

Article

Investigating Spatial Heterogeneity Patterns and Coupling Coordination Effects of the Cultural Ecosystem Service Supply and Demand: A Case Study of Taiyuan City, China

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Abstract: As a vital bridge linking human well-being with ecological processes, cultural ecosystem services (CESs) play a pivotal role in understanding the equilibrium of social–ecological systems. However, the spatial supply–demand relationships of CESs remain underexplored in rapidly urbanizing regions. This study establishes an integrated framework by synthesizing multi-source geospatial data, socioeconomic indicators, and the Maximum Entropy (MaxEnt) model to investigate the spatial dynamics of CESs in Taiyuan City. Key findings include the following: (1) A pronounced spatial heterogeneity in CES supply distribution, exhibiting a core-to-periphery diminishing gradient, with inverse correlations observed among different CES categories. (2) Accessibility, topographic features, and fractional vegetation cover emerged as primary drivers of spatial supply differentiation, while climatic factors and elevation exerted non-negligible influences on this Loess Plateau urban system. (3) Four spatial mismatch patterns were identified through the supply–demand analysis: high supply–high demand (38.1%), low supply–low demand (37.2%), low supply–high demand (13.6%), and high supply–low demand (10.9%). The coupling coordination degree of CESs in Taiyuan City indicated moderate coordination, with severe imbalances observed in urban–rural transitional zones. This study reveals nonlinear interactions between natural landscapes and anthropogenic factors in shaping CES spatial distributions, particularly the trade-offs between esthetic value and transportation constraints. By integrating big data and spatial modeling, this research advances CES quantification methodologies and provides actionable insights for optimizing green infrastructure, prioritizing ecological restoration, and balancing urban–rural CES provision. These outcomes address methodological gaps in coupled social–ecological system research while informing practical spatial governance strategies.

Keywords: cultural ecosystem services; supply–demand relationships; land space planning; spatial heterogeneity; ecosystem management; human well-being



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1. Introduction

A socio-ecological system is characterized by a complex amalgamation of social and ecological subsystems and their intricate interactions [1]. Historically, the perception of this relationship has been biased, emphasizing the negative impact of economic development

on ecological stability while overlooking bidirectional interactions. This bias has led to inefficient resource utilization and hindered socioeconomic development. Consequently, understanding the dynamic equilibrium of socio-ecological systems has emerged as a critical research imperative [2]. In this context, cultural ecosystem services (CESs) have garnered widespread attention. CESs are defined as the non-material benefits that humans derive from ecosystems through spiritual fulfillment, cognitive development, reflection, recreation, and esthetic experiences [3]. As a product of the interaction between human society and ecosystems [4], CESs serve as an intangible link between natural ecosystems and socioeconomic systems, connecting natural processes with social activities [3]. The supply–demand dynamics of CESs reflect the flux from natural ecosystems to human social systems. Investigating the coupling relationship between the CES supply and demand provides a novel paradigm for comprehending complex socio-ecological interactions. This approach elucidates the mechanisms underlying human–environment interactions, enhancing our understanding of human–land relationships and providing a robust scientific foundation for the sustainable coupling of human society and natural ecosystems [5].

CESs present unique challenges in quantitative assessment compared to other ecosystem services owing to their intangible nature and dependence on human subjective perceptions [6]. While traditional CES valuation methods, such as questionnaires [7] and interviews [8], are capable of exploring individual or group emotional values and personal experiences in depth, they are constrained by their subjectivity, instability, and spatiotemporal limitations. These constraints impede the comprehensive reflection of CESs' contributions to human well-being. Consequently, the development of more objective and stable methods with large-scale assessment capabilities has become a focal point of the current research. In recent years, spatially oriented analytical models have been widely applied to CES assessments. These models are operationally efficient and capable of comprehensively quantifying various types of cultural services to achieve the spatial mapping of CESs. The main approaches include biophysical methods [9,10], Public Participation Geographic Information Systems (PPGISs) [11–13], Social Values for Ecosystem Services (SolVES) models [11,14,15], and Maximum Entropy (MaxEnt) models [16–18].

Concurrently, social media data, as an emerging enormous data resource, have provided new avenues for CES research, owing to the large volume, rapid updates, and comprehensive coverage. Combining social media data with modeling or questionnaire methods [19–21] can mitigate the limitations of small-scale and traditional non-monetary evaluations in CES assessments. This integration allows for the quantitative evaluation of CESs supply and demand on a unified spatial scale. Through a spatial overlay analysis [22,23] and hotspot analysis [24,25], areas of CES supply–demand imbalance can be precisely identified, revealing spatial patterns and influencing factors of supply–demand matching. Integrating diverse data sources and analytical techniques represents a significant advancement in CES research, offering a more comprehensive and nuanced understanding of the complex interactions between human societies and ecosystems.

The integration of social media data with the MaxEnt model provides an innovative methodological framework for CES research. This approach enables a supply–demand matching analysis at finer spatial scales, enhancing matching precision and providing accurate evidence for identifying priority restoration areas and optimizing management measures. The MaxEnt analysis model explores the relationships between environmental variables and given observation points [16,26]. This allows for the objective mapping of CESs and facilitates the identification of key influencing factors, enabling an in-depth study of CES distribution mechanisms [16]. When combined with big data, this approach can more comprehensively characterize the multi-dimensional attributes of cultural services, expanding the expression and assessment of cultural service connotations [27,28]. This

facilitates the comprehensive consideration of ecosystem attributes, human preferences, and spatial accessibility, thus helping in formulating more scientific and rational land use planning and ecological protection policies. Furthermore, the MaxEnt model can be used to conduct quantitative attribution analyses and interactive studies of CES flows using multi-year data [29,30]. This capability allows researchers to focus on complex human–nature interactions both within regional systems and between different regions. This evaluation method provides a scientifically quantitative assessment of CESs, offering conceptual references for decision-making bodies to understand spatial utilization patterns, coordinate ecological, cultural, and economic benefits, and guide the optimization and upgrading of national land space [31].

Urbanization has intensified ecosystem service supply pressures while demand persists [32]. Research on the spatial differentiation characteristics and influencing factors of CES supply and demand is crucial for promoting coordinated regional social–ecological system development, optimizing land resource utilization, and enhancing human well-being. A CES is influenced by many natural and social factors that affect human well-being [33]. Studies have demonstrated that factors such as topography, human activity intensity, and land use changes can lead to the spatial differentiation of CESs [34–36]. However, the current research predominantly employs qualitative descriptions and correlation analyses of natural factors [25] and lacks a quantitative characterization of multi-dimensional social–ecological factors. Additionally, the existing research has predominantly focused on small-scale attribution analyses, neglecting the synergistic effects and scale-dependent variations in the influencing factors. CES supply and demand determinants exhibit complex regional, landscape, cultural, and topographical interactions. Comprehensive, multi-scale investigations are imperative to elucidate the intricate interplay between social and ecological factors in shaping CES supply–demand patterns.

The research on CES supply–demand relationships has evolved from early-stage supply assessments using land use matrix scoring to the dual spatial matching characterized by supply–demand ratios and Z-score standardization and further progressed to the current systematic optimization analysis through the coupling coordination degree [37]. This progression has gradually achieved the quantitative analysis of spatial mapping for CES supply–demand relationships and regional coordination. However, existing studies indicate that in the context of rapid urbanization, while the single coupling coordination index can reflect spatial coordination patterns of the CES supply–demand, it proves inadequate in deciphering the unique “supply-depressed areas and demand hotspots” spatial mismatch mechanism characteristic of high-density built-up areas. The spatial controllability of supply–demand matching across entire regions remains challenging, potentially hindering the subsequent spatial management and adjustment of CES relationships.

The rapid urbanization of Taiyuan City, the capital of Shanxi Province, China, has intensified socio-ecological tensions, resulting in significant spatial imbalances between the CES supply and demand, necessitating comprehensive CES management in this urban environment. As a typical valley basin city on the Loess Plateau, Taiyuan possesses unique geographical features (surrounded by mountains on three sides, bisected by the Fenhe River), rapid socioeconomic development, and rich heritage resources as a national historical and cultural city. This makes it an exemplary case for studying the spatial dynamics of CESs under rapid urbanization and complex terrain constraints. Revealing the spatial heterogeneity patterns and coupling coordination effects of the CES supply and demand in Taiyuan holds direct practical value for local ecological restoration, green infrastructure optimization, and an equitable cultural service provision between urban and rural areas. Moreover, the methodologies and findings can offer valuable insights for

urban regions globally facing similar challenges, such as topographic constraints, rapid urbanization pressures, and cultural heritage conservation.

Therefore, this study aims to achieve the following: (1) Establish an integrated framework synthesizing multi-source geospatial data (including POI), socioeconomic indicators, and the MaxEnt model to quantify the supply–demand and spatial distribution patterns of CESs in Taiyuan City; (2) identify the key natural and socioeconomic drivers of the spatial differentiation in the CES supply; (3) systematically analyze the spatial matching relationships and coordination levels between the CES supply and demand using Z-score standardization and a coupling coordination model; and (4) propose differentiated spatial optimization and management strategies based on supply–demand matching types and coupling coordination zones, providing a scientific basis for sustainable territorial spatial planning and ecosystem management in Taiyuan and similar regions. By uncovering the nonlinear interactions between natural landscapes and anthropogenic factors in shaping CES spatial distributions, particularly the trade-offs (e.g., esthetic value vs. accessibility), this research aims to advance CES quantification methodologies and provide actionable insights for optimizing green infrastructure, prioritizing ecological restoration, and balancing urban–rural CES provisions.

2. Materials and Methods

2.1. Study Area

Taiyuan City, situated in central Shanxi Province ($37^{\circ}27'–38^{\circ}25' \text{ N}$, $111^{\circ}30'–113^{\circ}09' \text{ E}$), encompasses 6988 km² within the northern Jinzhong Basin (Figure 1a). Administratively, the city is divided into 6 districts, 3 counties, and 1 county-level city comprising 55 subdistricts and 46 towns. Geomorphologically, Taiyuan is characterized by a north–south topographical descent, flanked by mountains on three sides (Figure 1b), with the Fenhe River bisecting the region longitudinally. This configuration contributes to a diverse landscape of mountains, hills, plains, basins, and valleys. Climatologically, the area is governed by a warm temperate continental monsoon climate, exhibiting a mean annual temperature and precipitation of 9.5 °C and 456 mm, respectively. Ecologically, the city is enriched by nature reserves and scenic areas (Figure 1c), including the upper Fenhe River and Yunding Mountain reserves. Furthermore, as a national historical and cultural center, Taiyuan is imbued with significant heritage sites, such as Mount Meng and Shuangta Temple. Demographically and economically, by 2022, the city's permanent population will reach 5.435 million, with a regional GDP of CNY 557.12 billion. However, concurrent with the rapid socioeconomic development, a worsening imbalance between the CES supply and demand has been observed. Specifically, an insufficient supply and quality deficiencies are critical constraints on residential well-being and social–ecological system development. Consequently, addressing this CES supply–demand disparity and fostering harmonious socioeconomic and ecological coexistence have emerged as essential challenges for Taiyuan's sustainable development, necessitating comprehensive research and targeted interventions to enhance urban sustainability and quality of life.

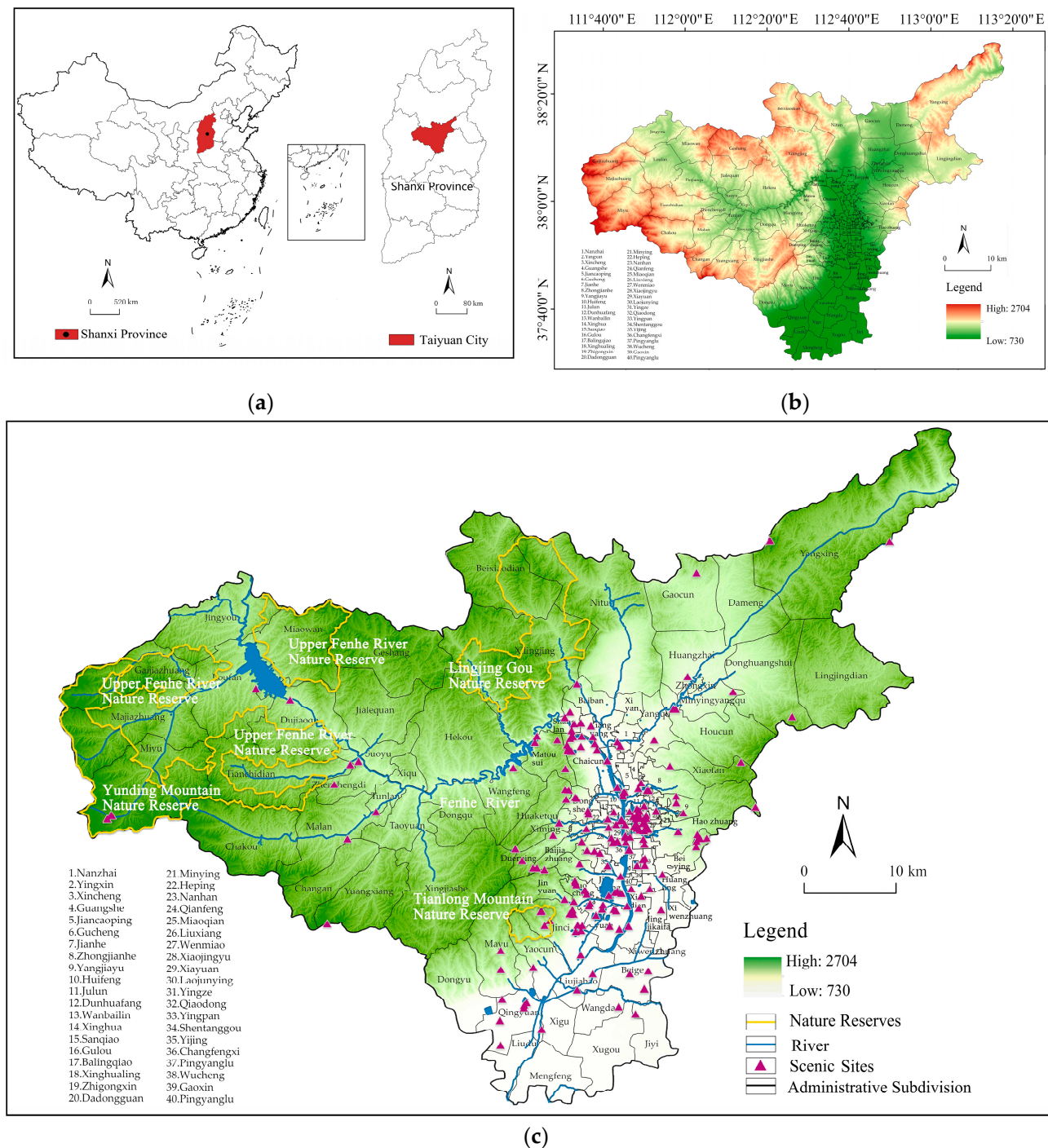


Figure 1. (a) Geographical location of Taiyuan City; (b) elevation of Taiyuan City; and (c) distribution of scenic sites and nature reserves in Taiyuan City.

2.2. Data Sources

This study integrated diverse datasets encompassing land use, digital elevation models (DEMs), meteorological temperature, socioeconomic variables, and points of interest (POIs). To ensure data accuracy, we supplemented and refined these sources using information from statistical yearbooks and official government portals. All raster data were resampled using ArcGIS 10.5 and standardized to the WGS_1984_UTM_Zone_49N coordinate system at a 30 m resolution (Table 1). For POI data related to cultural ecosystem services-related POI data, we utilized the GAODE Map owing to its comprehensive classification system, which facilitated efficient site filtering and curation. The dataset comprises 12 primary

categories—healthcare, leisure, residential services, commerce, finance, dining, and retail—providing a robust representation of visitor preferences for CESs.

Table 1. Data sources.

Date Name	Resolution	Year	Sources
Digital elevation model	30 m	-	Geospatial Data Cloud (https://www.gscloud.cn/) (accessed on 8 May 2024)
Land use data	30 m	2020	China Resources and Environment Science Data Center, CRESDC (https://www.resdc.cn/) (accessed on 8 May 2024)
Administrative division vector data	-	-	National Geographic Information Resources Catalog Service System (https://www.webmap.cn/). (accessed on 1 May 2024)
Points of interest (POIs) data	-	2022	Open platform of the GAODE map
Road network data	-	2020	Open Street Map website (https://www.openstreetmap.org/) (accessed on 6 May 2024)
Raster data for Gross domestic product (GDP) per unit area	1000 m	2020	China Resources and Environment Science Data Center, CRESDC (https://www.resdc.cn/) (accessed on 6 May 2024)
Population density	100 m	2020	WorldPop project (https://www.worldpop.org/) (accessed on 8 May 2024)
Normalized Difference Vegetation Index (NDVI)	30 m	2020	China Resources and Environment Science Data Center, CRESDC (https://www.resdc.cn/) (accessed on 1 May 2024)
Annual average temperature	1000 m	2020	National Earth System Science Data Center (http://www.geodata.cn/) (accessed on 8 May 2024)
Annual average precipitation	1000 m	2020	National Earth System Science Data Center (http://www.geodata.cn/) (accessed on 8 May 2024)
Nighttime light data	1000 m	2020	National Earth System Science Data Center (http://www.geodata.cn/) (accessed on 3 May 2024)

2.3. Methods

Considering the rich cultural heritage and natural landscapes within the study area, four categories of CESs were selected for assessment: native esthetic, recreation leisure, historical-cultural, and knowledge educational. This selection was based on three internationally recognized ecosystem service classification systems: the Millennium Ecosystem Assessment, the Economics of Ecosystems and Biodiversity, and the Common International Classification of Ecosystem Services, in conjunction with the relevant literature [3,17,38–40].

The CES supply and demand research framework for Taiyuan City (Figure 2) comprised four main steps:

- (1) Data collection and processing: POIs obtained from the Gaode Map API were screened and categorized to establish a POI dataset as social data. A comprehensive literature review identified the environmental factors influencing various CES supplies, and an environmental factor database was constructed.
- (2) Model input and analysis: The POI dataset and environmental factors were inputted into the MaxEnt model. CES supply maps were generated and quantified using both natural and anthropogenic variables. The determinant variables and their impacts on

the CES supply in Taiyuan City were quantified. CES demand levels were quantified from two dimensions: social and material demands.

- (3) Supply–demand coordination analysis: The research units are categorized into four distinct matching typologies through the supply–demand matching analysis, followed by an examination of coordinated development levels utilizing a coupling coordination model to assess the evolutionary progression of the supply–demand equilibrium.
- (4) Policy management and recommendations for sustainable development: Specific measures and suggestions for different types of coupling coordination development.

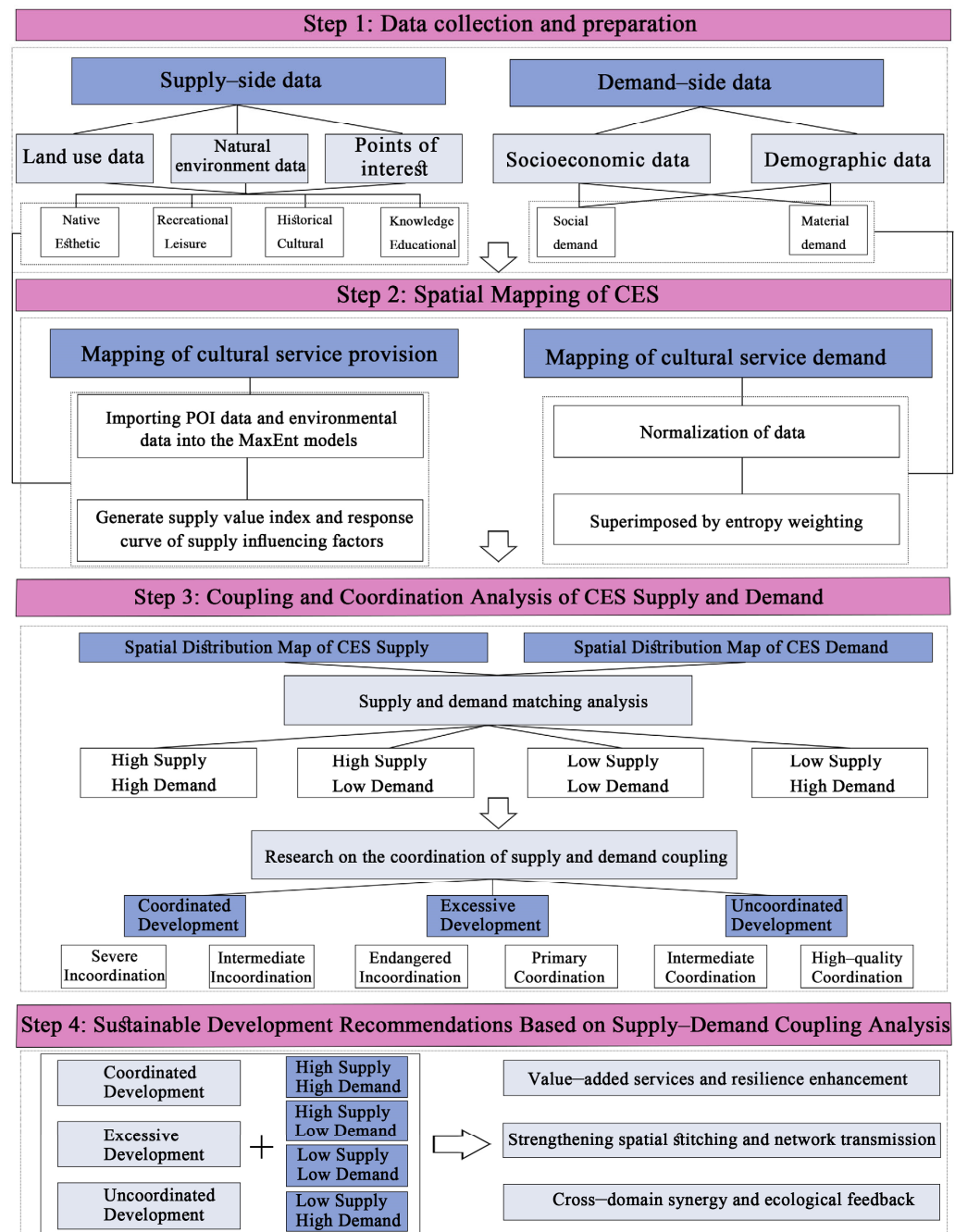


Figure 2. Analytical framework for spatial differentiation and influencing factors of CES supply and demand.

2.3.1. Quantification of CES Supply and Influencing Factors

This study comprehensively considers multiple aspects of CESs, including the service potential, opportunities, and processes. CES provision encompasses both potential and actual provisions. Potential provision refers to the theoretical capacity of ecosystems to deliver cultural services under specific environmental conditions, whereas actual provision requires an implementation through infrastructure and management interventions. By referencing the relevant literature, we conceptualized the CES supply in this study as the ecosystem's potential supply and the potential benefits humans may derive from this supply. Actual provision locations were marked using POI data, while supply potential was quantified through MaxEnt modeling, providing differentiated spatial decision-making bases for planning. POI data are widely utilized in geographical and social research due to their advantages in information richness, real-time updates, and precise positional/attribute details [22]. In the MaxEnt model, POI-marked actual provision locations were combined with environmental variables related to specific CES types to predict their potential spatial distribution. To ensure consistency between POI data and the natural, cultural, and social conditions of the study area, while considering potential logical causal relationships and functional overlaps among different CES types, detailed specifications for four CES categories and POI classification criteria were established based on references [6,41–43] (Table 2).

Table 2. Classification criteria for cultural ecosystem service points of interest.

Category	Description	Classification	Keywords	Quantity
Native Esthetic Service	Sites of Natural and Cultural Significance with Unique Esthetic Value	Scenic Sites, Natural Sites, and Nature Reserves	Agricultural Fields, Lakes, Rivers, Streams, Springs, Waterfalls, Wetlands, Caves, Parks, Gardens, Scenic Areas, Nature Reserves, etc.	671
Recreational Leisure Service	Venues for Local Recreational Experiences and Leisure Activities	Recreational Facilities, Dining and Entertainment Venues, Resort Destinations, and Commercial Areas	Tourist Orchards, Farms, Amusement Parks, Hotels, Rural Home Stays, Sanatoriums, Observation Towers, Pick-Your-Own Farms, Parks, etc.	507
Historical Cultural Service	Locations of Historical Heritage with Humanistic and Traditional Significance	Cultural Heritage Conservation Units, Folk Custom Venues, and Historical Relics	Cultural Sites, Former Residences, Pagodas, Bridges, Shrines, Ancestral Halls, Monuments, Traditional Pavilions, Ancient Wells, etc.	496
Knowledge Educational Service	Capacity to Provide Learning Resources and Venues for the Formation of Human Ideology and Enhancement of Cognition	Nature Education Bases and Science Popularization Centers	Innovation Training Bases, Ecomuseums, Scientific Research Centers, Educational Practice Gardens, etc.	499

CES-related tags and keywords were gathered from urban open data platforms and government websites as supplementary information for data collection. Initially,

237,290 raw data points were obtained. After the preliminary screening, 3571 valid POI data points were identified. To further enhance the data quality, a series of operations, including cleaning, classification, screening, and preprocessing, were performed on the original POI data, resulting in 2173 high-quality POI data points. The geographical location information of POIs was acquired through the Gaode Map API, and the coordinate conversion was conducted using ArcGIS 10.5 software to accurately map their spatial distribution (Figure 3).

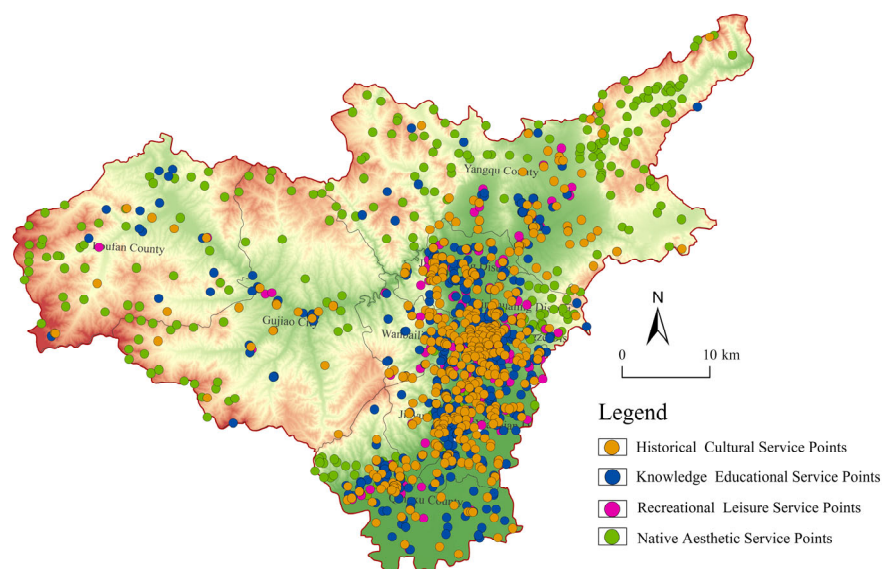


Figure 3. Distribution of cultural ecosystem service points in Taiyuan City.

In this study, the MaxEnt3.4.1 software, typically used for predicting species niches and distributions, was employed to measure the social value of ecosystems by integrating both natural and anthropogenic variables [16]. The core principle of the MaxEnt model is to maximize the entropy of the distribution information in unknown areas while satisfying known constraints. Let $P(x)$ denote the probability distribution of an unknown area x , and X represent the finite x set within the study area [44,45]. The entropy calculation formula for MaxEnt operations is expressed as follows:

$$H(P) = - \sum_{x \in X} P(x) \ln P(x) \quad (1)$$

The MaxEnt model's performance was evaluated using the Receiver Operating Characteristic (ROC) curve, with the Area Under the Curve (AUC) as a key indicator of simulation accuracy. Two AUC types were considered: Test AUC, which reflects the model's potential for value transfer applications, and Training AUC, which indicates the model's goodness of fit. AUC values range from 0 to 1, with values approaching 1 signifying a superior simulation performance [46,47].

This study integrated natural and socioeconomic characteristics, employing a Pearson correlation analysis to mitigate multicollinearity [16,17,40]. For screening potential environmental indicators, factors with correlation coefficients exceeding 0.75 were eliminated, ultimately selecting 15 variables (Table 3) comprising natural environmental variables (e.g., elevation and slope) and anthropogenic activity variables (e.g., distance to roads and residential areas) as key drivers of spatial heterogeneity in the CES supply, aiming to comprehensively elucidate the spatial differentiation mechanisms of CES provisions. Among these variables, the landscape diversity index was typically represented by Shannon's Diversity Index, with connectivity indices calculated using Fragstats 4.2.1 through

a moving window method, where window dimensions were set to reflect specific characteristics. These environmental variables were converted into the ASCII grid format in ArcGIS 10.5 for MaxEnt modeling, while POI data corresponding to four CES types were incorporated into the species distribution module. A random sampling approach allocated 75% of distribution points to the training dataset and 25% to the testing dataset for model validation [26,48]. Finally, the total cultural service value distribution was generated by aggregating values from four CES types through arithmetic summations of original value indices, followed by normalization using ArcGIS 10.5's fuzzy membership tool.

Table 3. Environmental variables for MaxEnt modeling.

Variable Category	Environmental Variable	Source and Processing
Natural environmental	Elevation	Geospatial Data Cloud (https://www.gscloud.cn/) (accessed on 8 May 2024)
	Slope	Calculated using ArcGIS 10.5
	Aspect	
	Annual Mean Temperature	National Earth System Science Data Center (http://www.geodata.cn/) (accessed on 8 May 2024)
	Annual Precipitation	
	Fractional Vegetation Cover	Derived from NDVI calculation in ENVI
	Landscape Diversity Index	Calculated using Fragstats 4.2.1
	Landscape Connectivity Index	
	Land Use Type	China Resources and Environment Science Data Center, CRESDC (https://www.resdc.cn/) (accessed on 8 May 2024)
	Distance to Water Bodies	Euclidean Distance
Anthropogenic activity	Distance to Natural Scenic Areas	Euclidean Distance
	Distance to Infrastructure	Euclidean Distance
	Distance to Roads	Euclidean Distance
	Distance to Transportation Stations	Euclidean Distance
	Distance to Residential Areas	Euclidean Distance

2.3.2. Quantification of CES Demand

This study defines the concept of CES demand as the collective willingness of social groups regarding the quantity and quality of CESs provided within the research area. Socioeconomic development factors constitute key drivers of the CES demand in the study region. Wang et al. categorized this demand into safety requirements, material needs, health requirements, and socio-cultural/spiritual needs, encompassing both subjective and objective dimensions [49]. Consistent with Wei et al.'s findings [23], socioeconomic development factors were identified as primary drivers of the urban park CES demand. Building upon this theoretical framework and constrained by data availability, this research operationalized the cultural service demand intensity across different social groups through three indicators: the population density, special population distribution, and economic development level. These indicators were selected based on references to the Millennium Ecosystem Assessment [3], the Common International Classification of Ecosystem Services [38], and prior scholarly works [50,51]. Practical utilization demands for cultural services were reflected through metrics of human activity intensity and urban development pressure. The demand framework was subsequently stratified into social and material dimensions (Table 4). Social demand represents quantitative and scalar requirements. Beyond economic factors, explicit consideration was given to local residents' needs and

special population requirements to comprehensively capture demand diversity. Material demand was quantified through indicators of human activity intensity and developmental pressures within urban clusters. These metrics were used to characterize potential demand concentration areas. Collinearity tests confirmed the validity of selected indicators, with all variance inflation factor (VIF) values below 10, meeting experimental requirements.

Table 4. Demand index and weights for cultural ecosystem services.

Category	Indicator	Indicator Description	Weight
Social Demand	Population Density	Changes in the spatial distribution of the population affect the demand level for CESs.	0.269
	GDP per Unit Area	Reflects the output density and economic development level within urban clusters. Higher GDP indicates higher internal development and economic concentration, leading to greater demand.	0.234
	Population Density of 60+ Years Old	The density of the population over 60 years old within the city.	0.098
	Population Density of Under 14 Years Old	Density of population under 14 years old within the city.	0.089
Material Demand	Development and Construction Intensity	This is measured by the proportion of built-up areas within the city, representing that higher urban construction levels lead to greater spatial demand for CESs.	0.144
	Human Activity Intensity	Measured by the nighttime light index within the city.	0.166

This study employed the entropy weight method to determine the weights of CES demands. As an objective weighting approach rooted in information entropy theory, the entropy weight method is primarily applied to multi-criteria comprehensive evaluations. Its fundamental principle states that indicators demonstrating greater dispersion contain more informational value and should therefore receive higher weights. By calculating weights based on the inherent distribution characteristics of data, this method eliminates subjective bias and proves particularly suitable for data-driven decision-making scenarios. The implementation process involved two key steps [52]: First, range standardization was applied to normalize all indicators to a 0–1 scale, ensuring dimensional consistency. Subsequently, the entropy weight method was utilized to derive specific weights for various CES demand indicators in Taiyuan City. Finally, a weighted superposition analysis was conducted to calculate the total CES demand. The detailed calculation formulas and implementation procedures are as follows:

(a) Indicator normalization:

$$Y_i = \frac{x_i - x_{imin}}{x_{imax} - x_{imin}} \quad (2)$$

In the formula, Y_i represents the standardized indicator value, x_i denotes the original indicator value, x_{imax} and x_{imin} correspond to the maximum and minimum values of the indicator, respectively. The subscript i ranges from 0 to n .

(b) The conversion of Y_i into proportion form P_i is achieved through

$$P_i = \frac{Y_i}{\sum_{i=1}^n Y_i} \quad (3)$$

where n represents the total number of indicators.

- (c) The information entropy value M_i for each indicator was calculated using the following formula:

$$M_i = -\frac{1}{\ln k} \sum_{i=1}^n P_i \ln P_i \quad (4)$$

where k denotes the number of samples.

- (d) The entropy weight s_i for the i -th indicator is defined as follows:

$$s_i = \frac{1 - M_i}{\sum_{i=1}^n 1 - M_i} = \frac{1 - M_i}{n - \sum_{i=1}^n M_i} \quad (5)$$

- (e) Calculating weighted composite scores for CES demand values

$$CES_i = \sum_{i=1}^n Y_i s_i \quad (6)$$

2.3.3. CES Supply–Demand Balance and Coupling Coordination

The study of supply–demand relationships, encompassing metrics such as the supply–demand ratio and Z-score method, primarily focuses on characterizing the immediate matching status at a unit scale. In contrast, the degree of the coupling coordination reveals the sustainability potential at the system level. The synergistic application of these two approaches enables not only the diagnosis of localized hotspots of supply–demand imbalance but also the assessment of broader regional coordination trends. This integrated methodology provides a more robust understanding of the distribution patterns of CES values within the study area, thereby facilitating policy-based spatial guidance and regulation.

Therefore, this study selected an urban area as the research unit. Based on the aforementioned assessment of the CES supply and demand, the Z-score method was introduced for data standardization. The standardized CES supply and demand values were represented along the X-axis and Y-axis, respectively, dividing the study area into four quadrants—Quadrant I (high supply–high demand), Quadrant II (low supply–high demand), Quadrant III (low supply–low demand), and Quadrant IV (high supply–low demand) [51]—representing different types of ecological zoning. This approach characterized the spatial matching relationship between the supply and demand. Furthermore, a coupling coordination model was employed to analyze the coordinated development level between the supply and demand. The coupling coordination model is typically used to measure the mutual interactions and consistency among two or more variables. In ecosystem service supply–demand studies, this model evaluates the spatial consistency between supply and demand while identifying their coordinated relationships. This study conceptualizes the CES supply and demand as two interactive systems. The calculation formulas of the coupling coordination model are as follows:

$$C = n \left\{ \frac{\{u_1 \times u_2 \times u_3 \cdots u_n\}}{\prod [u_i + u_j]^k} \right\}^{\frac{1}{k}} = \frac{2\sqrt{u_1 u_2}}{u_1 + u_2} \quad (7)$$

$$T = \alpha u_1 + \beta u_2 \quad (8)$$

$$D = \sqrt{C \times T} \quad (9)$$

In the model, u represents the supply and demand indices; C denotes the coupling degree between the supply and demand; T is the coordination index, where $T \in [0,1]$;

and α and β are coefficients to be determined. Here, it is assumed that the supply side and demand side are of equal importance; therefore, both α and β are assigned a value of 0.5. D represents the coupling coordination degree, where $D \in [0,1]$ [53]. A higher D value indicates a higher degree of coupling coordination between supply and demand. Based on the relevant literature [53–55], the D values are categorized into 10 levels of CES supply–demand coupling coordination. These levels are further classified into coupling coordination development types (Table 5).

Table 5. Classification of coupling coordination degrees.

Coupling Coordination Type	Coordination Degree	Coupling Coordination Index Range
Coordinated Development	High-quality Coordination	0.8–1
	Intermediate Coordination	0.6–0.8
Excessive Development	Primary Coordination	0.5–0.6
	Endangered Incoordination	0.4–0.5
Uncoordinated Development	Intermediate Incoordination	0.2–0.4
	Severe Incoordination	0–0.2

3. Results

3.1. Measurement and Spatial Expression of CES Supply in Taiyuan City

The MaxEnt model was employed to spatially predict the CES supply capacity across Taiyuan City, revealing regional variations in service provisions. Spatial clustering results and maximum index values derived from the model are illustrated in Figure 4. Notably, all the established CES supply prediction models exhibited AUC values exceeding 0.8 (Figure 5), indicating a robust model fit within the study area. The four CES types demonstrated consistent spatial distribution patterns, with supply capacity indices peaking in central urban areas. Further analysis revealed that high-supply areas for inherent esthetic and recreational values were more widely distributed, exhibiting an east–high and west–low gradient and forming dispersed core supply areas. In contrast, high-supply areas for historical, cultural, and educational values were more concentrated within the central urban zone (Table 6).

The spatial distribution of cultural values, as predicted by the MaxEnt model, was visualized at the subdistrict level (Figure 6). We categorized cultural values into five distinct levels (I–V), ranging from low to high, to facilitate a nuanced analysis of the spatial heterogeneity of cultural ecosystem services across the urban landscape. Taiyuan City’s distinctive geographical configuration engenders pronounced spatial heterogeneity in the CES supply. A consistent spatial gradient was observed across native esthetics, recreational leisure, knowledge educational, and historical–cultural services, with supply capacities diminishing from the central area towards the north and south. Notably, recreational, educational, and historical cultural services exhibited a relatively higher supply in the northwestern region than in the northeastern area. Conversely, the spatial distribution of inherent esthetic services showed an inverse pattern, with higher values in the northeast and lower values in the northwest.

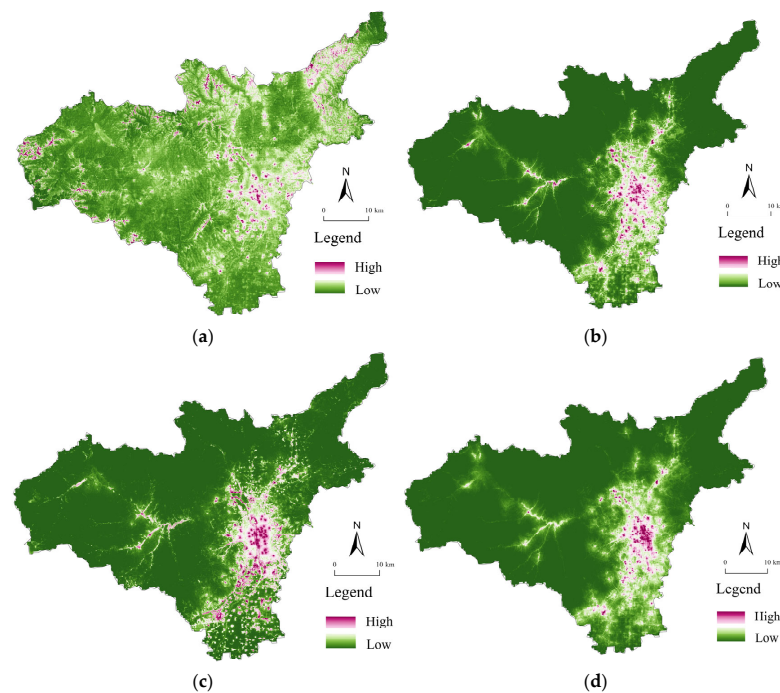


Figure 4. Spatial clustering results of cultural ecosystem services supply: (a) native esthetic; (b) recreational leisure; (c) historical cultural; and (d) knowledge educational.

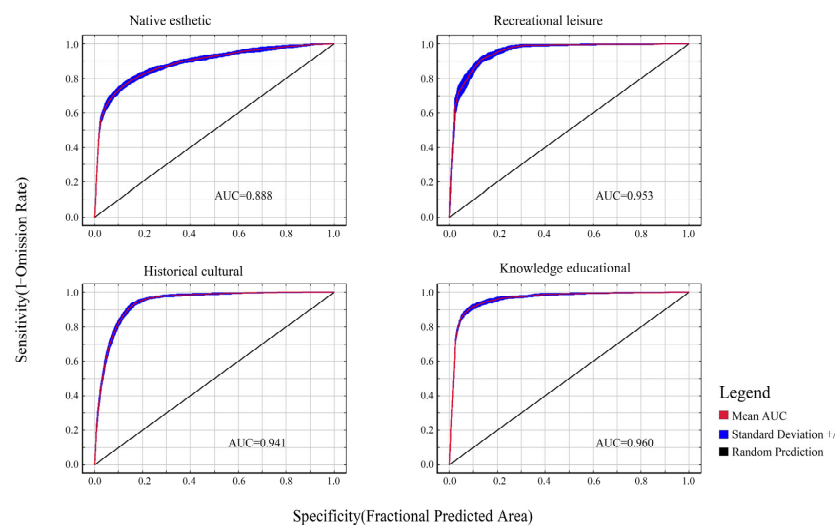


Figure 5. Validation curves for distribution results.

Taiyuan City's topography, characterized by mountains on three sides, significantly influenced its CES distribution. The northern and eastern regions with lower population densities and higher fractional vegetation cover, including natural reserves such as Lingjing Gou, exhibit prominent inherent esthetic service values. However, these areas demonstrate a relatively weak supply capacity for recreational, historical-cultural, and educational services owing to the lower road network density and the sparse distribution of natural scenic areas. Conversely, the latter three CES types are concentrated in central urban and town areas, characterized by a flat terrain, frequent human activities, abundant blue-green space tourism resources, and high traffic accessibility. Taking Huangzhai Village, Dujiaoqu Town, and Loufan County as examples, these core areas exhibit a lower intrinsic esthetic service supply due to their high population density, reduced vegetation coverage, diminished landscape heterogeneity, and increased anthropogenic disturbances.

Table 6. Model fit and classification criteria for four types of CES.

Cultural Service Type	AUC	TSS Threshold	TPT Threshold	Low-Level Zone		Medium-Level Zone		High-Level Zone	
				Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)
Native Esthetic	0.888	0.239	0.077	3089.62	44.21	2966.52	42.45	931.86	13.34
Recreational Leisure	0.959	0.145	0.037	4857.24	69.51	1260.17	18.33	870.59	12.16
Knowledge Educational	0.949	0.132	0.026	4652.01	66.57	1824.70	26.11	511.29	7.32
Historical Cultural	0.946	0.192	0.050	5234.06	74.90	1078.99	15.44	674.95	9.66

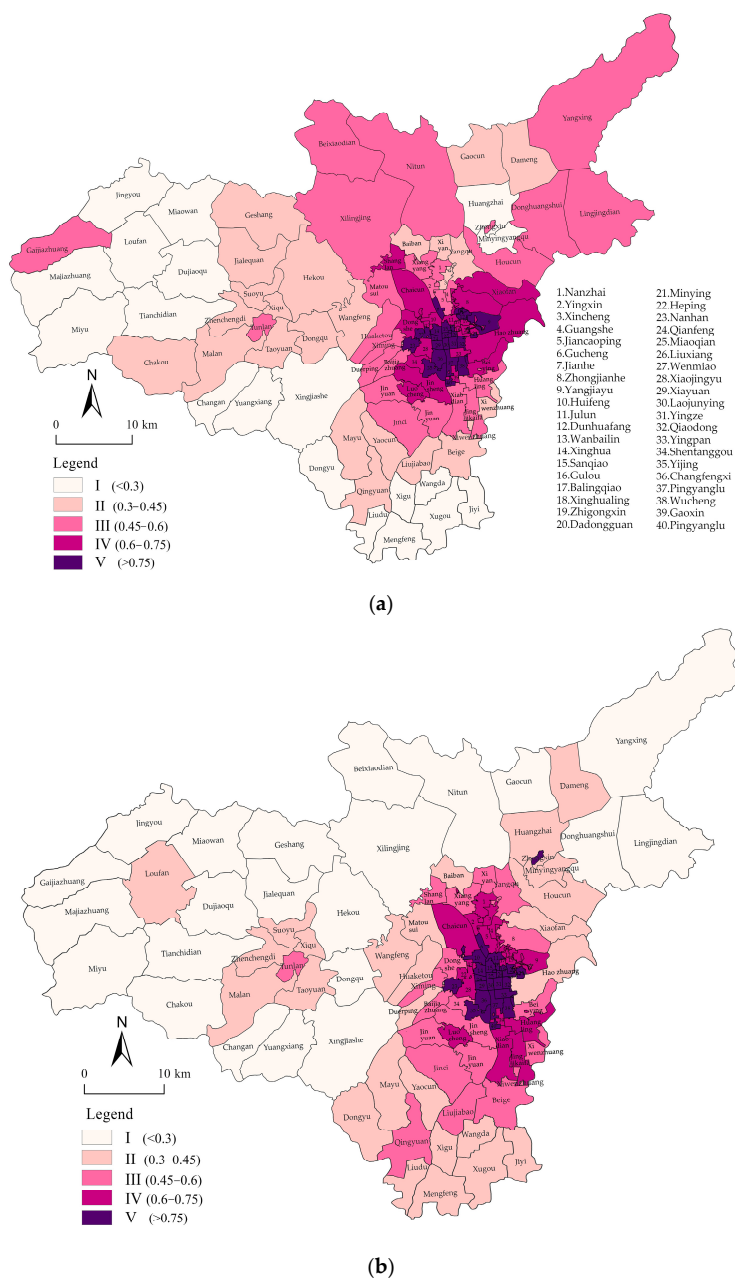


Figure 6. Cont.

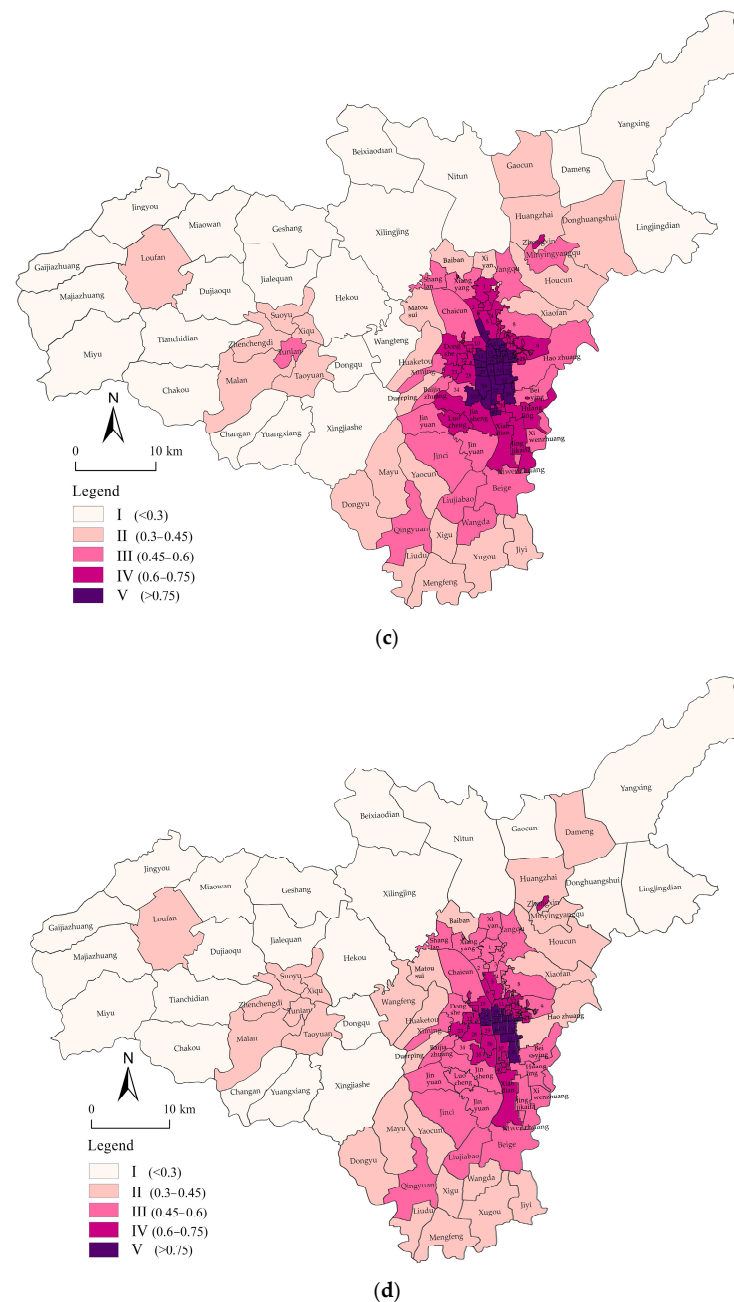
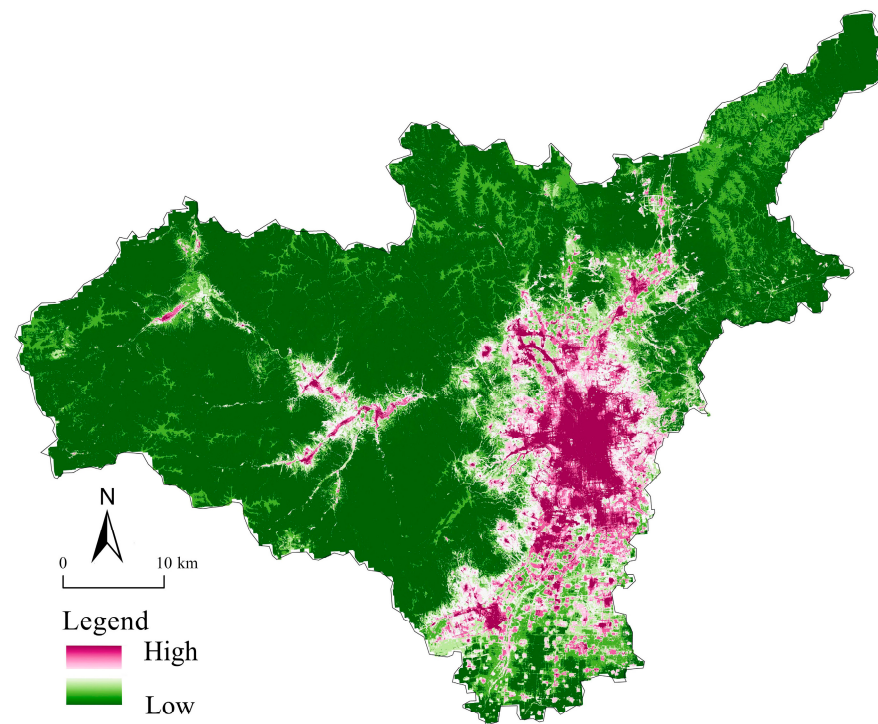
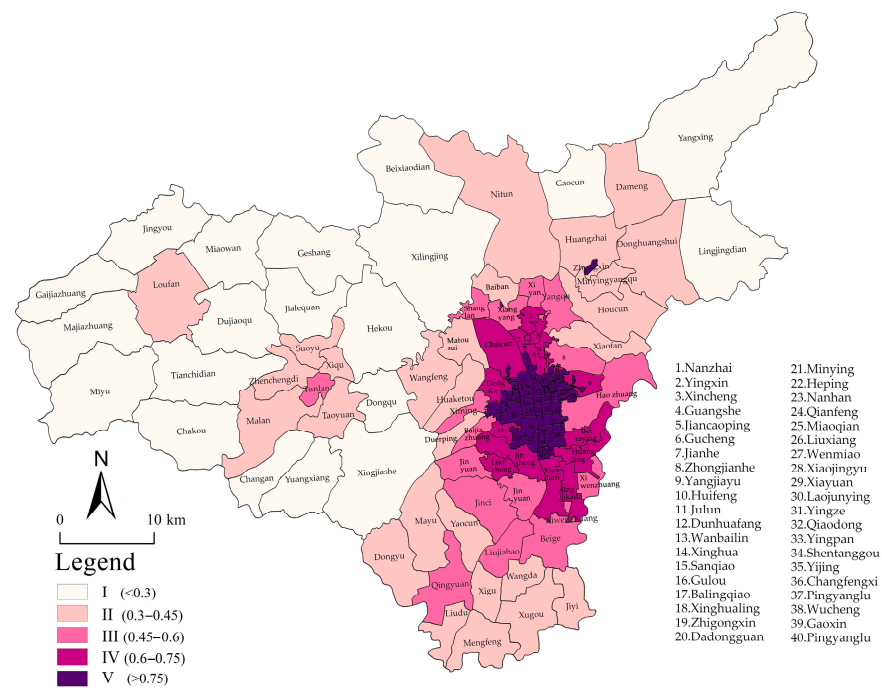


Figure 6. Distribution of four types of CES supply classified by subdistrict level: (a) native esthetic; (b) recreational leisure; (c) historical cultural; and (d) knowledge educational.

The analysis of the CES supply value in Taiyuan City reveals that high-value CES areas are spatially consistent with the distribution of urban scenic zones and nature reserves (Figures 1c and 7). However, certain nature reserves, such as the Upper Fenhe River, exhibit a relatively high potential esthetic value. Due to the natural topography and management constraints, the values of the three other service types remain comparatively low, resulting in an overall limited supply service value. Notably, inherent esthetic services extend into the northern and eastern regions, with high-supply areas predominantly located in areas with an elevated topography and rich landscape diversity. This spatial heterogeneity in the CES supply underscores the complex interplay between urban development, natural landscapes, and ecosystem service provisions (Figure 6).



(a)



(b)

Figure 7. Total supply map of CES: (a) spatial divergence map of CES supply and (b) CES supply map by subdistrict.

3.2. Analysis of Spatial Influencing Factors on CES Supply in Taiyuan City

The environmental variable impact analysis (Table 7) identified key factors influencing the spatial differentiation of CESs in Taiyuan City, including the distance to natural scenic areas and infrastructure, elevation, land use type, fractional vegetation cover, and road proximity (Figure 8). Notably, the distances to natural scenic areas and infrastructure

exhibited the highest cumulative contribution rates (>20%) across all four CES types, underscoring their comprehensive influence on environmental accessibility, experiential continuity, and social well-being. Elevation was significantly correlated with all CES types, contributing substantially to inherent esthetic services (25.1%) by shaping unique habitats and landscape diversity. However, its contribution to educational services was minimal (0.1%), likely owing to accessibility constraints.

Table 7. The importance and contribution rate (%) of environmental variables to the spatial distribution of CESs.

Environmental Variables	Native Esthetic		Recreational Leisure		Knowledge Educational		Historical Cultural	
	Importance	Contribution Rate	Importance	Contribution Rate	Importance	Contribution Rate	Importance	Contribution Rate
Elevation	7.0	25.1	3.6	1.2	0.6	0.1	1.1	4.8
Slope	3.7	1.9	2.4	1.8	0.4	1.5	0.8	1.9
Aspect	2.0	1.8	2.0	0.2	0.3	1.2	0.8	1.9
Annual Mean Temperature	0.6	4.4	1.7	0.5	3.1	0.4	1.6	1.7
Annual Precipitation	2.2	8.3	0.5	0.0	0.3	1.0	0.6	0.6
Distance to Water Bodies	2.8	1.4	1.8	2.1	0.2	1.1	0.4	1.9
Distance to Scenic Areas	38.6	20.4	10.0	17.6	10.3	11.1	36.3	38.3
Distance to Infrastructure	19.5	11.6	49.1	43.1	81.3	70.1	1.0	1.0
Distance to Roads	2.9	3.8	3.7	6.8	1.3	2.2	1.1	3.9
Distance to Transportation Hubs	3.8	4.1	1.3	4.6	0.3	0.9	1.0	3.5
Distance to Residential Areas	2.6	1.5	3.2	1.1	0.3	2.2	39.9	6.5
Fractional Vegetation Cover	5.0	5.0	6.4	8.5	0.8	5.1	6.8	24.5
Landscape Diversity Index	3.7	3.0	3.8	4.9	0.3	1.6	0.7	3.7
Landscape Connectivity Index	1.4	2.4	1.0	0.3	0.2	1.0	1.6	2.6
Land Use Type	4.2	4.2	9.5	7.3	0.3	0.5	6.3	3.2

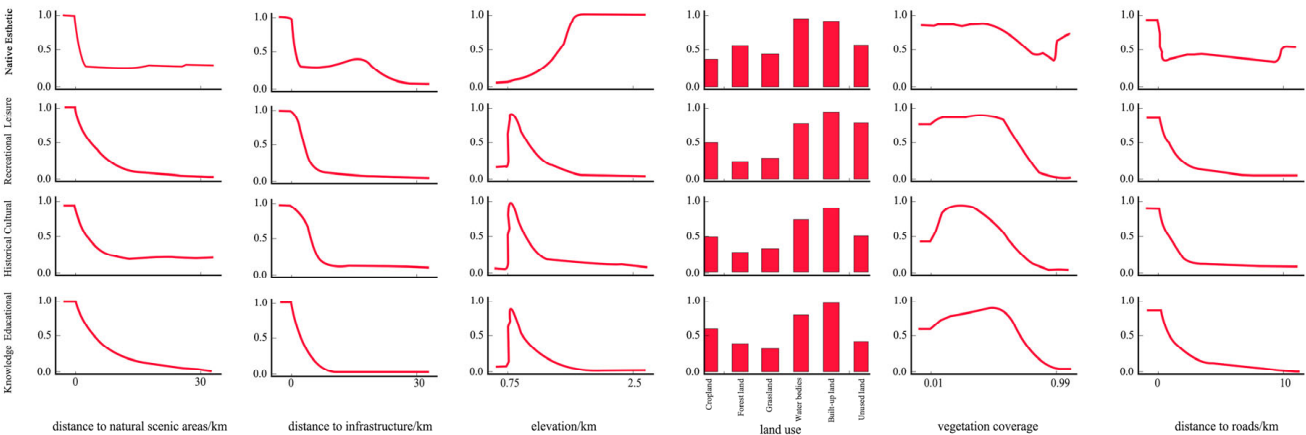


Figure 8. Response curves of supply spatial distribution to environmental factors.

The CESs in the Loess Plateau study area are significantly influenced by natural environmental factors, particularly climatic conditions and land use patterns. Climatic conditions critically shape vegetation growth and seasonal landscape dynamics, thereby affecting esthetic value perceptions. The land use diversity and fractional vegetation cover exert particularly prominent impacts on recreational and historical–cultural services, constructing complex interactive forces within compound ecosystem services and supporting recreational heterogeneity and accessibility. Notably, vegetation serves a dual function as both a physical carrier and spiritual symbol of cultural–historical memory while simultaneously maintaining and deepening historical–cultural services. Road proximity has emerged as a strong influencer across all CES types, underscoring the promotional effect of transportation accessibility on service provision. Enhanced road networks augment the connectivity between residential areas and scenic spots, facilitating element flow and increasing the CES supply capacity.

Despite their less pronounced contributions, factors such as the distance to water bodies, landscape diversity, and connectivity indices play integral roles in shaping inherent esthetic, recreational, and historical–cultural values. Slope and aspect exhibited minimal influences on recreational services (1.8% and 0.2%, respectively), whereas the annual average temperature (4.4%) and precipitation (8.3%) significantly impacted the inherent esthetic value. Notably, the distance to transportation hubs minimally affects educational value, which primarily targets specific learning groups and transcends spatial accessibility considerations by relying heavily on educational resource distribution. Conversely, the proximity to residential areas substantially influences historical–cultural values, reflecting the dependence of these services on human activity accumulation and cultural heritage preservation. This spatial relationship underscores the intricate interplay between settlement patterns and cultural landscape development.

3.3. Measurement and Spatial Expression of CES Demand in Taiyuan City

The spatial distribution of individual CES demand indicators exhibited relative consistency, characterized by a high central concentration with multiple dispersed cores (Figure 9). Peak population densities were observed in Taiyuan City’s central urban area, specifically in the southern Xinghualing District (Balingqiao, Xinghualing), western Yingze District (Qiaodong, Yingze), northern Xiaodian District (Pingyanglu, Wucheng), and Wanbailin District (Xiayuan, Changfengxi). These areas are distinguished by their concentrated service infrastructure, numerous historical and cultural sites, and tourist attractions. Conversely, remote urban county–township peripheries and regions, exemplified by Loufan County’s central metropolitan area, demonstrate lower population densities. These regions are characterized by expansive blue–green spaces, a lower development intensity, and sparse populations and infrastructure. Consequently, these areas maintain superior ecological quality and significant development potential while exhibiting a lower overall CES demand.

The spatial distribution patterns of specific demographic groups exhibit notable consistency. The elderly population (aged 60 and above) is primarily concentrated in Xinghualing District and Yingze District, while the youth population (under the age of 14) is predominantly clustered in Xiaodian District, Xinghualing District, and Yingze District, necessitating enhanced public services and robust social support systems. In contrast, natural factors, such as land use intensity, display more pronounced spatial heterogeneity. While concentrated in Taiyuan City’s central urban area, a high land use intensity is also prominent in the core areas of townships and county towns, directly influencing regional CES demands. High-intensity areas typically form CES demand hotspots, characterized by elevated population densities and economic activity levels. The human activity intensity and GDP closely align with the overall population density, exhibiting a “high center, low periphery” spatial pattern. This economic concentration strongly correlates with population density, further catalyzing the CES demand in these areas.

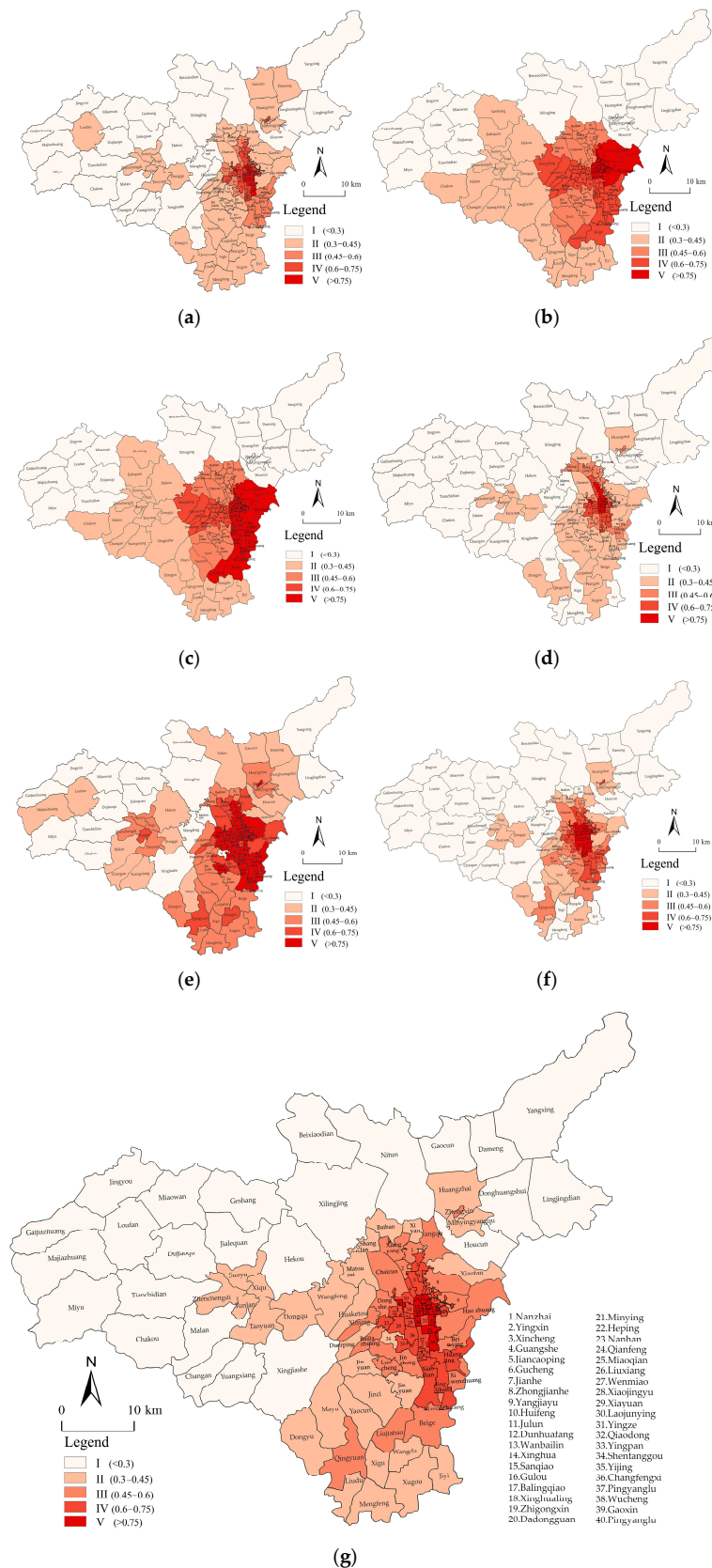


Figure 9. Classification map of cultural ecosystem services demand factors: (a) population density; (b) density of population over 60 years of age; (c) density of population under 14 years of age; (d) gross domestic product per unit area; (e) intensity of human activity; (f) development and construction intensity; and (g) classification map of total demand for cultural ecosystem services.

3.4. Analysis of CES Supply–Demand Balance and Coupling Coordination in Taiyuan City

The spatial matching analysis of the ecosystem cultural service supply and demand based on the Z-score standardization reveals four characteristic relationship patterns in Taiyuan City (Figure 10a,b): high supply–high demand (38.1%), low supply–low demand (37.2%), low supply–high demand (13.6%), and high supply–low demand (10.9%). High supply–high demand clusters predominantly concentrate along the Fen River corridor in the Xinghualing, Yingze, and Xiaodian Districts. These areas achieve a supply–demand synergy through concentrated historical relics (e.g., Kaihua and Shuangta Temples), favorable terrain conditions, and dense transportation networks. Low supply–low demand zones are extensively distributed across the Lüliang Mountain ranges in western regions and Xizhou Mountain areas in the northeast and are constrained by topographic fragmentation and sparse population density, forming dual-deficit depressions.

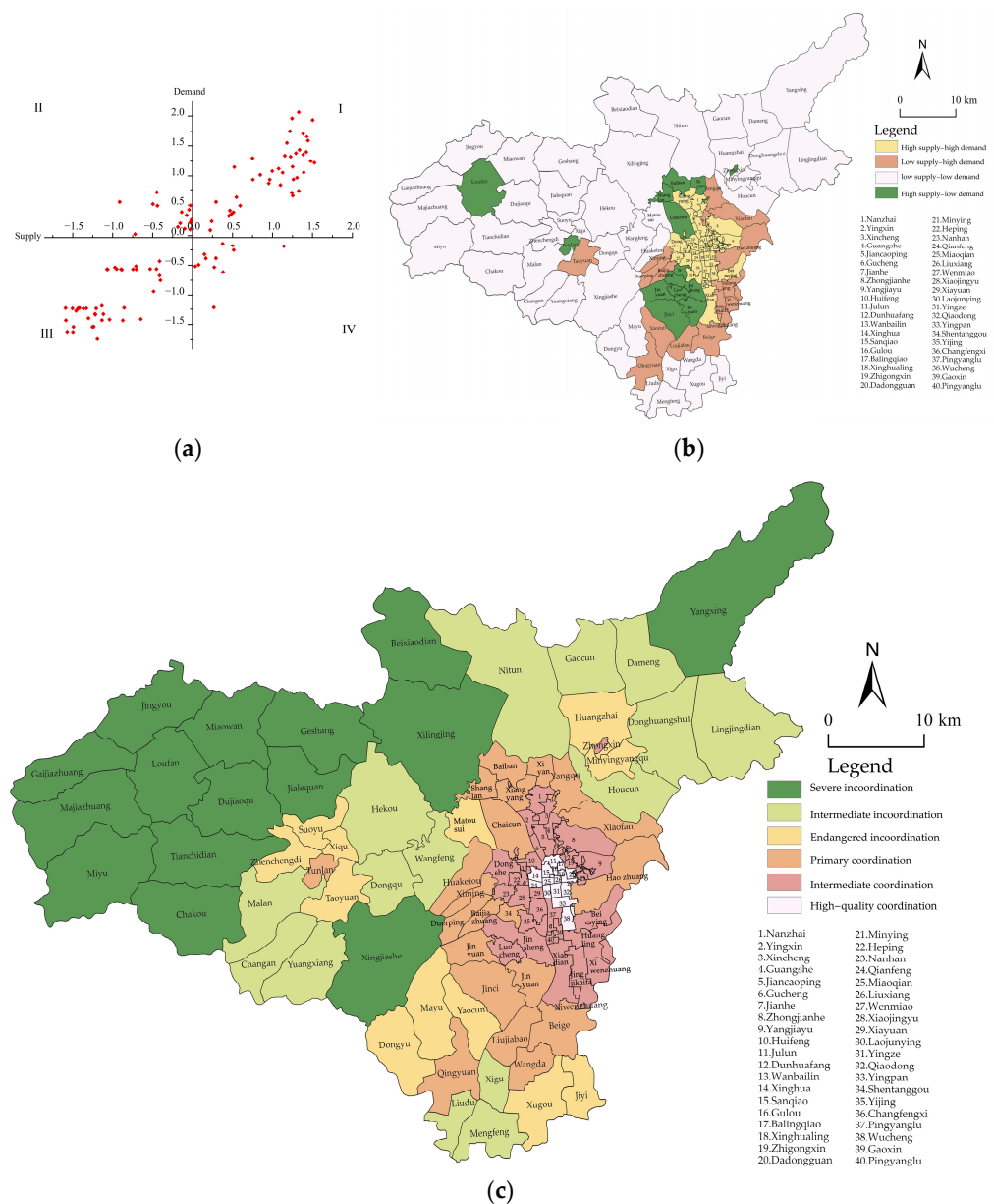


Figure 10. CES supply and demand diagram: (a) supply and demand scatterplot; (b) supply and demand balance diagram; and (c) CES supply and demand coupling harmonization.

Among mismatched types, low supply–high demand areas primarily cluster in transitional urban–rural zones, like Haozhuang Town (Yingze District) and Beige Town (Xiaodian

District), where acute contradictions between a high population density and inadequate cultural infrastructure coverage highlight service provision lags during rapid urbanization. Conversely, high supply–low demand areas occur in suburban ecological nodes, such as Jinci Town (Jinyuan District), where premium cultural heritage resources (e.g., Tianlong Mountain Grottoes) remain underutilized due to their low population density. Spatial matching patterns demonstrate that the topographic gradient and population density jointly shape heterogeneous supply–demand configurations, establishing a foundational framework for the subsequent coupled coordination mechanism analysis.

The analysis of the supply–demand coupling coordination model reveals significant spatial heterogeneity in the cultural service coordination across Taiyuan City (0.16–0.98), with its distribution pattern closely correlated with topographic features and rapid urbanization processes (Figure 10c). The average coordination degree of 0.65 indicates an overall primary coordination stage. Spatially, the coupling coordination degree demonstrates a concentric attenuation pattern radiating outward from core areas of high-quality coordination in historic urban centers, such as the Gulou, Sanqiao, and Balingqiao sub-districts. Intermediate coordination zones predominantly cluster along both banks of the Fen River in central urban areas. Primary coordination and endangered incoordination areas form concentric aggregations around intermediate coordination zones and certain county–township centers. Intermediate incoordination areas exhibit patchy distribution patterns in northern and central regions, while severed incoordination primarily occurs in western peripheries.

The coordination model analysis shows 43.64% of township-level units achieving coordinated development, mainly concentrated in the Fen River alluvial plain. Sixteen subdistricts (14.55%) attain high-quality coordination, characterized by spatial maxima in both supply and demand values. These areas benefit from a high population density and developed infrastructure, where historical–cultural assets (e.g., Chunyang Palace) and ecological landscapes (e.g., Xihaizi Park) synergistically create a positive feedback loop through cultural memory mechanisms, effectively transforming green space services into emotional identity carriers. Excessive development areas contain 18.19% primary coordination and 10.09% endangered incoordination zones, showing concentric distributions around coordinated development regions. These areas maintain positive feedback mechanisms through their favorable topography (Figure 1c) and concentrated populations (Figure 9a), enhancing the cultural service synergy. In contrast, 27.28% of uncoordinated development areas are concentrated in mountainous regions of the Lvliang and Taihang ranges. Severely uncoordinated townships, like Yangxing and Gaijiazhuang, exhibit “low supply–low demand” lock-in effects, revealing mountain social–ecological system vulnerabilities: topographic fragmentation impedes coordination through dual pathways—elevated altitudes directly reduce service accessibility, while population emigration indirectly weakens the cultural demand intensity.

Notably, the anomalous coordination degree peak in Loufan Town suggests that institutional interventions (ecological compensation policies) can partially overcome topographic constraints. Meanwhile, certain suburban subdistricts like Jinci Town (Jinyuan District), despite favorable terrain conditions, exhibit low supply characteristics, exposing spatial planning deficiencies in the delayed allocation of cultural land use during rapid urbanization. These findings contrast markedly with coordination mechanisms observed in plain cities’ cultural ecosystem services, validating the unique applicability of the “topography–institution–economy” tripartite driving model in mountainous urban contexts.

4. Discussion

4.1. Comparative Analysis of MaxEnt Model and Other Methods

This study selected the MaxEnt model integrated with POI data to quantitatively assess the spatial distribution value of CESs. The core advantage of the MaxEnt model lies in its ability to integrate multi-source geospatial data, including environmental variables and POI-based social preferences, and to predict the CES supply potential through probabilistic distribution mapping. Compared to other mainstream evaluation systems, such as SolVES and participatory mapping, MaxEnt demonstrates unique advantages in capturing the spatial heterogeneity and nonlinear interactions between natural and anthropogenic factors [37].

The SolVES model primarily relies on questionnaire-based social value mapping. While it can precisely quantify subjective perceived values, such as native esthetic or historical cultural values, it faces scalability challenges in rapidly urbanizing areas due to high survey costs and insufficient timelines. Currently, it is commonly applied to small- and medium-scale CES studies. For instance, Huo et al. evaluated the cultural ecosystem service value of southern ecological parks in Wuyi County using the SolVES model [56]. To address the model's subjectivity, they supplemented it with the willingness-to-pay method to enhance the result reliability, thereby better reflecting stakeholder preferences. Compared to the MaxEnt model, SolVES can quantify the social value of cultural services but requires extensive survey data for large-scale studies, with results constrained by sample sizes and temporal limitations. In contrast, the MaxEnt model, relying more on environmental variables and devoid of subjective data inputs, typically achieves higher AUC values and a superior prediction accuracy. This study further combines MaxEnt with POI data to comprehensively assess data-scarce scenarios, such as high-altitude areas in the study region.

Participatory mapping involves collaborative map creation by community members to reflect local spatial perceptions and resource needs. It is widely used in rural development, ecological planning, and small- to medium-scale CES studies. For example, Dumitru et al. investigated the cultural service value of Băneasa Forest through participatory mapping, demonstrating its effectiveness in capturing resident preferences and informing community planning [57]. However, compared to MaxEnt, participatory mapping results are more susceptible to respondents' subjective preferences, requiring a careful balance between efficiency and standardization. Additionally, its resource demands (time, funding, and expertise) pose greater challenges for large-scale studies. In comparison, MaxEnt constructs a flexible framework connecting objective facility distribution (via POI data as "presence points") with subjective visitation preferences, mitigating an excessive reliance on subjective biases inherent in participatory mapping.

In CES supply–demand relationship studies, scholars have combined MaxEnt and participatory mapping to separately investigate CES supply and demand values. Participatory mapping compensates for MaxEnt's neglect of social attributes, while MaxEnt enables a precise quantitative CES valuation. Future research could enhance the integration of these methods, such as using MaxEnt to delineate supply hotspots and employing internet-based participatory mapping to validate demand priorities. This integrated approach would achieve comprehensive CES assessments across multiple scales, preserving policy-relevant spatial outputs while enhancing inclusivity in cultural service planning through community engagement.

4.2. Spatial Distribution and Influencing Factors of CES Supply and Demand in Taiyuan City

This study addresses a crucial aspect in CES research by investigating the spatial relationships between supply and demand across different service categories, building

upon previous studies [58,59]. Taiyuan City was selected as the study area due to its representative status as a rapidly urbanizing region in China and its distinctive topographic characteristics within the Yellow River Basin. We developed a comprehensive CES supply–demand evaluation system and research framework incorporating multi-dimensional indicators, which simultaneously considers urban development patterns and geomorphological features. The framework was enhanced by incorporating a coupling coordination degree model to analyze the synergistic evolution mechanisms within the supply–demand system. Our analytical framework elucidates the spatial differentiation characteristics of the CES supply and demand while revealing potential mismatches. The results indicate that Taiyuan exhibits a distinct “central agglomeration and peripheral diminution” spatial pattern, demonstrating a gradual decrease from urban core areas to rural peripheries. This spatial configuration aligns with findings from previous urban ecosystem services studies [60–63].

Taiyuan City’s central areas, straddling the Fenhe River, exhibited a high CES supply capacity, predominantly concentrated around blue–green landscapes, historical relics, temples, and nature reserves. These areas provided a robust infrastructure for visitors and residents alike, corroborating previous findings that regions with abundant natural landscapes and cultural attractions demonstrate a high CES supply potential [16,23,64–67]. However, accessibility limitations may constrain areas with an exceptionally high CES supply capacity, particularly in protected nature reserves. Urban green spaces near the city center primarily offer recreational value, while peripheral areas such as the Taigang Suburban Forest Park attract visitors through unique esthetic services and specialized infrastructure. This study further substantiated the significance of historical and cultural heritage for CES-related stakeholder groups [68] and the association between superior urban infrastructure and an enhanced CES supply potential [69–72].

In alignment with Taiyuan City’s spatial planning and development strategy, this investigation identified high-demand areas for CESs as predominantly located in densely populated urban–rural central regions or areas characterized by a relatively flat terrain. The overall CES demand exhibited a spatial distribution pattern that closely mirrored socio-economic activities. Simultaneously, the CES supply and resident demand demonstrate a generally high degree of congruence; instances of mismatch persist, underscoring the complex nature of ecosystem service dynamics. Notably, simplistic approaches to augmenting or diminishing the CES supply may not effectively modulate the resident demand [73]. The alignment of the CES supply and demand is a multifaceted, dynamic process influenced by a constellation of factors, including spatial heterogeneity, scale effects, policy coherence, and planning adaptability. A unilateral emphasis on supply-side adjustments is insufficient to achieve dynamic coupling and an equilibrium between supply and demand across multiple hierarchical levels and spatial scales. For instance, limited accessibility in certain areas may constrain effective CES provisions, whereas poor ecological network connectivity may impede the flow and transmission of CESs within urban green infrastructure systems.

This investigation identified the key factors that significantly influence CESs, including the proximity to natural scenic areas and infrastructure, elevation, land use typology, fractional vegetation cover, and road network accessibility. These findings align with the extant literature on critical variables in CES assessments, which are closely linked to landscape complexity and connectivity [16,62,64,74,75]. Landscape complexity is a crucial driver of biodiversity, and topographic factors serve as key variables affecting this complexity. The integration of topographic factors with supply and demand areas facilitates the determination of hierarchical CES value structures, enhances stakeholder comprehension, and facilitates regional planning. While high-value regions generally exhibit balanced supply–demand dynamics, persistent supply gaps are observed. Areas

such as Mayu and Liudu town in Qingxu County and Nitun and Huangzhai towns in Yangqu County demonstrate significant potential for rural tourism development. However, inefficient road networks impede access to high-altitude natural areas, particularly in eastern and western mountainous regions. Furthermore, the CES spatial distribution and value assessment may fluctuate seasonally, notably in inherent esthetic services. These seasonal variations significantly influence the spatiotemporal congruence between the CES supply and demand, underscoring the need for dynamic and adaptive management approaches to urban ecosystem service planning and conservation.

4.3. Urban–Rural CES Supply–Demand Balance and Coupling Coordination in Taiyuan City

The nexus between human well-being and CESs is intricately intertwined with the supply capacity of urban blue–green spaces and demand preferences. The research on CESs at the urban–rural interface remains nascent, predominantly focusing on quantitative value assessments owing to methodological constraints and limited data availability [75–77]. Constructing comprehensive evaluation indicator systems for supply and demand dimensions, coupled with the spatial coupling analysis of supply–demand relationships, presents significant challenges in contemporary research paradigms.

This study employs Z-score quadrants and the coupling coordination degree to investigate the holistic supply–demand relationship. The findings reveal that over half of the study area exhibits a congruity between coupling coordination levels and supply–demand distributions, yet discrepancies persist in specific regions. Although a relatively high overall consistency exists between the CES supply and residential demand, persistent mismatches remain evident according to supply–demand relationships. These manifest primarily as a CES undersupply in urban core areas and an oversupply in peripheral zones. As shown in Figure 10, neighborhoods including Jinsheng and Luocheng maintain a coordinated development status in the coupling coordination degree, yet still demonstrate internal high supply–low demand mismatches. Conversely, areas such as the Zhongxin urban district in Yangqu County, Huangzhai, and Minyingyang exhibit low supply–low demand matching patterns. Nevertheless, their concentrated internal resources and relatively developed infrastructure facilitate coordinated and transitional development trends in supply–demand coupling. Furthermore, within the spatial distribution pattern, the development of the Tai–Xin Integrated Economic Zone has shifted urban expansion toward southern and eastern regions. These areas demonstrate distinct advantages in the quantity, scale, and diversity of ecological infrastructure. However, they simultaneously represent primary locations for supply–demand conflicts. In regions like Haozhuang, Xiaofan, and Yangqu, rapid urbanization has outpaced planning efforts, hindering rational resource allocations.

Furthermore, the complex topography and inadequate transportation infrastructure in western and northern mountainous areas emerge as significant contributors to localized CES supply–demand imbalances. This observation suggests that the natural geographical conditions characteristic of basin cities, coupled with the temporal sequence of urban development, may be pivotal in shaping CES dynamics. These findings underscore the need for a nuanced, spatially explicit approach to CES management. Future urban planning and policy initiatives should aim to rectify existing mismatches by adopting adaptive strategies that account for both heterogeneous landscape characteristics and evolving socioeconomic fabrics.

The CES provision in Taiyuan City exhibits a pronounced urban–rural gradient influenced by the complex interplay of accessibility, topography, and socioeconomic development trajectories. This spatial heterogeneity is intricately linked to the infrastructure distribution, a consequence of rapid urbanization. Urban ecosystems—characterized by anthropogenic elements, such as designed parks and engineered water systems—prioritize

direct experiential services. In contrast, rural areas dominated by natural and semi-natural ecosystems excel in cultural heritage preservation and knowledge educational dissemination. The ongoing urbanization process continually reshapes demographic structures and socioeconomic attributes, influencing the spatiotemporal differentiation of the CES demand. Urban centers experience an increased demand for esthetic appreciation and recreational services, whereas rural areas face the challenges of demographic aging and population hollowing, potentially attenuating traditional CES demands. This dynamic interplay among urbanization, ecosystem characteristics, and societal demands underscores the complexity of CES provisions. Future policy initiatives should aim to bridge the urban–rural CES divide while preserving the unique cultural and ecological values inherent to each landscape.

Future endeavors should prioritize the construction of an integrated urban–rural green infrastructure network and the enhancement of ecological corridor development to facilitate a seamless flow and efficient transmission of CESs across the urban–rural gradient. Critical measures for optimizing spatial supply–demand matching and mitigating the urban–rural disparity include improving the spatial connectivity and service-sharing capacity of urban and rural ecosystems and enhancing the transportation infrastructure in rural areas to augment residents’ accessibility to CES resources. In the process of spatial planning and policy formulation, a comprehensive consideration should be given to the heterogeneity of resource endowments and disparate development stages between urban and rural areas. By adopting this holistic strategy, policymakers can foster a more equitable distribution of CES benefits across the urban–rural continuum, thereby enhancing the overall regional sustainability and socio-ecological resilience.

4.4. Sustainable Development Management and Planning Recommendations Based on CES

Policy formulation and implementation play a pivotal role in mitigating CES supply–demand imbalances. The findings elucidate that the Fenhe River, serving as a significant geographical axis, crucially shapes the CES supply–demand pattern by functioning as an essential carrier of diverse services and a natural corridor guiding urban spatial optimization. Consequently, priority should be given to protecting and enhancing high-value CES areas within the Fenhe River basin to augment the overall CES value and sustainability. This study investigates CES supply–demand relationships using the Z-score quadrant method and a coupling coordination degree analysis. With reference to the relevant literature, we classified coupling coordination degrees into three categories (as shown in Table 8) [53,78]: Coordinated Development Zone, Excessive Development Zone, and Uncoordinated Development Zone, aiming to propose differentiated optimization measures for distinct development areas. Concurrently, this study employs the Z-score quadrant method to reflect the regional supply–demand status, providing targeted guidance for formulating internal optimization strategies within specific zones.

Table 8. Proportion of CES supply–demand coupling coordination degree categories in Taiyuan City.

Coupling Coordination Type		Coordination Degree	
Type	Percentage	Type	Percentage
Coordinated Development	38(43.64%)	High-quality Coordination	16 (14.55%)
		Intermediate Coordination	32 (29.09%)
Excessive Development	32(29.09%)	Primary Coordination	20 (18.19%)
		Endangered Incoordination	12 (10.09%)
Uncoordinated Development	30(27.28%)	Intermediate Incoordination	15 (13.64%)
		Severe Incoordination	15 (13.64%)

Differentiated optimization strategies should be implemented for regions exhibiting varying CES supply–demand relationships:

- (1) Coordinated Development Zone: Implement service value enhancements and resilience strengthening to improve the premium green space supply.

For high-supply–high-demand areas, focus on optimizing service precision in core zones. In regions with established CES foundations, enhance the management efficiency and service radiation capacity through policy guidance. For low-supply–high-demand areas, reinforce community co-governance mechanisms to create tourism routes connecting cultural facilities and scenic spots, promoting the coupling of ecological efficiency and cultural services for quality-oriented upgrades. Concurrently, strategically integrate unique cultural heritage resources with natural landscapes to develop distinctive eco-cultural tourism products. This approach enhances both the CES attractiveness and sustainable development capacity while safeguarding local biodiversity and historical–cultural heritage. Finally, given the relatively complete infrastructure in Coordinated Development Zones, establish a quality improvement system that prioritizes urban green space protection while upgrading infrastructure and monitoring mechanisms. Implement comprehensive, long-term monitoring and evaluation frameworks to ensure a dynamic supply–demand balance of CESs, achieving dual objectives of enhanced attractiveness and sustainable development.

- (2) Excessive Development Zone: Strengthen spatial connectivity and network transmission to activate green space service efficiency.

The Transitional Development Zone encompasses high-supply–low-demand, low-supply–high-demand, and low-supply–low-demand areas, primarily distributed in southern/western regions and county–town centers. For high-supply–low-demand areas, priority should be given to resolving spatiotemporal mismatches. This involves enhancing the systemic connectivity and functional complexity of recreational spaces like urban green areas, establishing flexible supply mechanisms to facilitate the transformation of single-function spaces into integrated nodes. For instance, in Jinci Town of the Jinyuan District, the optimization of CES facility types and spatial layouts should holistically consider the ecological carrying capacity, population distribution patterns, and industrial structure. While cultural tourism activities require rational development under policy support to stimulate local economic growth, cautious measures must prevent ecosystem degradation from overexploitation.

Concurrently, revitalizing underutilized facilities can enhance the CES supply's relevance and effectiveness. This should be complemented by strengthening ecological corridor construction to promote cultural exchange with supply-deficient areas and refining regional ecological compensation and benefit-sharing mechanisms. For low-supply–high-demand areas, the priority deployment of flexible service modules should target high-population-density zones. Composite ecological corridors along urban arterial roads should address green space service fragmentation and ecological efficiency attenuation. An emphasis should be placed on enhancing the CES transmission between new and old urban districts, achieving an adaptive transformation from rigid supply to flexible response systems.

- (3) Uncoordinated Development Zone: Implement cross-regional coordination and ecological reciprocity to reconstruct systemic service resilience.

The Uncoordinated Development Zone mainly comprises urban–rural fringe areas beyond central urban districts and certain townships, characterized by a relatively scarce resource distribution and weak overall attractiveness. Most townships belong to the low-supply–low-demand matching category. For nature reserves such as the Fenhe Reservoir and Yunding Mountain, the principle of protection priority with moderate development should be adhered to. Conduct comprehensive evaluations of natural elements including mountains, water bodies, forests, farmlands, lakes, and grasslands to strengthen ecosystem

conservation and restoration, thereby consolidating the ecological foundation for the CES supply.

On this basis, the strategic optimization of cultural–tourism infrastructure spatial layouts should be implemented to enhance CES accessibility and equity. Establish a cross-regional resource circulation through coordinated linkages with areas exhibiting higher supply levels, while developing distinctive tourism resources in pristine ecological zones. Specific intervention measures may include constructing specialized cultural facilities, attracting cultural industry investments, improving transportation networks, and enhancing protection measures in ecologically vulnerable areas. These collective efforts aim to promote socioeconomic development while minimizing adverse impacts on ecological environments.

4.5. Limitations of the Study and Future Prospects

The relationship between the CES supply and demand represents a complex and dynamic interplay between the natural and sociocultural ecosystems. Consistent with the extant literature, the MaxEnt model has been demonstrated to offer enhanced objectivity and efficacy compared to traditional qualitative approaches, such as questionnaires and interviews, providing robust spatial outputs and quantifying the relative influence of variables on resultant patterns [79]. Although this investigation demonstrates considerable scientific rigor and objectivity by synergistically combining the MaxEnt model with POI big data for regional CES supply mapping and assessments, certain methodological limitations persist.

First, although this study obtained high AUC values from the MaxEnt model, indicating an excellent prediction accuracy, the spatial mapping of POI data shows limitations in representing implicit CESs, such as local folk activities and informal social spaces. Simultaneously, the generation mechanism of POI data leads to an inadequate characterization of cultural demands from special populations, including elderly and low-income residents, thereby affecting the equity of the supply–demand matching analysis. Furthermore, the research lacks an exploration and assessment of cultural service preference differences among groups with varying ages, occupations, and socioeconomic backgrounds. Therefore, future studies could enhance the POI data selectivity by integrating subjective perception data from multiple stakeholders through questionnaires or participatory mapping before utilizing them as sample points, enabling a systematic analysis of cultural service preference disparities across social groups. Additionally, incorporating geographically tagged photographs or other social media data could verify the accuracy and representativeness of POI data points, helping correct spatial biases in POI datasets and improve the comprehensiveness of the demand characterization.

Second, due to the intangible nature of CESs and the scale limitations of the study area, we defined and quantified cultural service supply through multi-source literature references, employing POI data integrated with the MaxEnt model to assess the CES supply potential. However, it should be noted that while POI data do not directly reflect CES quality, the MaxEnt model captures ecological characteristics related to CES quality through environmental variable integration. Nevertheless, the model's environmental suitability focus excludes socio-institutional factors, such as governance capacity and stakeholder preferences. Future research could therefore incorporate field surveys or social media text data to reflect stakeholder preferences, thereby advancing investigations into the actual CES supply.

Simultaneously, due to challenges in acquiring comprehensive socioeconomic data, our demand indicator construction primarily considered static demands derived from social and natural environments. This approach failed to fully account for dynamic

demand fluctuations arising from population agglomeration, preference heterogeneity across demographic groups, and multifaceted demand characteristics associated with functional land uses, such as agricultural land, medical facilities, educational institutions, and commercial centers.

Therefore, future research endeavors should incorporate qualitative analytical methods, such as structured questionnaires, semi-structured interviews, and participatory mapping techniques, to obtain subjective cognitive data from a diverse range of stakeholders. Additionally, an emphasis should be placed on quantifying the perception differences among various sociodemographic groups. Through a more granular socioeconomic data collection and analysis, researchers can capture the dynamic demands and evolving preferences of different population segments, thereby facilitating the construction of multi-dimensional demand models.

While this study constructed an evaluation index system for the urban CES supply and demand, it did not fully address the driving mechanisms and internal principles governing how individual indicators influence the overall supply and demand levels, thereby constraining the optimization of supply–demand imbalances. Future research could employ system dynamics and structural equation models to analyze the interactions among various indicators and their impact on supply–demand relationships, enabling the development of more effective optimization strategies through the precise control of influencing factors. Furthermore, as this study primarily investigates CES supply–demand relationships on a single temporal scale, future studies should adopt multi-temporal scale analysis methods to capture dynamic demands and preference changes among different population groups, integrating long-term monitoring data to explore the dynamic changes and driving factors of supply–demand relationships across various temporal scales.

5. Conclusions

This study developed an integrated CES supply–demand evaluation framework for rapidly urbanizing regions by combining the MaxEnt model with a coupling coordination degree model, revealing the spatiotemporal differentiation mechanisms and regulatory pathways of CESs. The findings demonstrate that, influenced by both topographic factors and socioeconomic development in Taiyuan City, all four CES categories exhibited similar spatial supply patterns characterized by “core-high-value areas with a peripheral decline”, while demand showed a “highly centralized center with multiple dispersed cores” spatial configuration. The methodological framework integrating multi-source data and spatial modeling demonstrates scalability, providing scientific support for ecological collaborative governance in similar global cities.

- (1) Supply–Demand Coupling Coordination Analysis and Spatial Management Implications. The coupling coordination analysis revealed an average coordination degree of 0.65 across the city, with spatial patterns closely associated with topographic characteristics and rapid urbanization. High CES supply areas were concentrated along the Fen River’s historical relics and nature reserves, spatially coinciding with urban scenic zones and ecological infrastructure. Demand hotspots coupled with population density and economic vitality, showing significant supply–demand mismatches in urban–rural transition areas. High coordination zones benefited from positive feedback effects of flat terrains, transportation accessibility, and population agglomeration, while low coordination areas were distributed in the hinterlands of Lüliang and Taihang Mountains. The environmental factor analysis identified the terrain gradient and transportation accessibility as key drivers of the CES spatial differentiation. We recommend prioritizing ecological network restoration in low-supply areas to enhance service capacity, while activating cultural heritage resources in low-demand regions

- through cultural–tourism integration, such as incorporating underutilized heritage sites, like the Tianlong Mountain Grottoes in Jinci Town, into regional tourism routes.
- (2) **Methodological Innovations and Limitations.** Methodologically, this study innovatively integrated POI data with the MaxEnt model by analogizing the cultural service distribution to “species habitats”, enabling the objective quantification of the CES supply potential. The dual-dimensional supply–demand coupling framework overcame static limitations of traditional Z-score matching, identifying systemic imbalance origins in urban–rural systems. However, POI data’s inadequate coverage of informal cultural spaces (e.g., traditional villages) may introduce a spatial bias and underrepresent marginalized groups’ cultural needs. Future research should integrate participatory mapping and a social media sentiment analysis to establish an “objective facilities-subjective values” dual-dimensional index system, such as supplementing indigenous ritual site data through community interviews to enhance the assessment inclusiveness.
 - (3) **Framework Universality and Application Strategies.** The modular structure enables dynamic parameter adjustments for different urbanization stages and ecological contexts: in ecologically fragile mountainous cities (e.g., Kathmandu, Nepal), CES supply assessments could be enhanced by replacing terrain factors (emphasizing slope stability) and modifying local cultural POI classifications (adding religious sites and hiking trails). For industrial heritage transformation regions (e.g., Ruhr Area, Germany), analyses should focus on industrial heritage reuse and the green infrastructure supply–demand balance, incorporating economic transition indicators like industrial substitution rates. The cross-scale adaptability enables multi-level planning applications: a macro-level analysis could combine nighttime light data and transportation networks to identify regional CES flow corridors, while a micro-level implementation might utilize high-resolution remote sensing and a social media sentiment analysis to capture community demand dynamics. Addressing common challenges in rapid urbanization (e.g., ecological restoration vs. heritage preservation conflicts), our socio-ecological synergy model proposes strategies like digital platforms for cross-administrative cultural resource sharing and ecological compensation mechanisms to alleviate terrain constraints. Future research should validate the global applicability through a case database construction and parameter sensitivity testing, ultimately providing technical support for international cultural heritage conservation and urban sustainable development.

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References

- Ostrom, E. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* **2009**, *325*, 419–422. [[CrossRef](#)] [[PubMed](#)]
- Lu, D.; Liu, W. The Significance, Progress and Future Tasks of an Integrated Study of Geo-Dynamics Behind Regional Development. *Adv. Earth Sci.* **2003**, *18*, 12.
- MEA. *Millennium Ecosystem Assessment: Ecosystems and Human Well-Being*; Island Press: Washington, DC, USA, 2005.
- Zhao, Y.; You, W.; Lin, X.; He, D. Assessing the Supply and Demand Linkage of Cultural Ecosystem Services in a Typical County-Level City with Protected Areas in China. *Ecol. Indic.* **2023**, *147*, 109992. [[CrossRef](#)]
- Zhong, J.; Gao, M.; Han, Z.; Zhou, C.; Yan, X. Spatial reconstruction of the human-land relationship based on cultural ecosystem services. *ACTA Geogr. Sin.* **2024**, *79*, 1682–1699.
- Plieninger, T.; Dijks, S.; Oteros-Rozas, E.; Bieling, C. Assessing, Mapping, and Quantifying Cultural Ecosystem Services at Community Level. *Land Use Policy* **2013**, *33*, 118–129. [[CrossRef](#)]
- Tu, X.; Chang, Q.; Van Eetvelde, V.; Li, L. How Do Visitors' Perceptions Differ from the Supply of Cultural Ecosystem Services in Urban Parks? A Case Study from Beijing. *Int. J. Sustain. Dev. World Ecol.* **2023**, *30*, 883–896. [[CrossRef](#)]
- Schmidt, K.; Walz, A.; Jones, I.; Metzger, M.J. The Sociocultural Value of Upland Regions in the Vicinity of Cities in Comparison with Urban Green Spaces. *Mt. Res. Dev.* **2016**, *36*, 465–474. [[CrossRef](#)]
- Assandri, G.; Bogliani, G.; Pedrini, P.; Brambilla, M. Beautiful Agricultural Landscapes Promote Cultural Ecosystem Services and Biodiversity Conservation. *Agric. Ecosyst. Environ.* **2018**, *256*, 200–210. [[CrossRef](#)]
- Zhuang, S.; Gong, J.; Chen, K.; Li, J. Supply and demand matching characteristics of cultural ecosystem services of small parks and greenbelts in the Guangdong-Hong Kong-Macao Greater Bay Area. *Acta Ecologica Sin.* **2023**, *43*, 5714–5725.
- Bagstad, K.; Semmens, D.; Ancona, Z.; Sherrouse, B. Evaluating Alternative Methods for Biophysical and Cultural Ecosystem Services Hotspot Mapping in Natural Resource Planning. *Landsc. Ecol.* **2017**, *32*, 77–97. [[CrossRef](#)]
- Brown, G.; Montag, J.; Lyon, K. Public Participation GIS: A Method for Identifying Ecosystem Services. *Soc. Nat. Resour.* **2012**, *25*, 633–651. [[CrossRef](#)]
- Ridding, L.; Redhead, J.; Oliver, T.; Schmucki, R.; McGinlay, J.; Graves, A.; Morris, J.; Bradbury, R.; King, H.; Bullock, J. The Importance of Landscape Characteristics for the Delivery of Cultural Ecosystem Services. *J. Environ. Manage.* **2018**, *206*, 1145–1154. [[CrossRef](#)] [[PubMed](#)]
- Tian, T.; Sun, L.; Peng, S.; Sun, F.; Che, Y. Understanding the Process from Perception to Cultural Ecosystem Services Assessment by Comparing Valuation Methods. *Urban Green* **2021**, *57*, 126945. [[CrossRef](#)]
- Zhu, W.; Zhang, Z.; Zhang, H.; Tovvudorj, R. Integrating Spatial Patterns and Driving Factors of Cultural Ecosystem Services into Territorial Spatial Governance: A Case Study of the Horqin Sandy Land with Multi-Ethnic Settlements. *Habitat Int.* **2024**, *148*, 103093. [[CrossRef](#)]
- He, S.; Su, Y.; Shahtahmassebi, A.; Huang, L.; Zhou, M.; Gan, M.; Deng, J.; Zhao, G.; Wang, K. Assessing and Mapping Cultural Ecosystem Services Supply, Demand and Flow of Farmlands in the Hangzhou Metropolitan Area, China. *Sci. Total Environ.* **2019**, *692*, 756–768. [[CrossRef](#)]
- Zhong, J.; Gao, M.; Zhao, Y.; Peng, S.; Wang, M. Spatial variation of the cultural ecosystem services pattern and influencing factors in the coastal areas: Evidence from Ramsar Sites in China. *Acta Geogr. Sin.* **2024**, *79*, 76–96.
- Zuo, Y.; Zhang, L. Research on Local Ecosystem Cultural Services in the Jiangnan Water Network Rural Areas: A Case Study of the Ecological Green Integration Demonstration Zone in the Yangtze River Delta, China. *Land* **2023**, *12*, 1373. [[CrossRef](#)]
- Ghermandi, A. Integrating Social Media Analysis and Revealed Preference Methods to Value the Recreation Services of Ecologically Engineered Wetlands. *Ecosyst. Serv.* **2018**, *31*, 351–357. [[CrossRef](#)]
- Oteros-Rozas, E.; Martin-Lopez, B.; Fagerholm, N.; Bieling, C.; Plieninger, T. Using Social Media Photos to Explore the Relation between Cultural Ecosystem Services and Landscape Features across Five European Sites. *Ecol. Indic.* **2018**, *94*, 74–86. [[CrossRef](#)]
- Sinclair, M.; Mayer, M.; Woltering, M.; Ghermandi, A. Using Social Media to Estimate Visitor Provenance and Patterns of Recreation in Germany's National Parks. *J. Environ. Manage.* **2020**, *263*, 110418. [[CrossRef](#)]
- Li, X.; Xu, L.; Tian, S.; Yang, J.; Liu, M.; Liu, H. Human Settlements in China Based on the Geographical Scale. *Sci. Geogr. Sin.* **2022**, *42*, 951–962. [[CrossRef](#)]
- Wei, J.; Chen, M.; Chu, C.; Zhao, C.; Xia, X.; Li, Y. Assessing Cultural Ecosystem Services Supply–Demand Balance of Urban Parks in the Context of Old and New Urban Districts. *Ecol. Indic.* **2024**, *159*, 111688. [[CrossRef](#)]
- De Valck, J.; Broekx, S.; Liekens, I.; De Nocker, L.; Van Orshoven, J.; Vranken, L. Contrasting Collective Preferences for Outdoor Recreation and Substitutability of Nature Areas Using Hot Spot Mapping. *Landsc. Urban Plan.* **2016**, *151*, 64–78. [[CrossRef](#)]
- Qiao, X.; Gu, Y.; Zou, C.; Xu, D.; Wang, L.; Ye, X.; Yang, Y.; Huang, X. Temporal Variation and Spatial Scale Dependency of the Trade-Offs and Synergies among Multiple Ecosystem Services in the Taihu Lake Basin of China. *Sci. Total Environ.* **2019**, *651*, 218–229. [[CrossRef](#)] [[PubMed](#)]

26. Phillips, S.; Dudík, M. Modeling of Species Distributions with Maxent:: New Extensions and a Comprehensive Evaluation. *Ecography* **2008**, *31*, 161–175. [\[CrossRef\]](#)
27. Clemente, P.; Calvache, M.; Antunes, P.; Santos, R.; Cerdeira, J.O.; Martins, M.J. Combining Social Media Photographs and Species Distribution Models to Map Cultural Ecosystem Services: The Case of a Natural Park in Portugal. *Ecol. Indic.* **2019**, *96*, 59–68. [\[CrossRef\]](#)
28. Gosal, A.; Geijzendorffer, I.; Václavík, T.; Poulin, B.; Ziv, G. Using Social Media, Machine Learning and Natural Language Processing to Map Multiple Recreational Beneficiaries. *Ecosyst. Serv.* **2019**, *38*, 100958. [\[CrossRef\]](#)
29. He, S.; Hu, C.; Li, J.; Wu, J.; Xu, Q.; Lin, L.; Zhu, C.; Li, Y.; Zhou, M.; Zhu, L. Revealing Spatial Patterns of Cultural Ecosystem Services in Four Agricultural Landscapes: A Case Study from Hangzhou, China. *Int. J. Environ. Res. Public. Health* **2022**, *19*, 9269. [\[CrossRef\]](#)
30. You, C.; Qu, H.; Feng, C.-C.; Guo, L. Evaluating the Match between Natural Ecosystem Service Supply and Cultural Ecosystem Service Demand: Perspectives on Spatiotemporal Heterogeneity. *Environ. Impact Assess. Rev.* **2024**, *108*, 107592. [\[CrossRef\]](#)
31. Erskine, E.; Baillie, R.; Lusseau, D. Marine Protected Areas Provide More Cultural Ecosystem Services than Other Adjacent Coastal Areas. *One Earth* **2021**, *4*, 1175–1185. [\[CrossRef\]](#)
32. Xia, C.; Guo, H.; Zhao, J.; Xue, F.; Wang, C.; Zhou, J.; Sun, T.; Li, S.; Zhang, N. Dynamic responses of ecosystem services to urbanization at multi-spatial scales in the Beijing-Tianjin-Hebei region. *Acta Ecologica Sin.* **2023**, *43*, 2756–2769.
33. Kosanic, A.; Petzold, J. A Systematic Review of Cultural Ecosystem Services and Human Wellbeing. *Ecosyst. Serv.* **2020**, *45*, 101168. [\[CrossRef\]](#)
34. Kang, N.; Xie, G.; Liu, C. Assessment of Society's Perceptions on Cultural Ecosystem Services in a Cultural Landscape in Nanchang, China. *Sustainability* **2023**, *15*, 10308. [\[CrossRef\]](#)
35. Langemeyer, J.; Baró, F.; Roebeling, P.; Gómez-Baggethun, E. Contrasting Values of Cultural Ecosystem Services in Urban Areas: The Case of Park Montjuic in Barcelona. *Ecosyst. Serv.* **2015**, *12*, 178–186. [\[CrossRef\]](#)
36. Tenerelli, P.; Demsar, U.; Luque, S. Crowdsourcing Indicators for Cultural Ecosystem Services: A Geographically Weighted Approach for Mountain Landscapes. *Ecol. Indic.* **2016**, *64*, 237–248. [\[CrossRef\]](#)
37. Li, C.; Huang, X.; Zhao, J.; Zhao, Z.; Mei, Z.; Chen, S. Progress and prospects of research on cultural ecosystem services. *Acta Ecol. Sin.* **2025**, *12*, 1–13. [\[CrossRef\]](#)
38. Haines-Young, R.; Potschin, M. Common International Classification of Ecosystem Services (CICES, Version 4.1). *Eur. Environ. Agency* **2012**, *33*, 107.
39. Kumar, P. *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*; Routledge: Oxfordshire, UK, 2012; ISBN 1-84977-548-6.
40. Li, Y.; Zhang, D.; Wang, K.; Huang, L. Supply-demand relationships of cultural ecosystem services in rural areas: A case study of Huzhou City, Zhejiang Province. *Acta Ecologica Sin.* **2022**, *42*, 6888–6899.
41. Csurgó, B.; Smith, M. The Value of Cultural Ecosystem Services in a Rural Landscape Context. *J. Rural Stud.* **2021**, *86*, 76–86. [\[CrossRef\]](#)
42. Koh, Y.F.; Loc, H.H.; Park, E. Towards a “City in Nature”: Evaluating the Cultural Ecosystem Services Approach Using Online Public Participation GIS to Support Urban Green Space Management. *Sustainability* **2022**, *14*, 1499. [\[CrossRef\]](#)
43. Wang, Z.; Xu, M.; Lin, H.; Qureshi, S.; Cao, A.; Ma, Y. Understanding the Dynamics and Factors Affecting Cultural Ecosystem Services during Urbanization through Spatial Pattern Analysis and a Mixed-Methods Approach. *J. Clean. Prod.* **2021**, *279*, 123422. [\[CrossRef\]](#)
44. Martin, D.; Pititto, F.; Gil, J.; Paola Mura, M.; Bahamon, N.; Romano, C.; Thorin, S.; Schwartz, T.; Dutrieux, E.; Bocquenet, Y. Long-Distance Influence of the Rhone River Plume on the Marine Benthic Ecosystem: Integrating Descriptive Ecology and Predictive Modelling. *Sci. Total Environ.* **2019**, *673*, 790–809. [\[CrossRef\]](#) [\[PubMed\]](#)
45. West, A.M.; Kumar, S.; Brown, C.S.; Stohlgren, T.J.; Bromberg, J. Field Validation of an Invasive Species Maxent Model. *Ecol. Inform.* **2016**, *36*, 126–134. [\[CrossRef\]](#)
46. Di Pasquale, G.; Saracino, A.; Bosso, L.; Russo, D.; Moroni, A.; Bonanomi, G.; Allevato, E. Coastal Pine-Oak Glacial Refugia in the Mediterranean Basin: A Biogeographic Approach Based on Charcoal Analysis and Spatial Modelling. *Forests* **2020**, *11*, 673. [\[CrossRef\]](#)
47. Swets, J.A. Measuring the Accuracy of Diagnostic Systems. *Science* **1988**, *240*, 1285–1293. [\[CrossRef\]](#)
48. Merow, C.; Smith, M.J.; Silander, J.A., Jr. A Practical Guide to MaxEnt for Modeling Species' Distributions: What It Does, and Why Inputs and Settings Matter. *Ecography* **2013**, *36*, 1058–1069. [\[CrossRef\]](#)
49. Wang, M.; Wang, Y. Balance or Match? Multi-scenario Analysis and Optimization of Supply and Demand of Park Green Space with Ecological Wisdom. *Chin. Landsc. Archit.* **2021**, *37*, 37–42. [\[CrossRef\]](#)
50. Wang, M.; Zhu, A.; Wang, J.; Lu, T. Supply and demand analysis of urban park distribution based on social equity and justice: A case study of Xuhui District, Shanghai. *Acta Ecol. Sin.* **2019**, *39*, 7035–7046.

51. Gao, M.; Li, C.; Zhao, H. Spatiotemporal Pattern of Supply-Demand of Ecosystem Services and Influencing Factors in Jiangsu Province. *Res. Soil Water Conserv.* **2023**, *30*, 315–324. [\[CrossRef\]](#)
52. Chen, S.; Chen, L.; Hong, Y.; Liu, J.; Que, X.; Li, Y.; He, D.; Zhao, J. Ecological security evaluation and obstacle factors of Quanzhou Bay Wetland carbon pool. *J. Fujian Agric. For. Univ. Nat. Science Ed.* **2024**, *53*, 686–695. [\[CrossRef\]](#)
53. Zhao, H.; Li, C.; Gao, M. Investigation of the Relationship between Supply and Demand of Ecosystem Services and the Influencing Factors in Resource-Based Cities in China. *Sustainability* **2023**, *15*, 7397. [\[CrossRef\]](#)
54. Yang, Z.; Zhan, J.; Wang, C.; Twumasi-Ankrah, M.J. Coupling Coordination Analysis and Spatiotemporal Heterogeneity between Sustainable Development and Ecosystem Services in Shanxi Province, China. *Sci. Total Environ.* **2022**, *836*, 155625. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Zhang, D.; Chen, Y. Evaluation on Urban Environmental Sustainability and Coupling Coordination among Its Dimensions: A Case Study of Shandong Province, China. *Sustain. Cities Soc.* **2021**, *75*, 103351. [\[CrossRef\]](#)
56. Huo, S.; Huang, L.; Yan, L. Valuation of cultural ecosystem services based on SolVES: A case study of the South Ecological Park in Wuyi County, Zhejiang. *Acta Ecol. Sin.* **2018**, *38*, 3682–3691.
57. Duşcu, D.M.; Rîşnoveanu, G. Understanding Visitor Preferences: Perceived Importance of Anthropogenic and Natural Forest Features in Supplying Cultural Ecosystem Services. *For. Ecosyst.* **2025**, *13*, 100306. [\[CrossRef\]](#)
58. Ghasemi, M.; González-García, A.; Charrahy, Z.; Serrao-Neumann, S. Utilizing Supply-Demand Bundles in Nature-Based Recreation Offers Insights into Specific Strategies for Sustainable Tourism Management. *Sci. Total Environ.* **2024**, *922*, 171185. [\[CrossRef\]](#)
59. Liu, H.; Remme, R.; Hamel, P.; Nong, H.; Ren, H. Supply and Demand Assessment of Urban Recreation Service and Its Implication for Greenspace Planning-A Case Study on Guangzhou. *Landsc. Urban Plan.* **2020**, *203*, 103898. [\[CrossRef\]](#)
60. Bing, Z.; Qiu, Y.; Huang, H.; Chen, T.; Zhong, W.; Jiang, H. Spatial Distribution of Cultural Ecosystem Services Demand and Supply in Urban and Suburban Areas: A Case Study from Shanghai, China. *Ecol. Indic.* **2021**, *127*, 107720. [\[CrossRef\]](#)
61. Dang, H.; Li, J. Supply-Demand Relationship and Spatial Flow of Urban Cultural Ecosystem Services: The Case of Shenzhen, China. *J. Clean. Prod.* **2023**, *423*, 138765. [\[CrossRef\]](#)
62. Guo, R.-Z.; Lin, L.; Xu, J.-F.; Dai, W.-H.; Song, Y.-B.; Dong, M. Spatio-Temporal Characteristics of Cultural Ecosystem Services and Their Relations to Landscape Factors in Hangzhou Xixi National Wetland Park, China. *Ecol. Indic.* **2023**, *154*, 110910. [\[CrossRef\]](#)
63. Zhou, L.; Guan, D.; Huang, X.; Yuan, X.; Zhang, M. Evaluation of the Cultural Ecosystem Services of Wetland Park. *Ecol. Indic.* **2020**, *114*, 106286. [\[CrossRef\]](#)
64. Lorilla, R.; Kalogirou, S.; Poirazidis, K.; Kefalas, G. Identifying Spatial Mismatches between the Supply and Demand of Ecosystem Services to Achieve a Sustainable Management Regime in the Ionian Islands (Western Greece). *Land Use Policy* **2019**, *88*, 104171. [\[CrossRef\]](#)
65. Luo, Y.; Xu, H.; Zhang, J.; Chen, N.; Ye, H.; Lei, W. Magnifier or Refractor? Exploring the Impact of Geographical Indication on People's Perception of the Value of Cultural Ecosystem Services Based on the SolVES Model. *Front. Ecol. Evol.* **2023**, *11*, 1208169. [\[CrossRef\]](#)
66. Wang, L.; Huang, L.; Cao, W.; Zhai, J.; Fan, J. Assessing Grassland Cultural Ecosystem Services Supply and Demand for Promoting the Sustainable Realization of Grassland Cultural Values. *Sci. Total Environ.* **2024**, *912*, 169255. [\[CrossRef\]](#)
67. Chen, X.; Wu, C. Mapping and Assessing the Supply and Demand of Rural Recreation Services in National Parks: A Case Study of Qianjiangyuan, Zhejiang, China. *Land* **2025**, *14*, 302. [\[CrossRef\]](#)
68. Bachi, L.; Ribeiro, S.; Hermes, J.; Saadi, A. Cultural Ecosystem Services (CES) in Landscapes with a Tourist Vocation: Mapping and Modeling the Physical Landscape Components That Bring Benefits to People in a Mountain Tourist Destination in Southeastern Brazil. *Tour. Manag.* **2020**, *77*, 104017. [\[CrossRef\]](#)
69. Darvill, R.; Lindo, Z. The Inclusion of Stakeholders and Cultural Ecosystem Services in Land Management Trade-off Decisions Using an Ecosystem Services Approach. *Landsc. Ecol.* **2016**, *31*, 533–545. [\[CrossRef\]](#)
70. Kalinauskas, M.; Bogdzevic, K.; Gomes, E.; Inacio, M.; Barcelo, D.; Zhao, W.; Pereira, P. Mapping and Assessment of Recreational Cultural Ecosystem Services Supply and Demand in Vilnius (Lithuania). *Sci. Total Environ.* **2023**, *855*, 158590. [\[CrossRef\]](#)
71. Lan, X.; Tang, H.; Liang, H. A Theoretical Framework for Researching Cultural Ecosystem Service Flows in Urban Agglomerations. *Ecosyst. Serv.* **2017**, *28*, 95–104. [\[CrossRef\]](#)
72. Schaich, H.; Bieling, C.; Plieninger, T. Linking Ecosystem Services with Cultural Landscape Research. *GAIA Ecol. Perspect. Sci. Soc.* **2010**, *19*, 269–277. [\[CrossRef\]](#)
73. Burkhard, B.; Kroll, F.; Nedkov, S.; Müller, F. Mapping Ecosystem Service Supply, Demand and Budgets. *Ecol. Indic.* **2012**, *21*, 17–29. [\[CrossRef\]](#)
74. Wen, L.; Li, B.; Peng, Y.; Zhou, Y.; Weng, A.; Jin, Y.; Cai, G.; Lin, Y.; Chen, B. Exploring the Evolution of Coupled Natural-Cultural Ecosystem Services and Their Geographically Scaled Driven Modeling in a Coastal City of Southeast China. *J. Environ. Manage.* **2024**, *361*, 121265. [\[CrossRef\]](#) [\[PubMed\]](#)

75. Yang, Y.; Jiang, L.; Ma, X.; Liu, S.; Wang, L. A Comprehensive Approach to Identifying the Supply and Demand of Urban Park Cultural Ecosystem Services in the Megalopolis Area of Shanghai, China. *Land* **2025**, *14*, 455. [[CrossRef](#)]
76. Iniesta-Arandia, I.; Garcia-Llorente, M.; Aguilera, P.A.; Montes, C.; Martin-Lopez, B. Socio-Cultural Valuation of Ecosystem Services: Uncovering the Links between Values, Drivers of Change, and Human Well-Being. *Ecol. Econ.* **2014**, *108*, 36–48. [[CrossRef](#)]
77. Scholte, S.S.K.; van Teeffelen, A.J.A.; Verburg, P.H. Integrating Socio-Cultural Perspectives into Ecosystem Service Valuation: A Review of Concepts and Methods. *Ecol. Econ.* **2015**, *114*, 67–78. [[CrossRef](#)]
78. Yu, Y.; Yang, X.; L, X.; Qian, L.; Zhou, S. Supply-Demand Matching Evaluation and Coupling Coordination of Cultural Ecosystem Services in Urban Park Green Spaces. *Landsc. Archit.* **2025**, *32*, 90–99. [[CrossRef](#)]
79. Yoshimura, N.; Hiura, T. Demand and Supply of Cultural Ecosystem Services: Use of Geotagged Photos to Map the Aesthetic Value of Landscapes in Hokkaido. *Ecosyst. Serv.* **2017**, *24*, 68–78. [[CrossRef](#)]

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