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Urban Ecological Zoning Based on Ecosystem Services: A Case Study of Urumqi

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Abstract. Ecosystem services are fundamental to human survival and development.Assessing urban ecosystem services and implementing zoned management of ecological units can contribute to the improvement of the human living environment.This study establishes an indicator system for ecosystem services from four aspects:provisioning services,regulating services,supporting services and cultural services.The value of ecosystem services for different land use types is calculated using the equivalent value per unit area.The ecosystem service values of eight districts or counties in Urumqi in 2023 are evaluated. We employ spatial autocorrelation analysis to delineate ecological management units at the community level and propose strategies for ecological zoning regulation. The results indicate that: ① The total value of ecosystem services in Urumqi reached 10.595 billion yuan in 2023, exhibiting significant spatial variation. The highest value was 4.18 billion yuan in Urumqi County,while the lowest was 0.188 billion yuan in Tianshan District. ② seven districts and one county in Urumqi were classified into four types of urban ecological management zones:mountain ecological core protection zone, urban construction and development zone,desert ecological prevention and control zone, and ecological-economic transition zone. ③ Differentiated management measures are proposed in each zone,demonstrating that effective urban ecological zoning can balance various ecosystem service functions and optimize their benefits.The findings facilitate a comprehensive evaluation of urban ecosystem services in urbanized areas and provide a reference for refined management and differentiated regulation of regional ecological governance.

Keywords: land use type, ecosystem service value, spatial autocorrelation, ecological zoning, Urumqi

1. Introduction

Ecosystem service value (ESV) serves as a critical basis for balancing urban development and ecological conservation, reflecting the economic benefits ecosystems provide to human society [1,2]. Pioneering work by Costanza et al. quantified global natural capital value, laying the foundation for applying ESV in spatial management [1]. The United Nations Millennium Ecosystem Assessment established a four-dimensional framework—provisioning, regulating, supporting, and cultural services—that has become central to ESV research and its role in territorial planning [3]. In

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the context of China's ecological civilization development, ESV zoning has been incorporated into national guidelines, including the National Ecological Function Zoning and provincial ecological protection redline delineations, underscoring the policy relevance of ESV in guiding urban ecological management [4].

Empirical studies highlight the spatial variability of ESV as a key determinant in regional ecological security. Scientific zoning is essential for reconciling this spatial heterogeneity with management objectives [5]. International research has been diverse, focusing on either ecological elements or spatial scales. Studies on ecological management zoning tend to focus on specific ecosystem types, such as water source ecosystems [6,7], wetlands [8], and urban green spaces [9,10]. Scale-oriented studies address spatial differentiation at regional levels, particularly at administrative or grid scales, to refine management strategies[11-13]. However, significant gaps remain in urban community-scale research, which is critical for micro-level management but largely overlooked by current studies. Additionally, the integration of ESV into urban governance practices is often neglected in favor of focusing on ecological and geographical aspects.

As a key node along the China–Central Asia Corridor of the "Belt and Road Initiative," Urumqi's ecological security holds national strategic significance. The city faces dual ecological pressures: glacier retreat in the southern Tianshan Mountains reduces water conservation capacity [14], while urban expansion in the north accelerates desertification and wind erosion [15]. Current studies lack a systematic analysis of the spatial correlation of ESV in arid cities, leaving a gap in the scientific basis for zoning decisions [14]. This study evaluates ESV across eight administrative units in Urumqi in 2023, using an indicator system covering provisioning, regulating, supporting, and cultural services. Through spatial autocorrelation analysis, ecological management units are defined, and zoning strategies are proposed to guide Urumqi's development as an ecological barrier city.

2. Study area and data

2.1. Overview of the study area

Urumqi (86°37′33″–88°58′24″E, 42°45′32″–44°08′00″N) is located in the hinterland of the Eurasian continent and serves as the capital city of the Xinjiang Uygur Autonomous Region, China, as shown in Figure 1. Due to its inland location, most rivers are inland rivers primarily recharged by snow and ice melt. The climate is temperate continental, with an average annual precipitation of approximately 287 mm. Land use types are classified into nine categories, dominated by bare land and grassland. As a typical oasis city in the arid northwest, it is also the political, economic, cultural, and educational center of Xinjiang. Urumqi administratively consists of 7 districts and 1 county, covering a total area of 13,800 km². By the end of 2023, the city's permanent population reached 4.0848 million, with an urbanization rate of 96.56%. The annual gross domestic product (GDP) was 416.846 billion yuan. As a typical oasis city, Urumqi's ecological security highly depends on the water conservation function provided by glaciers, while simultaneously facing dual pressures of urban expansion and desertification. There is an urgent need to optimize spatial management through the assessment of ecosystem service value.

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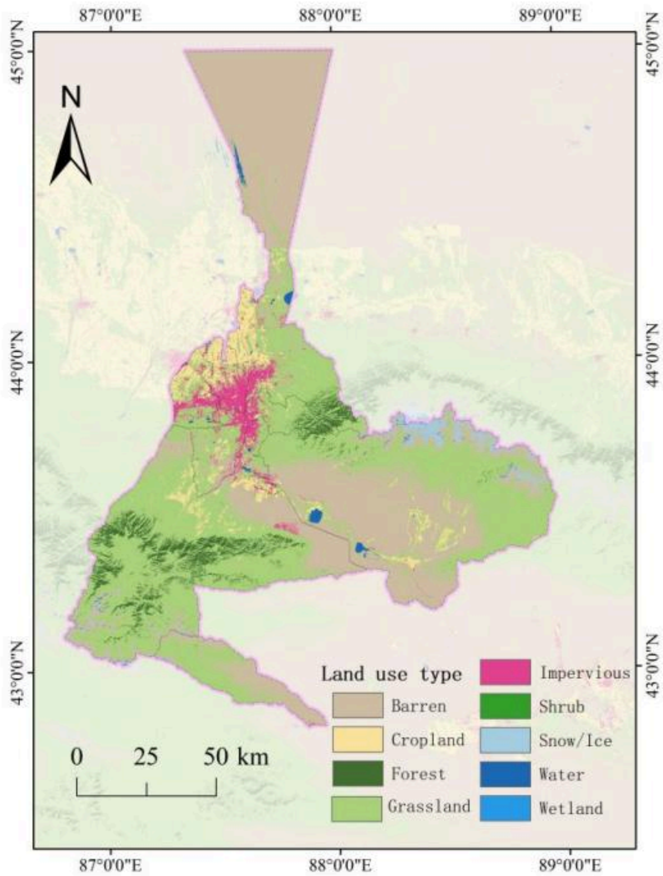

Figure 1. Land use distribution map of Urumqi 2023

2.2. Data sources

The 2023 land use data of Urumqi were obtained from the Zenodo platform (https://zenodo.org) with a spatial resolution of 30 m. Land use types are classified into nine categories: farmland, forest, shrubland, grassland, water bodies, snow/ice, bare land, impervious surface, and wetland. Data on grain yield and cultivated area for the year 2023 were collected from the Xinjiang Statistical Yearbook, while crop price data from 2000 to 2023 were sourced from the National Compilation of Cost and Benefit Data of Agricultural Products. Administrative boundary data were acquired from the Alibaba Cloud platform (https://datav.aliyun.com/portal).

2.3. Research methods

2.3.1. Selection and calculation of ecosystem service value indicators

Ecosystem services are typically categorized into four main types: provisioning services, regulating services, supporting services, and cultural services. This classification provides a classical theoretical framework for systematically constructing an indicator system, which has become a core reference for selecting ecosystem service indicators globally [3]. For regional-scale studies, Xie Gaodi and colleagues optimized the localization of ecosystem service classification in China, identifying ten core service indicators, including food production, climate regulation, and soil

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conservation. This addresses the challenge of applying globally universal indicators to regional contexts in China [16]. Based on the specific conditions of Urumqi, this study integrates these four categories and ten core service indicators to construct a system reflecting the overall level of various ecosystem service functions in the study area.

Since Costanza et al. first estimated the global value of ecosystem services in the late 20th century, multiple valuation paradigms have emerged, with market value-based methods at their core. Among these, the equivalent factor method for calculating ecosystem service value per unit area, developed by Xie Gaodi et al., has become a mainstream approach in China due to its localized adaptability [17-18]. This study uses the equivalent factor table for different terrestrial ecosystems in China, as provided in Table 1 by Xie Gaodi et al., to calculate the ecosystem service value of different land use types in Urumqi in 2023. Specifically, the equivalent factor for Urumqi was calculated to be 1718 yuan/ha, this unit equivalent value coefficient and the formula for calculating the ecosystem service value are as follows:

$$\mathrm{E_a} = \frac{1}{7} \times \frac{(\text{Wheat yield} \times \text{price} \times \text{proportion}) + (\text{Corn yield} \times \text{price} \times \text{proportion})}{\text{Total sown area}} \tag{1}$$

$$\mathrm{ESV} = \sum (\mathrm{A_k} \times \mathrm{VC_k}) \tag{2}$$

Where $\mathrm{E_a}$ is the unit equivalent value coefficient, ESV is the total ecosystem service value, $\mathrm{A_k}$ is the area of land use type k, $\mathrm{VC_k}$ is the value coefficient of ecosystem services for land use type k.

Table 1. Equivalent value of ecosystem services per unit area

Type	Provisioning Services			Regulating Services			Supporting Services			Cultural Services
	Food Production	Raw Material Production	Water Supply	Climate Regulation	Environmental Purification	HydrologicalRegulation	Soil Conservation	Nutrient Cycling	Biodiversity	Aesthetic Landscape
Cropland	1.36	0.09	2.63	0.57	0.17	2.72	0.01	0.19	0.21	0.09
Forest	0.31	0.71	0.37	7.03	1.99	3.51	2.86	0.22	2.6	1.14
Shrub land	0.19	0.43	0.22	4.23	1.28	3.35	1.72	0.13	1.57	0.69
Grassland	0.10	0.14	0.08	1.34	0.44	0.98	0.62	0.05	0.56	0.25
Water body	0.80	0.23	8.29	2.29	5.55	102.24	0.93	0.07	2.55	1.89
Snow/Ice	0	0	2.16	0.54	0.16	7.13	0	0	0.01	0.09
Bare Land	0	0	0	0	0.10	0.03	0.02	0	0.02	0.01
Wetland	0.51	0.50	2.59	3.6	3.60	24.23	2.31	0.18	7.87	4.73

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2.3.2. Spatial zoning method

Spatial autocorrelation is a fundamental statistical method used to quantify the spatial association of ESV, which helps identify spatial clustering or dispersion patterns of ESV, offering a quantitative basis for assessing regional ecological functions and guiding the delineation of ecological management zones [19]. In this study, spatial autocorrelation analysis, including both global and local measures, was employed to explore the spatial distribution of integrated ecosystem service functions in Urumqi. The global Moran’s I statistic was used to assess the overall spatial dependence of ESV at the pixel scale, while local Moran’s I was applied to identify localized spatial clustering patterns, as outlined by previous research [20-22]. These analyses played a crucial role in defining ecological management zones based on the spatial correlation of ecosystem services.

3. Results and analysis

3.1. Ecosystem service value by administrative region

An assessment of the ESV across the eight administrative regions of Urumqi was conducted. As shown in Table 2, the total ESV of Urumqi in 2023 was approximately 10.595 billion yuan. The southern and northern regions exhibited higher ecosystem service values compared to the central area. This spatial disparity is primarily due to the dominance of construction land in the central part of the city, which contributes lower ecosystem service value. As illustrated in Figure 2, high-value areas of ecosystem services are mainly distributed in Urumqi County, Dabancheng District, and Midong District, with ESVs of 4.180 billion yuan, 3.293 billion yuan, and 1.863 billion yuan, respectively. In contrast, Tianshan District recorded the lowest ESV, at approximately 188 million yuan. In terms of ecological function types, Urumqi County, Dabancheng District, and Midong District contributed significantly higher values in hydrological regulation and climate regulation compared to the other five administrative regions, playing a crucial role in maintaining the stability of Urumqi's ecosystem.

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Table 2. Evaluation results of ecosystem service value by functional characteristics (billion yuan)

Administrative area	Provisioning Services			Regulating Services			Supporting Services			Cultural Services	Sum
	Food Production	Raw Material Production	Water Supply	Climate Regulation	Environmental Purification	HydrologicalRegulation	Soil Conservation	Nutrient Cycling	Biodiversity	Aesthetic Landscape	
Tianshan District	0.005	0.002	0.014	0.022	0.012	0.106	0.01	0.001	0.011	0.005	0.188
Saybag District	0.013	0.006	0.022	0.057	0.021	0.072	0.025	0.003	0.024	0.011	0.254
Xinshi District	0.023	0.003	0.046	0.02	0.007	0.074	0.005	0.004	0.008	0.004	0.194
Shuimogou District	0.008	0.009	0.01	0.088	0.027	0.061	0.038	0.003	0.035	0.015	0.293
Toutunhe District	0.026	0.006	0.05	0.049	0.019	0.128	0.019	0.005	0.021	0.01	0.33
Dabancheng District	0.075	0.062	0.21	0.601	0.272	1.39	0.271	0.025	0.262	0.125	3.293
Midong District	0.072	0.034	0.151	0.315	0.158	0.77	0.138	0.017	0.141	0.066	1.863
Urumqi County	0.1	0.122	0.146	1.18	0.385	1.009	0.512	0.044	0.471	0.471	4.18
Sum	0.322	0.244	0.649	2.332	0.901	3.61	1.018	0.102	0.973	0.707	10.595

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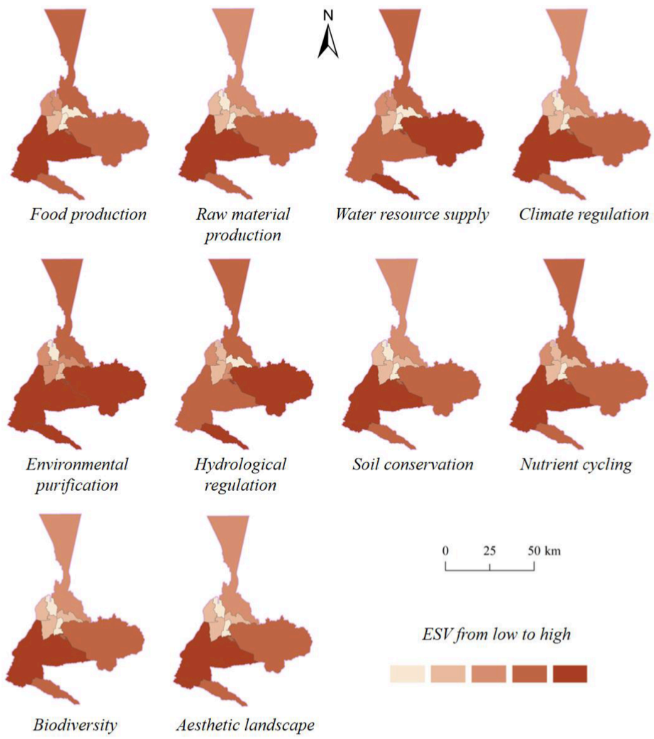

Figure 2. Spatial distribution of ecosystem service values in Urumqi at the district-county scale 2023

3.2. Spatial correlation of ecosystem service value

For the "mountain-oasis-desert" composite ecosystem of Urumqi, the global Moran's I index was used to analyze the distribution pattern of ESV. In 2023, the global Moran's I for the comprehensive ESV of 158,353 land use pixels was 0.142, with a Z-score of 748.580, far exceeding the critical value of 1.96, indicating strong positive spatial autocorrelation across Urumqi.

Local spatial autocorrelation, measured using local Moran's I, identified spatial clustering and dissimilarity. In Figure 3, areas with High-Low outliers were widely distributed across Shuimogou District, Urumqi County, southern Midong District, and Dabancheng District. Low-High outliers were concentrated in northern Midong District, Xinshi District, and the border zone between Dabancheng District and Urumqi County. These patterns reflect factors such as low precipitation, water scarcity, and the expansion of built-up areas, which have converted grassland and cropland into urban zones, creating sharp local value gradients. Non-significant areas covered a small portion of the study area, indicating that the spatial distribution of ESV is characterized by significant autocorrelation rather than randomness.

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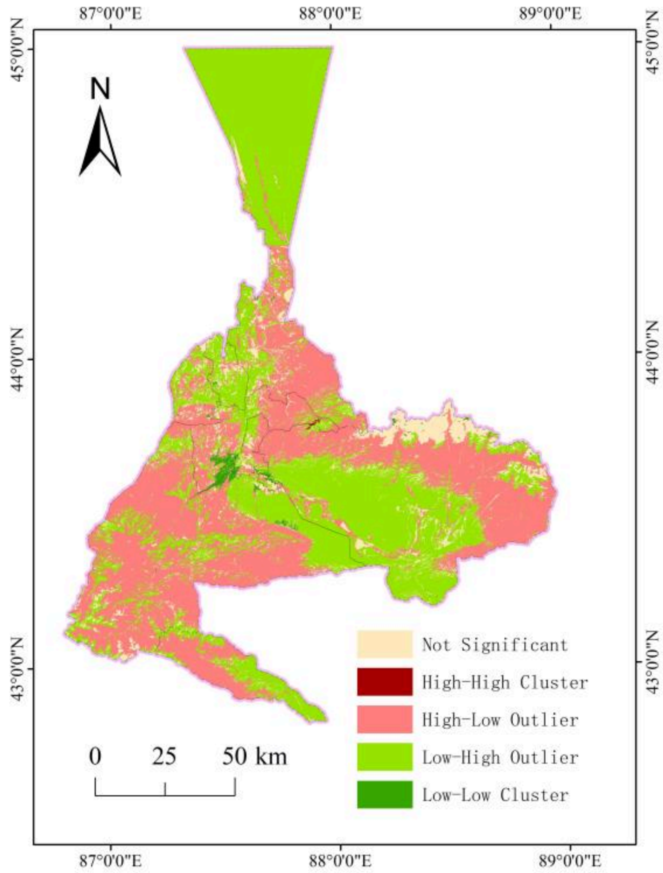

Figure 3. Local spatial autocorrelation distribution of comprehensive ESV

3.3. Urban ecological zoning and management

Based on the ESV assessment and spatial autocorrelation analysis, the study area in Urumqi is divided into four functional zones presented in Figure 4. Differentiated management measures are proposed for each zone to optimize ecosystem services and promote sustainable development [23].

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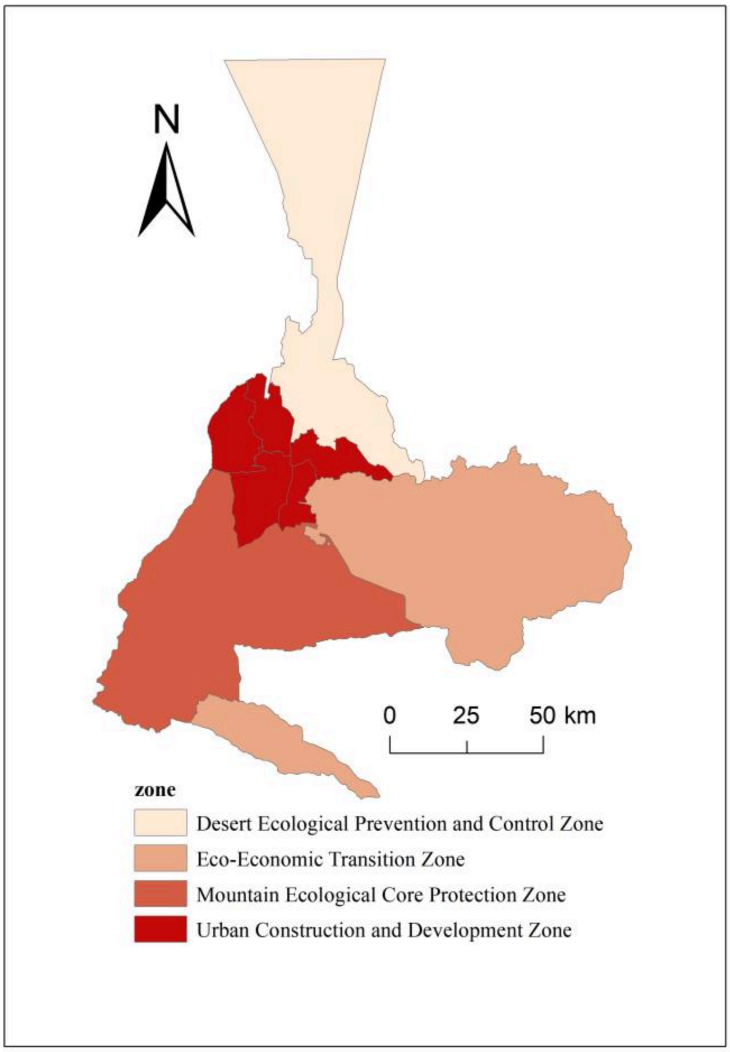

Figure 4. Ecological zoning results for Urumqi derived from ESV assessment

(1) Mountain Ecological Core Protection Zone: This zone includes Urumqi County and surrounding mountains. Non-ecological development is prohibited in the core area. Only low-impact activities, such as eco-tourism and research, are allowed in the control area. Ecological restoration projects should be promoted. A dynamic monitoring network should be set up to support decision-making.

(2) Urban Construction and Development Zone: This zone covers districts like Xinshi and Tianshan. Clear development boundaries are needed to prevent urban sprawl from encroaching on ecological spaces. Green industrial transformation should be encouraged. Ecological corridors should be protected, and urban ecological disturbances should be minimized.

(3) Desert Ecological Prevention and Control Zone: This zone includes Midong District, focusing on desertification control. Overexploitation in vulnerable areas must be restricted. A monitoring and early warning system should be established. Protective measures, such as sand barriers, should be implemented.

(4) Eco-Economic Transition Zone: This zone is located between Tianshan and Dabancheng Districts, with potential for eco-economic development. The focus should be on developing green

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industries like eco-agriculture and eco-tourism. Balancing ecological protection with economic development is key.

4. Conclusions

The ecological zoning pattern in Urumqi results from the long-term interaction between natural environmental factors and human activities. In 2023, the total ESV of Urumqi was approximately 10.595 billion yuan. The spatial distribution of ESV was higher in the south and lower in the center and north, with hydrological regulation and climate regulation as the main contributors. Based on spatial autocorrelation analysis, the study identified four functional zones: ecological core protection, urban development coordination, ecological prevention and control, and eco-economic transition. Specific management strategies were proposed for each zone to enhance ecological functions and promote sustainable urban development. However, the study has limitations. It cannot track temporal variations in ESV and lacks clear quantitative thresholds for management strategies. These gaps highlight the need for future research that incorporates time-series analysis and long-term ecological monitoring.

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