



OPEN ACCESS

EDITED BY

Guoxia Ma,
Chinese Academy for Environmental
Planning, China

REVIEWED BY

Shengqiang Zhai,
Peking University, China
Xiubo Yu,
Chinese Academy of Sciences (CAS), China

*CORRESPONDENCE

Zhanjun Quan,
✉ quanzj@craes.org.cn
Ying Zhang,
✉ zhangyin@bjfu.edu.cn

RECEIVED 16 June 2024

ACCEPTED 17 February 2025

PUBLISHED 13 March 2025

CITATION

Du L, Liu H, Liu H, Liu W, Li Z, Liu X, Li J,
Quan Z and Zhang Y (2025) Temporal-spatial
variation of regulating ecosystem services and
analysis of driving factors in Hainan Tropical
Rainforest National Park, China.
Front. Earth Sci. 13:1449816.
doi: 10.3389/feart.2025.1449816

COPYRIGHT

© 2025 Du, Liu, Liu, Liu, Li, Liu, Li, Quan and
Zhang. This is an open-access article
distributed under the terms of the [Creative
Commons Attribution License \(CC BY\)](#). The
use, distribution or reproduction in other
forums is permitted, provided the original
author(s) and the copyright owner(s) are
credited and that the original publication in
this journal is cited, in accordance with
accepted academic practice. No use,
distribution or reproduction is permitted
which does not comply with these terms.

Temporal-spatial variation of regulating ecosystem services and analysis of driving factors in Hainan Tropical Rainforest National Park, China

Leshan Du^{1,2}, Haiyan Liu¹, Haiou Liu¹, Wenhui Liu¹, Ziyuan Li¹, Xiaoyan Liu¹, Junsheng Li³, Zhanjun Quan^{1*} and Ying Zhang^{2*}

¹State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, China, ²School of Economics and Management, Beijing Forestry University, Beijing, China, ³Command and Center for Comprehensive Survey of Natural Resources, China Geological Survey Bureau, Beijing, China

The establishment of national parks is a critical measure for natural ecological protection in China, significantly contributing to biodiversity conservation and regional sustainable development. However, the analysis of temporal-spatial variations in ecosystem services within national parks, along with the factors influencing these variations, remains largely overlooked. This gap limits the effectiveness of ecological protection and refined management in these parks. Using Hainan Tropical Rainforest National Park (HTRNP) as a case study, this study integrates geospatial analysis ArcGIS with the InVEST model to evaluate the regulating ecosystem services (RESs) from 2000 to 2020 at 5-year intervals. The analysis examines the temporal evolution patterns and spatial distribution of RESs, utilizing LightGBM to identify the primary driving factors of these services. The findings reveal the following: (1) Temporally, the RESs exhibit significant fluctuations, with a trend of "initial decline followed by a subsequent rise". Climate regulation services accounted for the highest proportion at 61.4%, followed by water conservation and soil retention. (2) Spatially, the RESs in the eastern and central regions are slightly higher than those in the western region, demonstrating consistency across different years. The RESs in HTRNP show a strong spatial clustering effect (Moran's $I > 0.5$, $Z > 2.58$), with spatial hotspots (H-H) in the eastern and central regions, and spatial cold spots (L-L) in the western and northern regions. (3) In terms of driving factors, natural factors, including annual precipitation (PRE) and annual potential evapotranspiration (PET) alongside socio-economic factors such as land use and land cover (LULC) and the Human Footprint Index (HFI), make the highest marginal contributions to RESs. Specifically, RESs demonstrate the strongest correlation with LULC, a positive correlation with PRE, and negative correlations with PET and HFI. This study explores the dynamic changes and influencing factors of RESs, providing a scientific guideline for future ecological planning and effective management decisions within HTRNP.

KEYWORDS

Hainan Tropical Rainforest National Park, regulating ecosystem services(RESs), value assessment, temporal-spatial variation, driving factors

1 Introduction

In recent years, global ecological and environmental issues have become increasingly protruding, accompanied by frequent extreme weather events such as air pollution, desertification, and soil erosion. Ecosystem services, which are the benefits humans derive directly or indirectly from ecological processes (Costanza et al., 1997; Costanza et al., 2017), offer a crucial approach to addressing these challenges. Ecosystem Services include four service types, such as provisioning services, regulating services, cultural services, and supporting services (Arico et al., 2005). RESs, encompassing water conservation, soil retention, and climate regulation, among others, are considered the cornerstone of ecosystem services, playing a pivotal role in regional ecological protection and sustainable economic development.

There are differing opinions in the academic community regarding the evaluation of RESs. The concepts, models, and methods used to evaluate RESs vary based on different motivations. For instance, some evaluations are based on a national perspective, with the results supplementing the existing standard national economic system with concepts, such as the quaternary industry of ecological products (Wang et al., 2021; Ma et al., 2024). Other evaluations emphasize cost-benefit analyses (Francisco et al., 2024) or damage compensation assessments (Veklych et al., 2020) for specific projects to propose more reasonable policy recommendations or alternatives. Some evaluations aim to enhance awareness of the importance of ecosystems among governments, enterprises, or the public. Despite these differences, there is a general consensus that RESs should represent the ultimate benefits provided by ecosystems to humans, excluding intermediate process products like material cycling, energy flow, and information transfer. In terms of specific accounting methods, the evaluation methods for RESs are roughly divided into four paradigms: statistical surveys method, the equivalent factor method (Xie et al., 2008; Xie et al., 2015), emergy analysis (Xu et al., 2020; Nadalini et al., 2021), and model-based approaches (Villa et al., 2009; Sherrouse et al., 2022; Gao et al., 2024). Different scholars often select different evaluation models and baseline data, leading to significant discrepancies in the evaluation results of RESs. Therefore, results derived from different methods and evaluation models based on different ecosystem types are often not comparable. However, conducting temporal-spatial dynamic evolution analysis of RESs within the same region is highly significant for systematically understanding the status of the regional ecosystem (Haining et al., 2010; Ye and Wu, 2010). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is particularly prominent to address these issues and is widely used by scholars, due to its simplicity, ease of data acquisition, flexible parameter adjustment, and spatially expressible evaluation results (Qiu et al., 2023; Yang et al., 2023).

Hainan Tropical Rainforest National Park (HTRNP) is one of the first five national parks in China. It boasts the most concentrated, best-preserved, and largest contiguous tropical rainforest area in the country, forming an integral part of the world's tropical rainforests. HTRNP is also a critical area for tropical biodiversity conservation in China, serving as a global gene pool for germplasm resources and a biodiversity conservation hotspot (Myers et al., 2000; Francisco-Ortega et al., 2010). Most of the products provided by HTRNP are public goods. Due to their externality, these products require

government investment, maintenance, operation, and support. Therefore, conducting an ecosystem service valuation for HTRNP is crucial. On one hand, such an assessment can better analyze the costs and benefits of relevant activities in HTRNP, elucidating the purpose and value of establishing the national park, and ultimately providing a reference for policy decisions. On the other hand, it can help monetize the “tangible” and “intangible” natural capital, thereby vividly demonstrating the immense value of ecosystem services and raising public awareness among governments, enterprises, and the public regarding the “value of natural resources” (Quintas-Soriano et al., 2019; Peng et al., 2023).

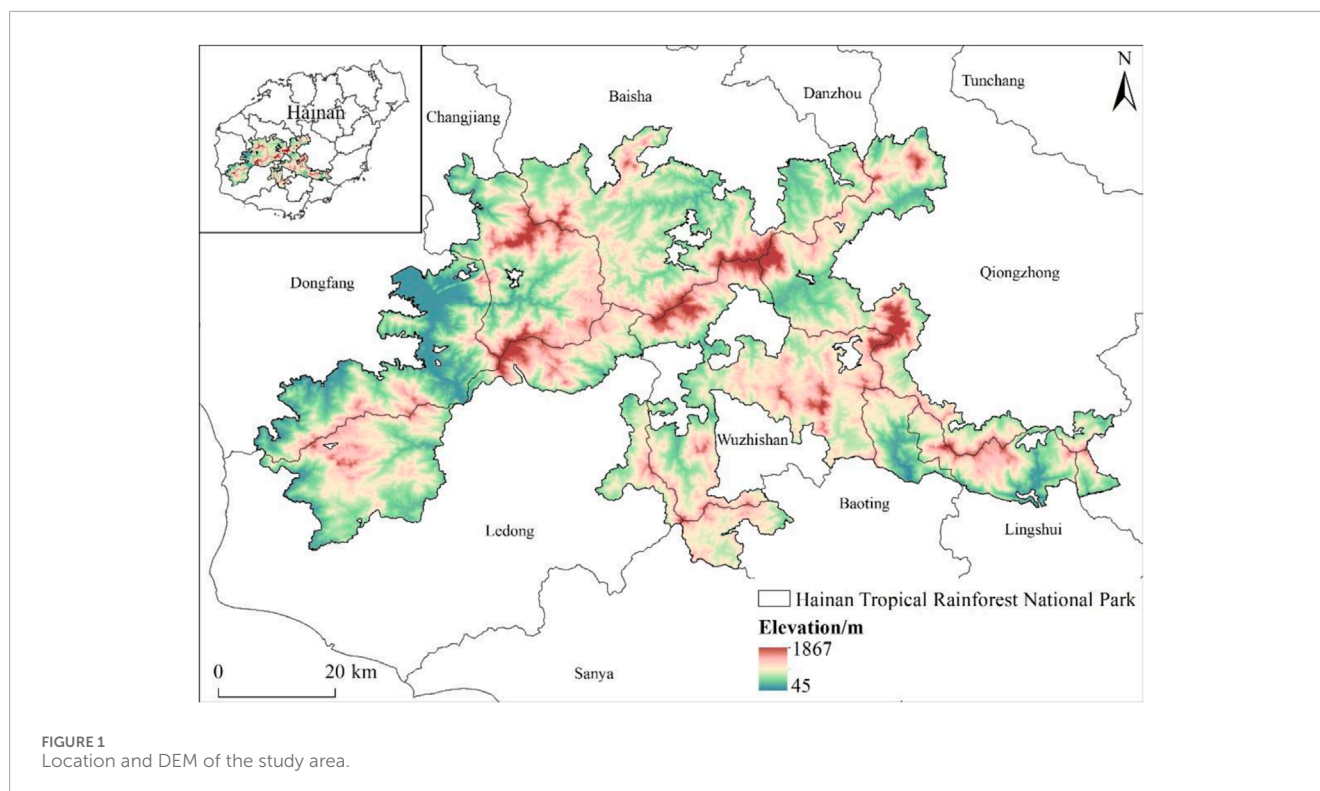
Previous studies on ecosystem services in HTRNP have addressed various aspects: Li et al. (2022) focused on the relationship between land use type and ecosystem services; Wu et al. (2023) examined ecosystem services and ecological compensation based on land utilization; Lin and Fu. (2023) explored the implications of ecosystem services on landscape pattern changes, and Zhong et al. (2023) investigated the effects of ecological restoration projects on ecosystem services. However, few studies have simultaneously focused on ecosystem services and their driving factors over a long time series, which may result in a lack of effective guidance for the management of HTRNP.

To explore the temporal-spatial variations of ecosystem services in national park, we selected HTRNP as a case study. Referring to the Millennium Ecosystem Assessment (MA) and the Gross Ecosystem Product (GEP) accounting system, we selected indicators with high academic recognition to represent RESs. These indicators include water conservation, soil retention, carbon sequestration, oxygen release, and climate regulation. The InVEST model was used to evaluate the biophysical quantity and monetary value of these services from 2000 to 2020 at 5-year intervals. This approach allows for a comprehensive understanding of the temporal-spatial variation patterns of RESs. Additionally, Global Moran's Index and Local Indicators of Spatial Association (LISA) are employed to study the spatial differentiation patterns of RESs within the region. Furthermore, the Light Gradient Boosting Machine (LightGBM) was used to reveal the driving factors behind these services. This paper provided scientific evaluations of the dynamic changes and driving factors of RESs, providing important guideline for the spatial planning and effective management policies for HTRNP.

2 Methodology and data

2.1 Study area

HTRNP is situated in the central part of Hainan Island, with geographical coordinates ranging from 108°44'32"E to 110°04'43"E and 18°33'16"N to 19°14'16"N. It spans across nine counties (cities): Wuzhishan, Qiongzong, Baisha, Dongfang, Lingshui, Changjiang, Leong, Baoting and Wanning (website <https://www.hntrnp.com>). The total area of HTRNP is 4,268.54 km², accounting for about 12.1% of Hainan Island's total area and 25.4% of the land area of the nine counties and cities it encompasses (Supplementary Appendix Table S1). The highest elevation within HTRNP is recorded at Wuzhishan Mountain (1867 m asl), which represents the highest peak on Hainan Island. Conversely, the lowest elevation (45 m asl) is situated in the Duzong River basin



within the Diaoluoshan Mountain of the national park (Figure 1). The national park enjoys abundant sunlight and favorable thermal conditions, with an annual average temperature ranging from 22.5°C to 26.0°C. It also receives significant rainfall, with an average annual precipitation of 1,759 mm, although the distribution of rainfall is uneven temporally and spatially, leading to distinct wet and dry seasons. The forest coverage rate across the park is 95.86%, with natural forests dominated by tropical rainforests accounting for approximately 76.56% of the area.

2.2 Indicator and methods for RESs

Referring to the MA, The Economics of Ecosystems and Biodiversity (TEEB), the GEP Accounting Technical Guidelines and other scholarly research, we selected five indicators with high academic recognition: water conservation, soil retention, carbon sequestration, oxygen release, and climate regulation. We conducted an ecosystem service valuation from both the biophysical quantity and monetary value perspectives. The biophysical quantity was primarily calculated using the InVEST model (Table 1; Supplementary Appendix Table S2). For the monetary value assessment, we employed the market value method as the basis, incorporating the shadow engineering method and the recovery cost method to estimate the value of each indicator (Table 1; Supplementary Appendix Table S2). Further biophysical quantities and monetary values accounting methods and models are provided in Supplementary Appendix Table S2. Finally, we adjusted the monetary values using local statistical bulletins and yearbooks to ensure that the results more accurately reflect the actual situation.

2.3 Research method

2.3.1 Analysis of temporal-spatial change

The Ecosystem Service Change Index (ESCI) was used to manifest the variations in RESs from 2000 to 2020 at 5-year intervals. The ESCI indicates the relative gains or losses of each ecosystem service (Kärkkäinen et al., 2020), thereby elucidating the temporal evolution patterns of these services. The calculation formula is as follows:

$$ESCI_x = \frac{ES_{CUR_x} - ES_{HIS_x}}{ES_{HIS_x}}$$

Here, $ESCI_x$ represents the change index of the value of a single regulating ecosystem service. ES_{CUR_x} represents the value of the regulating ecosystem service in the final state, in CNY. ES_{HIS_x} represents the value of the regulating ecosystem service in the initial state, in CNY.

2.3.2 Spatial autocorrelation analysis

Spatial autocorrelation analysis is a crucial method for examining the spatial clustering and interactions of geographic entities, which can be used to characterize the spatial homogeneity or heterogeneity (Ye and Wu, 2010). It is commonly represented by the Moran's Index, which comprises both the Global Moran's Index and the Local Moran's Index (Dai et al., 2020; Yang et al., 2024). These indices reveal the correlation between the properties of global spatial units and the attribute values of neighboring local spatial units (Haining et al., 2010).

The Global Moran's Index (Moran's I) can reflect the overall spatial autocorrelation characteristics of the study area. The

TABLE 1 Accounting framework for regulating ecosystem services in Hainan Tropical Rainforest National Park.

Accounting subject	Abbreviation	Biophysical quantity indicators	Biophysical quantity accounting method	Monetary value accounting method
Water conservation	WC	Water retained	Water Balance Equation	Shadow engineering
Soil retention	SR	Maintain soil fertility	Revised Universal Soil Loss Equation (RUSLE)	Recovery cost method
		Reduce sediment		Recovery cost method
Carbon sequestration	CS	Carbon dioxide fixed	Net Primary Productivity (NPP)	Recovery cost method
Oxygen release	OR	Oxygen released		Recovery cost method
Climate regulation	CR	Plant transpiration	Evaporation of Ecosystem	Recovery cost method
		Evaporation from water surface		

calculation formula is as follows:

$$\text{Moran's } I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2 \left(\sum_{i=1}^n \sum_{j=1}^n w_{ij} \right)}$$

Here, x_i and x_j represent the values of grid units i and j , respectively; n denotes the total number of samples in the study area; \bar{x} is the regional mean value; and w_{ij} is the spatial weight matrix established based on the distance function adjacency relationship. When Moran's $I > 0$, it indicates that the ecosystem services exhibit positive spatial autocorrelation, with larger values signifying stronger positive autocorrelation. When Moran's $I = 0$, it indicates no spatial correlation, suggesting a random distribution. Conversely, when Moran's $I < 0$, it indicates negative spatial autocorrelation, with smaller values indicating stronger negative autocorrelation.

The LISA can reflect the spatial differentiation patterns of regional RESs (Anselin, 1995). The calculation formula is as follows:

$$Lisa_i = \frac{(x_i - \bar{x})}{m_0} \sum_i W_{ij} (x_i - \bar{x})$$

$$m_0 = \sum_i (x_i - \bar{x}) / n$$

Here, W_{ij} represents the spatial weight matrix between grid units i and j ; X_i is the attribute value of grid unit i ; \bar{x} is the mean of all attribute values; and n is the total number of grid units in the area. When $Lisa > 0$, it indicates that the area is a high-high (H-H) value or low-low (L-L) value spatial cluster; conversely, when $Lisa < 0$, it indicates that the area is a high-low (H-L) value or low-high (L-H) value spatial cluster (Chen et al., 2020). On this basis, using the ArcGIS hotspot analysis tool, Getis-Ord G_i^* statistic index is applied to identify statistically significant hotspot and coldspot spatial clusters by calculating the Z-scores and P -values for each patch (Yi et al., 2018). The Lisa distribution map is then plotted to explore the spatial clustering characteristics of RESs (Li et al., 2022).

2.4 Analysis of driving factors

To further investigate the influencing factors of RESs value, 11 specific indicators were selected from two major categories: natural factors and socio-economic factors (Table 2). Firstly, natural factors, which form the foundation of ecosystem services, include meteorological factors such as PET and PRE, vegetation factors such as the Normalized Difference Vegetation Index (NDVI) and Net Primary Productivity (NPP), and soil and topographic factors including the Digital Elevation Model (DEM) and Soil Organic Matter (SOM). Secondly, socio-economic factors, which primarily influence ecosystem services by altering land use patterns, encompass LULC, population data such as population density (POP) and HFI, and economic data primarily including *per capita* Gross Domestic Product (GDP) and Nighttime Lighting Data (NL).

The spatial projection coordinates of the aforementioned raster data were standardized to the CGCS2000 national geodetic coordinate system. Using the Extract Values to Points under ArcGIS software, data of different resolutions were resampled to 30 m and aligned to the same grid. LULC data were converted into categorical variables, while other indices are normalized. Based on ArcGIS software, 6,122 sample points were generated annually from 2000 to 2020 at 5-year intervals. Using Python, the data was cleaned, removing null values, resulting in 25,610 samples used for constructing the decision tree. A stratified random sampling method with replacement was employed, dividing 80% of the samples into a training set and 20% into a testing set. LightGBM was utilized to analyze the contribution of various driving factors to the RESs in HTRNP. The results of the LightGBM model were graphically analyzed using the Shape package.

3 Results

3.1 RESs value and change

3.1.1 Temporal variation of RESs

This study employed the InVEST model to evaluate the biophysical quantity of RESs in the HTRNP. The findings reveal that

TABLE 2 The driving factors and data sources of regulating ecosystem services.

First-class indicators	Second-class indicators	Third-class indicators	Abbreviation	Data sources
Natural factors	Meteorological factors	Annual average Potential Evapotranspiration	PET	https://developers.google.cn/earth-engine/datasets/catalog/MODIS_061_MOD16A2 , resolution of 500 m
		Annual average Precipitation	PRE	National earth system science data center (http://www.geodata.cn/), resolution of 1 km
	Soil and terrain factors	Digital Elevation Model	DEM	Geospatial Data Cloud (https://www.gscloud.cn/), resolution of 30 m
		Soil Organic Matter content	SOM	Geographic remote sensing ecological network platform (http://gisrs.cn/infofordata?id=5e3a3a3c-29ec-4e9c-aa83-e3f288d4e79e), resolution of 500 m
	Vegetation factors	Normalized Difference Vegetation Index	NDVI	Calculated through Google Earth Engine based on LANDSAT
		Net Primary Productivity	NPP	MODIS MOD13Q1 Land thematic data product (resolution of 250 m, time interval of 16 days)
Socio-economic factors	Land use type	Land Use and Land Cover	LULC	Earth System Science Data (https://www.earth-system-science-data.net), resolution of 30 m
	Population data	Population density	POP	https://www.worldpop.org/ Due to the inability to obtain data for 2020, 2019 data was used instead
		Human Footprint Index	HFI	https://wchumanfootprint.org/
	Economic data	Per capita GDP	GDP	Resource and Environmental Science Data Platform (http://www.resdc.cn/DOI)
		Nighttime Lighting data	NL	Source: https://eogdata.mines.edu/products/vnl/

from 2000 to 2010, the water conservation capacity steadily declined, decreasing from $5.362 \times 10^9 \text{ m}^3$ to $3.931 \times 10^9 \text{ m}^3$, a reduction of 26.7%. However, from 2010 to 2020, the water conservation capacity gradually increased, rising from $3.931 \times 10^9 \text{ m}^3$ to $4.338 \times 10^9 \text{ m}^3$, an increase of 10.37%. The soil retention capacity showed a gradual decline from 2000 to 2020, decreasing from $1.77 \times 10^8 \text{ t}$ to $1.37 \times 10^8 \text{ t}$, a reduction of 22.60%. Notably, from 2010 to 2020, the soil retention capacity exhibited a fluctuating increase, rising from $1.37 \times 10^8 \text{ t}$ to $1.50 \times 10^8 \text{ t}$, an increase of 9.49%. Carbon sequestration and oxygen release peaked in 2015 at $2.6112 \times 10^6 \text{ t}$ and $6.9906 \times$

10^6 t , respectively, and they were at their lowest in 2005, at $2.332 \times 10^6 \text{ t}$ and $6.2431 \times 10^6 \text{ t}$, respectively. The climate regulation services showed minimal fluctuation across different years (Figure 2).

By quantifying and summing the values of various regulation services, the total value of RESs from 2000 to 2020 is determined to be CNY221.84 billion, CNY206.626 billion, CNY202.837 billion, CNY207.204 billion, and CNY209.067 billion, respectively (Figure 3). The per unit area value of RESs ranges from CNY0.04751 billion/km² to CNY0.05197 billion/km². The overall value of RESs remains stable over the long term, exhibiting a slight trend of “initial

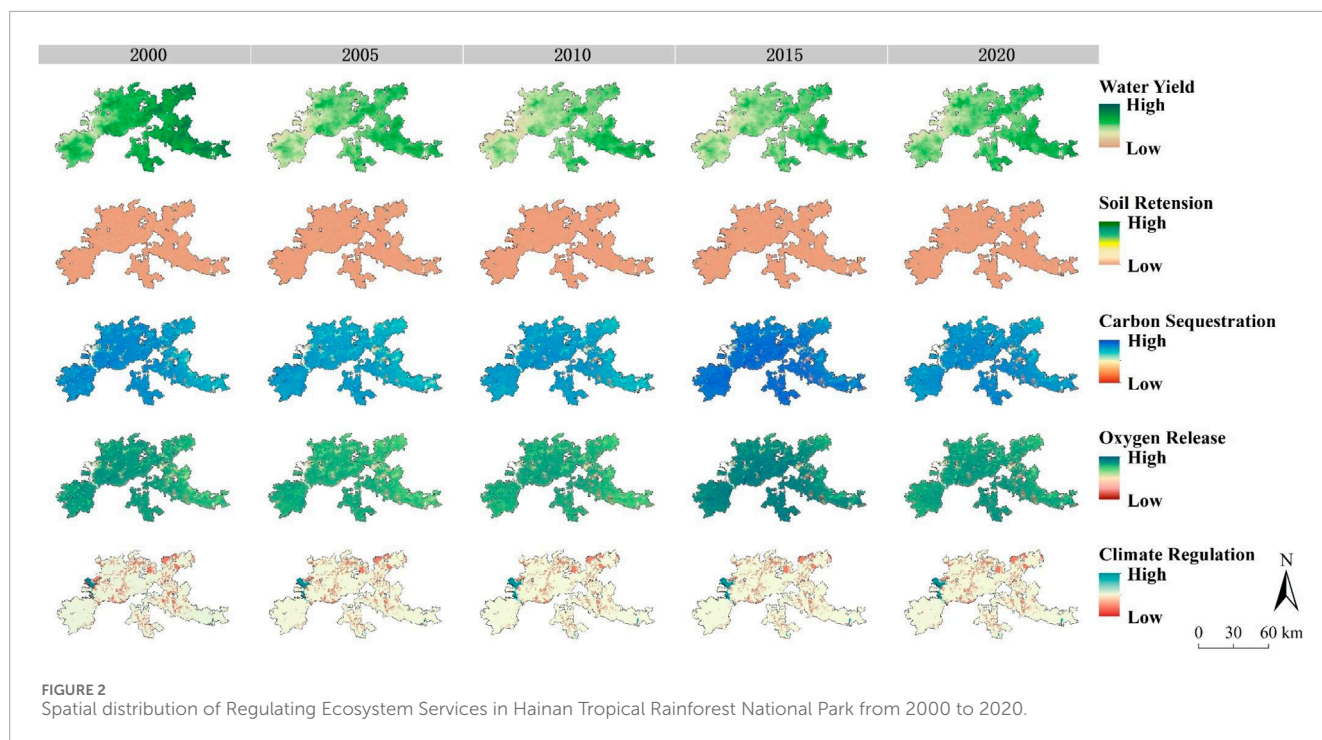


FIGURE 2 Spatial distribution of Regulating Ecosystem Services in Hainan Tropical Rainforest National Park from 2000 to 2020.

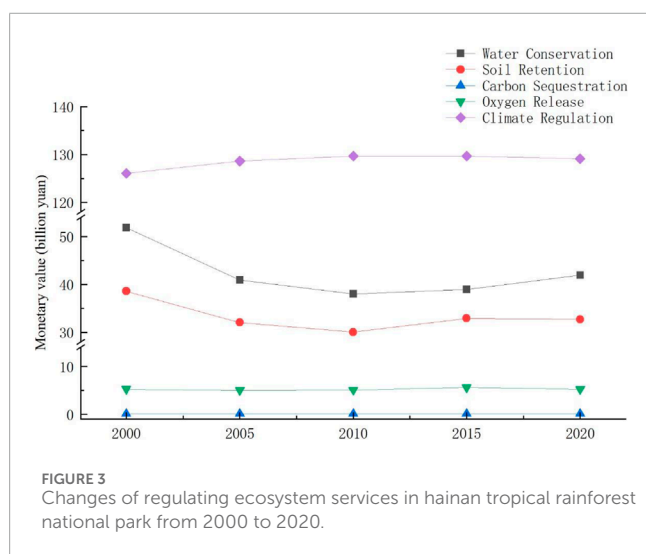


FIGURE 3 Changes of regulating ecosystem services in hainan tropical rainforest national park from 2000 to 2020.

decline followed by a subsequent rise.” In terms of the composition of RESs, climate regulation services had the highest value in 2020, accounting for 61.40%. Water conservation and soil retention services also had relatively high proportions, accounting for 20.21% and 15.74%, respectively. Carbon sequestration and oxygen release services had the lowest value, accounting for 2.84% (Figure 3).

3.1.2 Spatial differentiation of RESs

Using ArcGIS software to spatially visualize the value of RESs in HTRNP, the results indicate a certain differentiation in spatial distribution patterns. The values of RESs in the eastern and central regions of HTRNP are slightly higher than those in the

western regions. This pattern demonstrates good consistency across different years (Figure 4).

3.2 Spatial autocorrelation analysis

3.2.1 Global autocorrelation analysis

There may be spatial autocorrelation in RESs, and accurately measuring their spatial distribution patterns is of significant reference value for understanding regional spatial clustering characteristics. The spatial Moran’s Index is employed to analyze the spatial clustering characteristics of RESs in HTRNP. To balance spatial heterogeneity expression capability and computational workload, a 1 km × 1 km grid is selected as the spatial unit for the autocorrelation analysis of RESs. The results reveal that the Global Moran’s I index for RESs consistently exceeds 0.50 from 2000 to 2020, with Z-scores above 2.58, all passing the 0.001 significance test. This indicates that RESs exhibit strong positive spatial autocorrelation and clear spatial clustering characteristics. However, a decreasing trend was found in spatial autocorrelation in time scale, with Moran’s I decreasing from 0.6807 in 2000 to 0.5082 in 2020, suggesting that the clustering degree of RESs in HTRNP has been weakening over the past 20 years. Additionally, from 2000 to 2020, the spatial hotspots (H-H) generally exhibit a trend of “initial decline followed by a subsequent rise”, while the spatial cold spots (L-L) remain relatively stable (Table 3).

3.2.2 Local autocorrelation analysis

To further understand the local spatial clustering characteristics of RESs, a local autocorrelation analysis is conducted, and LISA maps are drawn for each year. The LISA maps clearly show spatial hotspots (H-H) in the eastern and central regions of HTRNP

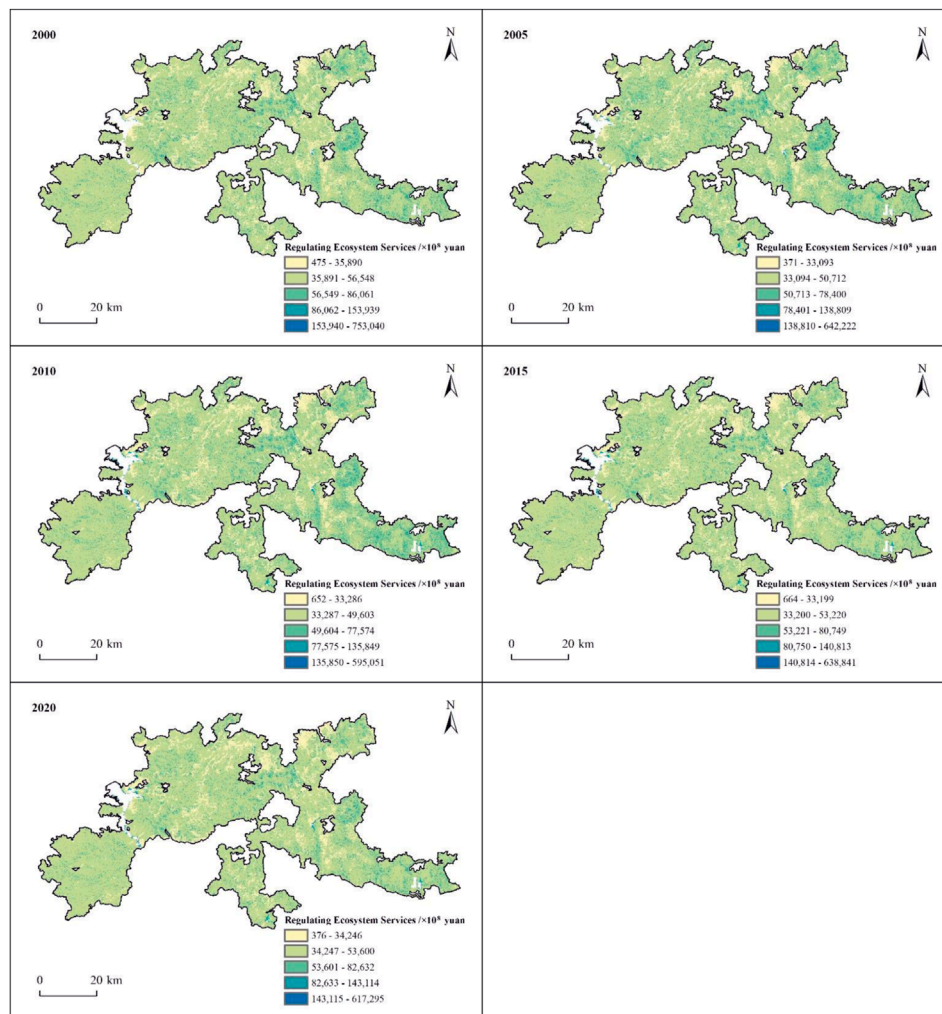


FIGURE 4 Distribution of regulating ecosystem services in hainan tropical rainforest national park from 2000 to 2020.

and spatial cold spots (L–L) in the western and northern regions, with consistent patterns across different years. The “H–H” type is concentrated in the eastern and central regions of HTRNP, aligning with the high-value areas of the spatial distribution of RESs value. The “L–L” type is primarily distributed in the western and northern regions of HTRNP. The “H–L” and “L–H” types are more scattered (Figure 5).

3.3 Analysis of driving factors

LightGBM model was used to conduct decision analysis on RESs from 2000 to 2020, and the results show that the explanatory power of various influencing factors on RESs reaches 68.3%. To further analyze the contribution of each driving factor to RESs, all sampling points are displayed using a hexbin plot. In this plot, SHAP values represent the weight of influence, and the size of each feature value is indicated by color. The wider the distribution area, the greater the impact of that factor. From the hexbin plot, LULC, PRE, and PET have the highest marginal contributions to RESs, making

them the primary factors influencing RESs in HTRNP (Figure 6). Among natural factors, RESs show a significant positive correlation with PRE and a significant negative correlation with PET. Other factors in descending order of impact include DEM with a negative correlation, NDVI with a positive correlation, SOM with a positive correlation, and NPP with a positive correlation, though their overall influence on RESs in HTRNP is relatively smaller. Among socio-economic factors, LULC has a significant impact on RESs in HTRNP. The HFI has a substantial negative impact on RESs. Other factors in descending order of impact include POP, NL, and GDP, though their overall influence on RESs in HTRNP is relatively small.

4 Discussion

4.1 Assessment results of RESs

This paper conducts the comprehensive analysis of temporal-spatial analysis from 2000 to 2020 in 5-year intervals of RESs in HTRNP. The results indicate that the value of RESs ranges

TABLE 3 Moran's I and hotspot analysis of regulating services in HTRNP.

Indicator		2000	2005	2010	2015	2020
Global Moran's Indicator	Moran's I	0.6807	0.5667	0.5140	0.5102	0.5082
	Z	53.07	44.20	40.09	39.79	39.63
	P	≤0.001	≤0.001	≤0.001	≤0.001	≤0.001
Area of Hotspot (km ²)	H-H	346.58	317.05	275.58	257.30	275.58
	H-L	40.77	45.70	40.77	42.88	49.21
	L-H	12.65	19.68	27.42	28.82	25.31
	L-L	235.51	233.40	234.80	227.07	236.21

from CNY202.837 billion to CNY221.84 billion, with the per unit area value of these services ranging from CNY0.04751 billion/km² to CNY0.05197 billion/km². These findings differ significantly from earlier studies (Xiao et al., 2000; Li et al., 2003) and deviated somewhat from a few recent studies (Li, 2022; Lin and Fu, 2023), but are similar to the majority of recent research findings (Supplementary Appendix Table S3). For instance, Chen et al. (2021) found that the total GEP of HTRNP in 2019 was CNY2,045.13 billion, with an average GEP per unit area of CNY0.046 billion/km². Du et al. (2023) reported that the total GEP of HTRNP in 2015 was CNY226.34 billion, with an average GEP per unit area of CNY0.0514 billion/km². The results of this study are also close to the official data published by Hainan Province. According to the Hainan Academy of Forestry, the total ecosystem production value of HTRNP in 2019 and 2020 was CNY204.513 billion and CNY205.143 billion, respectively (Chen et al., 2021).

Although the results of this study are similar to some existing researches, significant differences exist in specific indicators. For instance, in terms of soil retention, this study finds the soil retention value in HTRNP to be CNY32.711 billion, whereas previous studies, such as those by Chen et al. (2021) and Du et al. (2023), estimated it at CNY1.750 billion and CNY21.66 billion, respectively. These discrepancies arise from the diversity of evaluation methods, the subjectivity of parameter selection, and the multiplicity of data sources (Lin and Fu, 2023). HTRNP covers a vast area and spans a significant geographic range. The core areas of HTRNP are under strict protection, making access and sampling in most regions challenging. Consequently, obtaining localized parameters for the InVEST model is difficult. This study strives to select parameters based on related research in adjacent regions to align the research results with reality in a maximum way. However, using adjacent areas as references inevitably leads to some discrepancies between the research results and the actual conditions (Lin and Fu, 2023). Nevertheless, the framework and evaluation methods constructed in this study possess a certain degree of scientific and rational validity. The results derived using the same methods, models, and parameters are comparable over time and space, reflecting the ecological environment state and changes within HTRNP. These findings hold significant reference value for guiding the planning and management of national parks.

It is evident that different scholars, utilizing various models, methods, and parameters, produce significantly divergent evaluations of ecosystem service values. While the diversity of evaluation models and research methods for RESs is beneficial for advancing scientific research—allowing for the selection of different methods based on specific research objectives—there is a pressing need for further standardization from the perspective of refined management of the given regions. Clarifying research norms, ensuring the scientific soundness of methods, and maintaining consistency in model parameters are essential for conducting comparative analyses over temporal and spatial scales. This standardization will enhance understanding of the value and changing trends of ecosystem services within the national park. Additionally, it is recommended to establish regular monitoring and evaluation of the parameters required for RESs evaluation, thereby providing accurate data for assessing ecosystem service values, supporting ecological protection, and informing management decisions.

4.2 Temporal-spatial dynamics of RESs

From a temporal perspective, the RESs of HTRNP from 2000 to 2020 exhibit a “initial decline followed by a subsequent rise” trend, which pattern aligns with the previous studies (Lin and Fu, 2023; Zhong et al., 2023). The decline in RESs from 2000 to 2010 can be attributed not only to climate change but also to the expansion of tropical economic forests, such as rubber plantations in Hainan Province during this period (Han et al., 2022; Li et al., 2022). Statistics indicate that the area of rubber plantations on Hainan Island increased from 357,000 ha in 1998 to 455,000 ha in 2008, an expansion of 27.45% (Yu et al., 2016). However, the area of natural forests had sharply reduced 72,000 ha during this period (Hou et al., 2018). Compared to natural forests, rubber plantations have simpler community structures, fewer plant species, and lower carbon storage density, resulting in significant declines in water conservation, soil retention, and carbon sequestration services (Yao et al., 2024). Post-2010, Hainan Province initiated large-scale ecosystem restoration and preservation projects, such as the “Green Hainan Island” initiative, leading to nearly 200,000 ha of afforestation and greening. In 2019, the Chinese

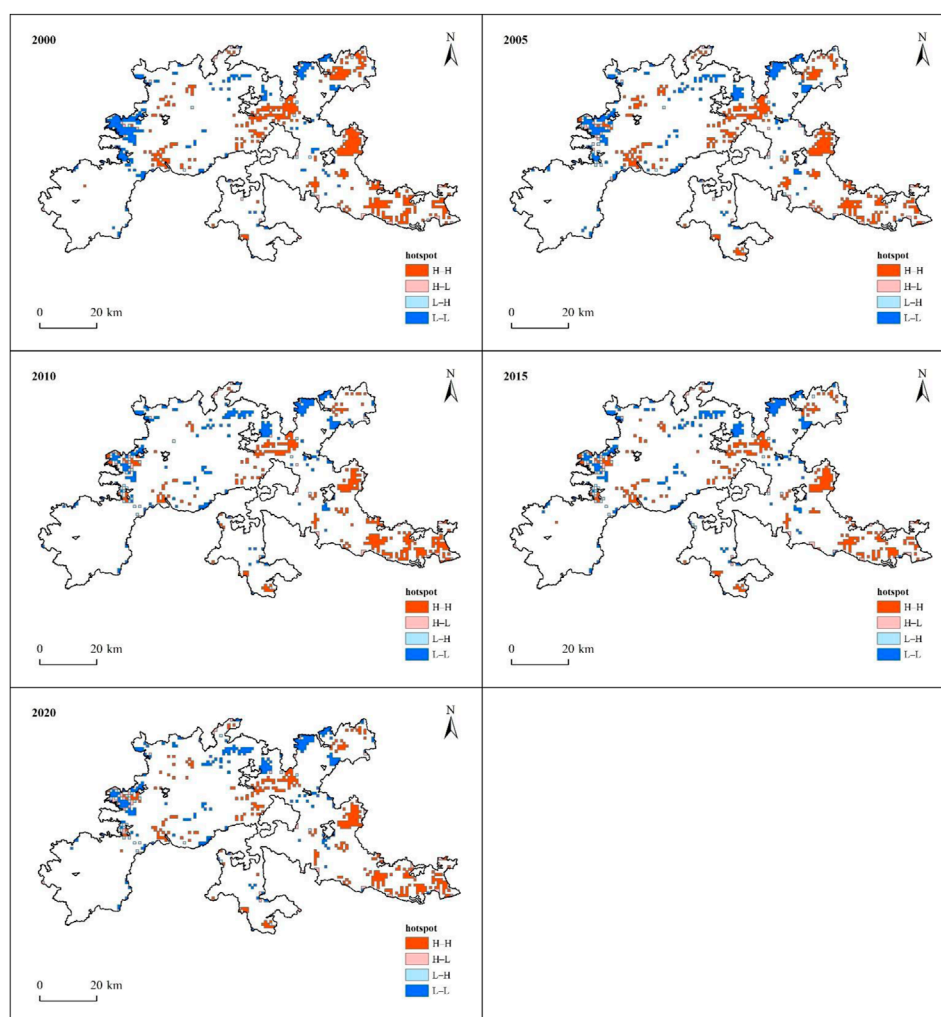


FIGURE 5
Distribution of Hotspot of regulating services in HTRNP from 2000 to 2020.

government officially commenced the pilot construction of HTRNP, alongside ecological relocation and restoration efforts, leading to the augmentation in the capacity of RESs (Xu et al., 2020). So, the overarching increase in RESs of HTRNP from 2010 to 2020 can be largely attributed to implementation of government-led ecological protection initiatives that were initiated (Jiang et al., 2024).

From a spatial perspective, the RESs exhibit higher values in the eastern and central regions and lower values in the western region of HTRNP, which coincided with the previous results (Du et al., 2023; Yao et al., 2024). This pattern is closely related to meteorological factors and human activities in Hainan Province. Firstly, Hainan Island is situated on the northern edge of the tropical zone, characterized by a tropical monsoon and tropical maritime climate. Influenced by the southeastern monsoon coming from the Pacific and the obstruction of central mountainous regions such as Wuzhishan Mountain, Limu Ridge, and Bawang Ridge, the average annual precipitation gradually decreases from east to west (Han et al., 2022). The eastern region receives an average annual precipitation of up to 2,400 mm, whereas the western region, such as Dongfang and Changjiang, receives only about

1,000 mm (Yao et al., 2024). Secondly, the eastern and central parts of HTRNP such as Qiongzhong County, Baoting County, and Wuzhishan City, are the main distribution areas of natural forests, which have high forest cover and a more complete multi-layer structures consisting of trees, shrubs, grasses, and vines, and provide better ecosystem services generally (Chen et al., 2019; Ma et al., 2021). This forest structure effectively reduces the kinetic energy of rainfall, while the well-developed root systems help stabilize the soil and intercept surface sediments, thereby significantly reducing rainwater runoff and soil erosion (Wen et al., 2017; Zhao and Pan, 2022). Additionally, the central high-altitude areas have a high proportion of natural forests with diverse and vigorous vegetation, leading to higher soil organic carbon content (He et al., 2022) and greater plant carbon sequestration capacity compared to other tree species (Alamgir et al., 2016; Liu et al., 2019). Thirdly, the western region of HTRNP is close to industrial areas with relatively fewer natural forests and extensive coverage of artificial vegetation such as rubber and eucalyptus plantations. This results in weaker water infiltration capacity and increased surface runoff (Deng et al., 2019). Furthermore, the evaporation

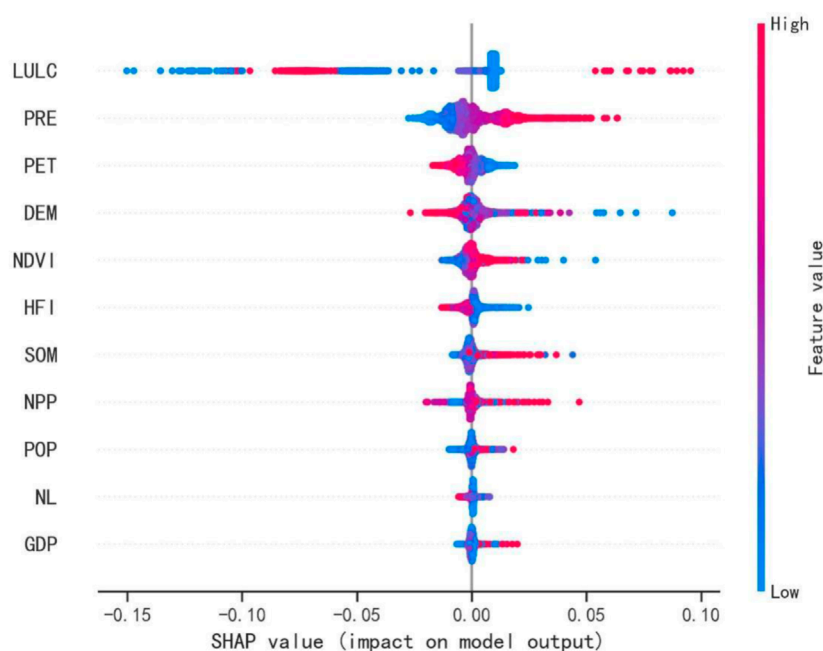


FIGURE 6
Shap plot of factors driving regulating ecosystem services in Hainan Tropical Rainforest National Park. Red for large values, blue for small values, and purple for values close to the mean.

rate in this region far exceeds its precipitation (with an average annual precipitation of about 1,000 mm and an average annual evaporation rate of 2,000–2,500 mm), which adversely affects the effective performance of RESs (Han et al., 2022; Li et al., 2022). These findings are corroborated by the local spatial autocorrelation analysis, which shows spatial hotspots (H-H) in the eastern and central regions of HTRNP and spatial cold spots (L-L) in the northern and western regions.

In summary, the RESs of HTRNP demonstrate temporal and spatial heterogeneity, underscoring the need for comprehensive protection and tailored management strategies. HTRNP, serving as an ecological highland and a critical ecological security barrier for Hainan Province, is aptly termed the “green lung”, “water tower”, and “natural oxygen bar” of Hainan Island. Future conservation and management endeavors should prioritize integrated planning and holistic protection, facilitating the integrity, authenticity, and diversity of tropical rainforests (Chen et al., 2023; Yang et al., 2023). Furthermore, implementing differentiated management measures across various time periods and regions is essential to enhance the provision of high-quality ecological products and fortify the ecological security barrier of Hainan Island.

4.3 Driving factors of RESs

Understanding the driving factors behind the RESs is paramount for crafting effective ecological management policies and strategies (Jiang et al., 2024). By comprehensively considering the interactions between the natural and socio-economic factors, policymakers can develop targeted interventions to promote sustainable practices

and bolster ecosystem service provision. Previous studies have shown that natural drivers tend to increase the RESs within the region, while the socio-economic drivers perform the opposite effect (Linders et al., 2020; Sun et al., 2023). This conclusion has been partially validated in our study.

Natural factors, encompassing meteorological factors (temperature, PRE, PET, etc.), vegetation factors (NDVI, NPP, etc.), and soil factors (soil depth, SOM, etc.), provide the material basis for ecosystem services. In this paper, RESs show a significant positive correlation with PRE and a significant negative correlation with PET in HTRNP. Because PET affects the growth rate of plants as well as community distribution (Daniela et al., 2019), while PRE influences soil retention functions and the hydrological cycle, making both factors the most significant factors affecting ecosystem services (Tang et al., 2018; Xiao and Ouyang, 2019). Other factors in descending order of impact include DEM with a negative correlation, NDVI with a positive correlation, SOM with a positive correlation, and NPP with a positive correlation, though their overall influence on RESs in HTRNP is relatively smaller. For instance, DEM affects the vertical distribution of vegetation; higher DEM means thinner soil depth and lower soil organ matter, thereby inhibiting carbon sequestration and soil retention services (Li and Zhang, 2021). Soil depth and SOM primarily influence plant growth, which in turn affects RESs as well.

Socio-economic factors, including LULC, POP, and economic aspects, significantly alter the production capacity of ecosystem services. LULC is considered as one of the most important influencing factors for RESs (Xu et al., 2020), which is consistent with our result of driving factors. Shifts in land use types, such

as from farmlands and forests to building lands, disrupt existing ecosystem structures and functions (Stephen et al., 2011), posing significant challenges to ecosystem stability (Hashem et al., 2019) and causing notable shifts in ecosystem service functions (Rahman and Szabó, 2021; Wu and Wang, 2024). Other factors in descending order of impact include HFI, POP, NL, and GDP, which could reflect intensive land development, environmental pollution, and human activities, thereby either promoting or inhibiting RESs (Ma et al., 2022). Although the overall influence of these factors on RESs is relatively small, they play a pivotal role in the effectiveness of management, due to lower cost and higher effectiveness compared with natural factors.

This study delved into the influence of anthropogenic-natural drivers on RESs across various spatial and temporal scales. The result revealed that PRE and PET among natural factors, and LULC and the HFI among socio-economic factors, serve as the primary drivers of RESs. These findings align with previous geographical detection analyses on the driving factors of RESs in Hainan Island (Han et al., 2022), and similar conclusions have been drawn in other regions such as Taihu Lake (Gu et al., 2018) and the Sanjiangyuan region (Lv et al., 2020) in China. However, given the complex interplay of factors influencing the spatial distribution and temporal evolution of RESs, further explorations need to be conducted. Firstly, driving factors can be any natural or anthropogenic element that plays a pivotal role in shaping the behavior, distribution, or dynamics of a particular ecosystem or environmental process (Xue et al., 2024), such as climate change, policy frameworks, conservation plans, value systems and others. Furthermore, many driving factors of ecosystem service changes are interlinked (Liu et al., 2023). These factors and their interactions warrant further exploration in future research. Secondly, the accuracy of basic data determines the reliability of the results. So it is recommended to leverage advanced technologies such as big data, the Internet of Things (IoT), and artificial intelligence (AI) to accurately obtain the further data on RESs in the context of climate change. Finally, the human activity also performed significant impacts on the temporal-spatial variations of RESs in HTRNP. So, stereoscopic remote sensing monitoring system based on multilevel platform collaboration, including space-based satellite, space-based remote sensing, aerial drones, mobile patrol monitoring vehicles and ground observation (Gao, 2022; Gao et al., 2023), should be effectively utilized to comprehensively manage and monitor human activities in HTRNP.

5 Conclusion

This paper evaluated five RESs (i.e., water conservation, soil retention, carbon sequestration, oxygen release, climate regulation) of HTRNP in 2000, 2005, 2010, 2015, and 2020 using the ArcGIS and InVEST models. The ESCI was employed to characterize the temporal-spatial variations of RESs, while the LightGBM model was utilized to investigate the driving mechanisms of RESs. The key conclusions can be summarized as follows: (1) Temporal Dimension: From 2000 to 2020, the RESs of HTRNP exhibited significant fluctuations, showing a trend of “initial decline followed by a subsequent rise”. Climate regulation services constituted the highest proportion at 61.4%, while water conservation and soil

retention services accounted for 20.21% and 15.74%, respectively. Carbon sequestration and oxygen release services represented the lowest proportion at 2.84%. (2) Spatial Dimension: The RESs in the eastern and central regions were slightly higher than those in the western region, maintaining consistency across different years. The RESs in HTRNP displayed strong spatial clustering effects (Moran's $I > 0.5$, $Z > 2.58$), with spatial hotspots (H–H) in the eastern and central regions and spatial cold spots (L–L) in the western and northern regions, consistent with the overall spatial distribution of RESs. (3) Driving Factors: Natural factors (PRE and PET) and socio-economic factors (LULC and HFI) had the highest marginal contributions to RESs. Among these, LULC had the greatest impact on RESs, with RESs positively correlated with PRE and negatively correlated with PET and HFI.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

LD: Investigation, Methodology, Software, Writing–original draft, Writing–review and editing, Conceptualization. HyL: Investigation, Methodology, Writing–original draft. HoL: Investigation, Writing–original draft. WL: Investigation, Writing–original draft. ZL: Investigation, Writing–original draft. XL: Software, Writing–original draft. JL: Writing–review and editing, Methodology. ZQ: Supervision, Writing–review and editing, Conceptualization, Methodology. YZ: Supervision, Writing–review and editing, Conceptualization, Methodology.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by GEF-Building Sustainability into PA Reforms to Conserve Globally Significant Biodiversity in China (ID: 9461), the National Natural Science Foundation of China (No. 72173011).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of

their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

- Alamgir, M., Turton, S. M., Macgregor, C. J., and Pert, P. L. (2016). Ecosystem services capacity across heterogeneous forest types: understanding the interactions and suggesting pathways for sustaining multiple ecosystem services. *Sci. Total Environ.* 566–567, 584–595. doi:10.1016/j.scitotenv.2016.05.107
- Anselin, L. (1995). Local indicators of spatial association—LISA. *Geogr. Anal.* 27, 93–115. doi:10.1111/j.1538-4632.1995.tb00338.x
- Arico, S., Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., et al. (2005). *Millennium ecosystem assessment. Ecosystems and human well-being: synthesis*. Washington: Island Press.
- Chen, W., Chi, G., and Li, J. (2019). The spatial association of ecosystem services with land use and land cover change at the county level in China, 1995–2015. *Sci. Total Environ.* 669, 459–470. doi:10.1016/j.scitotenv.2019.03.139
- Chen, W. X., Zhao, H. B., Li, J. F., Zhu, L. J., Wang, Z. Y., and Zeng, J. (2020). Land use transitions and the associated impacts on ecosystem services in the Middle Reaches of the Yangtze River Economic Belt in China based on the geo-informatic Tupu method. *Sci. Total Environ.* 701 (20), 134690–13469013. doi:10.1016/j.scitotenv.2019.134690
- Chen, Z. L., Lin, J. Y., and Huang, J. L. (2023). Linking ecosystem service flow to water-related ecological security pattern: a methodological approach applied to a coastal province of China. *J. Environ. Manag.* 345, 118725. doi:10.1016/j.jenvman.2023.118725
- Chen, Z. Z., Lei, J. R., Wu, T. T., Chen, D. X., Zhou, Z., Li, W. L., et al. (2021). Gross ecosystem product accounting of national park: taking hainan tropical rainforest national park as an example. *Chin. J. Appl. Ecol.* 32 (11), 3883–3892. doi:10.13287/j.1001-9332.202111.010
- Costanza, R., de-Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., et al. (2017). Twenty years of ecosystem services: how far have we come and how far do we still need to go? *Ecosyst. Serv.* 28, 1–16. doi:10.1016/j.ecoser.2017.09.008
- Costanza, R., Groot, R. D., Farberk, S., Belt, M. V. D., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387 (15), 253–260. doi:10.1038/387253a0
- Dai, X., Wang, L., Huang, C., Fang, L., Wang, S., and Wang, L. (2020). Spatio-temporal variations of ecosystem services in the urban agglomerations in the middle reaches of the Yangtze River, China. *Ecol. Indic.* 115, 106394. doi:10.1016/j.ecolind.2020.106394
- Daniela, B., de-Rogier, J., Michael, S., Reinhard, F., Hein, L., Kienast, F., et al. (2019). Ecosystem service change caused by climatological and non-climatological drivers: a Swiss case study. *Ecol. Appl. a Publ. Ecol. Soc. Am.* 29 (4), e01901. doi:10.1002/eap.1901
- Deng, L., Kim, D. G., Li, M. Y., Huang, C. B., Liu, Q. Y., Cheng, M., et al. (2019). Land-use changes driven by 'Grain for Green' program reduced carbon loss induced by soil erosion on the Loess Plateau of China. *Glob. Planet. Change* 177, 101–115. doi:10.1016/j.gloplacha.2019.03.017
- Du, A., Shen, Y. Q., Xiao, Y., and Ouyang, Z. Y. (2023). Research on accounting of ecological products value in National Parks. *Acta Ecol. Sin.* 43 (1), 208–218. doi:10.5846/stxb202112163575
- Du, L. S., Liu, H. O., Liu, W. H., Wang, H. R., Zhang, Y., and Quan, Z. J. (2023). Spatial and temporal variation of water conservation and driving factor analysis in tropical rainforests: a case study of Hainan Tropical Rainforest National Park. *Res. Environ. Sci.* 36 (9), 1716–1727.
- Francisco, A., Victor, M.-G., Emanuele, B., Heikki, L., Blasi, E., Lehtonen, H., et al. (2024). Cost benefit analysis of diversified farming systems across Europe: incorporating non-market benefits of ecosystem services. *Sci. Total Environ.* 912, 169272. doi:10.1016/j.scitotenv.2023.169272
- Francisco-Ortega, J., Wang, Z. S., Wang, F. G., Xing, F. W., Liu, H., Xu, H., et al. (2010). Seed plant endemism on Hainan Island: a framework for conservation actions. *Botanical Rev.* 76 (3), 346–376. doi:10.1007/s12229-010-9055-7
- Gao, J. X. (2022). The construction and application of remote sensing monitoring system based on multilevel platform for ecosystem. *Environ. Prot.* 50 (22), 13–19.
- Gao, J. X., Zhang, L. J., Chao, K., Ma, P. F., Feng, H. Y., Niu, R. F., et al. (2023). Stereoscopic remote sensing monitoring system based on multilevel platform collaboration and methods.
- Gao, X., Xiao, F., Liu, Q., Xu, Y., and Yu, C. (2024). Evolution of ecosystem services under the impact of urbanization using the InVEST model in the xiongan new area, China. *Environ. Res. Commun.* 6 (3), 035021. doi:10.1088/2515-7620/ad3268
- Gu, J. Y., Li, Y. P., and Du, W. (2018). Evaluation on water source conservation capacity and analysis of its variation characteristics of Taihu Lake Basin based on InVEST model. *Water Resour. Prot.* 34 (3), 62–67+84.
- Haining, R., Wise, S., and Ma, J. (2010). Exploratory spatial data analysis. *J. R. Stat. Soc.* 47 (3), 457–469. doi:10.1111/1467-9884.00147
- Han, N., Yu, M., and Jia, P. (2022). Multi-scenario landscape ecological risk simulation for sustainable development goals: a case study on the central mountainous area of Hainan Island. *Int. J. Environ. Res. Public Health* 19 (7), 4030. doi:10.3390/ijerph19074030
- Han, N. L., Liu, Z. R., Jia, P. H., and Zhang, W. X. (2022). Spatio-temporal changes and geographic detection of water conservation on Hainan Island from 1996 to 2020. *Buletin Soil Water Conservation* 42 (5), 193–201.
- Hashem, D., Parviz, A., and Mahdis, M. (2019). Land use change, urbanization, and change in landscape pattern in a metropolitan area. *Sci. Total Environ.* 655, 707–719. doi:10.1016/j.scitotenv.2018.11.267
- He, X. X., Sheng, M. Y., Wang, L. J., Zhang, S. L., and Luo, N. N. (2022). Effects on soil organic carbon accumulation and mineralization of long-term vegetation restoration in Southwest China karst. *Ecol. Indic.* 145, 109622. doi:10.1016/j.ecolind.2022.109622
- Hou, P., Hai, J., Cao, W., Yang, M., Cai, M. Y., and Li, J. (2018). Evaluation on ecosystem changes and protection of the national key ecological function zones in mountainous areas of central Hainan Island. *Acta Geogr. Sin.* 73 (3), 429–441.
- Jiang, H., Qin, M., Wu, X., Luo, D., Ouyang, H., and Liu, Y. (2024). Spatiotemporal evolution and driving factors of ecosystem service bundle based on multi-scenario simulation in Beibu Gulf urban agglomeration, China. *China Environ. Monit. Assess.* 196 (6), 542. doi:10.1007/s10661-024-12663-6
- Kärkkäinen, L., Haakana, H., Hirvelä, H., Reetta, L., and Tuula, P. (2020). Assessing the impacts of land-use zoning decisions on the supply of forest ecosystem services. *Forests* 11 (9), 931. doi:10.3390/f11090931
- Li, J. Y., and Zhang, C. (2021). Exploring the relationship between key ecosystem services and socioecological drivers in alpine basins: a case of Issyk-Kul Basin in Central Asia. *Glob. Ecol. Conservation* 29, e01729. doi:10.1016/j.gecco.2021.e01729
- Li, L. M. (2022). *Analysis of landscape pattern and spatio-temporal change for ecosystem service value in Hainan Tropical Rain Forest National Park*. Hainan University.
- Li, L. M., Tang, H. N., Lei, J. R., and Song, X. Q. (2022). Spatial autocorrelation in land use type and ecosystem service value in Hainan Tropical Rain Forest National Park. *Ecol. Indic.* 137, 108727. doi:10.1016/j.ecolind.2022.108727
- Li, Y. D., Chen, B. F., Zhou, G. Y., Zeng, Q. B., Wu, Z. M., and Luo, T. S. (2003). The values for ecological service function of tropical natural forest in Hainan Island, China. *For. Res.* (02), 146–152.
- Lin, X., and Fu, H. (2023). Optimization of tropical rainforest ecosystem management: implications from the responses of ecosystem service values to landscape pattern changes in Hainan Tropical Rainforest National Park, China, over the past 40 years. *Front. For. Glob. Change* 6, 1242068. doi:10.3389/ffgc.2023.1242068
- Linders, T. E. W., Bekele, K., Schaffner, U., Allan, E., Alamirew, T., Choge, S. K., et al. (2020). The impact of invasive species on social-ecological systems: relating supply and use of selected provisioning ecosystem services. *Ecosyst. Serv.* 41, 101055. doi:10.1016/j.ecoser.2019.101055
- Liu, L., Zheng, L., Wang, Y., Liu, C., Zhang, B., and Bi, Y. (2023). Land use and ecosystem services evolution in Danjiangkou Reservoir Area, China: implications for sustainable management of national projects. *Land* 12, 788. doi:10.3390/land12040788
- Liu, S. J., Li, W. G., Chen, X. M., and Tong, J. H. (2019). Study on the spatial-temporal variation characteristics of vegetation net primary productivity in Hainan province. *Ecol. Sci.* 38 (5), 52–57.
- Lv, L. T., Ren, T. T., Sun, C. Z., Zheng, D. F., and Wang, H. (2020). Spatial and temporal changes of water supply and water conservation function in Sanjiangyuan National Park from 1980 to 2016. *Acta Ecol. Sin.* 40 (3), 993–1003. doi:10.5846/stxb201808241804
- Ma, G. X., Sun, Y. Z., Wang, K., and Yu, F. (2024). Evolutionary logic and characteristics analysis about the Quaternary Industry of Ecological products. *Environ. Prot.* 52 (Z1), 26–30.
- Ma, S., Qiao, Y. P., Wang, L. J., and Zhang, J. C. (2021). Terrain gradient variations in ecosystem services of different vegetation types in mountainous regions: vegetation resource conservation and sustainable development. *For. Ecol. Manag.* 482 (1), 118856. doi:10.1016/j.foreco.2020.118856

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2025.1449816/full#supplementary-material>

- Ma, W. B., Yang, F., Wang, N., Zhao, L. J., Tan, K., Zhang, X. F., et al. (2022). Study on spatial-temporal evolution and driving factors of ecosystem service value in the Yangtze River Delta Urban Agglomerations. *J. Ecol. Rural Environ.* 38 (11), 1365–1376.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., Fonseca, G. A. B., and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature* 403 (6772), 853–858. doi:10.1038/35002501
- Nadalini, A. C. V., Kalid, R. d. A., and Torres, E. A. (2021). Emergy as a tool to evaluate ecosystem services: a systematic review of the literature. *Sustainability* 13 (13), 7102. doi:10.3390/su13137102
- Peng, J., Xia, P., Liu, Y. X., Xu, Z. H., Zheng, H. N., Lan, T. H., et al. (2023). Ecosystem services research: from golden era to next crossing. *Trans. Earth, Environ. Sustain.* 1 (1), 9–19. doi:10.1177/2754124x231165935
- Qiu, H. H., Zhang, J. Y., Han, H. R., Cheng, X. Q., and Kang, F. F. (2023). Study on the impact of vegetation change on ecosystem services in the Loess Plateau, China. *Ecol. Indic.* 154, 110812. doi:10.1016/j.ecolind.2023.110812
- Quintas-Soriano, C., Garcia-Llorente, M., Norstrom, A., Meacham, M., Peterson, G., and Castro, A. J. (2019). Integrating supply and demand in ecosystem service bundles characterization across Mediterranean transformed landscapes. *Landsc. Ecol.* 34, 1619–1633. doi:10.1007/s10980-019-00826-7
- Rahman, M. M., and Szabó, G. (2021). Impact of land use and land cover changes on urban ecosystem service value in Dhaka, Bangladesh. *Land* 10 (8), 793. doi:10.3390/land10080793
- Sherrouse, B. C., Semmens, D. J., and Ancona, Z. H. (2022). Social values for ecosystem services (SolVES): open-source spatial modeling of cultural services. *Environ. Model. Softw.* 148, 105259. doi:10.1016/j.envsoft.2021.105259
- Stephen, P., Erik, N., Derric, P., and Kris, A. J. (2011). The impact of land-use change on ecosystem services, biodiversity and returns to landowners: a case study in the State of Minnesota. *Environ. Resour. Econ.* 48 (2), 219–242. doi:10.1007/s10640-010-9407-0
- Sun, L., Yu, H. J., Sun, M. X., and Wang, Y. T. (2023). Coupled impacts of climate and land use changes on regional ecosystem services. *J. Environ. Manag.* 326, 116753. doi:10.1016/j.jenvman.2022.116753
- Tang, X., Zhao, X., Bai, Y. F., Tang, Z. R., Wang, W. T., Zhao, Y. C., et al. (2018). Carbon pools in China's terrestrial ecosystems: new estimates based on an intensive field survey. *Proc. Natl. Acad. Sci. U. S. A.* 115 (16), 4021–4026. doi:10.1073/pnas.1700291115
- Veklych, O., Karintseva, O., Yevdokymov, A., and Saorin, E. G. (2020). Compensation mechanism for damage from ecosystem services deterioration: constitutive characteristic. *Int. J. Glob. Environ. Issues* 19 (1-2-3), 129–142. doi:10.1504/ijgenvi.2020.114869
- Villa, E., Ceroni, M., Bagstad, K., Johnson, G., and Krivov, S. (2009). "ARIES (ARtificial Intelligence for Ecosystem Services): a new tool for ecosystem services assessment, planning, and valuation," in Proceedings of the 11th annual BIOECON conference on economic instruments to enhance the conservation and sustainable use of biodiversity. Venice, Italy, September 21–22, 2009.
- Wang, J. N., Ma, G. X., Wang, Z. K., Wang, X. H., Yu, F., Liu, G. H., et al. (2021). Development and application of indicator system about the quaternary industry of ecological products in China. *China Popul. Resour. Environ.* 31 (10), 1–8.
- Wen, Z., Zhao, H., Liu, L., Ouyang, Z. Y., Zheng, H., Mi, H. X., et al. (2017). Effects of land use changes on soil water conservation in Hainan Island, China. *Chin. J. Appl. Ecol.* 28 (12), 4025–4033. doi:10.13287/j.1001-9332.201712.017
- Wu, C., and Wang, Z. (2024). Multi-scenario simulation and evaluation of the impacts of land use change on ecosystem service values in the Chishui River Basin of Guizhou Province, China. *Ecol. Indic.* 163, 112078. doi:10.1016/j.ecolind.2024.112078
- Xiao, H., Ouyang, Z. Y., Zhao, J. Z., and Wang, X. K. (2000). Forest ecosystem services and their ecological valuation A case study of tropical forest in Jianfengling of Hainan Island. *Chin. J. Appl. Ecol.* 11 (04), 481–484.
- Xiao, Y., and Ouyang, Z. Y. (2019). Spatial-temporal patterns and driving forces of water retention service in China. *Chin. Geogr. Sci.* 29 (01), 100–111. doi:10.1007/s11769-018-0984-0
- Xie, G. D., Zhang, C. X., Zhang, L. M., Chen, W. H., and Li, S. M. (2015). Improvement of the evaluation method for ecosystem service value based on per unit area. *Journal Nat. Resource* 30, 1243–1254.
- Xie, G. D., Zhen, L., Lu, C. X., Xiao, Y., and Chen, C. (2008). Expert knowledge based valuation method of ecosystem services in China. *Journal Nat. Resource* 23, 911–919.
- Xu, J. Y., Chen, J. X., Liu, Y. X., Fan, F. F., and Wei, J. Y. (2020). Spatio-temporal differentiation of interaction of ecosystem services and regional responses in the "Belt and Road" area. *Acta Ecol. Sin.* 40 (10), 3258–3270. doi:10.5846/stxb201903270588
- Xu, Z., Wei, H., Dong, X., Liu, Y., and Xue, H. (2020). Evaluating the ecological benefits of plantations in arid areas from the perspective of ecosystem service supply and demand-based on emergy analysis. *Sci. Total Environ.* 705, 135853. doi:10.1016/j.scitotenv.2019.135853
- Xue, S., Yao, L., Xu, Y., and Li, C. (2024). Spatio-temporal dynamics and driving factors of ecosystem services in the Yellow River Delta, China. *Sustainability* 16 (8), 3466. doi:10.3390/su16083466
- Yang, H., Zhou, H., Deng, S., Zhou, X., and Nie, S. (2024). Spatiotemporal variation of ecosystem services value and its response to land use change in the Yangtze River Basin, China. *Int. J. Environ. Res.* 18 (2), 17. doi:10.1007/s41742-024-00569-7
- Yang, J., Li, J., Fu, G., Liu, B., Pan, L., Hao, H., et al. (2023). Spatial and temporal patterns of ecosystem services and trade-offs/synergies in Wujiang River Basin, China. *Remote Sens.* 15 (16), 4099. doi:10.3390/rs15164099
- Yang, J., Zhai, D., Fang, Z., Alatalo, J. M., Yao, Z. L., Yang, W., et al. (2023). Changes in and driving forces of ecosystem services in tropical southwestern China. *Ecol. Indic.* 149, 110180. doi:10.1016/j.ecolind.2023.110180
- Yao, X., Zhou, L., Wu, T., Yang, X., and Ren, M. (2024). Ecosystem services in national park of hainan tropical rainforest of China: spatiotemporal dynamics and conservation implications. *J. Nat. Conservation* 80, 126649. doi:10.1016/j.jnc.2024.126649
- Ye, X., and Wu, L. (2010). Analyzing the dynamics of homicide patterns in Chicago: ESDA and spatial panel approaches. *Appl. Geogr.* 31 (2), 800–807. doi:10.1016/j.apgeog.2010.08.006
- Yi, H., Güneralp, B., Kreuter, U. P., Güneralp, i., and Filippi, A. M. (2018). Spatial and temporal changes in biodiversity and ecosystem services in the San Antonio River Basin, Texas, from 1984 to 2010. *Sci. Total Environ.* 619, 1259–1271. doi:10.1016/j.scitotenv.2017.10.302
- Yu, B. W., Rao, E. M., Yao, X. L., Shi, J. K., Zhang, C. P., Xu, W. H., et al. (2016). Evaluating the effectiveness of nature reserves in soil conservation on Hainan Island. *Acta Ecol. Sin.* 36 (12), 3694–3702.
- Zhao, T., and Pan, J. (2022). Ecosystem service trade-offs and spatial non-stationary responses to influencing factors in the Loess hilly-gully region: Lanzhou City, China. *Sci. Total Environ.* 846, 157422. doi:10.1016/j.scitotenv.2022.157422
- Zhong, J. H., Cui, L. L., Deng, Z. Y., Zhang, Y., Lin, J., Guo, G., et al. (2023). Long-term effects of ecological restoration projects on ecosystem services and their spatial interactions: a case study of Hainan Tropical Forest Park in China. *Environ. Manag.* 73 (3), 493–508. doi:10.1007/s00267-023-01892-z