Supply-Demand Relationship and Spatial Optimization of Urban Green Infrastructure Ecosystem Services: A Case Study of Xi’ an City Postprint

Authors: Liu Wei

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Abstract

Maintaining the supply-demand balance of urban ecosystem services is fundamental to building livable cities and improving urban residents’ well-being, while also holding significant importance for regional economic and sustainable development. Taking Xi’ an’ s built-up area as a case study, this research constructs measurement models for ecosystem service demands including food demand, water resources demand, and recreational services, as well as ecosystem service provisions including carbon sequestration and oxygen release, air purification, heat regulation, and noise reduction, based on multi-source data from 2018 including remote sensing data, statistical data, and field surveys. Using analytical tools such as ArcGIS, the spatial matching relationship between supply and demand of urban green infrastructure (UGI) services in the study area is evaluated and analyzed. Finally, the minimum cumulative resistance model is applied to identify ecological source areas and ecological corridors to optimize the UGI spatial pattern of Xi’ an. The results indicate that: (1) UGI in Xi’ an’ s built-up area is unevenly distributed, with high fragmentation and poor connectivity. The total value of ecosystem services provided by UGI is less than the total value of services demanded by residents, showing significant spatial mismatch. (2) Different ecosystem services exhibit varying supply-demand matching conditions. Heat regulation, air purification, and recreational services show supply exceeding demand with better matching status, while food supply, carbon sequestration and oxygen release, water conservation, and noise reduction services show supply falling short of demand, resulting in supply-demand deficits. (3) The supply and demand of ecosystem services in the study area demonstrate significant spatial heterogeneity. With increasing population aggregation, the spatial matching degree of most ecosystem services (such as heat regulation and noise reduction) declines significantly, showing a gradient from severe imbalance in the city center to good matching at the periphery. (4) Ecological source patches in the study area are relatively small, highly fragmented, and have low connectivity, with the UGI network lacking main ecological corridors. By constructing a UGI network consisting of two ecological corridors along the Wei River and the northern foothills of the Qinling Mountains, seven ecological conservation zones along the Feng River, Ju River, Ba River, etc., and green belts along roads, the spatial relationship between ecosystem service supply and demand can be made more coordinated.

Full Text

Supply-Demand Relations of Ecosystem Services of Urban Green Infrastructure and Spatial Optimization: A Case Study of Xi’ an City

LIU Wei, ZHOU Zhongxue, LANG Ruiting

School of Geography and Tourism, Shaanxi Normal University, Xi’ an, Shaanxi, China

Abstract

Urban green infrastructure (UGI) is a critical component of the urban natural ecosystem that provides various ecosystem services for residents. Exploring the spatial dependence of ecosystem service supply-demand relationships is significant not only for revealing the relationship between ecology and economy but also for building a livable environment. However, better quantitative evaluation and spatial mapping of ecosystem service demand, and in particular analysis of the relationship between demand and supply of ecosystem services, are still missing. Taking the built-up area of Xi’ an City in Shaanxi Province as an example, this study developed several evaluation models for the demand of ecosystem services such as high temperature regulation and noise reduction based on remote sensing, population, and environmental monitoring data from 2018. The spatial relationships of supply and demand of different ecosystem services were analyzed on a pixel scale. Furthermore, we propose an optimized landscape pattern for UGI in Xi’ an by identifying ecological sources and ecological corridors based on the minimum cumulative resistance model.

The results show that: (1) UGI in the built-up area of Xi’ an is unevenly distributed, exhibiting a high degree of fragmentation and poor connectivity. The total value of residents’ demand for ecosystem services reaches 224$\times10^{8}$ yuan, whereas the total value of UGI ecosystem service supply is just 28$\times10^{8}$ yuan, presenting a serious mismatch between supply and demand. (2) The degree of spatial matching between supply and demand varies across ecosystem services. The supply of high temperature regulation, air purification, and leisure and entertainment services exceeds residents’ demand, showing good matching status. In contrast, food supply, carbon sequestration and oxygen release, water conservation, and noise reduction services fall short of demand, resulting in serious supply-demand deficits. (3) The matching of supply and demand shows significant spatial heterogeneity. Overall, with increasing population density, the spatial matching degree of most ecosystem services (such as high temperature regulation and noise reduction) decreases significantly, transitioning from severe imbalance in the urban core to good matching at the periphery. (4) Ecological source patches in the study area are small, highly fragmented, and poorly connected, and the UGI network lacks main ecological corridors. We propose constructing a UGI network composed of two ecological corridors (along the Wei River and the northern foothills of the Qinling Mountains), seven ecological conservation areas (including along the Ba River, Ju River, and Ba River), and numerous green belts along roads. This network will coordinate the spatial matching between supply and demand of ecosystem services and optimize the landscape pattern in Xi' an City. This work not only provides an enriched method for ecosystem services demand evaluation but also offers guidance for applying ecosystem service knowledge to ecological management, which will aid the promotion of UGI and sustainable ecosystem development in Xi' an.

Key words: ecosystem services; green infrastructure; supply-demand relation; spatial pattern optimization; Xi' an City

1 Introduction

Urban green infrastructure (UGI) refers to natural or artificial green spaces within and around cities, including not only forests, grasslands, and farms, but also water bodies, reclaimable mines, and native lands that are connected through corridors to form a network space, providing natural landscapes and ecosystem services for urban areas. The concept of green infrastructure was proposed early in natural planning activities in the United States. With the continuous development of theories and methods in ecology, landscape ecology, and landscape planning, scholars have further proposed concepts such as ecological networks and ecological corridors, promoting the development of UGI structure research. In the early 20th century, some European countries promoted the practical application of UGI in urban environmental planning to improve urban biodiversity and other functions. International research on UGI services has focused on cultural services, carbon sequestration services, flood regulation, climate change, and biodiversity protection. In recent years, with China' s increasing emphasis on urban ecological construction, domestic research on UGI has also been extensively conducted, mainly concentrating on UGI identification and optimization, ecological restoration design, and delineation of ecological green belts.

UGI constitutes the main component of urban natural landscapes and ecosystems and is the primary provider of urban ecosystem services, playing a critical "infrastructure role" in urban ecology. However, current research on UGI and its ecosystem services is still relatively lacking, particularly regarding UGI ecosystem service quantification, supply-demand relationships, and spatial pattern optimization, which require further in-depth study.

In the past decade, foreign scholars have conducted substantial research on ecosystem service supply-demand theory and applications. For example, Cotinovis et al. used performance analysis methods to map comprehensive ecosystem service supply-demand values during urban transformation and conducted quantitative spatial analysis. Lorilla et al. performed spatial matching analysis of supply-demand values for food provision, climate regulation, and leisure and entertainment services in the Ionian Islands on Greece' s west coast. Bukvareva et al. proposed assessment methods for air and water purification service supply and demand, analyzing relationships among ecosystem service supply, demand, and consumption. Domestic research on ecosystem service supply and demand is still in its infancy. Xie Gaodi et al. proposed an analytical framework of "ecosystem service production-consumption-valuation" based on econometrics and ecosystem service theory, providing a foundation for ecosystem service consumption theory research. Subsequently, Yan Yan et al. examined the connotations and characteristics of ecosystem service supply, demand, and consumption. Liu Huimin et al. and Xiao Yu et al. analyzed ecosystem service flow carriers, facilitating accurate identification of hotspots for ecosystem service supply and demand. In recent years, scholars have begun studying the spatial relationships of multiple ecosystem services supply and demand across different regions. For instance, Liu Licheng et al. analyzed and evaluated the supply-demand matching status of ecosystem services in Lanzhou City, while Wang Zhuangzhuang et al. assessed the spatiotemporal characteristics of ecosystem service supply-demand risks by mapping water yield service supply and demand in Shaanxi Province. However, current ecosystem service demand quantification still lacks unified evaluation methods, and indicator selection presents difficulties. Characterizing and measuring demands for services such as leisure and entertainment, air purification, carbon sequestration and oxygen release, and biodiversity protection remain challenging, and spatial mapping of ecosystem service supply, especially demand, is still exploratory. Spatially, ecosystem service supply-demand research has primarily focused on large scales such as regions and countries, while studies on supply-demand relationships within urban built-up areas—where ecosystem service demands are highly concentrated and supply-demand contradictions are sharp—need strengthening.

1.1 Study Area

Xi' an City is located in the central Guanzhong Plain, mainly comprising various landforms including the Qinling Mountains, Wei River Plain, and Loess Tableland. The terrain slopes from southwest to northeast with significant elevation differences, and the area features a temperate semi-humid continental climate with distinct seasons. In recent decades, with the implementation of the Western Development Strategy, the Belt and Road Initiative, and the Guanzhong-Tianshui Economic Zone Plan, Xi' an's urbanization has accelerated continuously, with large-scale population agglomeration and rapid urban land expansion. In 2018, the city' s permanent population reached 10.2035 million, and the built-up area reached 729.14 km^2, with a per capita green space area of 9.98 m^2, lower than the national average of 14.1 m^2. Spatially, green space is scarce in the central and old urban areas but relatively abundant in suburban areas, which does not match the spatial distribution patterns of population and economy. Green infrastructure is an important natural factor in urban spatial structure that influences ecosystem service functions and affects urban residents' quality of life and health. Therefore, exploring the supply-demand value of UGI ecosystem services and their spatial relationships and optimizing the UGI spatial pattern in Xi' an are of great practical significance for addressing urban ecological environmental problems, building Xi' an into a more livable city with greater happiness.

The study area is the built-up area of Xi' an City, with specific boundaries comprehensively determined based on construction land scope, the Xi' an City Master Plan (2008-2020), and the Xi' an Urban Green Space System Plan.

1.2 Data Sources and Processing

The study area data were obtained through visual interpretation of 2018 Xi' an "Gaofen-1" imagery using ArcGIS 10.2 software, with corrections made based on field surveys and recent land use change conditions in Xi' an. Temperature data were obtained from Landsat 8 OLI data through atmospheric correction module for land surface temperature retrieval. Social and economic data were derived from the Xi' an Statistical Yearbook (2019), food crop prices from the China Rural Statistical Yearbook, and population data from the sixth national census. Population density was spatialized using the method based on residential point density from Yan Qingwu et al.

This study addresses prominent urban ecological problems in Xi' an' s rapid development process, including insufficient natural landscapes, significant heat island effects, water resource shortages, high carbon emissions, and severe pollution. Seven typical ecosystem services were selected: food production, carbon sequestration and oxygen release, water conservation, air purification, high temperature regulation, noise reduction, and leisure and entertainment. Supply and demand calculation models were constructed to measure service values and analyze supply-demand relationships based on 30 m × 30 m grid cells. Building on this, a minimum cumulative resistance model was used to identify ecological sources and corridors in the area, proposing UGI pattern optimization schemes. This is of great significance for achieving effective allocation of land resources, building a livable environment, constructing urban ecological security patterns, and promoting urban ecological civilization in Xi' an.

2 Methods

2.1 Ecosystem Service Supply Calculation

2.1.1 High Temperature Regulation Service Urban heat island effects form due to dense high heat-capacity buildings and roads, waste heat emissions, and poor heat diffusion. Green vegetation and water bodies can lower surrounding temperatures through shading and evapotranspiration, providing high temperature regulation services. The supply of high temperature regulation services can be measured by the difference between near-surface atmospheric temperature covered by UGI and maximum temperature, combined with the value of energy consumption for air conditioning cooling in summer. The calculation formula is:

$$S_i = (T_{max} - T_i) \times C \times S$$

where S_i represents the supply value of high temperature regulation service on grid cell i (yuan); T_{max} is the maximum near-surface temperature in the study area during summer (°C) (obtained from remote sensing data); T_i is the near-surface atmospheric temperature on grid cell i (°C) (retrieved through land surface temperature inversion from remote sensing data); C is the cost of artificial cooling per unit space (yuan $\cdot$ m^{-2}) (referencing Li Mengtao et al.); and S is the area of a single grid cell (m^2).

2.1.2 Calculation of Other Ecosystem Services Other ecosystem services in this study mainly include food production, water conservation, carbon sequestration and oxygen release, air purification, noise reduction, and leisure and entertainment services. Their supply was calculated based on existing research results.

2.2 Ecosystem Service Demand Calculation

2.2.1 Food Demand Calculation Urban residents' food consumption constitutes food demand. This study used per capita food demand to estimate food demand services. The assessment was monetized based on main food prices and then spatialized using a population density map. The calculation formula is:

$$F_i = W_{pop} \times P \times a$$

where F_i represents the food demand service value on grid cell i (yuan); W_{pop} is population density (people $\cdot$ $grid^{-1}$); P is per capita food demand (kg $\cdot$ $person^{-1}$); and a is the average price of main food crops (yuan $\cdot$ kg^{-1}).

2.2.2 Water Resources Demand Calculation This study used the total amount of domestic water, living water, and ecological water for urban residents as water resources demand. The demand was monetized using reservoir construction costs and spatialized using a population density map. The calculation formula is:

$$W_i = W_{pop} \times M \times C$$

where W_i represents the water resources demand value on grid cell i (yuan); M is per capita water consumption ($m^3 \cdot person^{-1}$); W_{pop} is population density ($people \cdot grid^{-1}$); and C is the average construction cost per unit of reservoirs in China, taken as 6.3655 $yuan \cdot m^{-3}$.

2.2.3 Carbon Sequestration and Oxygen Release Service Demand Calculation Residents' consumption of fossil fuels and oxygen and emission of CO_2 during production and life exacerbate climate warming, creating demand for carbon sequestration. This study used urban residents' per capita annual CO_2 emissions and corresponding oxygen consumption as the demand for carbon sequestration and oxygen release services. According to the law of mass conservation, producing 44 kg of CO_2 simultaneously consumes 32 kg of O_2. Valuation was based on the carbon tax method and oxygen production price. The calculation formula is:

$$C_i = W_{pop} \times (R \times P_c + R \times \frac{32}{44} \times P_o) \times S$$

where C_i represents the carbon sequestration and oxygen release demand value on grid cell i (yuan); W_{pop} is population density ($people \cdot grid^{-1}$); R is per capita annual CO_2 emissions for urban residents, taken as 2.13 $t \cdot a^{-1}$; P_c is the value for fixing unit mass of CO_2, referencing the Swedish carbon tax at 1.137 $yuan \cdot kg^{-1}$; and P_o is the average oxygen price published on the Ministry of Health website, taken as 1.2 $yuan \cdot kg^{-1}$.

2.2.4 Air Purification Service Demand Calculation Fossil fuel use and vehicle exhaust emissions in urban areas cause air pollution and declining air quality, creating residents' demand for clean air and environment. This study measured air purification service demand by the gap between actual air quality conditions and clean air conditions, assuming the cost of purifying pollutants in the air to achieve clean air status as the demand value. The assessment was based on purification treatment costs of main pollutants (such as $PM_{2\cdot5}$) and spatially mapped considering residents' living space distribution and population density. The calculation formula is:

$$P_i = \sum_j Q_{ij} \times P_j \times S \times H$$

where P_i is the annual air purification demand value on grid cell i (yuan); S is the area of a single grid cell (m^2); H is height, taken as the height of an ordinary

6-story residential building (18 m); Q_{ij} is the concentration of pollutant j on grid cell i ($g \cdot m^{-3}$); and P_j is the treatment cost of pollutant j (where $PM_{2 \cdot 5}$ treatment cost is 6.3655 yuan $\cdot$ kg^{-1} and PM_{10} treatment cost is 1.137 yuan $\cdot$ kg^{-1}).

2.2.5 Leisure and Entertainment Service Demand Calculation The fast-paced work and life in cities create residents' spiritual demand for leisure activities such as fitness, sports, and recreation in natural environments like parks, green spaces, or lakesides to release pressure and improve mood. Since urban residents' leisure and entertainment are closely associated with green space, referencing Larondelle et al., this study used per capita green space area as a proxy indicator for residents' demand for leisure and entertainment services. Assuming that reaching the national urban per capita green space level can satisfy residents' basic leisure and entertainment needs in daily work and life, the study used the product of national urban per capita green space area and population quantity to evaluate leisure and entertainment service demand, monetized by the average value of leisure and entertainment services provided per unit green space area. The calculation formula is:

$$E_i = W_{pop} \times C_{green} \times C_{value}$$

where E_i represents the leisure and entertainment demand value on grid cell i (yuan); C_{value} is the average value of leisure and entertainment services provided per unit green space area (yuan $\cdot$ m^{-2} $\cdot$ person^{-1}); W_{pop} is population density (people $\cdot$ grid^{-1}); and C_{green} is the national urban per capita green space area, taken as 14.1 m^2 $\cdot$ person^{-1} from the 2018 China Statistical Yearbook.

2.2.6 Noise Reduction Demand Calculation Urban residents are affected by various noises such as traffic and construction in daily life. When noise exceeds certain limits, it seriously interferes with normal work and life and even harms physical health, creating demand for noise pollution reduction. This study used the difference between actual noise monitoring data and national standard noise limits (decibels) as the demand for noise reduction services, with valuation based on noise reduction costs. The calculation formula is:

$$V_i = (W_i - R_i) \times P \times S$$

where V_i represents the noise reduction demand value on grid cell i (yuan); W_i is the measured noise decibel level on grid cell i [dB(A)]; R_i is the national standard noise limit on grid cell i [dB(A)]; P is the noise reduction cost, taken as 1.137 yuan $\cdot$ dB(A)$^{-1}$; and S is the area of a single grid cell (m^2).

2.2.7 High Temperature Regulation Service Demand Calculation During hot summer and autumn seasons, people need to use air conditioning and fans for cooling, creating demand for high temperature regulation services. This study measured high temperature regulation service demand by the difference between the lower limit temperature at which people typically turn on air conditioning for cooling and the actual near-surface atmospheric temperature, monetized by the cost of artificial cooling per unit space. The calculation formula is:

$$T_i = (T_i - T_{threshold}) \times C \times S$$

where T_i represents the high temperature regulation demand value on grid cell i (yuan); T_i is the near-surface atmospheric temperature on grid cell i (°C); $T_{threshold}$ is the lower limit temperature at which people typically turn on air conditioning for cooling, taken as 26°C; C is the cost of artificial cooling per unit space; and S is the area of a single grid cell (m^2).

2.3 Ecosystem Service Supply-Demand Relationship

This study used the difference between actual ecosystem service supply value and local residents' demand value to express the supply-demand relationship of ecosystem services. To eliminate dimensional differences among different service values, supply and demand values for each service were first normalized before analyzing the ecosystem service supply-demand difference (ES_i) to evaluate the matching degree. The calculation formula is:

$$ES_i = \frac{S_i - D_i}{S_i + D_i}$$

where ES_i represents the matching degree between supply and demand of ecosystem service i; S_i is the supply value of ecosystem service function i; and D_i is residents' demand value for ecosystem service i. When $ES_i > 0$, it indicates that the service supply is in surplus (supply exceeds demand); when $ES_i < 0$, it indicates an ecosystem service deficit (supply falls short of demand). Based on ES_i values, ecosystem service supply-demand matching is classified into five levels (Table 1).

Table 1 Classification of ESi indicators

ESi Value Range	Supply-Demand Matching Degree
-1.0 ~ -0.5	Severe imbalance
-0.5 ~ 0	Mild imbalance
0 ~ 0.2	Basic balance
0.2 ~ 1.0	Good matching

2.4 Ecological Resistance Surface Construction

Ecosystem service flows are hindered by natural and socio-economic factors during movement. This study selected landscape type, normalized difference vegetation index (NDVI), terrain, slope, and population density as resistance surface components. Different weights were assigned to different resistance surface components using the expert scoring method (Table 2) to generate a comprehensive resistance surface.

Table 2 Components and weights of resistance surface

Factor Category	Component	Weight
Natural factors	NDVI	0.25
	Terrain	0.15
	Slope	0.10
Socio-economic factors	Population density	0.30
	Landscape type	0.20

3 Results

3.1 Analysis of Overall Supply and Demand Characteristics of Ecosystem Services

The total area of UGI in the study area is 34,431.5 hm^2, accounting for 75.0% of the total study area. Grassland has the largest area (31.9%), while water bodies have the smallest (only 4.8%). UGI is mainly distributed along both sides of residential areas and roads, with small patches clustering together. Large and medium patches are concentrated in urban parks and at the edges of the built-up area, such as the Chan-Ba National Wetland Park in the northeast, along the Wei, Chan, and Ba Rivers, where patches are larger, more connected, and richer in variety.

The ecosystem service supply and demand value assessment results show that the total ecosystem service supply value is approximately 28$×10^{8}$ yuan, with significant differences among different ecosystem services. The supply value of high temperature regulation services is prominent, accounting for about 45% of the total value, while water conservation service value accounts for the smallest proportion at about 3%. The results indicate that ecosystem service supply value in the study area is influenced by UGI distribution patterns, showing a gradual increase from the central urban area to the periphery. In the urban center, where urbanization level is high and building density is large with scarce green space landscapes (such as Lianhu District where UGI accounts for only 14.5% of the district' s total area), ecosystem service supply value is low. In contrast, Baqiao District in the east has lower population density and abundant green space landscapes, including natural water bodies such as the Ba River, Jingyu Gully, and Chan-Ba National Wetland Park. The ecological corridors along rivers are well protected with high landscape connectivity, forming large UGI patches that provide high-value water conservation, carbon sequestration, and oxygen release services.

The total value of ecosystem services demanded by urban residents in Xi' an' s built-up area is 224$×10^{8}$ yuan, which differs greatly from the supply value and shows a spatial pattern of gradual decrease from the center to the periphery. The highest demand value is in Yanta District, accounting for 24.3% of total demand value, while the lowest is in Baqiao District, accounting for only 9.8%. Yanta District, with a total area of 14,910 hm^2, contains two national-level economic development zones (Xi' an High-tech Industrial Development Zone and Qujiang New District), serving as the center of economy, commerce, scientific research, and residential areas in Xi' an with a population exceeding 1.25 million and high population density, resulting in high ecosystem service demand. Baqiao District has relatively less construction land and lower population density, leading to obviously lower ecosystem service demand.

The spatial matching degree of ecosystem service supply and demand values in Xi' an shows obvious spatial mismatch in the built-up area, indicating that UGI distribution is spatially misaligned with urban population and economic development. Overall, the area with good supply-demand matching is small, only sporadically distributed at the edge of the study area, such as the southwest of Chang' an District, southeast of Baqiao District, and along the Wei River. These suburban areas have good vegetation coverage, abundant water sources, and fewer population and commercial activities, resulting in high ecosystem service supply and low demand, thus showing a good situation of supply exceeding demand. In the urban central area, UGI is lacking, ecosystem service supply is low, while population and building land are highly concentrated with large-scale economic activities, creating high ecosystem service demand. Except for leisure and entertainment services which have relatively good spatial matching, other services show low matching degrees and severe imbalance. Many large heritage parks in Xi' an' s urban area, such as Daming Palace Heritage Park, Tang Paradise, and Qujiang Pool, have large forest and water landscapes that not only provide high leisure and entertainment services but also significantly increase total ecosystem service supply, making the supply-demand spatial matching more balanced.

3.2 Spatial Relationship Analysis of Individual Ecosystem Service Supply and Demand

Ecosystem service demand is closely related to population density and economic development level. This study divided the study area into four zones based on population density: high agglomeration area (1.8$×10^{{4}−2.4×10}${4}$ people·km^{-2}), medium-high agglomeration area (1.0$×10^{{4}−1.8×10}${4}$ people·km^{-2}), medium agglomeration area (0.3$×10^{{4}−1.0×10}${4}$ people·km^{-2}), and low agglomeration area (<0.3$×10^{4}$ people·km^{-2}). Bivariate correlation analysis of ecosystem service supply and demand values was conducted using ArcGIS to reveal the influence of population and economic agglomeration on ecosystem service supply-demand relationships (Table 3).

Table 3 Correlation coefficients of supply and demand of ecosystem services in different population concentration areas

Population Zone	High Temperature Regulation	Air Purification	Noise Reduction	Carbon Sequestration & Oxygen Release	Water Conservation	Food Supply	Leisure & Entertainment
Low agglomeration	-0.52**	-0.41**	-0.38**	-0.45**	-0.31*	-0.22	0.15
Medium agglomeration	-0.48**	-0.39**	-0.35**	-0.42**	-0.28*	-0.25	0.12
Medium–high agglomeration	-0.55**	-0.43**	-0.41**	-0.48**	-0.33*	-0.24	0.18
High agglomeration	-0.63**	-0.51**	-0.58**	-0.52**	-0.36*	-0.21	0.16

Note: * indicates significance at the 0.05 level; ** indicates significance at the 0.01 level.

In high agglomeration areas, the correlation coefficients for high temperature regulation (-0.63) and noise reduction (-0.58) services both passed significance tests, showing significant negative spatial correlation, consistent with supply-demand matching calculations. These areas are mainly commercial and residential zones with frequent economic activities and concentrated building land, creating high ecosystem service demand. However, UGI is scarce, leading to serious supply shortages and large areas of supply-demand imbalance. Many large heritage parks in Xi' an' s urban area, such as Daming Palace Heritage Park, Tang Paradise, and Qujiang Pool, have large forest and water landscapes that not only provide high leisure and entertainment services but also significantly increase total ecosystem service supply, making supply-demand spatial matching more balanced.

In medium-high agglomeration areas concentrated in Yanta and Lianhu districts (main residential, commercial, and cultural-educational zones), the proportion of mild imbalance area is relatively large, followed by severe imbalance. However, overall, the proportion of supply surplus areas is greater than in high agglomeration areas. The supply surplus areas for carbon sequestration and oxygen release, high temperature regulation, air purification, and noise reduction services all exceed 60%, with carbon sequestration and oxygen release having the highest proportion of good matching areas (25.3%), distributed near Daming Palace Heritage Park. Covering about 3.2 km^2 with abundant grassland and forest, Daming Palace Heritage Park provides high ecosystem service value and serves as an important ecological source in this area.

In medium agglomeration areas mainly distributed in the southern Weiyang District (a major industrial comprehensive zone), total supply and demand services show significant negative correlation (-0.48), with relatively prominent spatial mismatch. All services show mild imbalance as the main pattern. The absolute value of the correlation coefficient for noise reduction service is smaller than in high, medium-high, and low agglomeration areas, indicating slightly better spatial matching status. The supply surplus areas for carbon sequestration and oxygen release, high temperature regulation, air purification, and noise reduction services all exceed 50%, with carbon sequestration and oxygen release having the highest proportion of good matching areas (18.7%).

Low agglomeration areas occupy a large proportion of the study area, mainly distributed in the north, southwest, and southeast, serving as major ecological tourism and science-education comprehensive zones. In these areas, most service supply and demand show negative correlation, with high temperature regulation having the largest absolute correlation coefficient, indicating relatively significant spatial mismatch. However, all services have supply surplus areas with proportions higher than in high, medium-high, and medium agglomeration areas. Although this zone contains many universities and research institutions (such as the National Civil Aerospace Base and Chang' an University Town) with high ecosystem service demand, it also has extensive park and water areas (such as Chan-Ba Wetland Park) and rich natural vegetation along the Wei and Ba Rivers, providing strong ecosystem service supply. Therefore, ecosystem service supply-demand is basically coordinated in this zone.

Overall, the correlation coefficient between total ecosystem service supply and demand in the study area is -0.52, passing the significance test, indicating obvious negative spatial correlation (spatial mismatch). Most ecosystem service correlation coefficients are negative and pass significance tests, showing that areas with high demand values have low supply values, with significant spatial misalignment between supply and demand services, consistent with the overall spatial distribution pattern of ecosystem service supply and demand (Figure

3). The correlation coefficient between supply and demand values for leisure and entertainment services is positive, indicating no spatial misalignment. This is because both supply and demand for this service are related to population density and economic development level, but the supply value is far lower than the demand value, still showing supply-demand imbalance. With increasing urban population agglomeration, the supply-demand matching degree of some ecosystem services significantly decreases (Figure 5). For example, for high temperature regulation and noise reduction services, as population density increases, the proportion of mild imbalance areas continuously increases while the proportion of balanced areas decreases. For carbon sequestration and oxygen release, air purification, and water conservation services, as population density increases, the proportion of severe imbalance areas continuously increases, indicating that larger urban scale and greater population and economic agglomeration place more severe pressure on UGI, leading to more significant ecosystem service supply-demand imbalance.

3.3 Identification of Ecological Sources and Corridors

3.3.1 Identification of Ecological Sources Based on Spatial Distribution of Ecosystem Service Value Ecological sources are ecological lands of major significance for maintaining regional ecological stability and security, with high ecosystem service value and connectivity, mainly concentrated around large areas of forest land and water bodies. This study used patches with high ecosystem service value as candidate ecological sources, applied hotspot analysis tools to analyze spatial agglomeration degree of each patch, and classified them according to their agglomeration degree. Patches with area greater than 10 hm^2, high ecosystem service value, and hotspot spatial agglomeration were selected as ecological sources.

The hotspot analysis of ecosystem service value in the study area (Figure 6) reveals the spatial agglomeration degree of ecosystem service supply value, identifying ecological sources covering 5,832.58 hm^2, accounting for 12.7% of the total study area, mainly comprising cultivated land and forest land. These are mainly distributed at the edge of the study area and in urban parks, such as southeast Baqiao District, southwest Chang' an District, and along the Wei River. Daming Palace Heritage Park and Han City Wall Heritage Park have concentrated UGI distribution and can provide high leisure and entertainment service value, forming hotspot areas and becoming main ecological sources in the urban area. In contrast, the urban center has mostly construction land with small, fragmented, scattered UGI patches, poor ecosystem service supply, forming cold spots.

Ecological sources show banded distribution, concentrated along the northern Wei River coast and southern Qinling Mountains foothills, with uneven spatial distribution. Ecological corridor density and connectivity are low, lacking main ecological corridors. By constructing a network composed of two ecological corridors along the Wei River and Qinling Mountains foothills, seven ecological conservation areas along the Feng River, Ju River, Ba River, etc., and numerous green belts along roads, the spatial pattern can be optimized.

3.3.2 Identification of Ecological Corridors Based on Minimum Cumulative Resistance Model Different natural and human factors create resistance to species migration, diffusion, and energy flow. This study comprehensively considered terrain, slope, NDVI, landscape type, and population density to construct a comprehensive ecological resistance surface describing resistance magnitude for species or energy flow movement. Ecological corridors are strip-shaped areas connecting ecological sources for species, information, and energy flow with certain width, playing important roles in maintaining ecosystem connectivity and stability. Using the minimum cumulative resistance model based on the ecological resistance surface, minimum cumulative resistance paths were identified and combined with actual UGI distribution to identify ecological corridors and sources (Figure 7). A total of 45 ecological corridors were identified, with total length of 405 km, roughly covering the entire study area but showing obvious spatial differences.

Ecological sources overall show a pattern of scarcity in central urban areas and abundance in new development zones. For example, Xincheng District and Yanta District lack ecological sources, while Chang' an District contains many universities and research institutions whose campus green spaces constitute main ecological sources. The 滨河 park along the Wei River in the north has become the main ecological source in Weiyang District. Western ecological sources are dominated by cultivated land. In urban central areas, UGI mainly consists of street-side green spaces, community parks, and attached green spaces, but patch areas are too small to form ecological sources. Overall, ecological sources are mainly distributed along the Wei River, Ba River, and northern foothills of Qinling Mountains, while central urban areas lack main ecological corridors and have poor connectivity.

3.3.3 UGI Spatial Pattern Optimization Analysis Based on the analysis of spatial relationships between ecosystem service supply and demand in the study area, the existing ecological sources and corridors were identified to optimize the UGI pattern (Figure 8). First, ecological conservation areas were constructed based on existing ecological sources. These are high ecosystem service supply areas focused on protection and construction, reducing patch isolation and fragmentation to enhance disturbance resistance. Large ecological wetland park conservation areas were built along the Wei River and Ba River; riverside green landscape belts were created along the Feng River and combined with agricultural land (cultivated land) in Doumen and Xiliu streets to build Feng River ecological conservation areas; ecological green belts were constructed along the Ju River and combined with Xi' an City Ecological Park and large campus green spaces in Guodu University Town to form clustered ecological conservation areas. Ecological conservation areas for park green spaces were formed around Big Wild Goose Pagoda, Tang Paradise, Qujiang Pool, Xi' an Botanical

Research Institute, and Duling Heritage Ecological Park. In Baqiao District, 白鹿原 and Cherry Valley were used to build ecological tourism conservation areas.

Second, two major north-south ecological corridors were constructed. Referencing the dominant wind direction (northeast wind), two east-west green landscape corridor axes were created along the Wei River coast and Qinling Mountains foothills to connect north-south ecological conservation areas. One corridor is the Jingwei Forest Belt along the Wei River, connecting landscape nodes and ecological conservation areas from west to east, including Chan-Ba Wetland Park, Wei River City Sports Park, and Feng-Wei Ecological Landscape Area. The other is the Qinling Mountains foothills ecological tourism belt based on the southern Qinling Mountains natural protection area to protect important natural resources like forests. These two axes help connect ecological conservation areas and promote ecological, energy, and species flows.

The urban central area is a region with high population density, dense construction land, and severe ecosystem service supply-demand imbalance. Wide ecological green rings can be constructed along the 环城 park and Third Ring Road green belts to provide ecological transition zones and strengthen internal-external connectivity. Meanwhile, road green belts can be built along main urban roads such as Taihua Road-Qujiang Road, Lianhu Road-Changle Road, Weiyang Road-Chang' an Road, Kunming Road-Xianning Road, Zhangba West Road-Yannan Fourth Road, and Hancheng Road-Zhangba North Road-Zhangba Third Road. Combined with heritage protection green belts and urban street parks, small ecological corridors can be built within the city to introduce important green resources from fringe areas into the urban center, strengthening internal-external ecological flows and species movement.

Specific measures for spatial pattern optimization include: (1) Protecting and enhancing quality of existing large UGI patches. Large municipal parks such as Weiyang Lake Amusement Park, Tang Paradise, and Qujiang Pool Heritage Park should be expanded and protected, with new street parks and road greening built around large UGI patches to increase ecological nodes and enhance radiation range. (2) Adding new green spaces. Existing ecological sources are more abundant in the south and north but scarce in the east and west, so urban greening projects should increase UGI in east-west directions and build ecological conservation areas. (3) Strengthening ecological corridor construction to enhance connectivity between ecological sources. First, existing parks should implement "wall removal for green exposure" by demolishing walls to increase green space and integrate with streets. Second, rely on UGI within main urban areas and major external traffic arteries to build ecological corridors, forming a urban green skeleton. (4) Planning and cultivating characteristic landscape nodes. For example, Chan-Ba Wetland Park, with water ecosystems as its base, should focus on protecting water quality in the Ba River basin, reducing hard boundary frequency in the park to decrease ecological resistance and facilitate biological flow and biodiversity protection. Daming Palace Heritage Park, Qujiang Heritage Park, and Tang Paradise should increase landscape heterogeneity combined with historical relic protection to maintain urban ecosystem stability. Ultimately, an optimized UGI pattern can be formed comprising two east-west ecological corridors, multi-regional ecological conservation areas, and multiple ecological corridors based on urban road green belts as the matrix.

4 Discussion

Currently, quantitative evaluation of ecosystem service supply and trade-off relationship analysis are relatively mature in domestic and international research, but quantitative measurement, mapping, and supply-demand relationship studies of ecosystem service demand remain challenging. This study selected seven typical ecosystem services based on the basic characteristics of UGI in Xi' an, especially exploring and constructing demand evaluation models for services such as high temperature regulation and noise reduction. The demand status of UGI ecosystem services was evaluated and mapped at the pixel scale. The results show that these evaluation models can objectively describe urban ecosystem service demand and its spatial heterogeneity, contributing to current quantitative evaluation methods and mapping research on ecosystem service demand and enriching research methods for ecosystem service supply and demand.

As an important national central city in western China, Xi' an has experienced accelerating urbanization in recent years, with large-scale population and economic agglomeration placing great pressure on urban ecosystems. Therefore, future construction of landscape-beautiful and ecologically livable urban environments is particularly urgent. This study analyzed the spatial matching degree between UGI ecosystem services and human demand from a new perspective of supply-demand relationships, comprehensively considered natural and human factors affecting species migration and ecological flows, analyzed UGI patterns, ecosystem service supply-demand matching relationships, and existing problems through a comprehensive ecological resistance surface model, and proposed construction and optimization schemes based on the current status of Xi' an' s urban green space system planning. The results show that increasing population and economic agglomeration in urban built-up areas places severe pressure on the balance of UGI ecosystem service supply and demand. This research approach can integrate current knowledge from urban geography, landscape ecology, and ecosystem services research into ecosystem planning, management, and decision-making, particularly in applying ecosystem service research results to practice, which has certain reference significance for ecological management and helps promote UGI enhancement and sustainable ecosystem development in Xi' an.

Ecosystem service demand is closely related to population distribution and urban residents' preferences. This study used street-level population density data to spatialize the supply and demand of major ecosystem services, which has certain limitations. The survey of individual preferences among urban residents was insufficient, which may affect the evaluation results of leisure and entertainment service demand to some extent. Meanwhile, due to difficulties in obtaining some data (such as limited meteorological and noise monitoring stations), the spatial expression of ecosystem service demand is not sufficiently detailed, though this does not affect the overall spatial pattern and trends of noise reduction service demand. Ecosystem service supply and demand are influenced by ecosystem structure, function, biogeochemical processes, regional population and economic development, scientific and technological progress, and many other aspects, making them complex and dynamic. Further research is needed to explore the mechanisms of ecosystem service generation, demand, and flow, and to construct measurement indicators and methods for ecosystem service supply, especially demand, to advance ecosystem service supply-demand research.

5 Conclusions

(1) UGI distribution in Xi' an' s built-up area is concentrated at urban edges and along main roads, with uneven distribution, high fragmentation, and poor central urban connectivity. The total ecosystem service supply value is 28×10^{8} yuan, showing a decreasing trend from southwest and northeast toward the center. Residents' total ecosystem service demand value is 224×10^{8} yuan, which differs greatly from the supply value and shows a spatial pattern transitioning from severe imbalance in the urban center to good matching at the edges.

(2) Different ecosystem services show varying supply-demand matching status. High temperature regulation, air purification, and leisure and entertainment services have supply exceeding demand with good matching status, indicating that urban green belts significantly enhance regional ecosystem services. Food supply, carbon sequestration and oxygen release, water conservation, and noise reduction services have supply falling short of demand, indicating insufficient UGI construction to meet urban residents' demands for some ecosystem services.

(3) Ecosystem service supply and demand show significant spatial heterogeneity, with population and economic agglomeration having significant impacts on spatial matching. With increasing population agglomeration, the spatial matching degree of most ecosystem services (such as high temperature regulation and noise reduction) decreases significantly, showing a negative correlation of high demand and low supply. This indicates that densely populated urban central areas have serious ecosystem service supply-demand deficits dominated by spatial mismatch of low supply and high demand, while urban fringe areas show supply surplus characteristics with good matching of high supply and low demand.

(4) Ecological sources in the study area show banded distribution, concentrated along the northern Wei River coast and southern Qinling Mountains foothills with uneven spatial distribution. Ecological corridor density and connectivity are low, lacking main ecological corridors. Constructing a UGI network composed of two ecological corridors along the Wei River

and Qinling Mountains foothills, seven ecological conservation areas along the Feng River, Ju River, Ba River, etc., and numerous green belts along roads can achieve spatial pattern optimization.

References

[1] Wu Wei, Fu Xie. The concept of green infrastructure and review of its research development[J]. Urban Planning International, 2009, 24(5): 67-71.

[2] Fábos J G. Greenway planning in the United States: Its origins and recent case studies[J]. Landscape and Urban Planning, 2004, 68(2-3): 321-342.

[3] Benedict M, Macmahon E T. Green infrastructure: Smart conservation for the 21st century[J]. Renewable Resources Journal, 2002, 20(3): 12-17.

[4] Weber T, Sloan A, Wolf J. Maryland' s green infrastructure assessment: Development of a comprehensive approach to land conservation[J]. Landscape & Urban Planning, 2006, 77(1-2): 94-110.

[5] Hanski I, Gilpin M. Metapopulation dynamics: Brief history and conceptual domain[J]. Biological Journal of the Linnean Society, 1991, 42(1): 3-16.

[6] Snäll T, Lehtomäki J, Arponrn A, et al. Green infrastructure design based on spatial conservation prioritization and modeling of biodiversity features and ecosystem services[J]. Environmental Management, 2016, 57(2): 251-256.

[7] Terkenli T S, Bell S, Toškovi O, et al. Tourist perceptions and uses of urban green infrastructure: An exploratory cross cultural investigation[J]. Urban Forestry & Urban Greening, 2020, 49: 126624, doi: 10.1016/j.ufug.2020.126624.

[8] Chen W Y. The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: A nationwide estimate[J]. Cities, 2015, 44: 112-120.

[9] Li L, Collins A M, Cheshmehzangi A, et al. Identifying enablers and barriers to the implementation of the green infrastructure for urban flood management: A comparative analysis of the UK and China[J]. Urban Forestry & Urban Greening, 2020, 54: 126770, doi: 10.1016/j.ufug.2020.126770.

[10] Candela de la Sota Sández, Ruffato Ferreira V, Ruiz Garcia L, et al. Urban green infrastructure as a strategy of climate change mitigation: A case study in northern Spain[J]. Urban Forestry & Urban Greening, 2019, 40: 145-151.

[11] Nakamura F, Ishiyama N, Yamanaka S, et al. Adaptation to climate change and conservation of biodiversity using green infrastructure[J]. River Research and Applications, 2020, 36(6): 921-933.

[12] Li Wenjun, Li Junfeng. Identification and optimization of small and medium sized green infrastructure based on GIS: A case study of Nanxi wetland ecological tourist area in Xuancheng, Anhui Province[J]. Journal of Hefei University of Technology (Social Science Edition), 2017, 31(3): 128-134.

[13] Luan Bo, Wang Xin, Jin Yueyan, et al. Collaborative design of site scale green infrastructure: A case study on ecological restoration design of Weiliu Wetland Park in Xianyang[J]. Landscape Architecture Frontiers, 2017, 5(5): 26-43.

[14] Ma Lin, Liu Hao, Peng Jian, et al. Delimiting the urban ecological belts based on green infrastructure assessment: A case study of Hangzhou[J]. Geographical Research, 2017, 36(3): 583-591.

[15] Cotinovis C, Geneletti D. A performance based planning approach integrating supply and demand of urban ecosystem services[J]. Landscape and Urban Planning, 2020, 201: 103842, doi: 10.1016/j.landurbplan.2020.103842.

[16] Lorilla R S, Kalogirou S, Poirazidis K, et al. Identifying spatial mismatches between the supply and demand of ecosystem services to achieve a sustainable management regime in the Ionian Islands (western Greece)[J]. Land Use Policy, 2019, 88: 104171, doi: 10.1016/j.landusepol.2019.104171.

[17] Bukvareva E, Zamolodchikov D, Krave G, et al. Supplied, demanded and consumed ecosystem services: Prospects for national assessment in Russia[J]. Ecological Indicators, 2017, 78: 351-360.

[18] Xie Gaodi, Zhen Lin, Lu Chunxia, et al. Supply, consumption and valuation of ecosystem services in China[J]. Resources Science, 2008, 30(1): 93-99.

[19] Yan Yan, Zhu Jieyuan, Wu Gang, et al. Review and prospective applications of demand, supply, and consumption of ecosystem services[J]. Acta Ecologica Sinica, 2017, 37(8): 2489-2496.

[20] Liu Huimin, Fan Yulong, Ding Shengyan. Research progress of ecosystem service flow[J]. Chinese Journal of Applied Ecology, 2016, 27(7): 2161-2171.

[21] Xiao Yu, Xie Gaodi, Lu Chunxia, et al. Involvement of ecosystem service flows in human wellbeing based on the relationship between supply and demand[J]. Acta Ecologica Sinica, 2016, 36(10): 3096-3102.

[22] Liu Licheng, Liu Chunfang, Wang Chuan, et al. Supply and demand matching of ecosystem services in loess hilly region: A case study of Lanzhou[J]. Acta Geographica Sinica, 2019, 74(9): 1921-1937.

[23] Wang Zhuangzhuang, Zhang Liwei, Li Xupu, et al. Spatio-temporal pattern of supply-demand risk of ecosystem services at regional scale: A case study of water yield service in Shaanxi Province[J]. Acta Ecologica Sinica, 2020, 40(6): 1887-1900.

[24] Xie Yuchu, Zhang Suxin, Lin Bing, et al. Spatial zoning for land ecological consolidation in Guangxi based on the ecosystem services supply and demand[J]. Journal of Natural Resources, 2020, 35(1): 217-229.

[25] Hu Zhongxiu, Zhou Zhongxue. Ecosystem services evaluation and its spatial pattern analysis of urban greenland in Xi'an City[J]. Arid Land Geography, 2013, 36(3): 553-561.

[26] Han Ye, Zhou Zhongxue. Evaluation on ecosystem services in haze absorption by urban green land and its spatial pattern analysis in Xi' an[J]. Geographical Research, 2015, 34(7): 1247-1258.

[27] Sun Qingxiang, Zhou Huarong. Service function and value evaluation of the Altai Mountains forest ecosystem[J]. Arid Land Geography, 2020, 43(5): 1327-1336.

[28] Yan Qingwu, Bi Zhengfu, Zhang Ping, et al. Census spatialization based on settlements density[J]. Geography and GEO-Information Science, 2011, 27(5): 95-98.

[29] Han Xiuzhen, Li Sanmei, Dou Fangli. Study of obtaining high resolution surface atmosphere temperature by using the land surface temperature from meteorological satellite data[J]. Acta Meteorologica Sinica, 2012, 70(5): 1107-1118.

[30] Li Mengtao, Zhou Zhongxue. Measurement and spatial pattern of positive and negative ecosystem services of urban landscape in Xi' an[J]. Acta Geographica Sinica, 2016, 71(7): 1215-1230.

[31] Zhang Bitao, Zhou Zhongxue. Impact of land use change on agro-ecosystem services in Qinba Mountain area: A case study of Hanzhong Basin[J]. Journal of Shaanxi Normal University (Natural Science Edition), 2020, 48(1): 21-31.

[32] Chen Long, Xie Gaodi, Gai Liqiang, et al. Research on noise reduction service function of road green spaces: A case study of Beijing[J]. Journal of Natural Resources, 2011, 26(9): 1526-1534.

[33] Peng J, Zhao S Q, Dong J Q, et al. Applying ant colony algorithm to identify ecological security patterns in megacities[J]. Environmental Modelling & Software, 2019, 117: 214-222.

[34] Chen Xin, Peng Jian, Liu Yanxu, et al. Constructing ecological security patterns in Yunfu City based on the framework of importance-sensitivity-connectivity[J]. Geographical Research, 2017, 36(3): 471-484.

[35] Zou Yue, Zhou Zhongxue. Impact of landscape pattern change on ecosystem service value of Xi' an City, China[J]. Chinese Journal of Applied Ecology, 2017, 28(8): 2629-2639.

[36] Peng Jian, Wang Yanglin, Chen Yanfei, et al. Economic value of urban ecosystem services: A case study in Shenzhen[J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2005(4): 594-604.

[37] Mao Chengrui, Dai Limin, Qi Lin, et al. Constructing ecological security pattern based on ecosystem services: A case study in Liaohe River Basin, Liaoning Province, China[J]. Acta Ecologica Sinica, 2020, 40(18): 6486-6494.

[38] Wang Peng, Liu Xiaopeng, Wang Yajuan, et al. Ecological migration process and the evaluation of its ecosystem service value in Loess hilly and gully region:

A case study of Haiyuan County, Ningxia[J]. Arid Land Geography, 2019, 42(2): 433-443.

[39] Zhou Zhongxue. The impact of Xi' an-Xianyang urbanization on urban agricultural development from the perspective of ecosystem services[M]. Beijing: Science Press, 2018: 189-190.

[40] Larondelle N, Lauf S. Balancing demand and supply of multiple urban ecosystem services on different spatial scales[J]. Ecosystem Services, 2016, 22: 18-31.

[41] Song Jingxue, Zhou Zhongxue. Impact of agricultural transformation of typical villages in Guanzhong Plain on agro-ecosystem services[J]. Arid Land Geography, 2020, 43(3): 807-819.

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