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Quantifying marginal utilities of ecosystem services for sustainable management

Yang Bai [a,b,c,*], Maroof Ali [a,b,c], Yi Zhou [d], Shiliang Yang [e,**]

[a] Center for Integrative Conservation & Yunnan Key Laboratory for Conservation of Tropical Rainforests and Asian Elephants, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla, 666303, China
[b] Yunnan International Joint Laboratory of Southeast Asia Biodiversity Conservation, Menglun 666303, China
[c] University of Chinese Academy of Sciences, Beijing, 100049, China
[d] Yangtze River Delta Ecological Development Co., LTD, JiaXing, 314050, China
[e] School of Management Science and Engineering, Guizhou University of Finance and Economics, Guiyang, 550025, China

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ABSTRACT

Understanding the marginal characteristics of ecosystem services (ESs) is crucial for sustainable management. However, there is limited research on quantifying thresholds for ESs, making it challenging for policymakers to plan effectively. This study established a framework to assess the influencing factors and marginal characteristics of cultural and regulatory ecosystem services (RES) in the Taihu Lake Basin of China and its wetland parks. The framework uses a Structural Equation Model to analyze the impact of visitors' attributes on the perception of different types of cultural ecosystem services (CES). It also employed the InVEST model to quantify the spatial patterns of RES in the basin. Multiple regression analysis and marginal utility theory were used to examine the influencing factors and marginal utilities for different types of cultural and regulatory services. The findings reveal that 1) Education level, income, gender, and age significantly influence the perception of five types of CES provision, with different factors affecting each type. 2) Most park characteristics influence the CES provision score, with their maximum and marginal utility peaks. For instance, as patch density (PD) increases, the score for recreational services initially decreases, then increases, and finally decreases again, reaching a peak of 0.50 at a PD of 325.60. The marginal utility of PD follows a similar pattern, initially increasing and then decreasing, with an increase in utility observed in the range of $0 < PD < 187.80$. When PD reaches 187.80, it attains its maximum utility, indicating the point of highest efficiency for PD's impact on recreational services. 3) Heterogeneity exists in the spatial distribution of RES within the basin, with different landscape features providing varying marginal benefits for services like water supply, water purification, carbon storage, and soil erosion prevention. Carbon storage demonstrates an 'increase-then-decrease' pattern in response to rising FP (Percentage of forest area), reaching a maximum value of 13129.3 t/km^2 at FP of 66.4. The marginal utility of FP also exhibits a 'rise-then-fall' trend, increasing up to FP of 30.4, where it peaks at 230.5. This peak represents the point of maximum efficiency in FP's influence on carbon storage services. 4) The effects of park and landscape characteristics on cultural and regulatory services exhibit marginal utilities that can be used to determine the optimal scale and location of these features to maximize ecological benefits. This research aims to expand the scope of ESs assessment and provide insights from wetland parks for broader environmental planning and optimization.

1. Introduction

Ecosystem services (ESs) refer to the various beneficial functions natural ecosystems provide to human society (Daily, 1997). These functions are crucial for addressing climate change, biodiversity conservation, and human well-being (Richards et al., 2022; Onoh et al., 2024). Current research focuses on quantifying the economic value of these services, highlighting the importance of natural capital for

* Corresponding author. Center for Integrative Conservation & Yunnan Key Laboratory for Conservation of Tropical Rainforests and Asian Elephants, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla, 666303, China.
** Corresponding author.
E-mail addresses: baiyang@xtbg.ac.cn (Y. Bai), max388@126.com (S. Yang).

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sustainable development (Costanza, 2020; Ouyang et al., 2020). As economic development progresses, ecological and environmental issues become more prominent, increasing the focus on ESs supply capacity (Parolini and Romano, 2024). Meanwhile, innovative methods such as remote sensing and big data analysis are being used to explore ecosystem interactions and trends in service changes, driving more precise assessments and management strategies for ESs (Raffaelli et al., 2014; Zhu et al., 2019). Daily categorized ESs into four types in 1997, including cultural services (Daily, 1997). In the same year, Costanza classified ESs into 17 types, including cultural services (Costanza et al., 1997). In 2005, the United Nations' Millennium Ecosystem Assessment defined cultural services as non-material ecosystem benefits, including spiritual and aesthetic enjoyment (Nations, 2005).

The delicate balance between human activities and ecological conservation is a crucial issue in environmental management, particularly in wetland ecosystems (Bai et al., 2021; Aleissa et al., 2023). The cultural services of wetland ecosystems hold significant value for biodiversity, recreational opportunities, and local communities (Kumar et al., 2024). Wetlands' unique natural landscapes offer spaces for public leisure and recreation, fostering interaction between people and nature (Gearey, 2024). For instance, they provide opportunities for birdwatching, photography, and other recreational activities, enhancing public environmental awareness and promoting tourism development (Ghoochani et al., 2020). Additionally, wetlands positively impact the economic and social development of local communities by serving as venues for traditional and cultural activities, enhancing employment opportunities, and strengthening the economic and social resilience of the community (Hoelting et al., 2024). Wetlands are precious natural ecosystems, and wetland parks are integral components of wetland conservation, preserving ecological functions and providing cultural services to humanity (Canning et al., 2021). Cultural and regulatory services, including recreational, aesthetic, and spiritual benefits, as well as climate regulation, water purification, and flood control, form the foundation of these wetland parks (Ali and Kamraju, 2023). However, these services are increasingly threatened by rapid urbanization, pollution, and unsustainable land-use practices (Li et al., 2023). This highlights the urgent need for a robust framework to assess the factors and characteristics impacting cultural and regulatory services within wetland parks.

Wetland ecosystems are precious natural ecosystems, known for their high per-unit area service value (Hu et al., 2018). They provide essential support for wildlife habitats, providing food, water, and shelter for fish, birds, and other animals (Costanza, 2006). Waterlands are also crucial for maintaining ESs like improving water quality, flood reduction, and carbon sequestration (Tiner, 2010; Wang et al., 2022). Moreover, wetlands are referred to as the "lungs of the Earth" due to their significant climate regulation capabilities. Previous research has focused on the services offered by wetlands, specifically provisioning, regulating, and supporting services.

Cultural ecosystem services (CES) are intangible and difficult to measure, leading to issues in research, including redundant calculations, difficulty in determining causes of change, and reliance on subjective perception (Cabana et al., 2020). CES are essential for informed decision-making in sustainable management practices (Kenter et al., 2016). Wetland parks, which incorporate artificial elements into wetland ecosystems, are better equipped to provide CES and have a high research value. The establishment of wetland parks nationwide has been crucial for protecting wetland ecosystems and increasing public access to wetlands, thereby enhancing the volume of ESs provided. However, there is a significant gap between the importance of CES in sustainable development and the current state of research. A humanities perspective, incorporating landscape, sense of place, and cultural identity, is required for practical applications (Leyshon, 2014; Ryfield et al., 2019). Therefore, there is an urgent need to intensify and deepen quantitative research on CES in wetland ecosystems. Within the realm of ecological research, the marginal value or resilience characteristics of ES refer to the capacity of the quality or quantity of ES to respond to external pressures or changes in management practices. Marginal analysis plays a crucial role in resource allocation (Williams, 2012; Zhong et al., 2014). As marginal analysis unfolds within ES, quantitative research focusing on CES offers a breakthrough opportunity.

The marginal characteristics and thresholds of ESs are key concepts for understanding and managing these services (Wu et al., 2022; Richards and Lavorel, 2023). Marginal characteristics refer to the impact of incremental changes in services on human well-being, while thresholds are critical points where services undergo qualitative changes under certain conditions (Longato et al., 2019; Zhang et al., 2018). Current research focuses on three main areas: Firstly, the marginal benefits and costs of ESs are often nonlinear (Ghoochani et al., 2020). Initial ecological restoration measures bring significant benefits, but as restoration progresses, marginal benefits diminish. This phenomenon is particularly evident in water resource management, carbon sequestration, and soil protection (Hao et al., 2017). Secondly, threshold effects are crucial considerations in ecosystem management (Farley, 2012). When services reach a critical point, the system may undergo dramatic changes, leading to sudden losses or sharp declines in services (Saito et al., 2021; Yang et al., 2022). For example, when the nutrient load in a lake exceeds a certain threshold, the lake can quickly shift from clear to turbid, causing severe degradation of water quality and services (Wei et al., 2022). Similar effects have been reported in forest degradation, coral bleaching, and grassland desertification (Baartman et al., 2007). Lastly, researchers explore methods for identifying and predicting marginal characteristics and thresholds (Kontogianni et al., 2010). Long-term monitoring and modeling can help identify critical points and implement preventive measures to avoid exceeding thresholds (Valatin et al., 2022). Remote sensing technology and big data analysis show substantial potential in providing high-precision real-time data on ecosystem status and service levels, informing management decisions (Manley et al., 2022; Wang et al., 2022).

However, traditional methods of calculating marginal characteristics have overlooked cultural attributes, park features, and watershed landscape elements that are closely connected to sustainable development (Felipe-Lucia et al., 2022; Hernández-Morcillo et al., 2013). Therefore, based on the current research gaps, this paper integrates cultural attributes and park landscape features into the marginal characteristics of ESs. By applying marginal utility theory in conjunction with spatial heterogeneity analysis, this approach presents a valuable breakthrough and entry point. In the context of the ecological principle that "Green mountains and clear waters are equal to mountains of gold and silver," incorporating both cultural and regulatory services into the analysis and considering two different scales, watershed and park landscapes, provides a breakthrough in the framework of marginal characteristics analysis. This approach allows us to understand the influencing factors and underlying mechanisms.

The Taihu Lake Basin (TLB), is known for its wetland parks and represents the relationship between humans and nature (Yang et al., 2023). It is a region of ecological and cultural importance, where human activities have had a significant impact. The basin faces the challenge of balancing developmental demands and conservation (Tao et al., 2023). The marginal characteristics of ESs must be considered to manage the river basin effectively. This helps understand the threshold for environmental changes that affect these services and informs management strategies. For example, the TLB boasts a rich cultural heritage and historical sites, yet the marginal characteristics of its CES remain unclear and overlooked (Bai et al., 2020). Initial restoration measures for regulating services such as water purification and climate regulation have shown significant effects, but as investment increases, the marginal benefits diminish, making sustained efficiency challenging. This inability to predict ecological thresholds and potential risks leads to delayed management actions, hindering timely responses to sudden environmental issues.

Based on this context, the current research proposes a comprehensive framework for assessing the dynamic factors that affect cultural and regulatory services in Taihu Lake wetland parks. It also proposes to explore the marginal characteristics of these factors, and to explore feasible park planning and management strategies. Thus, the specific objectives of the present study were: 1) to investigate the perceptual characteristics of CES in the Taihu Lake wetland parks and the impact of visitor attributes on the scores of CES; 2) to uncover the primary factors and marginal characteristics influencing the provision scores of CES by park attributes; 3) to reveal the spatial variation patterns of regulatory ecosystem services (RESs) within the basin and elucidate the marginal characteristics of RESs in relation to landscape features. The overall aim was to reveal how the attributes of visitors and the intrinsic characteristics of the wetland parks themselves influence the perception of CES provision and the intrinsic laws of how landscape features affect the marginal characteristics of RESs, intending to provide a reference for rational park planning, optimization of resource allocation, and high-quality, coordinated development of the region.

2. Materials and methods

2.1. Study area

The TLB (30°7′19″N–32°14′56″N, 119°3′1″–121°54′26″E) is a significant freshwater lake ecosystem situated in the eastern part of China. It covers a total area of 36,900 km^2 with seven main types of land use (Fig. 1a), including urban, agricultural, and natural landscapes. The TLB has a profound influence on the local climate, water resources, biodiversity, agriculture, and fisheries. Nestled within the TLB is Taihu Lake (Fig. 1b), located on the southern fringe of the Yangtze River Delta (30°55′40″N – 31°32′58″N, 119°52′32″E – 120°36′10″E). As the third largest freshwater lake in China, Taihu Lake covers a lake area of 2427.8 km^2 with an aquatic area of 2338.1 km^2. It has a total shoreline length of 393.2 km. The western and southwestern sides are characterized by hilly and mountainous terrain, while the eastern side predominantly features plains and a network of waterways. Situated in a subtropical zone, the area experiences a mild and humid climate, typical of a monsoon region.

The Taihu Lake region has a rich cultural heritage and is historically known for its economic prosperity. The urban areas surrounding Taihu Lake have a large population, which creates a significant demand for CES provided by nearby wetlands. However, the environmental protection and sustainable development of the TLB region, including its wetland ecosystems, have become a major concern for the Chinese government and various societal sectors due to threats posed by rapid urbanization and economic advancement.

The study focused on wetland parks in the region, including various types of wetland ecosystems such as lakes, marshes, rivers, and wet meadows. Initially, all parks that met the criteria of being "within 10 km, evenly distributed, and well-constructed" were initially considered. However, due to some parks lacking planning maps, discrepancies between actual plans and publicly available information, or being closed for maintenance, a total of 25 wetland parks along the shores of Taihu Lake were selected, as indicated.

2.2. Theoretical framework

An operational framework showing the influencing factors and

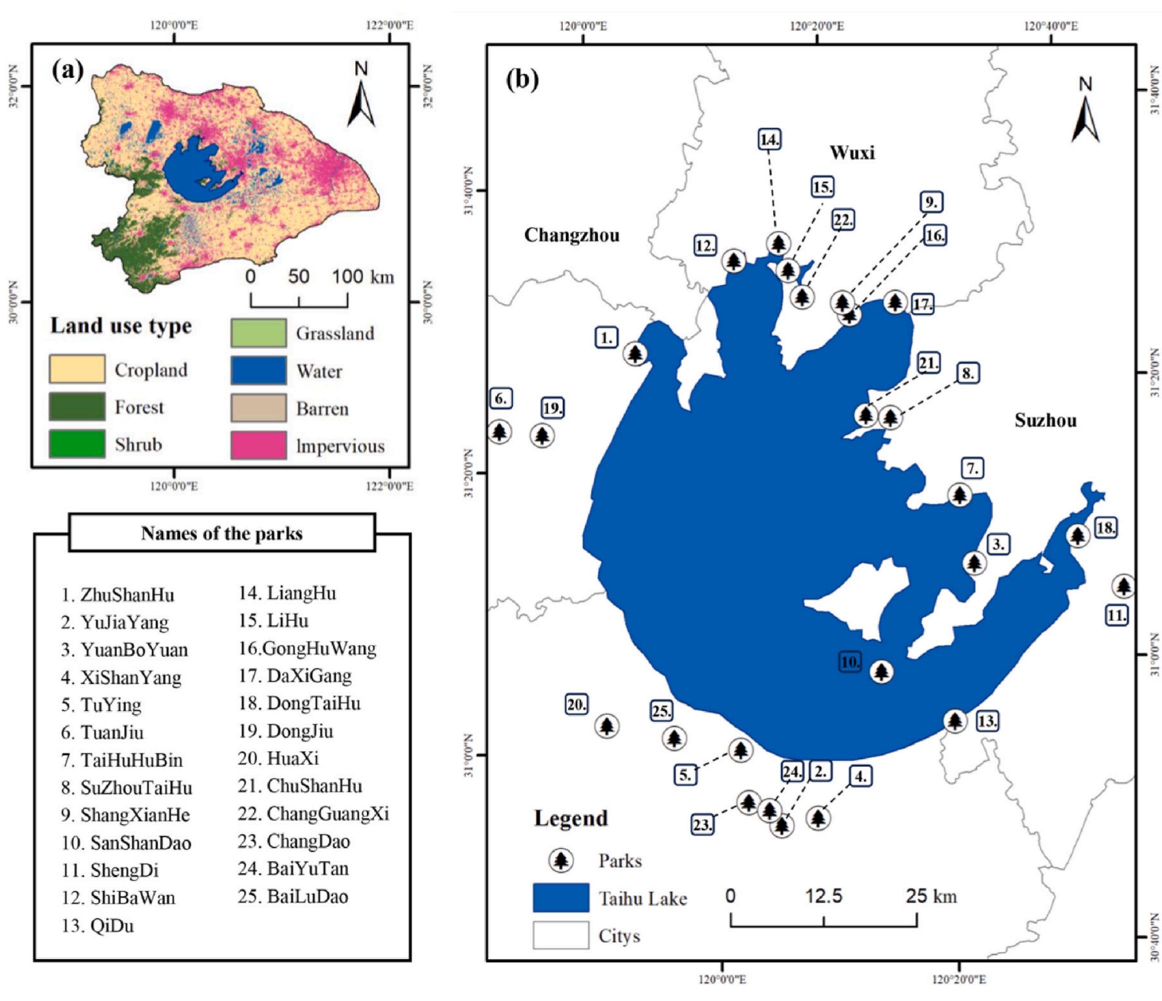

Fig. 1. (a) land use types of the basin, (b) 25 wetland parks along the TLB.

marginal characteristics of cultural and regulatory ESs is presented (Fig. 2). First, the assessment of CES and the acquisition of visitor attributes were conducted through survey questionnaires, which collected evaluations of the park CES provision and characteristics such as the social attributes of visitors. Structural equation modeling was applied to analyze the influence of individual visitor attributes on the perception of different types of CES.

Secondly, park characteristics were acquired. Satellite remote sensing imagery was used to create land use maps of the parks based on visual interpretation. Landscape pattern indices and other park features are derived from these maps. Structural equation modeling and multiple regression analysis, along with marginal utility theory, were applied to quantify the extent and significance of different influencing factors and to delineate the marginal utility and characteristics of park features on CES.

Third, the data was prepared based on manual interpretation of remote sensing data. The InVEST model was employed to estimate ESs regulation. Similarly, multiple regression analysis and marginal utility theory were used to analyze the impact factors and marginal utilities of basin landscape characteristics on regulation services. Finally, based on these findings, a framework was developed for sustainable planning and management of watersheds and national parks.

2.3. Research method

2.3.1. Questionnaire

A questionnaire survey refers to a method of data collection whereby respondents are asked to answer a meticulously designed questionnaire (Roopa and Rani, 2012). We systematically conducted the process in steps, starting with the design, followed by collection, processing, and finally, the validation of the questionnaires.

1) Questionnaire Design: The questionnaire consisted of two parts: respondents' ratings of the park's ecosystem, CES, and personal information. Based on Costanza's "recreation and cultural services" concept, this study categorized the ten aspects of CES into five types: recreation, aesthetics, historical culture, popular science education, and relaxation, considering the context of the Taihu Lake area. These services were explained in layman's terms within the questionnaire, and a five-point Likert scale was used for ratings.

Ecosystem cultural services connect human society with the natural environment, and their provision and benefits are closely related to the characteristics of the recipients (Daniel et al., 2012). Natural, social, and transportation-relevant attributes significantly influence respondents' perceptions and satisfaction with park CES (Figueroa-Alfaro and Tang, 2017). In constructing the SEM model, we selected the following indicators: natural attributes (e.g., scenery and air quality, indirectly influencing park visit frequency), social attributes (education level, monthly income, gender, age), and transportation-related attributes (residential distance, transportation mode and time) (Riechers et al., 2018; Zhou et al., 2020). These indicators are based on the characteristics of parks in the Taihu Basin and are applicable to evaluating various urban parks.

2) Questionnaire Collection: After completing the initial questionnaire design, a pre-survey was conducted in April and May 2021 using both online (Wenjuanxing) and offline questionnaires to test their structure and content. A total of 81 questionnaires were distributed, and after excluding incomplete or inconsistent responses, the effective recovery rate was 77.78%. Based on pre-survey feedback, the questionnaire was revised. The revised questionnaire was then used for surveys in 25 parks around the Taihu Lake area in May, June, and September 2021, with 50 questionnaires collected from each park. Due to low visitor numbers, approximately 30 questionnaires were collected from three parks.
3) Questionnaire Processing: During the screening of the returned questionnaires, we excluded those with identical scores for all items (all highest or lowest) and those with contradictory answers. Questionnaires with missing or duplicate responses to the same question were also excluded. Ultimately, 1192 questionnaires were collected, of which 912 were valid, resulting in an effective rate of 76.51%.

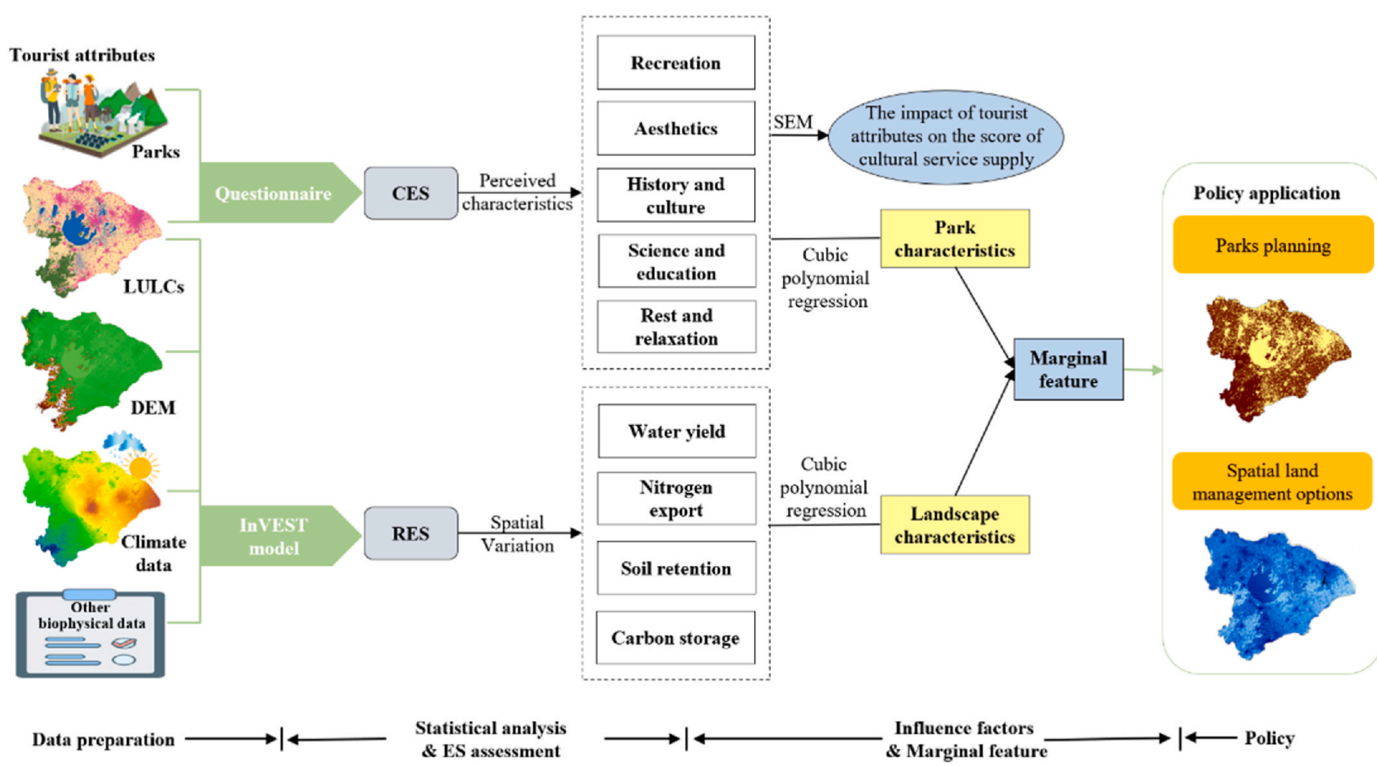

Fig. 2. Theoretical framework applied in the present analysis.

4) Questionnaire Validation: Reliability and validity testing are applicable to evaluating subjective questions in scale-based questionnaires to achieve accurate and reliable measurements. Since objective information like age and gender have clear answers, reliability and validity testing are not necessary for these factors. For respondents' ratings of CES provided by the parks, we used the same scale with the same group of respondents at different times and calculated the correlation coefficient of the results. The high correlation coefficient indicates the high test-retest reliability of the scale. Additionally, we had experts review the questionnaire items to ensure they covered all aspects of the research topic, ensuring content validity.

2.3.2. Structural equation model

Structural Equation Model (SEM) is a statistical method that analyzes relationships between variables based on their covariance matrix. It is an essential tool for multivariate data analysis (Schumacker and Lomax, 2004). In practice, many social sciences issues are complex and not caused by a single factor. Instead, they arise from multiple interactions. Therefore, as a multivariate statistical method, SEM is particularly well-suited to addressing such problems. SEM can deal with relationships between observed and latent variables. It's a powerful tool used to describe, evaluate, and test complex statistical relationships. The main components of SEM are:

Measurement model: It describes the relationships between observed variables and latent variables, usually estimated through factor analysis. Formulated as:

$$x_i = \lambda_{xi}\eta + \delta_i$$

$$y_j = \lambda_{yj}\xi + \epsilon_j$$

where x_i represents the observed variable, η is the latent variable, λ_{xi} is the factor loading between the observed and latent variables, δ_i is the error term, y_j, ξ, λ_{yj}, and ϵ_j corresponds to another latent variable and its related observed variable, respectively.

Structural model: It describes the relationships among latent variables and can be represented using multiple regression equations. Formulated as:

$$\eta = B\eta + \Gamma\xi + \zeta$$

where B is the regression coefficient matrix among latent variables, Γ is the regression coefficient matrix between latent variables and external variables, ζ is the error term.

In this study, SEM was used to quantitatively analyze the weights and influence paths of factors affecting CES demand. The Amos26 software was utilized in this research for SEM model creation, aiming to examine the interrelationships between variables and their underlying causes.

2.3.3. Cubic polynomial regression

Cubic polynomial regression is a specific form of polynomial regression that seeks to model the relationship between a predictor variable and a response variable through a cubic equation (Royston and Sauerbrei, 2007). This type of regression can be useful when the data exhibit a more complex pattern that is inadequately captured by linear or quadratic models. One of the advantages of cubic polynomial regression is its ability to capture more intricate nonlinear trends in the data. The formula is as follows：

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \beta_3 X^3 + \epsilon$$

where Y is the response variable. X is the predictor variable. β_0 is the intercept. β_1, β_2, and β_3 are the regression coefficients, representing the impact of the predictor variable and its respective powers on the response variable. ϵ is the error term.

2.3.4. Marginal utility

In microeconomics, marginal utility refers to the additional benefit (or decrease in benefit) derived from each additional (or reduced) unit of a good or service (Kauder, 2015). It represents the slope of the "utility-quantity of goods or services" graph. Economics generally holds that as the quantity of a product or service increases, the marginal utility will gradually decrease, a principle known as the Law of Diminishing Marginal Utility. In this study, the marginal utility is derived by differentiating the service score function ($f(x)$) and the value of a certain characteristic (x) through a cubic polynomial. The calculation formula is as follows:

$$E = \frac{d(f(x))}{d(x)}$$

where E represents the Marginal Utility, d($f(x)$) represents the change in total utility, and $d(x)$ represents the change in the quantity of the goods or services consumed.

2.3.5. InVEST model

This study employed the internationally common and mature ESs and trade-offs comprehensive assessment model InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) to calculate several common ERSs (Bai et al., 2018): water yield, water purification, soil conservation, and carbon storage services. In the InVEST model, the Water Yield module was used to evaluate the spatiotemporal variations of watershed water supply services, the Nutrient Delivery Ratio module for assessing the spatiotemporal variations of water purification services, and the Sediment Delivery Ratio module for determining the spatiotemporal variations of soil conservation services. Carbon storage refers to the ecosystem function of absorbing carbon dioxide and fixing carbon through vegetation and soil. These services enable decision-makers to assess ecosystem trade-offs.

Within InVEST, the Water Yield (WY) Model is a water balance-based estimation method, where the water yield of each pixel is calculated as precipitation minus actual evapotranspiration. For water purification (NDR Model), nutrient sources across the landscape were identified in the Nutrient Delivery Ratio module based on changes in land use and different nitrogen and phosphorus loading capacities. The nitrogen and phosphorus quantities delivered to rivers are calculated to assess water quality changes. Reducing the amount of nitrogen and phosphorus flowing into rivers can decrease water pollution. Soil conservation refers to the interception of soil by vegetation or forest cover against rainwater erosion, aimed at protecting soil resources and water quality. The Sediment Delivery Ratio module (SDR Model) uses a sediment delivery model to represent soil sediment generation and transport to rivers. Ecosystem carbon stocks typically include four basic carbon pools: aboveground and belowground biomass, soil, and dead organic matter. The InVEST suite of tools (Version.3.9.0; see Supplementary Information (SI) part 1) enables decision-makers to assess trade-offs between ESs.

2.4. Data processing and preparation

The data used in the InVEST model simulation included land use/land cover (LULC), digital elevation model (DEM), climate, soil, and biophysical parameters (Tables S2 and S5 in SI). Specific data requirements for park characteristics and watershed landscape characteristics are shown in (Table 1). Meanwhile, the survey questionnaire, respondents' preference data, and the validation of SEM assumptions can be found in (Part 2–3 of SI). Firstly, for the selection of park characteristic indicators: Many environmental factors influence the supply of CES, such as park shape, connectivity, and landscape diversity, as well as distance indicators related to human activities, such as distance from city centers and tourist attractions (He et al., 2019). Therefore, this study selected several landscape indicators and distance indicators based on the actual conditions of wetland parks around Taihu Lake.

Table 1
Definitions or calculation methods of the park characteristics and watershed landscape characteristics.

Types	Indicators	Definitions or calculation method
Park characteristics	Distance to the nearest Taihu Lake (Lake_dist)	Calculation of euclidean distance function using ArcGIS
	Distance to the nearest place of interest (In_dist)	
	Distance to the nearest neighborhood (Nei_dist)	
	Distance to the nearest city center (City_dist)	Using Gaud maps for surveying
	Shannon's evenness index (SHEI)	Calculate using Fragstats soft
	Park landscape shape index (PLSI)	
	Water patch contiguity index (WPCI)	
	Patch density (PD)	Denotes the degree of landscape fragmentation
	Largest patch index (LPI)	The proportion of the largest patch to the landscape area
	Total Area (TA)	Total park area
	Percentage of green area (GP)	Green patches as a percentage of the total park area
	Percentage of build area (BP)	Percentage of construction land in total park area
Landscapecharacteristics of TLB	Percentage of forest area (FP)	Proportion of forest patches in a landscape
	Percentage of water area (WP)	Proportion of water patches in a landscape
	Landscape diversity index (LDI)	Richness and complexity of landscape types
	Landscape fragmentation index (LFI)	Fragmentation of a landscape
	Landscape shape index (LSI)	Changing the shape of the landscape
	Landscape connectivity index (LCI)	Connectivity among patches of each landscape type

Additionally, indicators related to the park area were selected. Secondly, for the selection of landscape characteristic indicators: Land use/cover changes will cause variations in landscape characteristics. In this study, three criteria were used to determine landscape characteristic indicators for calculating overall landscape benefits: 1) represent key landscape components, 2) have direct or indirect links to selected ESs indicators, and 3) be associated with management schemes (Wong et al., 2015). Based on these criteria, the factors listed in the table were selected as landscape characteristic indicators (Bai et al., 2020).

3. Results

3.1. Perceptual characteristics of CES

A cohort of 912 respondents evaluated the provision of five CES at the parks they visited at the time of the survey. Each service was rated on a scale from 0 to 1. The distribution of scores for the provision of the five services across the 25 parks is shown in (Fig. 3a). The score for each service at each park was represented by its mean value. Despite a few outliers due to the unique characteristics of a minority of parks or other factors, the overall distribution remained relatively concentrated.

Recreational services saw six parks scoring zero or low, and aesthetic services had two parks with negative scores, specifically YuanBoYuan Park (−0.125) and YuJiaYang Park (−0.027). YuanBoYuan Park had significantly lower aesthetic evaluations due to construction and maintenance activities during the survey period, which disrupted its visual appeal and visitor experience. In contrast, YuJiaYang Park's lower aesthetic scores may be attributed to less vibrant vegetation or poor maintenance of certain attractions. Historical-cultural services had 22 parks scoring negatively, and science education services had 21 parks with negative scores, whereas all parks scored positively for relaxation services. Overall, there was a significant variance in the provision scores among the five services, with historical-cultural and science education services predominantly negative and markedly lower than the other three services.

In contrast, aesthetic and recreational services were mainly positive, and rest and relaxation services were universally positive. Notably, LiHu and BaiLuDao parks had positive scores across all five services. ShiBaWan and ZhuShanHu Parks recorded substantial negative scores for historical-cultural and science education services, with scores of (−1.053, −0.895) and (−0.810, −1.143), respectively.

The bubble chart (Fig. 3b) depicts the distribution of scores for each service across 25 parks. Larger bubbles closer to the bottom right corner indicate that most visitors rated the service highly, and their opinions were consistent. In other words, the park's service is considered better if its bubble is larger and closer to the bottom right corner. The bubbles for aesthetic and relaxation services are generally larger and more clustered towards the bottom right, showing high and consistent visitor satisfaction for these services. Entertainment service bubbles, although near the bottom right, vary in size, suggesting differences in satisfaction levels between parks for this service. On the other hand, bubbles for historical-cultural and science education services are smaller and further from the bottom right corner, indicating lower scores and greater diversity in visitor opinion for these services across most parks.

3.2. The influence of visitor attributes on CES provision scores

The various fit indices for the five services have all met the established benchmarks, indicating that the SEM demonstrates a satisfactory fit. The SEM for the five services is shown in (Fig. 4). Herein, the ratio of Chi-square to DF (Chi/DF) was within the acceptable range (greater than 2 but less than 3). The Goodness of Fit Index (GFI) is consistently above 0.9 but less than 1, as is the Adjusted Goodness of Fit Index (AGFI), while the Root Mean Square Error of Approximation (RMSEA) is uniformly below 0.05. (Note: ***$P < 0.001$, ** $0.001 < P < 0.01$, * $0.01 < P < 0.05$).

Visitor attributes that positively influence the evaluation of entertainment services include age (0.13), while a negative influence is observed with monthly income (−0.08). Holding other conditions constant, individuals with higher incomes rate the provision of recreational services less favorably. In contrast, older individuals tend to provide more favorable evaluations. Regarding aesthetic services, none of the visitor attributes significantly impact the evaluation of the park's aesthetic offerings. The education level attribute negatively impacts the evaluation of historical and cultural services, with an influence weight of 0.11. Under similar conditions, individuals with higher levels of education tend to rate the provision of historical and cultural services less favorably. For science education services, visitor attributes that have a negative impact include monthly income (−0.09) and educational level (−0.13). Holding other conditions constant, individuals with higher education and income levels rate the provision of science education services less favorably. Attributes that have a positive impact on the evaluation of relaxation services include gender (0.08) and age (0.11). Under similar conditions, females tend to evaluate these services more positively than males, and older individuals more positively than younger ones. All services have a significant positive effect on the frequency of visitors' park visits; that is, the higher the score for a service, the more frequently respondents visit the park.

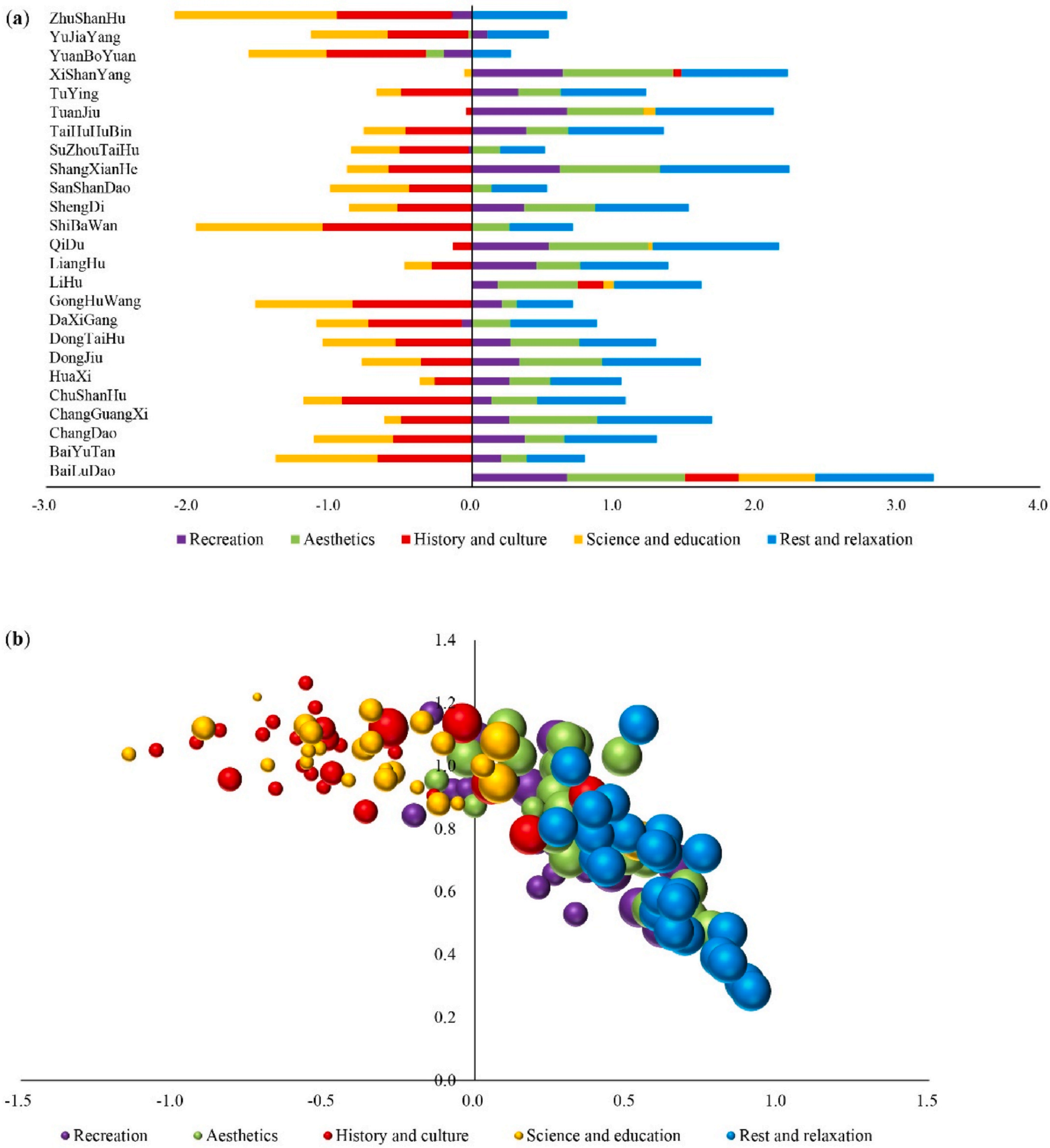

Fig. 3. (a) Scores of five CES in 25 parks around the TLB, (b) bubble chart of scores. (The horizontal axis represents the average score of a certain service supply in a certain park, the vertical axis represents the overall standard deviation, and the bubble diameter represents the exponential function ($y = e^x$) value of the mode based on the natural constant *e*.).

3.3. The marginal characteristics of park features on the provision scores of CES

Through multiple regression analysis of all park characteristic indicators on the evaluation of CESs, the influence and significance of each factor were determined (see SI Table S11). The factors significantly affecting the provision of CESs in wetland parks include: PD, LPI, BP, GP, WPCI, and Nei_dist. Other factors were excluded due to lack of significance. However, the specific influential factors vary for different types of CES (see SI Table S12). The marginal utility of most factors on the provision scores for certain services was not monotonic (Fig. 5). For recreational services, the marginal utilities of PD, LPI, and BP initially

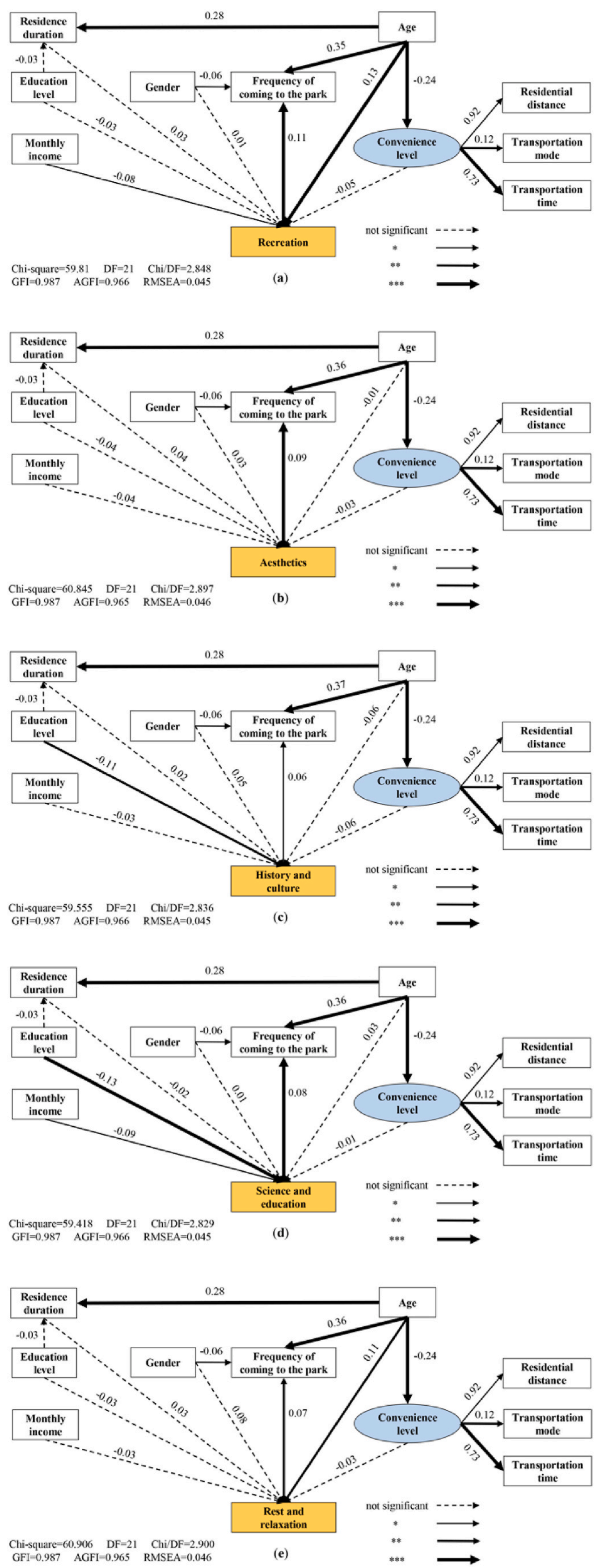

Fig. 4. Structural equation model results for five services.

increase and then decrease; For aesthetic services, LPI and BP show a similar pattern, while WPCI marginal utility decreases monotonically. For historical and cultural services, GP's marginal utility decreases and then increases, whereas Nei_dist first increases and then decreases. For science education services, PD and LPI exhibit an initial increase and subsequent decrease in marginal utility, while GP and BP exhibit an initial decrease followed by an increase. For the provision of relaxation and leisure services, PD and LPI's marginal utility initially increases and then decreases, with WPCI showing a monotonic decrease. The marginal characteristics of all park features are detailed (see SI Fig. S3).

For example, as PD increases, the trend in the provision scores for recreational services follows a "decrease-increase-decrease" pattern, with a peak value of 0.50 at a PD of 325.60. The trend in marginal utility is "rising then falling," with an increase in marginal utility under the condition of PD $<$ 187.80. When PD reaches 187.80, the marginal utility reaches its maximum, indicating the peak efficiency of PD's impact on recreational services, after which it begins to decline. It is noteworthy that with the increase in the WPCI, the trend in the provision scores for aesthetic services is "monotonically increasing," reaching a maximum value of 0.44 when WPCI is 1.00. Conversely, the trend in marginal utility is "monotonically decreasing"; the marginal utility is at its maximum when WPCI is 0, denoting the highest efficiency of WPCI's impact on aesthetic services, and continues to decline after that. The threshold values for marginal effects of all factors are shown (Table 2).

3.4. The marginal characteristics of landscape features on the provision of RESs

The spatial variation patterns of various RESs are illustrated (Fig. S1 in SI) as follows: High water yield within the watershed is primarily concentrated in the western part, reaching up to 1112.73 mm; areas with low water yield are mainly located on the eastern side, with the minimum being 0. Areas with high nitrogen export are predominantly found in the northern part of the watershed, with a maximum of 0.86 t/km^2. In contrast, regions with low nitrogen export are distributed in the southwestern area, with the minimum being 0. Soil retention levels are high in the southwest region of the watershed, achieving up to 111.08 $\times$ 10^4 t/km^2; areas with low soil levels are spread around the remaining periphery, with the least being 6.5 t/km^2. High carbon storage is also principally focused in the southwestern region of the watershed; areas with low carbon storage are mainly in the eastern part. Overall, these four RESs exhibit heterogeneity in their spatial distribution across the watershed.

In our study, six representative landscape feature indicators were selected. A spatial random sampling of 1000 points was employed to conduct regression and marginal effect calculations, yielding service curves and marginal curves as depicted (Fig. 6). The marginal characteristics of all landscape features are detailed (see SI Fig. S4). For carbon storage, with the increase in FP, the trend of change was "increase then decrease", reaching a maximum value of 13,129.3 t/km^2 at FP 66.4. The marginal utility trend was characterized by a "first increase, then decrease" pattern, with utility increasing under the condition of 0 $<$ FP $<$ 30.4, reaching a peak marginal utility of 230.5 at the FP threshold of 30.4, indicating the point of maximum efficiency of FP's impact on carbon storage services before it starts to decline. Similarly, it was noteworthy that with the increase in the LSI, the trend for carbon storage services was "monotonically increasing," reaching a maximum value of 6169.5 at LSI 4.0. Conversely, the marginal utility trend was "monotonically decreasing," with a maximum value at LSI 1.0, indicating that LSI had the highest impact efficiency on carbon storage services at this point, although it would not increase indefinitely. The threshold values for the marginal effects of all factors are shown (Table 3).

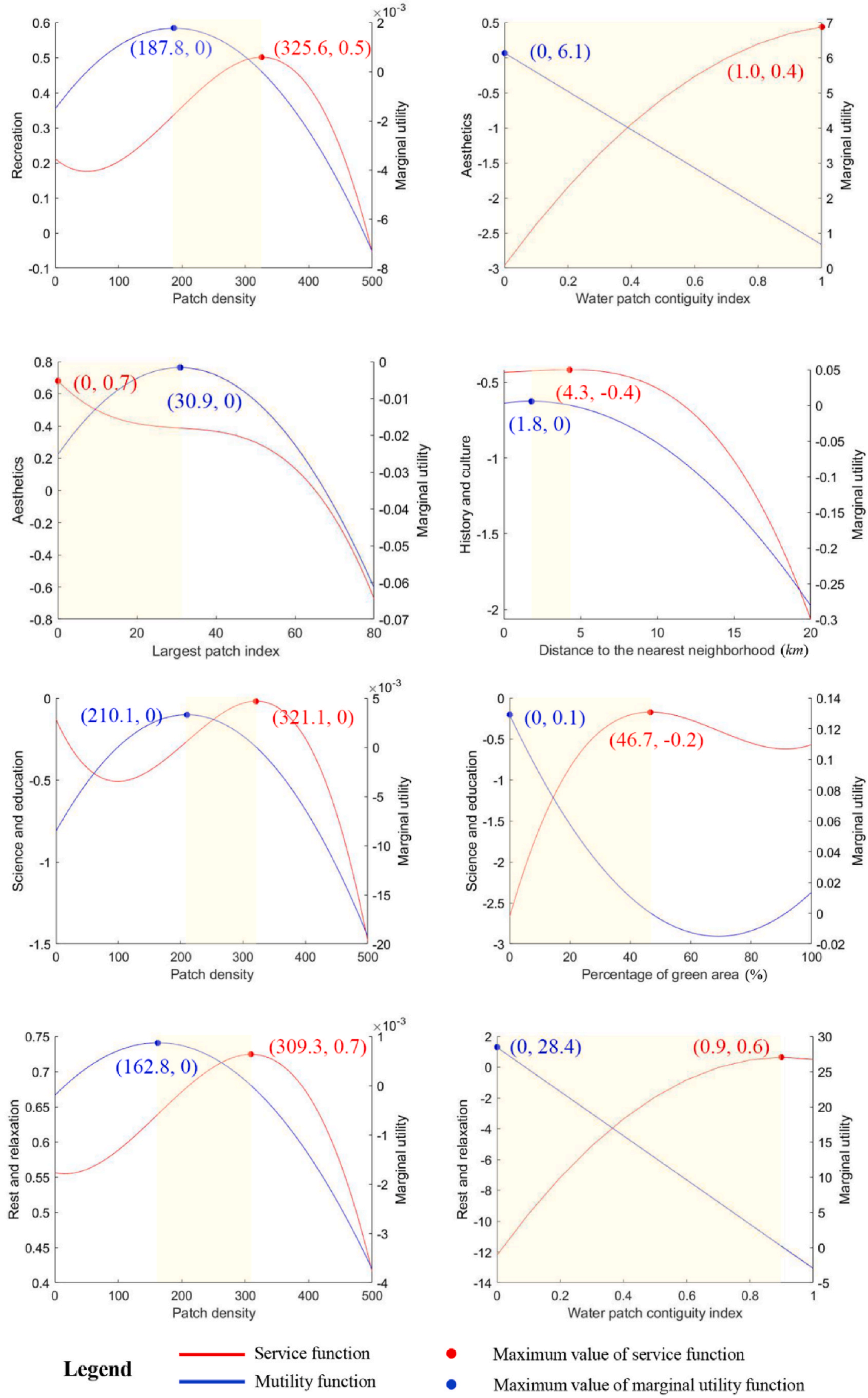

Fig. 5. The influence of each factor on CES and marginal utility function.

Table 2
Coordinates of maximum value of service function and marginal utility function about CES.

CES	Park characteristic factor	Maximum value of service function		Maximum value of marginal utility function	
		Abscissa	Ordinate	Abscissa	Ordinate
Recreation	PD	325.60	0.50	187.80	0.00
	LPI	0.00	0.71	31.40	0.00
	BP	22.60	0.44	11.10	0.02
Aesthetics	WPCI	1.00	0.44	0.00	6.13
	LPI	0.00	0.68	30.90	0.00
	BP	20.00	0.50	5.40	0.01
History and Culture	Nei_dist	4.30	−0.42	1.80	0.01
	GP	22.50	−0.32	100.00	0.01
	PD	321.10	−0.02	210.10	0.00
Science and Education	LPI	35.50	−0.20	20.10	0.01
	GP	46.70	−0.17	0.00	0.13
	BP	13.20	−0.25	0.00	0.04
Rest and Relaxation	PD	309.30	0.72	162.80	0.00
	WPCI	0.90	0.64	0.00	28.43
	LPI	0.00	0.90	39.50	0.00

4. Discussion

4.1. Visitor attributes and park characteristics collectively influence the provision of CES

In the planning of urban parks, it is essential to consider the perceptual differences in CES among diverse groups to promote equity and sustainable development (Gould et al., 2020). Our findings reveal that visitors' demographic characteristics, including educational level, income, gender, and age, significantly influence their preferences for different types of CES. For instance, visitors with higher educational qualifications tend to be more discerning about the cultural and educational content in parks. In contrast, those with higher incomes are more demanding of entertainment and educational services. In alignment with our perspective, (Riechers et al., 2018) contend that varying social groups have distinct perceptions of CES. In their study of Berlin's urban green spaces, factors including educational attainment and age could account for the preferences in CES among different groups. Young visitors exhibit a preference for interactive and educational experiences, whereas older individuals favor tranquil spaces for contemplation and reflection. This concurs with life stage needs and leisure theories, which suggest that individuals seek varying experiences at different stages of their lives (Bingley et al., 2023).

Furthermore, there is evidence to suggest that women tend to have a higher preference for leisure services, while older individuals exhibit higher levels of satisfaction with entertainment and leisure offerings. The ease of access and duration of residence do not significantly impact the evaluation of CES. This indicates that services are perceived similarly by residents and external visitors. The provision of CES in parks is considered sustainable, as an increase in visitation frequency does not diminish visitor satisfaction with the services.

Simultaneously, we determined that the majority of park features have their respective optimal values and marginal utility peaks for the CES provision scores. The interval between these two maxima, corresponding to the values of park characteristics, delineates the ideal range for these features in practical planning scenarios. The park attributes (such as DP, WPCI, and BP) are vital for the pivotal role in the delivery of CES. Exceeding the optimal range of values for these characteristics leads to a decline in services. A diverse landscape with effective water connectivity can greatly enhance visitors' recreational and aesthetic experiences (Ko and Son, 2018).

Conversely, extensive areas of single-use land (like excessive construction or green spaces) diminish educational and restorative experiences for visitors. This indicates that urban green space planning should incorporate a diversified landscape design to cater to the varying demands for different CES (Kabisch, 2015). For parks like YuanBoYuan and YuJiaYang with lower aesthetic scores, regular maintenance, improved landscape design, and maintaining vibrant vegetation year-round can significantly enhance their visual appeal. Additionally, minimizing construction and maintenance activities during peak visitor times can reduce disruptions to the visitor experience.

4.2. Response of RES to landscape characteristics

Through a meticulous analysis of different landscape characteristics, we have discerned that these features possess varied marginal benefits in providing RES, like water supply, water purification, climate regulation, carbon sequestration, and soil erosion protection (Bai et al., 2020). First, an increase in LSI within the landscape significantly bolsters the marginal utility for enhancing services like soil conservation and carbon storage. This exhibits comparatively identical marginal benefit curves. However, as the proportion of LSI increases, the marginal contribution of each additional unit of LSI to soil conservation and carbon sequestration gradually diminishes. This suggests that quality rather than mere quantitative expansion should be emphasized when designing and planning for LSI.

Moreover, our analysis revealed that the LDI has an identical service curve for soil retention and carbon storage. The marginal utility of control services increases at first and then decreases. Varied topography and land use can effectively disperse rainwater flow, reducing soil loss (Nunes et al., 2011; Ochoa et al., 2016). Nonetheless, this effect wanes beyond a certain diversity threshold. Second, water body features (WP), including lakes, rivers, and wetlands, exhibit high marginal utility in providing flood control services. These features are vital to flood prevention by absorbing and storing excess rainwater. However, this marginal utility also decreases with the expansion of water bodies. This indicates that an optimal balance of ecological and social benefits must be considered when increasing water bodies. The analysis of the marginal utility of landscape characteristics can help determine the optimum scale and location for park features and landscape attributes. This ensures that ecological benefits are maximized.

4.3. Marginal utility can be used to guide park planning and management

In the context of wetland parks, it is critical to understand the characteristics of the margins, which refer to how ESs change with incremental changes in inputs or environmental conditions. Researchers have integrated the microeconomic concept of marginal utility into the study of ESs to explore the threshold effects and elasticities of factors that influence ecosystem management and optimization (Ma et al., 2021). Based on this study's findings, the following recommendations are suggested for wetland park planning and construction.

1) Adopting a Visitor-Centric Approach: Consider the diverse cultural needs and preferences of the public and tailor cultural activities and services for different visitor groups (e.g., families, student groups, seniors). Enhance the park's appeal by exploring historical sites and cultural sources to create popular attractions and collaborating with local cultural institutions to introduce high-quality activities.
2) Marginal Utility Analysis in Park Planning: Conduct a marginal utility analysis for each service during park planning to determine the utility changes with increased resource inputs (e.g., additional green space, water bodies, or facilities). Prioritize resource allocation to services or facilities with the highest marginal utility until the point of diminishing returns is reached, ensuring efficient use of resources to maximize benefits.
3) Regularly monitor park service usage and establish a user feedback mechanism to assess changes in marginal utility. For example, when the patch density (PD) was 325.60, the marginal utility of recreational services was optimized; however, this may vary across

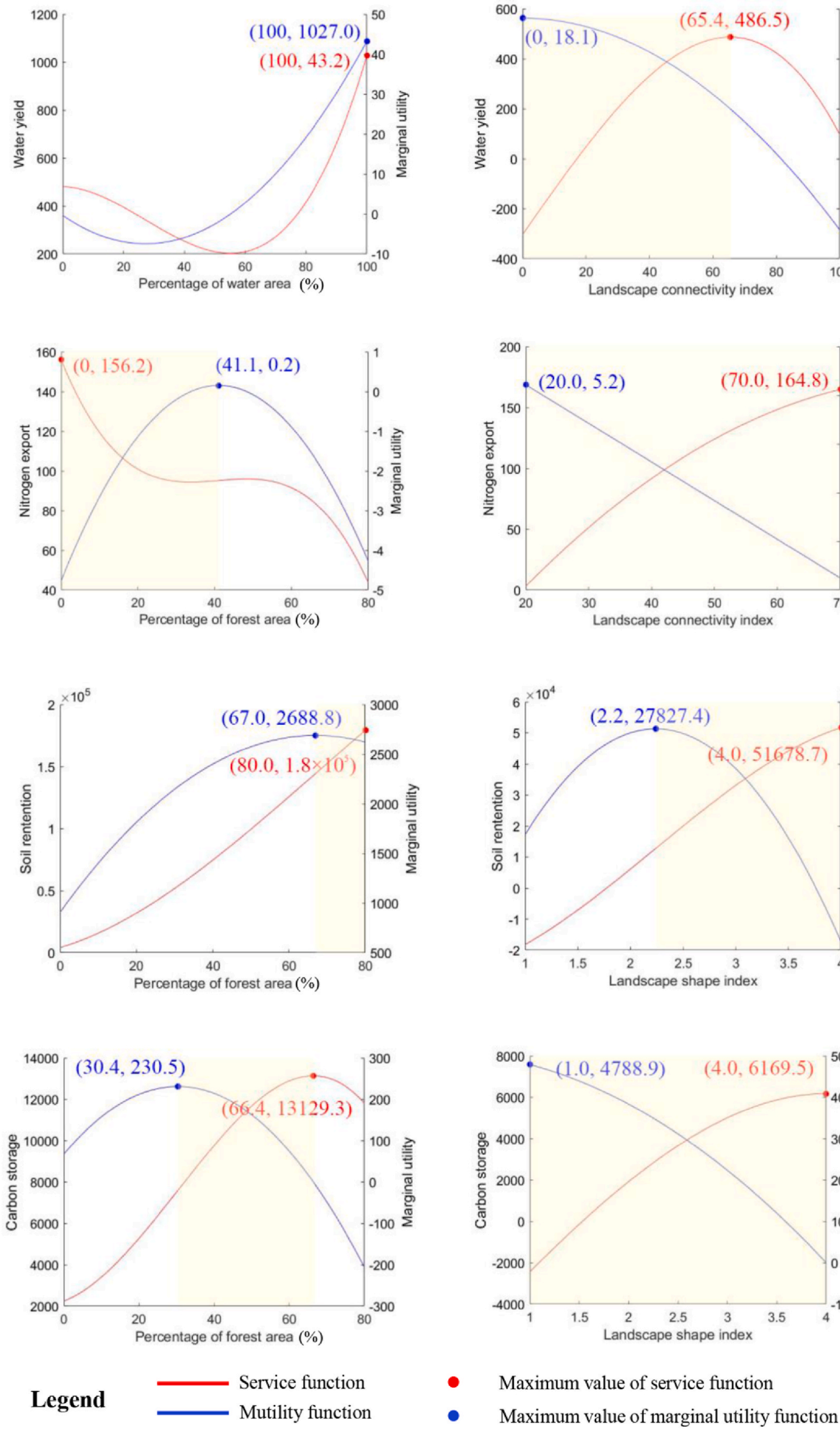

Fig. 6. The influence of each factor on RESs and marginal utility function.

Table 3
Coordinates of maximum value of service function and marginal utility function about RESs.

RESs	Landscape characteristic factor	Maximum value of service function		Maximum value of marginal utility function	
		Abscissa	Ordinate	Abscissa	Ordinate
Water yield	WP	100.00	43.22	100.00	1026.98
	LCI	65.39	486.51	0.00	18.12
Nitrogen export	FP	0.00	156.20	41.10	0.20
	WP	10.70	141.60	70.00	6.40
	LCI	70.00	164.80	20.00	5.20
Soil retention	FP	80.00	1.8×10^5	67.00	2688.80
	LDI	0.00	2.16×10^5	0.90	1.32×10^5
	LFI	20.30	58145.20	14.70	7453.70
	LSI	4.00	51678.70	2.20	27827.40
Carbon storage	FP	66.40	13129.30	30.40	230.50
	LFI	20.70	6319.70	13.30	450.90
	LSI	4.00	6169.50	1.00	4788.90
	LDI	0.00	11640.50	0.80	10268.30

different years. Thus, by flexibly adjusting resource allocation, planners can improve the efficiency and quality of cultural and regulatory services in wetland parks.

4.4. Strengths and limitations

The innovation of this study is primarily manifested in the following areas: 1) Through field research, a profound interpretation of the perceptual characteristics of CES concerning the attributes of visitors has been articulated. 2) From the perspective of economic marginal characteristics, a theoretical framework for the pattern and influencing threshold factors of cultural and regulatory service changes in parks located in watersheds has been established. 3) Considering regional differences, the threshold range of the impact of park and landscape characteristics on cultural and regulatory services has been concurrently examined.

This study has certain limitations. For instance, in the design of the questionnaire, the variability of visitors' moods and the bias in evaluations due to different times of visitation, particularly the sampling collected during holidays and regular days, may lead to demographic disparities. Meanwhile, we have yet to analyze some tourist perceptions and social media data. In the future, we will use social media APIs or web scraping techniques to collect user comments and related data. After cleaning and preprocessing the data, we will employ NLP to perform text mining and sentiment analysis on tourist perceptions and social media data, assessing the overall sentiment of visitors towards the park. Additionally, the marginal utility analysis only considered park features and landscape pattern indicators. This omitted potential biases introduced by factors including habitat quality and biodiversity. Addressing these biases will assist our future research endeavors.

5. Conclusions

In this study, we explored the perceptual characteristics of CES and RES in TLB, as well as the impact of visitor attributes and park features on the evaluation of these services. Quantitative results indicate that visitors' education level and income significantly affect CES scores, while the landscape composition of parks and their distance from residential areas are also key factors. Specifically, we found that landscape features exhibit significant differences in marginal benefits when providing RESs such as water supply, water purification, climate regulation, carbon storage, and soil erosion prevention. For example, as the forest percentage (FP) increases, carbon storage follows a "first increase, then decrease" pattern, reaching a maximum value of 13129.3 t/km^2 at an FP of 66.4. Additionally, the thresholds of landscape features significantly impact the provision of CES and the enhancement of RESs, with patch density (PD) reaching its peak entertainment service score of 0.50 at a PD of 325.60.

From a qualitative perspective, these findings highlight the importance of a visitor-centered approach that considers the diverse cultural needs and preferences of the public. By precisely identifying the intervals corresponding to the maximum marginal utility and peak service values of landscape features, targeted guidance can be provided for the practical planning of wetland parks. Our results show that visitor attributes such as age, income, education level, and gender significantly influence the evaluation of CES, further emphasizing the importance of considering demographic factors in urban park planning. Future research should include additional factors such as habitat quality and biodiversity to refine our understanding and address potential biases.

CRediT authorship contribution statement

Yang Bai: Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Maroof Ali:** Writing – review & editing. **Yi Zhou:** Writing – original draft, Data curation. **Shiliang Yang:** Writing – review & editing, Writing – original draft, Data curation.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.We deeply appreciate your consideration of our manuscript, and we look forward to receiving comments from the reviewers. If you have any queries, please don't hesitate to contact me at the address below. Thank you and best regards.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143353.

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