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Integrating Cultural Ecosystem Services into the Optimization of Ecological Space in the Northern Foot of the Qinling Mountains

Yuanyuan Qin

School of Tourism & Artificial Intelligence, Xi'an International Studies University, Xi'an 710128, Shaanxi, China

ABSTRACT

Incorporating the assessment of Cultural Ecosystem Services (CES) into territorial spatial planning contributes to a comprehensive understanding of ecosystem service values and the optimization of ecological space layout. Due to the intangible nature of CES, objective evaluation and quantitative analysis face great challenges. Consequently, existing research on ecosystem services mostly focuses on tangible ecosystem services including provisioning, regulating and supporting services, while spatial assessment studies of CES remain scarce. How to quantify and spatially map CES, integrate it into the ecosystem service assessment framework and support spatial planning decision making has become a key topic in ecosystem service evaluation. Therefore, based on the general social ecological system framework, this study proposes an innovative approach to integrate cultural ecosystem services into the assessment of Biophysical Ecosystem Services (BES). Combining participatory questionnaire surveys with biophysical models, this study quantifies, optimizes and reorganizes four CES indicators and five BES indicators. It fully accounts for different scenarios of priority ranking of key ecological spaces before and after the inclusion of CES. The results show that: (1) Respondents reported the highest willingness to pay for mental health values; (2) CES presents an east high west low spatial distribution pattern; (3) Among BES, provisioning services are mainly distributed in the northern plains, whereas regulating and supporting services concentrate in the southern mountainous areas; (4) After incorporating CES, the priority levels of provisioning, regulating and supporting services change significantly. Some zones experience rank rises or declines caused by improved cultural functions or human disturbances. This research provides suggestions for ecological space optimization and sustainable land development in the northern foot of the Qinling Mountains.

KEYWORDS

Cultural Ecosystem Services; Biophysical Ecosystem Services; Spatial Distribution

1. INTRODUCTION

Ecosystem services play a vital role in providing fundamental ecosystem benefits for human well-being, safeguarding regional ecological security and improving residents' quality of life[1]. The Millennium Ecosystem Assessment (MEA) by the United Nations categorized cultural services as one of the four major groups of ecosystem services, alongside provisioning, regulating and supporting services[2]. Cultural services refer to non-material and socio-ecological benefits that people obtain through interactions with ecosystems, including spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences[2]. Nevertheless, compared with biophysical-dimensional evaluations of provisioning, supporting and regulating services, theories, methodologies and practical applications for assessing cultural ecosystem services still lag behind[3].

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Core bottlenecks include insufficient understanding of connotations and mechanisms, as well as fragmented assessment indicators lacking systematic integration[4, 5]. Systematic sorting and summary of existing studies are thus required. Optimizing ecological-space structure by incorporating cultural ecosystem services helps deepen cognition of natural-resource values, enhance capacity for benefit evaluation and problem diagnosis of ecological spaces, deliver evidence for trade-offs between conservation and development, and further promote coordinated human-land relationships.

Characterized by intangibility and difficulties in quantification, Cultural Ecosystem Services (CESs) are frequently underestimated. Their values are often embedded within total ecosystem-service value estimations, making them hard to isolate and apply effectively. In recent years, growing efforts have been made to integrate CES with biophysical-assessment outputs for spatial optimization, which substantially elevates the recognition and practical application of CES values. For instance, Vigna et al. adopted participatory mapping to acquire local stakeholders' spatial perceptions and scores for CES, constructing a wildfire-risk-assessment framework integrated with CES, which triggered prominent shifts in watershed risk grades[6]. Karimi et al. obtained value-related datasets via Public Participation GIS (PPGIS), identified biophysically high-value zones with the Zonation software based on species distributions, and quantified spatial overlaps of social-ecological hotspots using multiple importance thresholds (10 %, 30 %, 50 %) and spatial-overlay methods, producing hotspot-identification guidelines adaptable to different data conditions[7]. Bagstad et al. employed the SolVES model to obtain 11 value indicators via PPGIS, quantified four biophysical indicators such as carbon sequestration and water yield using the ARIES model, and compared six hotspot-identification approaches (including quantile-based, area-based and Getis-Ord Gi* statistics) to select optimal methods for landscape-scale planning[8]. Lin et al. quantified six biophysical indicators including carbon storage and habitat quality through the InVEST model, acquired 12 value indicators from crowdsourced surveys with the SolVES model, built a multi-scenario spatial-priority-analysis framework combining land-use-suitability models and Zonation software, and explored spatial trade-offs and synergies between two service categories via social-ecological matrices[9]. Although these approaches deliver valuable qualitative insights, they lack quantitative methodologies needed for embedding CES into township-scale ecological-space-optimization frameworks. Taking Horqin Sandy Land as a case, Zhu proposed a CES-BES framework integrating spatial patterns, driving factors of cultural ecosystem services and their interactions with biophysical ecosystem services. This framework mitigates dual pressures of ecological degradation and cultural conservation and generates practical recommendations for sustainable land development across Horqin Sandy Land[10].

Typical approaches for acquiring CES-perception information in current studies are survey-interview methods, covering open-ended in-depth interviews[11], semi-structured interviews[12] and willingness-to-pay surveys[13]. However, these approaches are constrained by sample sizes and site accessibility. The emergence of new data sources such as social-media data[14], maturation of participatory-mapping techniques[15], and application of MaxEnt-based SolVES models[16] enable systematic and comprehensive CES assessment. In fact, complex contradictions exist between human aspirations for nature and the carrying capacity of cultural ecosystem services supplied by natural environments. Therefore, analyzing spatially visualized integration relationships between cultural services and biophysical services, and generating maps identifying cold-spot and hot-spot zones of high-value social-biophysical services help planners and administrators clarify relationships between social and ecological values and offer new perspectives for territorial-spatial optimization. For example, Alessa et al. overlaid participatory-mapping-quantified perceived biological values with net primary-productivity outputs to produce social-ecological-hotspot maps[17]. Divergent indicator selections for CES directly produce deviations in spatial-optimization outcomes. Due to the complexity of CES connotations, indicator systems vary greatly across existing literature. Adopting overly niche and highly targeted indicators not only raises assessment difficulty but also reduces result universality and planning compatibility. Referring to internationally accepted classification systems and adhering to principles of simplified and practical-oriented planning indicators, this paper

selects four widely-adopted representative indicators covering core dimensions of residents' cultural demands, improving compatibility between assessment outputs and territorial-spatial planning. Significant divergences persist between supply-side and demand-side CES-assessment pathways, and demand-oriented evaluation fits practical planning better. Supply-side assessment merely focuses on biophysical properties of ecological spaces; some ecologically sound regions witness limited actual public utilization due to poor accessibility or insufficient socio-cultural recognition. By contrast, demand-side assessment centers on residents' practical usage preferences and spatial perceptions, better matching planning implementation requirements. Chan et al.[18], Haines-Young et al.[19] and the United Kingdom National Ecosystem Assessment (UK NEA) project pointed out that measuring human subjective feelings and perceptions of ecosystems from the demand dimension facilitates deepened understanding of CES value typologies[20]. CES lacks standardized monitoring-data systems. Available assessment datasets originate from interviews, PPGIS data, social-media big data and other sources. Multi-source-data integration faces considerable obstacles, and assessments for data-scarce regions remain challenging, introducing potential uncertainties into evaluation outputs. This study compensates for data gaps with physical-model simulations and delivers a feasible assessment scheme for the study area.

As a key component of the Qinling National Park, the northern foot of the Qinling Mountains performs critical functions in water-source conservation, soil-water retention and biodiversity maintenance, acting as a vital ecological barrier for Xi'an. Meanwhile, endowed with abundant natural landscapes and human-cultural resources, this region possesses high cultural-ecosystem-service values and serves as a core recreational "back garden" for citizens of Xi'an and surrounding populations. Building upon existing studies, this paper proposes an integrated CES-BES innovation framework, whose core is systematically embedding public-perception dimensions of CES into conventional biophysical-assessment systems for BES. It aims to evaluate discrepancies between assessment outputs with and without participatory-mapping-derived public input incorporated into traditional ecosystem-service evaluations. Three primary tasks are completed: first, quantify and evaluate spatial distributions and public preferences for four CES categories (mental health, landscape aesthetics, recreation-tourism and ecological education) across the study area through questionnaire surveys and the SolVES model; second, assess spatial patterns of five BES categories (biodiversity conservation, soil-water retention, water-source conservation, carbon sequestration and grain yield) using NPP-based quantitative indicators; third, integrate CES into BES evaluations with a CES-BES spatial-reconstruction-rule matrix, compare assessment differences under two scenarios, and ultimately advance ecological-space optimization for the northern foot of the Qinling Mountains. This methodology incorporates public perspectives into landscape planning and regional governance, enables local-resident participation in decision-making, and provides methodologies and recommendations for regional ecological conservation and sustainable development.

2. STUDY AREA

Located in the transition zone between the Qinling mountain range and the Guanzhong Plain, the northern foot of the Qinling Mountains covers four administrative units of Xi'an City: Zhouzhi County, Huyi District, Chang'an District and Lantian County, including 79 townships with a total area of approximately 7471.68 km^2. Characterized by a warm-temperate semi-humid continental monsoon climate, the region records annual average temperatures of 13-15 °C and annual precipitation of 600-800 mm. It hosts national first-class protected plants such as Abies chensiensis and Taxus chinensis, as well as multiple national first-class wild-animal species including giant panda, golden snub-nosed monkey and takin. Tributaries of the Wei River such as the Feng River, Lao River, Hei River and Ba River flow through this zone, which constitutes a critical water-source-conservation site and ecological-security barrier for Xi'an. Boasting diverse mountain, forest, river and wetland landscapes alongside profound historical-cultural heritage, the region possesses exceptional tourism

resources, containing eight national 4A-level or higher tourist attractions, one provincial-level nature reserve, and 14 municipal-level or higher cultural-relic-protection units (including eight Major Historical and Cultural Sites Protected at the National Level), receiving over 50 million tourist visits each year.

3. RESEARCH METHODS AND DATA SOURCES

3.1. Methods

An overview of analytical workflows adopted in this research is presented in Figure 2. Three sequential steps are implemented: first, quantification of cultural ecosystem services. Four relevant cultural-service indicators are selected referencing international-classification systems and regional-cultural characteristics. Questionnaire surveys generate source datasets; participatory-survey approaches evaluate stakeholder preferences for each value category, combined with the model analysis to compensate for missing sampling-site data and predict complete CES spatial distributions. Second, biophysical-indicator selection guided by policy objectives. Indicators are classified referencing the Millennium Ecosystem Assessment framework. Spatial mapping is conducted via NPP-quantitative methods and corresponding mathematical formulas. Third, layer combination of CES-BES datasets using a spatial-reconstruction-rule matrix. Two scenarios (with CES included / without CES included) are established; scenario-specific outputs are compared to propose spatial-guidance and optimization strategies for sustaining and enhancing CES within the study area.

3.1.1. CES-Assessment Methodology

Participatory mapping associates ecosystem-cultural-services utilized in daily human life with specific locations and geographic features, reflecting respondents' perceptions of their living environments. Thirty-four Grade-A scenic spots across the four counties and districts are selected as CES-value sampling points. Four categories of cultural-service values are assigned to respondents, who mark representative scenic sites for each value on paper-based maps (one point scored for each mark; multiple values may be assigned to a single location) (Table 1).

Table 1 Description of cultural-ecosystem-service-value typologies for the Qinling Mountains in Xi'an

Type of Cultural-Service Value	Description
Mental-health value	Functions of cultural ecosystem services that affect human brain structure and cognition and thereby improve human mental well-being.
Landscape value	Functions of cultural ecosystem services delivering aesthetic experiences and spiritual pleasure for humans, and further elevating values of surrounding land and real-estate properties.
Recreation-tourism value	Functions whereby aesthetic landscapes of ecosystems and co-existing human-cultural landscapes provide recreational-entertainment opportunities for humans.
Ecological-education value	Functions of ecosystems, their components and processes supplying foundational materials for formal and informal educational activities.

3.1.2. BES-Assessment Methodology

Following the Guidelines for Delimitation of Ecological-Protection Redlines[21] and the Technical Guidelines for Evaluating Resource-Environmental Carrying Capacity and Territorial-Spatial-Development Suitability (Trial)[22], five core biophysical-ecosystem-service indicators are identified: grain yield, water-source conservation, carbon sequestration, biodiversity conservation and soil-water retention, assigned to provisioning, regulating and supporting service categories respectively[23] (Table 2). Spatial quantification is performed for the five selected biophysical-ecosystem-service indicators. The Raster Calculator tool embedded in ArcGIS is utilized for mathematical-formula-driven computation. All factor datasets are standardized to 250-m-resolution raster data.

Table 2 Description of ecosystem-service indicators and corresponding methodologies

Primary Classification	Secondary Classification	Formula	Description and References
Provisioning	Grain yield	$Gij = (NDVIij / NDVImeanj) \times Gj$	Where i denotes the i-th grid cell within cultivated land of county j; Gij represents grain yield allocated to the i-th cultivated-land grid cell in county j; Gj stands for total grain yield of cultivated land in county j; NDVIij is NDVI value for the i-th cultivated-land grid cell in county j; NDVImeanj denotes average NDVI value of cultivated land within county j.Grain-yield supply forms the material foundation for local residents' livelihood and constitutes an ecosystem service[24]. Cultivated land represents the dominant land-use type for grain production. Normalized Difference Vegetation Index (NDVI) effectively reflects grain-yield potentials[25]. In this study, total grain yield is allocated to each grid cell proportional to the ratio between grid-cell NDVI and county-average cultivated-land NDVI, so as to estimate grain yield for each grid across the study area[26].
Regulating	Water-source conservation	$WR = NPPmean \times Fsic \times Fpre \times (1 - Fslo)$	Water-source conservation refers to ecosystem functions of intercepting, infiltrating and accumulating precipitation via unique ecosystem structures and water-ecosystem interactions, alongside regulating water flow and hydrological cycles through evapotranspiration. Service manifestations include mitigating surface runoff, recharging groundwater, smoothing seasonal river-flow fluctuations, flood regulation, water supply guarantee and water-quality maintenance[27, 28].
Regulating	Carbon sequestration	$CSi = 1.63 \times NPPi$	Carbon sequestration (CS) is evaluated based on net primary productivity (NPP) derived from vegetation photosynthesis, representing carbon

Primary Classification	Secondary Classification	Formula	Description and References
			uptake by plants minus respiratory carbon losses. Per unit NPP, vegetation sequesters 1.63 units of carbon[29].
Supporting	Biodiversity conservation	Sbio =NPPmean ×Fpre×Ftem ×Fdem	Biodiversity conservation represents ecosystem functions sustaining genetic, species and ecosystem diversity, closely correlated with richness of rare, endangered and endemic flora and fauna[30, 31].
Supporting	Soil-water retention	Spro = NPPmean ×(1−K)×(1 – Fslo)	As a core regulating service, soil-water retention describes ecosystem processes mitigating soil-loss risks through ecosystem structures and ecological processes[32, 33].

3.1.3. CES-BES Reconstruction Rules

This study constructs a CES-BES spatial-combination-rule matrix. First, BES outputs are classified into five grades (very low, low, medium, high, very high) via the natural-breaks method. Aggregated CES values are incorporated into BES assessments to evaluate changes triggered by CES inclusion. Land-use-transition matrix (Table 3) is adopted to combine CES and BES datasets and generate township-scale spatial-optimization layout maps.

Table 3 Combination rules for value-based land transitions

		Aggregated CES				
		Very high	High	Medium	Low	Very low
Provisioning Regulating Supporting	Very high	Very high	Very high	High	High	Medium
	High	Very high	High	High	Medium	Medium
	Medium	High	High	Medium	Medium	Low
	Low	High	Medium	Medium	Low	Low
	Very low	Medium	Medium	Low	Low	Very low

3.2. Data Sources

3.2.1. Collection of Social-Survey Data

Questionnaire surveys are implemented through on-site field investigations, including pilot surveys and formal surveys. Pilot investigations were conducted in mid-to-late June 2024 (\(n=45\), response rate 91.8 %) to validate questionnaire feasibility. Formal surveys were administered from June 28 to July 2, targeting residents aged 16 years or older in Lantian County, Chang'an District and Zhouzhi County of Xi'an City. A total of 218 questionnaires were recovered, with a response rate of 94.1 %. Questionnaires consist of four sections: Part 1 covers respondents' preferences and satisfaction toward four categories of cultural-ecosystem-service values; Part 2 investigates respondents' perceptions and impacts related to cultural-service values; Part 3 collects respondents'

socio-demographic background information; Part 4 records value-index information, i.e., locations perceived by respondents as possessing high cultural-ecosystem-service values alongside assigned scores. Referencing evaluation cases from San Isabel National Forest in the United States, Part 2 selects four cultural-service-value categories closely associated with Qinling ecological-cultural features in Xi'an, with appropriately revised value-category descriptions for respondent selection. Cultural-service-value allocations for interpreted photographs are assigned according to average values of each cultural-service-value indicator derived from on-site questionnaires.

3.2.2. Spatial-Data Sources

Geospatial datasets consist of vector, raster, processed within ArcMap 10.8 (Table 4).

Vector datasets: Administrative-division boundaries originate from the National Geomatics Center of China. Land-use types are categorized into six classes: cropland, forestland, grassland, water bodies, built-up land (urban settlements, rural residential sites, mining areas) and unused land. Cultural-service-value-point layers are generated by vectorizing value-marking points from respondent questionnaires within ArcGIS.

Raster datasets: Land-use data are obtained from the Resource and Environment Science and Data Center, Chinese Academy of Sciences, at 500-m spatial resolution. Digital-Elevation-Model (DEM) datasets are downloaded from the Geospatial-Data-Cloud website; slope layers are computed from DEM and clipped by study-area boundaries at 30-m resolution. Euclidean-distance tools within ArcGIS calculate distance-to-road (DTR) and distance-to-waterbody (DTW) raster layers derived from road and water-system vector datasets respectively. Monthly-averaged NDVI datasets are acquired from the National Tibetan Plateau Data Center. NPP datasets stem from national remote-sensing-based ecological-status-investigation-and-assessment outputs. NDVI and NPP datasets possess 250-m spatial resolution. Soil datasets originate from the Cold and Arid Regions Science Data Center with 1-km resolution.

All datasets are unified to raster format for raster-scale analysis, standardized to 250-m spatial resolution, and projected under the WGS_1984_Albers coordinate system.

Table 4 Detailed information of datasets

Serial Number	Dataset Name	Format	Data Source
1	Administrative-division boundary	Vector	National Geomatics Center of China (http://www.ngcc.cn)
2	Land-use dataset	Raster	Resource and Environment Science and Data Center, CAS (https://www.resdc.cn)
3	Digital Elevation Model (DEM)	Raster	Geospatial-Data-Cloud (https://www.gscloud.cn)
4	Distance-to-road layer	Raster	Vector digitization from Tianditu (https://www.tianditu.gov.cn)
5	Distance-to-water-system layer	Raster	Vector digitization from Tianditu (https://www.tianditu.gov.cn)
6	NDVI dataset	Raster	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn)
7	NPP dataset	Raster	National remote-sensing-based ecological-status-investigation-and-assessment outputs
8	Soil dataset	Raster	Cold and Arid Regions Science Data Center
9	Meteorological dataset	Raster	China Meteorological Data-Sharing Service Network (http://data.cma.cn)

4. RESULTS AND ANALYSIS

4.1. Respondent Demographics and Preference Selections

4.1.1. Demographic Analysis of Respondents

SPSS and Excel software are applied for statistical analysis of 219 valid questionnaires. Summary profiles of respondents are presented in Table 6. Male respondents account for 50.6 % and female respondents 49.3 %, with a male-to-female ratio of 1.03:1. Local Xi'an residents constitute 95.1 % of the sample. 61.6 % of respondents hold bachelor's or higher educational degrees. High educational attainment facilitates questionnaire comprehension and reduces survey-response errors. Age groups are relatively evenly distributed: 49.2 % of respondents are aged 16-35 years, and 37.3 % are aged 36-55 years. Occupational composition is dominated by freelancers (27.8 %) and enterprise employees (21.9 %). The largest income group earns 3000-5000 CNY per month (39.2 %). Adopting the widely-used 1-5-point Likert-scale questionnaire methodology, results reveal high overall public recognition of cultural-ecosystem-service values of the Qinling Mountains in Xi'an. Nevertheless, 14.1 % of respondents consider ecological-education values of the Qinling Mountains non-significant. More than 60 % of respondents are highly willing to recommend mental-health and landscape-aesthetic values of the Qinling Mountains to others, yet 18.2 % are reluctant to recommend participation in relevant ecological-educational activities.

4.1.2. Willingness-to-pay Estimation

One hundred virtual tokens are allocated by respondents across four categories of cultural-ecosystem-service values. Statistical outputs show that mental-health values receive the highest total allocation of 6465 virtual tokens, indicating outstanding overall contributions to cultural-value generation. Landscape values receive 4685 virtual tokens, recreation-tourism values 4260 virtual tokens, and ecological-education values 3790 virtual tokens, demonstrating total-value discrepancies across CES typologies. Mental-health-related cultural values attract comparatively higher public attention and engagement.

Refer to respondent willingness-to-pay distribution charts. The mode of willingness-to-pay for mental-health values equals 30 virtual tokens, whereas the mode for the other three value categories equals 20 virtual tokens. Distribution characteristics of willingness-to-pay for each value type are summarized. For mental-health values, willingness-to-pay averages 33.67 virtual tokens and clusters around the modal value of 30 virtual tokens. A standard deviation of 16.86 indicates substantial inter-individual divergence, with some respondents assigning far higher or lower values due to personal experiences and priority disparities. Willingness-to-pay for landscape values presents relatively even and ordered distributions with a mode of 20 virtual tokens and a mean value of 24.40 virtual tokens slightly exceeding the mode; a standard deviation of 12.63 suggests moderate dispersion. Recreation-tourism-value willingness-to-pay has a mode of 20 virtual tokens and a mean of 22.19 virtual tokens, with a comparatively large standard deviation of 14.26, reflecting dispersed distributions and heterogeneous public valuation benchmarks shaped by recreational-activity experiences and cost variations. Ecological-education-value willingness-to-pay features a mode of 20 virtual tokens and a mean of 19.74 virtual tokens close to the mode; its relatively small standard deviation of 12.14 demonstrates concentrated distributions, although segments of target audiences assign high perceived value to ecological-education services.

4.2. Spatial-Distribution Results of Cultural Ecosystem Services

Counting selection frequencies for each value type derived from respondent-drawn CES-distribution maps (Figure 1): mental-health value accumulates 513 marks, landscape value 309 marks, recreation-entertainment value 250 marks, and ecological-education value 222 marks.

Respondents demonstrate particularly strong preference for mental-health values. Sites such as Qinling National Botanical Garden and Taiping National Forest Park feature dense vegetation and tranquil environments. Activities including forest bathing and hiking enable visitors to escape urban noise, relieve stress and stabilize emotions, attaining “very high” mental-health-value rankings, corresponding to respondent counts ranging 48-60. By contrast, human-oriented or plain-land scenic sites such as Aguquan Peony Garden suffer heavy urban-environmental disturbances and deliver limited mental-stress-relief benefits, recording low selection frequencies with respondent counts concentrated within 0-12. Overall distribution traits show high-value and high-popularity scenic sites concentrated across central-western zones, while peripheral scattered sites register low values and low visitation.

Landscape values predominantly aggregate within eastern zones. Sites combining human-cultural relics and mountain-water scenery such as Bailuyuan Movie Town and Liuyu Feixia boast powerful visual aesthetic appeal and achieve high selection frequencies, with respondent counts of 24-36. Northern plain-land zones feature monotonous landscape configurations and low visitor attractiveness, with respondent counts mostly within 0-12. Accordingly, landscape-value magnitude correlates positively with distinctive natural geomorphology and strong visual impacts; eastern and southern mountainous zones stand out, while northern plain-land areas perform weakly.

High-value recreation-tourism sites are mostly situated in zones integrating unique natural scenery and profound historical-cultural heritage, for instance Bailuyuan Movie Town and South Wutai Mountain of Zhongnan Mountain. Sound infrastructure supports diverse recreational activities

including hiking, camping and summer retreats, forming popular mass-tourism destinations with respondent counts of 24-36. By comparison, undeveloped remote segments of Hei River Forest Park suffer poor transportation accessibility and deficient facilities and therefore possess low recreation-tourism values, with respondent counts of 0-12. This demonstrates tight correlations between recreation-tourism value, regional development intensity and visitor accessibility.

Ecological-education values concentrate within nature reserves and geoparks abundant in popular-science resources. These zones, furnished with popular-science signage, interpretive services and interactive facilities, constitute preferred venues for ecological-education practices, with respondent counts of 24-36. Certain mountainous sections of Lantian County lacking popular-science interpretive installations record low ecological-education values with respondent counts of 0-12, proving that ecological-education values are directly constrained by popular-science-resource allocations.

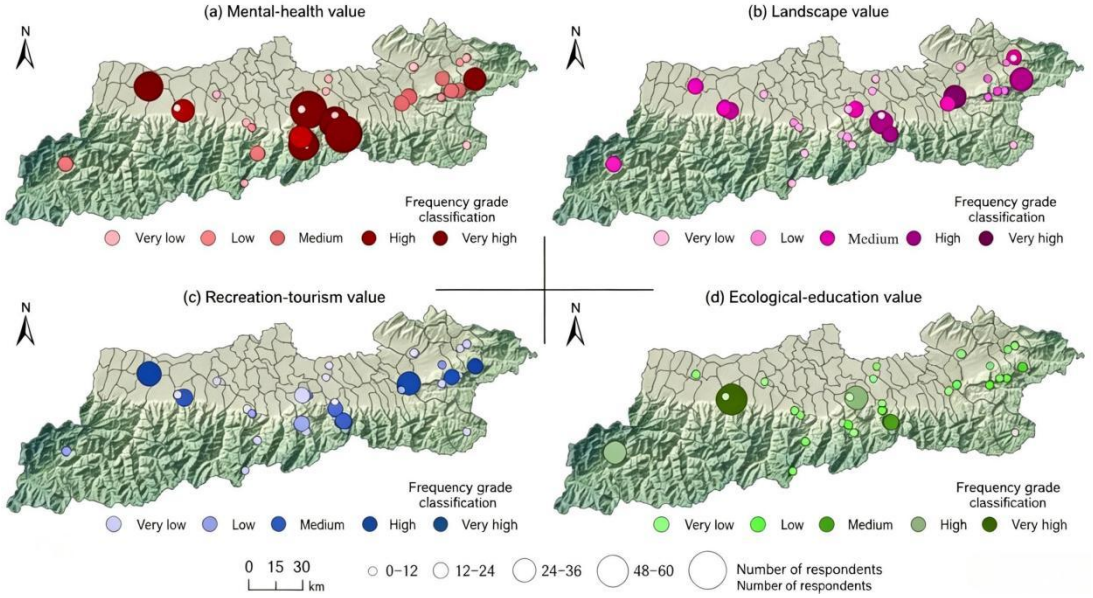


Figure 1 CES distribution map mapped by respondents, showing the number of respondents and selection frequency of each area.

4.3. Spatial-Distribution Results of Biophysical Ecosystem Services

Spatial patterns of biophysical-ecosystem-service importance across the northern foot of the Qinling Mountains are displayed in Figure 2. Among five service categories:

For biodiversity conservation: areas graded very-low occupy 2776.87 km², accounting for 37.20 % of total study-area extent, largely distributed across human-disturbed northern plain-land populated zones. High-grade and very-high-grade areas cover 1434.32 km² and 1205.04 km² respectively (19.22 % and 16.14 % of total area). Combined high-and-very-high grades exceed 35 % of total area, predominantly within southern forest-ecosystem zones hosting giant-panda-national-park components and national- or provincial-level nature reserves, delivering favorable habitats for rare wild flora and fauna.

For water-source conservation: very-low-grade and low-grade areas cover 2089.76 km² and 1774.15 km² (28.20 % and 23.94 % of total area), mainly situated on northern plains. High-grade and very-high-grade areas cover 1305.94 km² and 529.17 km² (17.62 % and 7.14 % of total area). Southern mountainous zones feature high elevation, abundant precipitation and well-developed river systems. Serving as headwater zones for Hei River, Feng River, Chan River and Ba River, towns such as Houzhenzi and Yushan possess strong water-source-conservation capacity.

Soil-water-retention services exhibit mosaic-interleaved spatial patterns. Very-low-grade areas occupy 2468.56 km² (33.06 % of total area). High-grade and very-high-grade areas cover 916.44 km² and 340.66 km² (12.27 % and 4.56 % of total area), concentrated in southeastern high-vegetation-cover zones capable of effective soil-erosion mitigation.

For carbon sequestration: very-low-grade and low-grade areas cover merely 223.12 km² and 1074.84 km² (2.99 % and 14.39 % of total area). High-grade and very-high-grade areas occupy 2504.63 km² and 1469.36 km² (33.53 % and 19.67 % of total area), distributed along the northern-Qinling foothill-ring-belt. Ample precipitation accelerates vegetation growth, enhancing plant productivity and biomass and promoting carbon sequestration and oxygen release within forest ecosystems.

For grain yield: very-low-grade areas cover 5408.98 km² (72.41 % of total area). High-grade and very-high-grade areas occupy 823.64 km² and 519.82 km² (11.03 % and 6.96 % of total area). Grain-production capacity demonstrates prominent spatial heterogeneity; grain-yield hotspots are concentrated on flat northern plains dominated by cultivated land suitable for agricultural activities. Huyi District and Chang'an District record the highest grain output, followed by Lantian County, while Zhouzhi County ranks lowest.

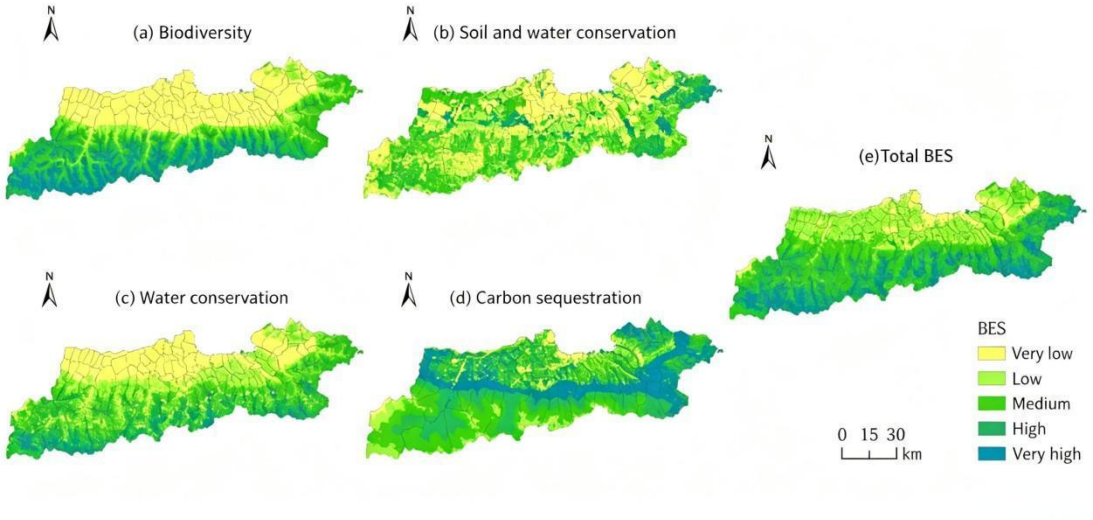


Figure 2 Assessment of BES

4.4. Analysis of Evaluation Outcomes After CES Integration into BES

Overlaying and re-grading spatial outputs, area statistics and township-quantity variations are computed for provisioning, regulating and supporting services under two alternative scenarios (CES excluded vs. CES included), as shown in Figure3.

Scenario without CES inclusion: Among 82 townships, provisioning services follow a north-high-south-low spatial pattern. Very-low-grade areas cover 4156.76 km² (55.64 % of total area, the dominant grade). High-grade and very-high-grade areas cover 961.50 km² and 798.27 km² (12.87 % and 10.68 % of total area), predominantly distributed across northern plains with dense human populations, sufficient labor supply and traditional grain-production advantages, delivering strong provisioning-service capacity.

Regulating services follow a south-high-north-low pattern. Very-low-grade areas occupy 564.83 km² (7.56 % of total area). High-grade and very-high-grade areas cover 2404.19 km² and 1420.93 km² (32.18 % and 19.02 % of total area), concentrated in zones south of the northern-Qinling foothill ring-belt. Abundant precipitation sustains luxuriant forest growth and enhances water-regulation capacity.

Supporting services also present a south-high-north-low pattern. Very-low-grade areas occupy 1047.66 km² (14.02 % of total area). High-grade and very-high-grade areas cover 1955.89 km² and 2683.23 km² (26.18 % and 35.91 % of total area). Dense primary forests across southern mountainous zones deliver strong soil-water-retention performance and high net-primary-productivity, providing high-quality habitats and refuges for fauna and microorganisms and supporting robust biodiversity-conservation capacity[46].

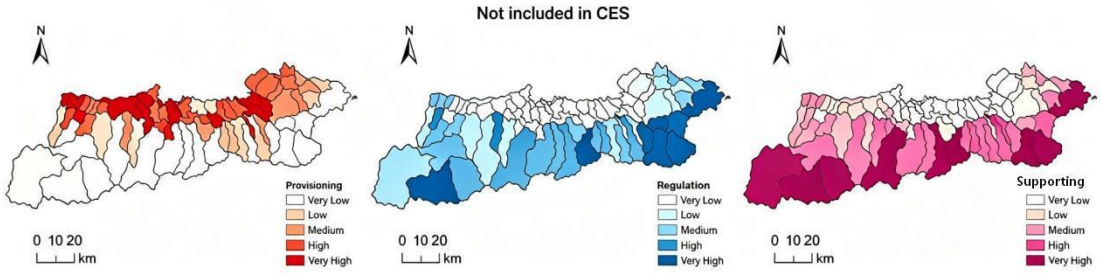


Figure 3 is not included in the CES classification assessment

Scenario with CES inclusion: Noticeable shifts emerge in outputs (Figure 4). Among 82 townships, provisioning-service grades change within 34 townships (both upward and downward shifts). Very-low-grade provisioning-service areas shrink to 2901.18 km² (38.83 % of total area), representing substantial grade-structure transformation compared with the scenario excluding CES. High-grade and very-high-grade provisioning-service areas reach 638.74 km² and 460.57 km² (8.55 % and 6.16 % of total area). High-grade zones expand toward southern and eastern territories. The Yili Industrial Park in the east witnesses prominent provisioning-service-grade elevation; its dairy-product supply supports local employment and economic development.

Regulating-service grades experience large-magnitude changes, with grade adjustments occurring across 47 out of 82 townships (both upward and downward shifts). Very-low-grade regulating-service areas cover 737.56 km² (9.87 % of total area). Medium-grade and high-grade areas constitute the dominant components of regulating services, covering 2604.95 km² and 2159.35 km² (34.87 % and 28.90 % of total area), jointly accounting for 63.77 % of total extent. After CES incorporation, forest-and-water-body zones in central and eastern territories (including sites such as South Wutai Mountain of Zhongnan Mountain, Cuihua Mountain and Liuyu Feixia) with prominent cultural values attain elevated regulating-service grades for central-eastern townships. By contrast, northern zones lacking cultural-service assets suffer regulating-service-grade declines, highlighting the significance of cultural services for regulating-service evaluation.

Supporting-service grades also undergo adjustments across 37 of 82 townships (bidirectional grade shifts). Very-low-grade supporting-service areas cover merely 355.81 km² (4.76 % of total area). High-grade and very-high-grade supporting-service areas cover 3289.59 km² and 1441.43 km² (44.03 % and 19.29 % of total area), jointly representing 63.32 % of total area and forming the principal body of supporting services. Township grades rise markedly across central-eastern zones. Ecosystems surrounding Cuihua Mountain, Wangchuan Karst Cave and Shui-lu-an Temple sustain local flora-fauna survival and perform critical functions maintaining regional biodiversity and ecosystem structures.

Following CES inclusion, grade variations for three service categories follow an east-rising-west-declining pattern across townships. High-grade zones become more dispersed, consistent with CES spatial-distribution patterns. Eastern territories host numerous scenic sites and constitute hotspots for human activities, while western zones possess fewer tourist attractions.

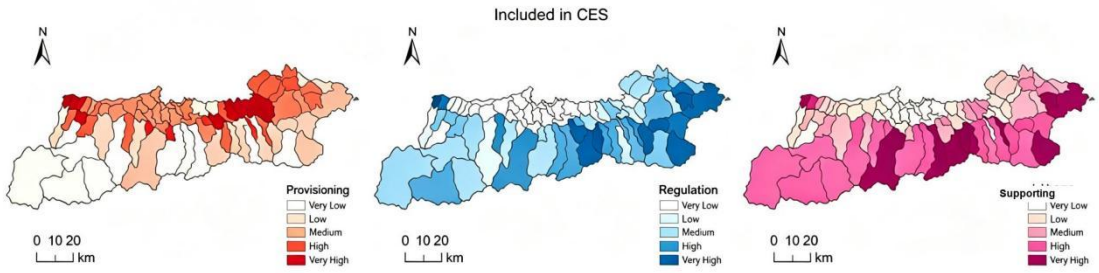


Figure 4 is included in the CES classification assessment

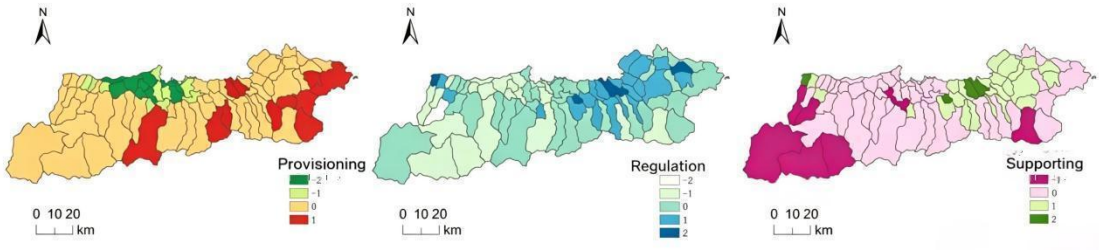


Figure 5 Changes in CES classification assessment

5. DISCUSSION

5.1. Relationships Between Distribution Characteristics of Different Cultural-Service-Value Categories and Spatial-Landscape Traits

A single landscape can deliver multiple values including mental-health, aesthetic-landscape, recreation-tourism and ecological-education services; nevertheless, human perception intensity varies across different CES typologies. This study identifies mental-health values as the most broadly perceived CES category among the public, consistent with findings reported by Ridding et al. for southern Wiltshire, England[34]. Landscape-aesthetic values rank second and recreation-entertainment values rank third. One contributing factor is that visually attractive scenery is generally associated with intact ecosystem functions and natural ecological processes, which jointly facilitate ecotourism, outdoor sports and social interactions[35]. This result deserves attention: participation in outdoor recreation can motivate pro-environmental public attitudes, and visitor CES perceptions during natural-environment experiences constitute important driving forces for eco-civilization-oriented behaviors[36]. Public perception of ecological-education-oriented CES remains comparatively low, yet ecological-education services exert vital influences on fostering public environmental-protection awareness and philosophies. Distributions of various CES typologies are correlated with environmental-landscape traits and recreational-activity patterns. Landscape characteristics significantly shape human acquisition of CES benefits. Existing literature confirms that visual scope, proximity to water bodies and vegetation-cover conditions correlate with human access to CES values[37].

5.2. Significance of Incorporating CES

Cultural ecosystem services are widely recognized as novel interpretive lenses for human-environment relationships[38]. A growing number of nations and scholars acknowledge the importance of embedding cultural services into landscape planning and management. Integrating cultural-ecosystem-service functions into landscape planning and management reveals public perceptions of multi-faceted utilitarian and non-utilitarian landscape values, encourages conservation of high-CES-value zones, and stimulates multi-functional landscape performance, particularly by activating CES values frequently overlooked by biophysical and economic ecosystem-service

assessments[39]. For example, this study finds that certain eastern zones within the northern foot of the Qinling Mountains are not identified as biophysically-prioritized conservation hotspots yet possess extremely high mental-health and landscape-aesthetic values. Compared with conventional economic and environmental-model-driven evaluations, this research supplies complementary methodologies applying cultural-service and ecosystem-service concepts to protected-area planning and environmental governance. Participatory-mapping-based CES assessment for urban parks establishes public-participation workflows, generates pathways for collecting public information, improves quality and generalizability of planning-decision outputs, and mitigates disputes triggered by insufficient consideration of public demands and preferences[40,41]. Meanwhile, this methodology effectively distinguishes priority-management zones and delivers approaches targeting multi-value ecosystem-management objectives.

5.3. Insights for Integrating Cultural Ecosystem Services into Sustainable Governance

Spatial visualization of ecosystem services exerts positive influences on landscape-planning and local-decision-making workflows[42]. The northern foot of the Qinling Mountains features diverse landscape typologies and convenient transportation, concentrating most geological relics and human-historical scenic sites and possessing advantages in cultural-heritage and educational-service provision. Future actions should strengthen conservation and publicity of these resources to enhance external understanding of the northern foot of the Qinling Mountains[43]. Rural infrastructure remains under-developed across western and southern segments of the study area, restricting recreational-environment advantages[44]. These zones should overcome inherent adverse natural-environment constraints, improve connectivity with external societies through road-network upgrades and internet-application deployment, highlight sense-of-place service strengths, advance natural-environment restoration, and enhance mountain-zone ornamental and recreational functions to satisfy modern-human aspirations for pristine township scenery and emotional attachment to traditional rural imprints[45]. In addition, given spatial overlaps among diverse categories of cultural-ecosystem services, policy formulation should account for landscape multi-functionality[46].

Ecosystems constitute living environments upon which rural residents depend; their well-being maintains tighter links with ecosystems, enabling stronger perceptions of diversified cultural-ecosystem-service categories. Local-community residents' knowledge and experiences contribute toward sustainable ecosystem utilization[47]. Farmers represent major stakeholders for township-scale cultural-ecosystem-service governance. Local-resident perceptions and viewpoints regarding cultural-ecosystem services should be fully respected and embedded within decision-making workflows to enhance public support for ecosystem management.

6. CONCLUSIONS

Based on a social-ecological-system framework, this paper proposes an innovative methodology integrating Cultural Ecosystem Services (CES) into Biophysical Ecosystem Services (BES) assessments. Taking the Xi'an-segment northern foot of the Qinling Mountains as the study area, this research quantifies CES (including mental-health, landscape-aesthetic, recreation-entertainment and ecological-education values) and BES (including biodiversity conservation, soil-water retention, water-source conservation, carbon sequestration and grain yield) through questionnaire surveys, process-based modeling and land-use-transition matrices. Evaluation outputs are contrasted for two scenarios: CES excluded and CES included. The research finds that respondents report the highest willingness-to-pay for mental-health values; CES presents an east-high-west-low spatial-distribution pattern. Among BES, provisioning services are concentrated across northern plains, while regulating and supporting services predominantly distribute within southern mountainous zones. After incorporating CES, spatial distributions and grade proportions for provisioning, regulating and

supporting services change substantially. Partial zones experience grade elevations or declines triggered by enhanced cultural functions or human disturbances. This study demonstrates that integrating CES into BES assessments facilitates local-resident participation and delivers scientific evidence for ecological conservation and sustainable development within the northern foot of the Qinling Mountains. When transferred to alternative contexts, this methodology also supports formulation of ecosystem-service-management plans for local territories.

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