Postprint: Spatiotemporal Patterns and Trade-offs of Land Multifunctionality in the Middle Reaches of the Heihe River Based on Multi-source Geographic Data Fusion

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Abstract

Multifunctional land use represents an important pathway for enhancing land use efficiency, alleviating human-land conflicts, and promoting regional sustainable development. This study constructed a "production-living-ecology" functional evaluation index system for land multifunctionality. Based on a 3 km$\times$3 km grid, it integrated multi-source geographic data including remote sensing, statistical data, and POI, and employed a projection pursuit model to evaluate land multifunctionality in the middle reaches of the Heihe River. Through variable correlation analysis and bivariate local spatial autocorrelation analysis, the study revealed trade-off and synergistic relationships among land functions, and utilized a combination of RGB three-channel synthesis and two-step cluster analysis for land functional zoning. The results indicate: (1) The middle reaches of the Heihe River exhibit distinct functions under different utilization patterns. In the Corridor Plain region, land functions are dominated by production functions, supplemented by living and ecological functions. Production functions demonstrate clear advantages in the Corridor oasis agricultural area. High-value areas of living functions are concentrated in towns and regions with superior infrastructure conditions. The Qilian Mountains and Longshou Mountains function as ecological barriers. (2) During the study period, land multifunctionality steadily enhanced. The spatial patterns of land multifunctionality and primary functions remained stable, coordination among land functions generally improved, and different functions increasingly overlapped in space. (3) According to dominant utilization directions, land can be categorized into key development zones, optimized development zones, and moderate development zones focusing on agricultural production and urban space, as well as ecological barrier zones, ecological buffer zones, and ecological restoration zones primarily comprising ecological space. (4) There remains considerable room for

improvement in multifunctional land use, particularly through strengthening attention to non-dominant functions and coordinating inherent contradictions among functions. It is essential to comprehensively advance ecological restoration, focus on natural capital appreciation, and explore new growth points for land value from the perspective of constructing a regional pattern of lucid waters and lush mountains.

Full Text

Spatial-Temporal Pattern and Trade-Offs of Land Multi-Function in the Middle Reaches of the Heihe River Based on Multi-Source Geographic Data Fusion

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Abstract: Multifunctional land use is an important pathway to improve land-use efficiency, alleviate human-land contradictions, and promote regional sustainable development. This study constructed a land multi-function evaluation index system based on the "production-living-ecology" framework. Using a 3 km × 3 km grid, we integrated multi-source geographic data including remote sensing, statistical, and point-of-interest (POI) data, and employed a projection pursuit model to evaluate land multi-functionality in the middle reaches of the Heihe River. Through variable correlation analysis and bivariate local spatial autocorrelation analysis, we revealed the trade-off and synergy relationships among land functions. We also combined RGB composite with two-step cluster analysis for land functional zoning. The results show that: (1) Land in the middle reaches of the Heihe River exhibits different functions under various utilization patterns. In the corridor plain area, production function dominates, supplemented by living and ecological functions. Production function shows clear advantages in the corridor oasis agricultural zone, high-value living function areas concentrate in towns and regions with better infrastructure, and the Qilian Mountains and Longshou Mountains serve as ecological barriers. (2) During the study period, land multi-functionality steadily increased. The spatial patterns of land multi-functionality and primary functions remained stable, coordination among land functions generally strengthened, and different functions increasingly overlapped in space. (3) According to the dominant utilization direction, land can be divided into key development zones, optimization development zones, and moderate development zones that focus on agricultural production and urban space, as well as ecological barrier zones, ecological buffer zones, and ecological restoration zones that primarily serve ecological functions. (4) There remains room for improvement in land multi-functional utilization, particularly through strengthening attention to non-dominant functions and coordinating inherent contradictions among functions. Collaborative ecological restoration should be promoted, natural capital appreciation should be emphasized, and new growth points for land value should be explored by constructing a regional pattern of lucid waters and lush mountains.

Keywords: land multi-function; multi-source geographic data; spatial-temporal pattern; trade-offs and synergies; functional zoning; middle reaches of the Heihe River

Introduction

Land use represents purposeful, proactive development and utilization of land resources by humans to obtain needed products or services. The capacity of various land-use patterns to provide products or services constitutes land-use function. With accelerating urbanization and continuous population growth, human consumption demands keep increasing, placing new requirements on land and demanding new products or services. Particularly as available land resources become increasingly scarce, diversified land use has become inevitable. Since enhancing one function of a land system often comes at the expense of others, research on trade-off and synergy relationships helps accurately analyze and compare relationships among land functions, thereby improving human well-being.

The concept of "multifunctionality" first emerged in the 1980s in Japan' s "rice culture" as "agricultural multifunctionality." In 1992, the Organization for Economic Co-operation and Development (OECD) further defined the concept of agricultural multifunctionality and proposed an analytical framework. Building on this concept and integrating ecosystem services and landscape functions while considering the balance among the three dimensions of sustainability—economic, social, and environmental—the European Union' s Sixth Framework Program "Sustainability Impact Assessment: European Land Use and Environmental, Social, and Economic Effects" formally proposed the concept of land-use multifunctionality in 2004. Subsequently, scholars have identified and classified land multi-functions from different perspectives, such as "production-living-ecology," "production-living-ecology-social security," and "production-living-ecology-culture" dimensions. Different land functions often manifest as trade-offs (where one function increases at the expense of another) or synergies (where functions mutually enhance each other). In recent years, researchers have employed statistical methods, spatial analysis, scenario simulation, and ecosystem service flow analysis to study trade-offs and synergies among land system functions.

The middle reaches of the Heihe River represent the most densely populated, most concentrated oasis area, and most economically developed region in the Heihe River Basin, accounting for 95% of the artificial oasis, 91% of cultivated land, 91% of population, and 80% of GDP. However, the ecosystem in this area is extremely fragile and sensitive. Unreasonable land-use patterns can easily cause ecosystem damage, leading to land salinization, desertification, and other ecological and environmental problems. With increasing population and accelerated urbanization in the middle reaches of the Heihe River, large amounts of agricultural land have been converted to construction land, while wasteland around the oasis has been reclaimed as farmland. The contradictions among overloaded population, rapidly developing economy, inherently fragile ecological environment, and limited natural resources have become increasingly prominent. Therefore, deeply exploring land-use multifunctionality is key to coordinating land-use conflicts and achieving sustainable land resource utilization.

Reviewing existing research reveals several limitations: (1) Data sources are mostly limited to socio-economic statistics and land-use data, with rare integration of remote sensing, nighttime light, and POI data with strong timeliness to reflect human socio-economic activity information. (2) Evaluation scales are mostly based on administrative units, making it difficult to accurately depict the specific spatial distribution of land functions. (3) Research on trade-offs and synergies mostly focuses on cultivated land multifunctionality, lacking studies on the multi-functionality of entire land systems. This study, based on a grid scale and integrating multi-source geographic data, aims to reveal the spatial-temporal patterns and trade-off/synergy relationships of land multifunctionality in the middle reaches of the Heihe River, with the goal of deeply exploring land-use multifunctionality to coordinate land-use conflicts and achieve sustainable regional land resource utilization.

1.1 Study Area Overview

The Heihe River is China' s second largest inland river system, originating from the northern slope of the middle Qilian Mountains, flowing through the middle Hexi Corridor, and disappearing into the East and West Juyanhai in Ejin Banner. The section between Yingluoxia and Zhengyixia constitutes the middle reaches, located in the middle Hexi Corridor, with a total basin area of approximately 1.96×10^4 km^2. The geomorphology can be broadly divided into high mountains, medium-low mountains, and corridor plains, with terrain sloping from high in the south to low in the north, and slightly higher in the east than in the west. The central part is a corridor plain where oasis and Gobi are interspersed [Figure 1: see original paper]. The area has a temperate continental arid climate, with annual evaporation reaching 1700 mm and precipitation ranging from 54.9 to 436.2 mm, distributed very unevenly throughout the year. Most agricultural production in some areas depends on artificial irrigation. For a long time, the middle reaches of the Heihe River have been a traditional agricultural oasis. However, with changes in national industrial layout and economic development strategy, the proportion of the three industries has shifted from 58.06:3.23:38.71 to 21.9:22.3:55.8, showing a transformation from traditional farming agriculture to comprehensive industries. Correspondingly, regional land-use functions have also changed from single agricultural and pastoral production to multi-functional utilization with increasing industrial and tertiary industry land, and from focusing on production functions to emphasizing integrated “production-living-ecology” functions.

1.2 Data Sources

Administrative boundaries, road, and water system data were obtained from the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn/). Land-use data came from the Geospatial Data Cloud (http://www.gscloud.cn/). Soil erosion intensity data (2013, 2016) with 1 km spatial resolution and population grid data (2013, 2016) with 1 km spatial resolution were acquired from the Resources and Environmental Data Cloud Platform (www.resdc.cn/Default.aspx). Nighttime light data (2013, 2016) were obtained from the NOAA National Centers for Environmental Information (https://www.ngdc.noaa.gov/eog/index.html). Socio-economic statistics came from statistical yearbooks of Zhangye City’ s districts and counties (2013, 2016) and the CNKI Gansu Province Economic and Social Development Statistical Database (http://data.cnki.net/area/home/index/D28). Points of interest (POI) data for 2016, including transportation, living, and medical facilities, were acquired through the Application Programming Interface (API) from the Baidu Maps Open Platform (http://lbsyun.baidu.com/). After preprocessing through deduplication, random verification, and vectorization, point data layers were formed.

2.1.1 Construction of the Indicator System

Drawing on the “production-living-ecology” framework, this study divided land functions into three dimensions: production, living, and ecological functions. Production function refers to land’ s capacity to support product production and sustained economic development. Living function refers to land’ s capacity to support human employment, provide social security, and serve as residential space. Ecological function refers to land’s capacity to maintain ecosystem stability and provide high-quality ecological environments. Considering the industrial structure, living standards, and prominent ecological issues in the middle reaches of the Heihe River, eight secondary functions were identified under the primary functions: agricultural production, economic production, transportation, employment support, residential living, health security, ecological maintenance, and pollution reduction. Given the complex multi-dimensional relationships between indicators and land functions, and following principles of systematicity, dominance, conciseness, and operability, 13 indicators were selected .

2.1.2 Indicator Spatialization and Standardization

Since socio-economic statistical data were based on township administrative units, to reveal internal spatial heterogeneity and enable integration with natural environment data, this study used high-spatial-resolution geographic proxy data including land use, nighttime light, and population grid data to spatially discretize agricultural production (X_1), economic production (X_4), employment support (X_8), and pollution reduction (X_{13}) data, obtaining indicator values at a 3 km × 3 km grid scale. For transportation (X_5), living (X_9), and medical facility (X_{11}) data, we employed kernel density estimation for spatialization. Kernel density estimation is a non-parametric method that converts point data into continuous density fields. Taking facility point i as the center and h as the bandwidth, density values gradually decrease with increasing distance from the facility point, decaying to zero at distance h. The calculation formula is:

$$f(x, y) = \frac{1}{h^2} \sum_{i=1}^{n} K\left(\frac{d_i}{h}\right)$$

where $f(x,y)$ is the kernel density estimate at location (x,y); h is the bandwidth, set at 10 km based on multiple trials and empirical judgment; n is the number of facility points within distance $\leq h$ from location (x,y); d is the distance between location (x,y) and the i-th facility point; and $K(x)$ is the kernel function determining the distance decay magnitude. Based on Silverman' s quadratic kernel function, the formula is:

$$K(x) = \frac{3}{4}(1 - x^2) \quad \text{for} \quad |x| \leq 1$$

Additionally, soil erosion intensity (X_{12}) was calculated as the average value of all raster cells within each grid; forestland proportion (X_3) was the percentage of forestland area within each grid; and tap water beneficiary household ratio (X_{10}) was obtained by overlaying township statistical data with grids.

According to the direction of indicator effects on evaluation results, extreme value standardization was applied for both larger-is-better and smaller-is-better types.

2.1.3 Projection Pursuit Model Based on Accelerated Genetic Algorithm

The projection pursuit model is an exploratory data analysis model driven directly by sample data, suitable for analyzing non-linear, non-normal high-dimensional data. Its principle is to synthesize n-dimensional indicator data $\{x \mid j = 1, 2, \cdots, n\}$ into a one-dimensional projection value z using projection direction $a = \{a_1, a_2, \cdots, a\}$:

$$z_i = \sum_{j=1}^{n} a_j x_{ij} \quad (i = 1, 2, \cdots, m)$$

During projection, local projection points should be as dense as possible while overall projection point clusters should be as dispersed as possible. Therefore, the projection objective function can be constructed as:

$$Q(a) = S_z D_z$$

where S_z is the standard deviation of projection values Z and D_z is the local density of Z. The calculation formulas are:

$$S_z = \sqrt{\frac{\sum_{i=1}^{m}(z_i - E(z))^2}{m-1}}$$

$$D_z = \sum_{i=1}^{m}\sum_{h=1}^{m}(R - r_{ih}) \times u(R - r_{ih})$$

where $E(z)$ is the mean of $\{z\}$; R is the local density window radius, taken as $0.1S\_z$; $r \; = |z \text{ - } z|$ is the distance between samples; and $u(t)$ is the unit step function, equal to 1 when $t \geq 0$ and 0 when $t < 0$.

The best projection direction that maximally exposes the high-dimensional data structure can be found by solving the maximum of the projection objective function:

$$\max : Q(a) = S_z D_z$$

Subject to the constraint:

$$\sum_{j=1}^{n} a_j^2 = 1$$

The real-coded accelerated genetic algorithm can perform continuous and effective global searches, showing good performance in finding the optimal projection direction. This study implemented the algorithm in Matlab 2016, setting the parent initial population size to 400, elite individual number to 10, crossover probability $p\_c = 0.80$, and mutation probability $p\_m = 0.05$. After 200 iterations, the algorithm entered an accelerated cycle with 10 acceleration times. The obtained optimal projection direction vector was linearly adjusted to sum to 1 and used as the weight for corresponding indicators , which were then substituted into formula (1) to obtain the comprehensive land multi-function score.

2.2.1 Variable Correlation Analysis

Variable correlation analysis provides quantitative indicators of interrelationships among variables, intuitively reflecting trade-off and synergy relationships. Spearman' s rank correlation coefficient analysis, a non-parametric method, is more suitable for geographic data that are often non-linear and non-normal.

This study used SPSS 24' s correlation analysis function for variable correlation analysis.

2.2.2 Bivariate Local Spatial Autocorrelation Analysis

Local spatial autocorrelation measures the relationship between each spatial location and neighboring locations for the same attribute value, revealing spatial local non-stationarity and more accurately reflecting the distribution characteristics of geographic elements in local space. This study adopted Anselin' s bivariate spatial autocorrelation to measure spatial correlations among multiple attributes. The Getis-Ord G index was used to determine whether significant high-value or low-value clusters exist at local positions. At a given significance level, a positive and significant index indicates a high-value cluster (hotspot), while a negative and significant index indicates a low-value cluster (coldspot).

2.2.3 Two-Step Cluster Analysis

Cluster analysis reveals natural groupings in datasets and identifies land function combination patterns to support comprehensive zoning. Two-step cluster analysis can handle both continuous and categorical variables simultaneously, making it suitable for multi-type data fusion analysis. This study used the two-step clustering function in SPSS 24, using elevation, primary land function evaluation values, primary function cold/hotspot types, and primary function trade-off/synergy types as input variables to cluster grid units.

3.1 Spatiotemporal Characteristics of Land Multi-Functionality

Production function is the dominant function in the middle reaches of the Heihe River. From 2013 to 2016, production function increased from 44.11% to 57.54%; living function was secondary (around 25%) with little change; ecological function decreased significantly, with its contribution rate dropping from 38.84% to 25.12%. The natural breaks method, proposed by Jenks, is a map classification algorithm that clusters data based on the principle of minimizing within-group variance while maximizing between-group variance. Accordingly, this study classified land multi-functionality comprehensive scores into five levels . The results show [Figure 3: see original paper] that grids with low and relatively low land multi-functionality accounted for the absolute majority (82.9%) in 2013, while high and relatively high grids only accounted for 5.89%. By 2016, low and relatively low grids decreased to 77%, while medium, relatively high, and high grids increased. This indicates significant spatial heterogeneity in land multi-functionality in the middle reaches of the Heihe River.

From 2013 to 2016, land multi-functionality in the central parts of Shandan and Minle counties and Shandan Horse Ranch increased, while it decreased in the southwestern part of Gaotai County. The high-value clusters in Gaotai, Linze, and Ganzhou counties connected to form a continuous high-value belt across the corridor.

3.1.1 Production Function

As shown in [Figure 5: see original paper], high-value production function areas mainly appear in the central parts of Ganzhou, Linze, and Gaotai counties, distributed along the corridor oasis agricultural zone and forming high-value clusters. Medium production function areas mainly appear near major roads in Shandan and Minle counties. Low-value areas mainly appear in deserts, Gobi regions, and the Qilian and Longshou mountain areas, forming significant low-value clusters, reflecting restrictions on land resource development due to natural conditions and ecological protection policies. From 2013 to 2016, production function increased in central Shandan and Minle counties, while it decreased in southwestern Gaotai County. The high-value clusters in these areas connected into an integrated whole.

3.1.2 Living Function

[Figure 6: see original paper] shows that high-value living function areas are mainly distributed in central Ganzhou district and near county seats of Gaotai, Linze, Shandan, and Minle, with most parts of Ganzhou district and central Linze and Minle forming high-value clusters. Low-value living function areas are mainly distributed in northwestern regions and the Qilian and Longshou mountains, forming low-value clusters. From 2013 to 2016, living function near county government seats clearly strengthened, with expanded high-value areas, while changes in other areas were not obvious.

3.1.3 Ecological Function

[Figure 7: see original paper] shows that high-value ecological function areas mainly appear at the foothills of the Qilian Mountains, Shandan Horse Ranch, and Longshou Mountains, forming high-value clusters that reflect the ecological barrier function of these mountains. Low-value areas mainly appear in northwestern deserts and Gobi regions and in oasis agricultural areas of Linze and Gaotai, forming significant low-value clusters. From 2013 to 2016, ecological function strengthened in central Ganzhou district, and high-value clusters expanded at the foothills of Longshou Mountain. Ecological function weakening mainly occurred in central and southern parts of Minle and Shandan counties, with large low-value clusters appearing in central Minle County, primarily due to non-point source pollution from heavy fertilizer application.

3.2 Trade-Offs and Synergies

3.2.1 Global Characteristics

Spearman correlation coefficients among primary land functions are shown in . Production and living functions show significant synergy that strengthened over time, reflecting enhanced overall coordination. Trade-off relationships between ecological function and both production and living functions strengthened over time, reflecting intensified encroachment of production- and living-oriented land development activities on the ecological environment.

Spearman correlation coefficients among secondary land functions show that secondary functions under production and living functions all have significant synergies that strengthened over time, reflecting the development of increasingly strong transportation and employment functions in traditional agricultural production spaces. Ecological maintenance function has significant synergies with agricultural production, economic production, employment support, and health security functions, reflecting the preference of these functions for good ecological environments. Pollution reduction function has significant trade-offs with all secondary functions, with most intensifying, reflecting increasing pressure on the ecological environment.

3.2.2 Local Characteristics

Bivariate local spatial autocorrelation analysis reveals the spatial patterns of trade-offs and synergies among primary land functions [Figure 8: see original paper]. In 2013 and 2016, the trade-off and synergy patterns were similar, with hotspot areas appearing in: (1) Oasis agricultural areas. Irrigation oasis agricultural areas around the Heihe River system generally show "high production-high living" synergy, reflecting the basic human-land relationship characteristic of "living by water and grass" in arid region agricultural oases. Settlements at all levels are point-distributed in various oases, with production levels and living quality showing mutually reinforcing characteristics. However, in some oasis agricultural areas of Gaotai, Linze, and Minle, "high production-low ecological" trade-offs exist; by 2016, the trade-off area in Minle County covered almost all oases within the county. These trade-offs reflect the encroachment on ecological functions in pursuit of enhanced production functions. (2) Qilian and Longshou mountain areas. Areas such as Mati Township in Sunan County, southern Minle County, Shandan Horse Ranch, and northern Shandan County show "low production-low living-high ecological" trade-offs, reflecting that due to natural factors like terrain and climate and ecological conservation policies, agricultural production suitability is poor, living functions are greatly restricted, while ecological functions are more suitable to play. These areas should be protected as ecological security barriers for the entire basin. (3) Gobi and desert areas. Areas such as Minghua Township in Sunan County and western Gaotai County show "low production-low living-low ecological" co-variation relationships. In these ecologically fragile desert Gobi areas with very low resource-environment carrying capacity, land-use planning should focus on ecological conservation, reduce human socio-economic activity interference, and enhance ecological functions.

3.2.3 Land Functional Zoning

Using RGB composite to display the contribution of each primary function to land multi-function (2016), we obtained the spatial pattern of dominant land functions in the middle reaches of the Heihe River [Figure 9: see original paper]. Based on this and two-step cluster analysis results [Figure 9: see original paper], we ultimately classified the land into six functional zones [Figure 9: see original paper]:

(1) **Key Development Zones** are mainly located in central and southern Ganzhou district and near Gaotai and Minle county seats. These areas have flat terrain, relatively abundant water resources, good transportation conditions, dense population, and highly developed production and living functions with minimal negative environmental impact. They are suitable for continuing to undertake high-density socio-economic activities but should strictly limit high-pollution, high water-consumption industries.

(2) **Optimization Development Zones** are mainly located in oasis agricultural areas of Minle, Linze, and Gaotai counties. These areas have relatively good location conditions and are traditional agricultural oases, but production activities have caused significant impacts on ecological functions. Future efforts should appropriately control pesticide and fertilizer application to reduce non-point source pollution and protect ecological functions. Meanwhile, high value-added industries such as Chinese herbal medicine cultivation can be developed to transform production toward environment-friendly, knowledge-based, management-intensive, and regionally distinctive modes.

(3) **Moderate Development Zones** are mainly located in transition areas from oasis edges to deserts. These areas have scarce water resources and poor suitability for agriculture- and urban-oriented development. They are suitable for developing industries with minimal environmental impact such as photovoltaic and wind power. Relying on the advantage of high living function security, facility agriculture can be moderately developed, introducing arid region sand industry technology to compensate for natural condition limitations. Development intensity should be strictly controlled, and the scale of newly reclaimed wasteland should be limited.

(4) **Ecological Barrier Zones** are mainly located in the piedmont areas of the Qilian and Longshou mountains, less disturbed by human activities, with high forest and grass coverage, relatively abundant precipitation, and relatively complete ecosystems that serve as ecological barriers. Ecological protection policies and measures should be strengthened to prevent soil erosion, maintain biodiversity, and continuously enhance ecological functions. Meanwhile, natural science education and eco-tourism activi-

ties can be appropriately developed in the Qilian Mountain National Park to deeply explore the value of lucid waters and lush mountains.

(5) **Ecological Buffer Zones** are mainly located in northeastern Shandan County, western Gaotai County, and Minghua Township in Sunan County. These areas have warm-dry climate, strong winds, and are dominated by desert landscapes with sporadic cultivated land distribution. Gradual implementation of returning farmland to grassland and natural vegetation restoration should be carried out, controlling human activities within resource-environment carrying capacity and guiding natural ecosystem recovery.

(6) **Ecological Restoration Zones** are mainly located in desert areas of northern Gaotai and Linze counties. Compared with ecological buffer zones, these areas have sparser vegetation, more severe soil erosion, and very fragile ecological environments. Stricter ecological protection policies should be implemented, all development activities should be prohibited, and systematic artificial restoration projects such as grass grid sand fixation and water supplementation should be carried out.

4 Conclusions

(1) Land functions in the middle reaches of the Heihe River show significant heterogeneity in both composition structure and spatial pattern. Structurally, production function dominates, supplemented by ecological and living functions, reflecting the comparative advantages of traditional agricultural oases. Spatially, high multi-functionality areas mainly appear in corridor plain oasis agricultural zones and county administrative centers. High production function areas are distributed along traditional oasis agricultural zones. High living function areas are located in towns with superior infrastructure conditions and dense population. The Qilian and Longshou mountain areas have strong ecological functions, while agricultural areas with heavy fertilizer application and environmentally fragile desert areas have weak ecological functions.

(2) Land multi-functionality in the middle reaches of the Heihe River has steadily increased in recent years. During the study period, the spatial patterns of land multi-functionality and primary functions showed no obvious changes, reflecting overall stability. The number of grids with medium or higher multi-functionality scores increased significantly, coordination between production and living functions strengthened, and synergies among most secondary functions also strengthened, reflecting that different functions gradually overlapped in space and land multi-functionality was increasingly enhanced.

(3) There remains room for improvement in land multi-functional utilization in the middle reaches of the Heihe River. Trade-off results reveal inherent conflicts among different functions. Low ecological function trade-off

areas reflect the encroachment of human development activities on land ecological functions. Some oasis edge areas with good development conditions and the Qilian Mountains' high-quality eco-tourism and science education resources are not fully utilized, consistent with related research. Future land-use planning and resource development must trade off different functions, fully explore land multi-functionality, coordinate inherent contradictions, and discover new growth points.

(4) The middle reaches of the Heihe River need to strengthen attention to non-dominant functions. Based on land functional zoning results, the area needs to coordinate production and living space layout to enhance living function levels. It should rely on technology and management elements to coordinate inherent contradictions among land functions, transform toward environment-friendly high value-added industries, and reduce ecological burdens. Collaborative promotion of natural ecosystem recovery and artificial restoration should be emphasized, with attention to natural capital appreciation and exploration of new land value growth points through constructing a regional pattern of lucid waters and lush mountains.

5 Discussion

This study introduced Internet map POI data. Compared with traditional statistical data-based indicators, POI data for transportation, living, and service facilities have higher spatial resolution and stronger timeliness, more intuitively and accurately measuring related services provided by land. However, since Internet map POI data sharing services only began in 2015, earlier data are difficult to obtain, limiting the study' s temporal span.

Using land function cold/hotspot types and trade-off/synergy types in functional zoning can reflect both the spatial clustering status of single functions and the internal relationships among multiple functions from two dimensions, indicating land suitability and carrying capacity for different functions. Considering these characteristics in land functional zoning can more accurately distinguish suitable land uses, improving zoning accuracy and practicality for land spatial planning and resource management.

When interpreting bivariate spatial autocorrelation results, co-variation effects should be noted. For example, in central Linze County' s oasis agricultural area, fertilizer application leads to weak ecological function, while developed agricultural production provides conditions for strong living function. Identifying a "high production-low ecological" trade-off relationship is reasonable, but determining whether a "high living-low ecological" trade-off exists is difficult. Therefore, comprehensive consideration of land function interaction types, pathways, and regional natural environment and socio-economic characteristics is needed for more reliable conclusions.

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