the water bodies and forested areas of Meishan as the foreground, and construction land and cultivated land as the background, MSPA analysis is used to derive the landscape type of the core area. Subsequently, fragmented patches are removed to obtain large-scale core areas, thereby laying the groundwork for landscape connectivity analysis.

Landscape connectivity is an important index to test patch connectivity in the landscape. Removing a certain patch will have a certain impact on the entire landscape connectivity, and the magnitude of this effect reflects the important role of this index in the entire landscape connectivity. dPC_i is calculated using Equation (4).

$$dPC_i = \frac{PC - PC_{re}}{PC} \times 100\% \tag{4}$$

where PC_{re} refers to the landscape connectivity index of the region following the removal of patch i.

A resistance surface refers to the obstruction a species encounters when moving between different landscape units, which helps estimate its migration path in an environment with resistance. In this study, the Minimal Cumulative Resistance (MCR) model is utilized to simulate the process of species traversing various land classes. The calculation formula for the MCR model is defined in Equation (5).

$$MCR = f_{min} \sum_{j=n}^{j=m} D_{ij} \times R_i \tag{5}$$

where f_{min} denotes a positive correlation function linking the minimum cumulative resistance value to ecological processes;
min indicates the operation of taking the smallest value among different cumulative resistances;
D_{ij} represents the distance a specific species must traverse from location j to location i;

R_i is the resistance coefficient of location i in the specie migration.

The MCR model was used to obtain the overall resistance of the Meishan ecosystem, and the geometric center point was taken as the origin. The minimum cost path between each patch was obtained successively, while the redundant parts were excluded and yield the preliminary ecological corridors. This study apply gravity model to predict and analyze spatial interaction for ecological corridors, as shown in Equation (6).

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left(\frac{ln(S_i)}{P_i}\right) \times \left(\frac{ln(S_j)}{P_j}\right)}{\left(\frac{L_{ij}}{L_{\max}}\right)^2} \quad (6)$$

where L_{max} is the maximum cumulative resistance of all corridors in the region;
S_i is the area of patch i;
S_j is the area of patch j;
L_{ij} is the cumulative resistance value of the potential ecological corridor between patches i and j;
P_i and P_j are the resistance values of patches i and j;
G_{ij} is the interaction force between patches i and j.

3. Analysis of Spatio-Temporal Changes in Land Use

This study examines land use changes in Meishan City from 1990 to 2020, utilizing multi-source data including land use classification, climate, social-economic, and geographical data. The comprehensive dynamic degree of land use increased gradually, signifying significant shifts in land use structure driven by urbanization, economic growth, and policy interventions. Dynamic degrees of different land use types varied across periods, corresponding to changes in urbanization pace, ecological awareness, and development demands. Land use transfer matrix analysis further illustrates substantial interconversions among land types, with urbanization-induced encroachment on arable land being a prominent feature, posing challenges to ecological protection and agricultural sustainability.

3.1 Source and Processing of Data

The data required for this study primarily consist of land use classification data, climate factor data, social factor data, and geographical factor data related to Meishan City. The detailed data are presented in Table 1.

Data	Data sources
30 meter resolution land use classification data for 1990, 2000, 2010 and 2020	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http: //www.resdc.cn)
China national border, provincial, municipal and county administrative zoning map	National Geographic Information Public Service Platform
China 1KM resolution annual mean temperature data, China 1KM resolution annual precipitation data and China 1KM resolution NDVI data for 2022	Earth resource cloud (www.gis5g.com)
2022 GDP, total population	Statistical Yearbook
DEM	Geospatial Data Cloud (https://www.gscloud.cn/)

Table 1. Research data sources

Image preprocessing was employed such as mosaicking, clipping based on the study area. Reclassifying and the coordinate projection was completed for the four land use data images from different periods. Eventually, the land use maps of four periods were obtained. as shown in Figure1.

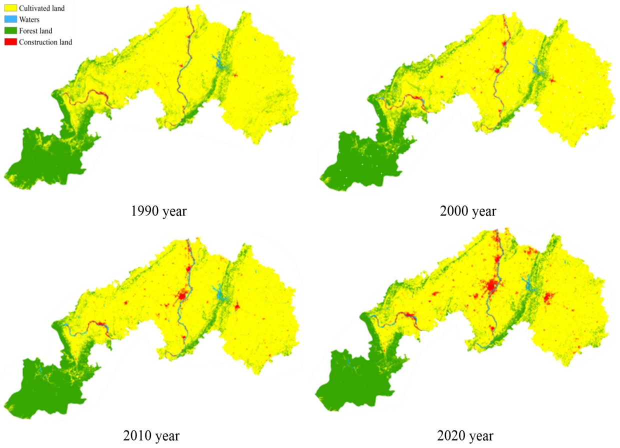

Figure 1. Land use spatial distribution maps of Meishan City from 1990 to 2020.

3.2 Extraction of Land Use Type Area

Area statistics are conducted on the land use spatial distribution maps of Meishan City from 1990, 2000, 2010, and 2020, categorized by different land use types. The findings are presented in Table 2.

Year	Cultivated land (km^2)	Forest land (km^2)	Waters (km^2)	Construction land (km^2)
1990	5405.17	1643.39	84.7	57.26
2000	5274.04	1763.06	75.55	77.87
2010	5420.57	1553.51	100.53	115.92
2020	5147.71	1747.14	97.01	198.67

Table 2. Land use area from 1990 to 2020.

As indicated in Table 2, notable shifts have occurred in Meishan City's land use structure between 1990 and 2020. Cultivated land area exhibited a pattern of initial growth followed by a decline, with a net reduction of 257.46 km² over the three decades—this trend mirrors the effects of urbanization and adjustments in agricultural frameworks on cultivated land resources. Forest land area fluctuated during the period, rising from 1643.39 km² in 1990 to 1747.14 km² in 2020, an expansion of 103.75 km², which implies the positive outcomes of ecological conservation policies. Water areas remained relatively stable, with only a minor increase observed. Construction land, however, saw consistent growth, expanding from 57.26 km² in 1990 to 198.67 km² in 2020, a clear sign of accelerating urbanization processes.

3.3 The Variation in the Number of Land Use Types

Figure 2 visually displays the annual area variation and ratios for each land category.

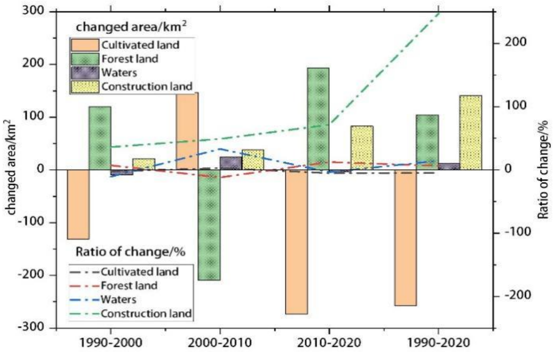

Figure 2. The changes in land use area and proportion from 1990 to 2020.

As illustrated in Figure 2, the composition of land utilization in Meishan City underwent substantial transformations between 1990 and 2020 years. The area of cultivated land decreased first and then remained stable. It shrank by 131.13 km², which could be associated with the policy of forest environmental protection. Forest land area kept growing, with the steepest rise 119.67 km²occurring between 2000 and 2010 years, reflecting the emphasis on ecological protection in Meishan City. The total increase was 103.75 km² by 2020 years. The area of water bodies slightly increased by 12.31 km², perhaps due to the appropriate measures for water resource protection. Construction land area kept expanding, growing by 82.75 km² between 2010 and 2020 years, indicating the acceleration of the urbanization process and the rapid development of the economy and society.

3.4 Changes in the dynamic degree of land use

Figure 3 presents the dynamic shift degrees of different land use types as well as the comprehensive dynamic degree of land use in the period from 1990 to 2020 years.

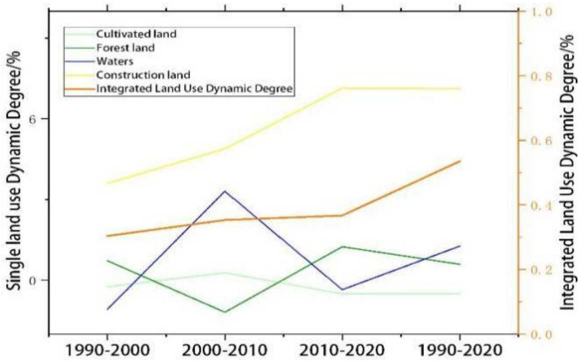

Figure 3. The dynamic degree of land use from 1990 to 2020.

As illustrated in Figure 3, Meishan City's comprehensive land use dynamic degree rose gradually from 0.30% to 0.37%, indicating notable shifts in land use structure driven by urbanization, economic development, and policy factors.

From 1990 to 2000, cultivated land showed a dynamic degree of -0.24%, with its area shrinking—a trend linked to urbanization, agricultural restructuring, and land degradation. Forest land, by contrast, had a dynamic degree of 0.73%, and its expansion mirrored growing ecological awareness. Water areas saw a dynamic degree of -1.08%, with their reduction possibly tied to water conservancy projects. Construction land, meanwhile, expanded rapidly, boasting a dynamic degree of 3.60%.

Between 2000 and 2010, cultivated land rebounded with a dynamic degree of 0.28%, resuming growth. Forest land's dynamic degree stood at -1.19%, its decline stemming from demands of economic development. Water areas grew with a dynamic degree of 3.31%, likely due to strengthened ecological protection efforts. Construction land's dynamic degree reached 4.89%, reflecting accelerated urbanization.

From 2010 to 2020, cultivated land experienced a significant decrease, with a dynamic degree of -0.50%, as urbanization advanced. Forest land continued to expand but at a slower pace, with a dynamic degree of 1.25%. Water areas declined more slowly, with a dynamic degree of -0.35%. Construction land's dynamic degree hit 7.14%, marking a peak in urbanization.

3.5 Assessment on land use area transfer

The structural shifts in land use types are specifically illustrated via the land use area transfer matrix. ArcGIS software was employed to statistically analyze the conversion of various land types over the past 30 years, and the statistical results were organized, as reported in Table 3.

Year	Land type	2020			(km^2)
		Cultivated land	Forest land	Waters	construction land
1990	Cultivated land	4905.58	323.80	21.68	5405.17
	Forest land	1.97	1.15	16.05	57.26
	Waters	223.25	1418.22	0.20	1643.39
	construction land	16.92	3.96	59.07	84.70

Table 3. Land use area transfer matrix of Meishan City from 1990 to 2020.

As indicated in Table 3, Meishan City has substantial changes in its land use structure from 1990 to 2020 years. Cultivated land converted to construction land cumulatively reached 166.12 km^2, underscoring the encroachment of urbanization on arable resources. Forest land was primarily converted to cultivated land, construction land, and water areas, though the shift to cultivated land gradually diminished due to a result of stricter land protection policies. Construction land expanded from 49.89 km² to 198.67 km², driven by conversions from cultivated land, forest land, and water areas, signaling accelerating urbanization. Water areas grew from 64.58 km² to 80.69 km², a change possibly linked to the enforcement of water area protection policies. While these shifts align with urban development needs, they also pose challenges to the ecological environment and agricultural production, demanding close attention and targeted responses.

4. Analysis of Ecological Network Pattern in Meishan City

4.1 Ecological source identification

Employing the MSPA method, fragmented patches smaller than 1 km² were eliminated from forest land, cultivated land, and water areas, resulting in 42 core patches. Subsequent landscape connectivity analysis via Conefor software identified 13 core patches with a dPC value exceeding 0.1, which were designated as ecological source areas. These source areas cover a total of 1355.74 km², making up 18.85% of the region's total area. Their distribution is uneven, clustering mainly in the central and western parts. Among them, Hongya County boasts the largest area of ecological sources, while Dongpo District has the smallest.

4.2 Constructing ecological resistance influence factors

Eight resistance-related variables were selected, encompassing land use category, elevation, gradient, vegetation density, population, GDP, annual rainfall and temperature. Each variable was split into four levels. Resistance scores are allocated to each resistance layer. The weights for each variable were computed using the Analytic Hierarchy Process (AHP), which in turn enabled the calculation of Meishan City's ecological resistance coefficient. Therefore, the integrated ecological resistance layer for Meishan City was developed.

Among these variables, land use category and population density contributed the most to ecological resistance, with construction land assigned the highest score due to intense human disturbance, while high vegetation coverage areas obtained low scores for facilitating ecological connectivity. Spatially, the resistance layer exhibited distinct regional differences: urban agglomerations with high GDP and population density, such as Dongpo and Pengshan Districts, formed high-resistance clusters, while mountainous areas with dense vegetation and low human activity showed low resistance. This scientifically constructed resistance layer laid a robust foundation for the subsequent identification of ecological corridors via the MCR model, ensuring the rationality of corridor extraction by accurately reflecting the difficulty of ecological process circulation.

4.3 Constructing Ecological Corridors

Taking the 13 ecological sources as the research objects and starting points, the MCR model was applied in conjunction using the minimum cost path method in geospatial analysis to identify twenty ecological corridors. These corridors have a total length of 461.77 kilometers. Among these, important ecological corridors contain six, and the remaining were classified as general ecological corridors.

The six important ecological corridors, mainly distributed between core ecological patches, play a pivotal role in maintaining regional ecological connectivity, with shorter lengths and lower resistance, ensuring efficient material and energy exchange. General corridors, by contrast, expand the network coverage, bridging scattered ecological sources and mitigating landscape fragmentation. Spatial distribution shows corridors are concentrated in areas with mild terrain and less human disturbance, while fragmented regions lack effective connections. This pattern provides a basis for targeted ecological corridor optimization and ecological security pattern improvement.

4.4 Construction of Ecological Security Network

The ecological security pattern of Meishan City was analyzed through the process of "ecological source area identification–resistance surface construction – ecological corridor extraction and node selection". Based on this, 13 ecological source areas, 20 ecological corridors (including 6 important ones and 14 general ones), and 3 ecological nodes in Meishan City were identified, and the ecological security network of Meishan City was constructed.

As shown in Figure 4, Dongpo District, Pengshan District, and Renshou County exhibit higher ecological resistance, attributed to fewer ecological sources and dense ecological corridors. These regions feature rapid economic growth, dense populations, and frequent human activities, which exert significant interference on the ecological environment. In response, it is advisable to carry out unified ecological restoration in these key areas to ensure the continuity of restoration efforts. Additionally, protective forest belts should be established around ecological sources to mitigate the impact of human activities and preserve the existing ecological value.

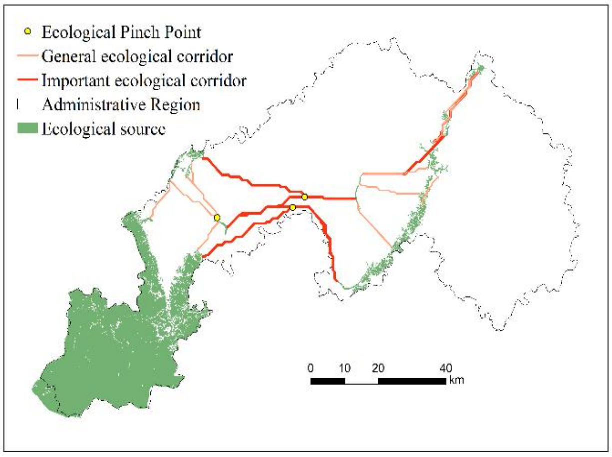

Figure 4. Ecological security network of Meishan City.

Furthermore, integrating the distribution of cultivated land and tea gardens in Meishan City, this study proposed establishing an ecological ditch system, using tea gardens as ecological barriers, and building additional ecological corridors. These measures aim to further strengthen and consolidate Meishan City's ecological security pattern.

Specifically, ecological ditches can intercept agricultural non-point source pollution, improve water circulation between cultivated land and natural ecosystems, and complement the functions of existing ecological corridors. Tea gardens, as characteristic ecological barriers, can leverage their dense vegetation cover to reduce soil erosion and enhance landscape connectivity, aligning with agricultural development characteristics.

Newly added corridors should prioritize low-resistance areas such as river valleys and gentle slopes, connecting scattered ecological patches to compensate for connectivity deficiencies in high-resistance urbanized regions. These targeted measures realize the coordination of agricultural production and ecological protection, laying a solid foundation for the sustainable evolution of Meishan's ecological security network.

5. Conclusion

This study delves into the spatio-temporal evolution of land use patterns and the construction of ecological networks in Meishan City in China from 1990 to 2020. Key findings reveal that the city’s land use structure underwent marked transformations during this period: construction land expanded rapidly, while cultivated land resources dwindled gradually. These shifts were shaped by a mix of drivers, including urbanization and ecological protection policies.

In analyzing the ecological network, the research identifies 13 core ecological sources in Meishan City, along with 20 ecological corridors, six of them are classified as important and 14 ones as general. These corridors play a vital role in boosting connectivity between ecological sources and sustaining ecosystem stability and biodiversity. However, the study also highlights 3 ecological pinch points: as critical junctions linking corridors, they have emerged as weak spots in ecological protection, requiring immediate attention.

Additionally, this research offers valuable insights for similar work in other comparable regions. Meishan City confronts multiple challenges in land use and ecological conservation. Some efforts should focus on optimizing land use structures, strengthening ecological network development, and enhancing ecosystem service functions to advance regional sustainable development.

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