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Value Assessment and Prediction of Regulating Ecosystem Services in Hainan Tropical Rainforest National Park, China

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Abstract: Ecosystem services serve as a bridge between the ecological environment and human society. The quantitative analysis and forecasting of ecosystem services can provide references for regional eco-environmental assessments and land-use planning for the future. In this study, taking Hainan Tropical Rainforest National Park (HTRNP) as an example, the value of regulating ecosystem services (RESs) in 2020 was assessed via ArcGIS 10.1 and the InVEST 3.5 model, and the per-unit value of RESs was calculated for different LULC types. In addition, in accordance with the *Overall Planning for HTRNP* and the objective of optimizing RESs, the value of RESs in short-term (to 2030) and long-term (to 2050) scenarios was forecast via a linear programming model. The results are as follows: (1) The RES value of HTRNP in 2020 was CNY 2090.67 $\times$ 10^8, with climate regulation accounting for the largest proportion; the spatial distribution of RESs in the eastern and central areas was higher than that in the western area, but different indicators of RESs differed in their spatial patterns in varied geographic units. (2) The natural forest ecosystem in HTRNP accounts for 76.94% of the total area but 84.82% of the total value of RESs. The per-unit value is ranked from highest to lowest as follows: montane rainforests > wetlands > lowland rainforests > lowland secondary rainforests > tropical coniferous forests > deciduous monsoon rainforests > tropical cloud forests > shrub forests > timber forests > economic forests > rubber forests > grasslands > farmlands > settlements. (3) In the short-term scenario, the value of RESs is CNY 2216.64 $\times$ 10^8, an increase of CNY 118.97 $\times$ 10^8 compared to 2020, with an increase rate of 5.67%. In the long-term scenario, the value of RESs is CNY 2472.48 $\times$ 10^8, an increase of CNY 374.81 $\times$ 10^8 compared to 2020, with an increase rate of 17.87%. The results reveal the significance of ecosystem services in the national park and can inform more targeted and scientifically sound decision-making in the future.

Keywords: national park; ecosystem services; spatial distribution; scenario setting; simulation prediction

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1. Introduction

In recent years, under the dual pressure of global climate change and industrial restructuring, China has been facing the challenges of resource constraints and ecological environment deterioration [1,2]. A series of environmental problems, such as mudslides in mountainous areas, floods in urban areas, and climate warming, are threatening regional eco-security and sustainable development [3]. Protected areas (PAs), such as national parks, nature reserves, nature parks, forest parks, wetland parks, marine parks, and scenic spots, are now commonplace for addressing these problems. As some of the most strictly protected and managed areas, it could protect habitats with the least external interference to allow nature to sustain itself [4,5]. Ecosystem services (ESs), referring to ecological characteristics, functions, or processes that directly or indirectly benefit humans, are key to human well-being and eco-balance and thus attract considerable attention from the fields of ecology, geology, economics, and sociology [6,7]. Numerous studies in recent years have analyzed ESs, focusing on the following perspectives: classification indicators [8], quantitative analysis [9–11], driving analysis [12–14], tradeoffs/synergies [15–17], supply–demand relationships [18–20], flow [21–23], etc. As research progressed, global attention has shifted towards spatial analysis [24,25] and multi-goal optimization [26,27], which perform increasing guidelines for decision-making processes related to the eco-economy, eco-compensation, eco-planning, and other decision-making processes [28]. However, diverse methods and rich case studies are still needed.

LULC is capable of directly changing the structure and function of the natural ecosystem [29] and, therefore, further influences the function and value of ESs. Exploring how LULC influences ESs and further forecasting changes in ESs in different LULC scenarios [30,31] are key to realizing regional eco-security and economic sustainable development [9,29,32]. Studies on the relationship between LULC and ESs focus on the following aspects: Firstly, based on historical data, the interaction mechanism between LULC and ESs has been studied through the quantitative analysis of temporal–spatial evolution, supply–demand relationships, tradeoffs/synergies, etc. [33,34]. Secondly, future changes in ESs have been studied based on multi-scenario patterns, specifically in the natural scenario, conservation scenario, and development scenario [35–37]. Lastly, the responses of ESs to governmental decision-making processes have been studied, namely, by applying the spatial distribution pattern of ESs to land conservation planning and the establishment of eco-security patterns [34,38]. It is common for studies to interpret remote-sensing images and land-use change data to reflect past and current LULC and to simulate future LULC in different scenarios by using the PLUS model [39–41], the mixed-cell cellular automata model (MCCA) [42,43], CA-Markov model [44–47], etc. However, policy-background-based multi-objective linear programming models have hardly been used in previous studies. This approach is easy to operate, requires fewer data, and can reduce errors produced by the inaccuracy of model parameters.

National parks, located at the top of the pyramid of nature conservation in China, have larger protected areas, more integrated ecosystems, and higher management layers. As regional eco-security barriers, national parks play key roles in protecting the local biodiversity and providing more ecosystem services. Hainan Tropical Rainforest National Park (HTRNP) is one of the first batches of the five approved national parks in China, with the most concentratedly distributed, best-preserved, and largest continuous “island-type” tropical rainforest. HTRNP is also known as one of the priority areas for biodiversity conservation in China and a hotspot for global biodiversity conservation. In addition, it plays a key role in preserving eco-security and economic sustainable development for Hainan Province. To systematically assess the status of HTRNP and promote refined management, it is important to accurately assess the status quo of RESs and predict their changes and fluctuation trends in the future. Here, we took HTRNP as an example and conducted the study in three parts: (1) we selected distinct but highly recognized indicators of RESs and applied ArcGIS 10.1 and the InVEST 3.5 model to evaluate their value and analyze their spatial patterns; (2) we calculated the per-unit value for different ecosystems; and (3) we used a short-term scenario (2030) and a long-term scenario (2050) and established objective functions and constraint equations to evaluate the RESs by using a linear programming model. These results could provide references for the realization of land-use adjustment, eco-environment conservation, and refined management in the future.

2. Methodology and Data

2.1. Study Area

Located in the central part of Hainan Island, HTRNP is the intersection between the north–south thermal dividing line and the east–west precipitation dividing line on the island. The geographic location is 108°44′32″~110°04′43″ E, 18°33′16″~19°14′16″ N. The total area of HTRNP is 4268.54 km^2, accounting for 12.1% of Hainan Island (Figure 1). The core protected area covers an area of 2331 km^2, accounting for 54.6% of HTRNP, while the general control area covers an area of 1938 km^2, accounting for 45.4% of HTRNP. The national park is biologically diverse: it is primarily estimated that there are 3653 species of vascular plants and 540 species of terrestrial vertebrates [48], and it is also the only home to *Nomascus hainanus* on a global scale.

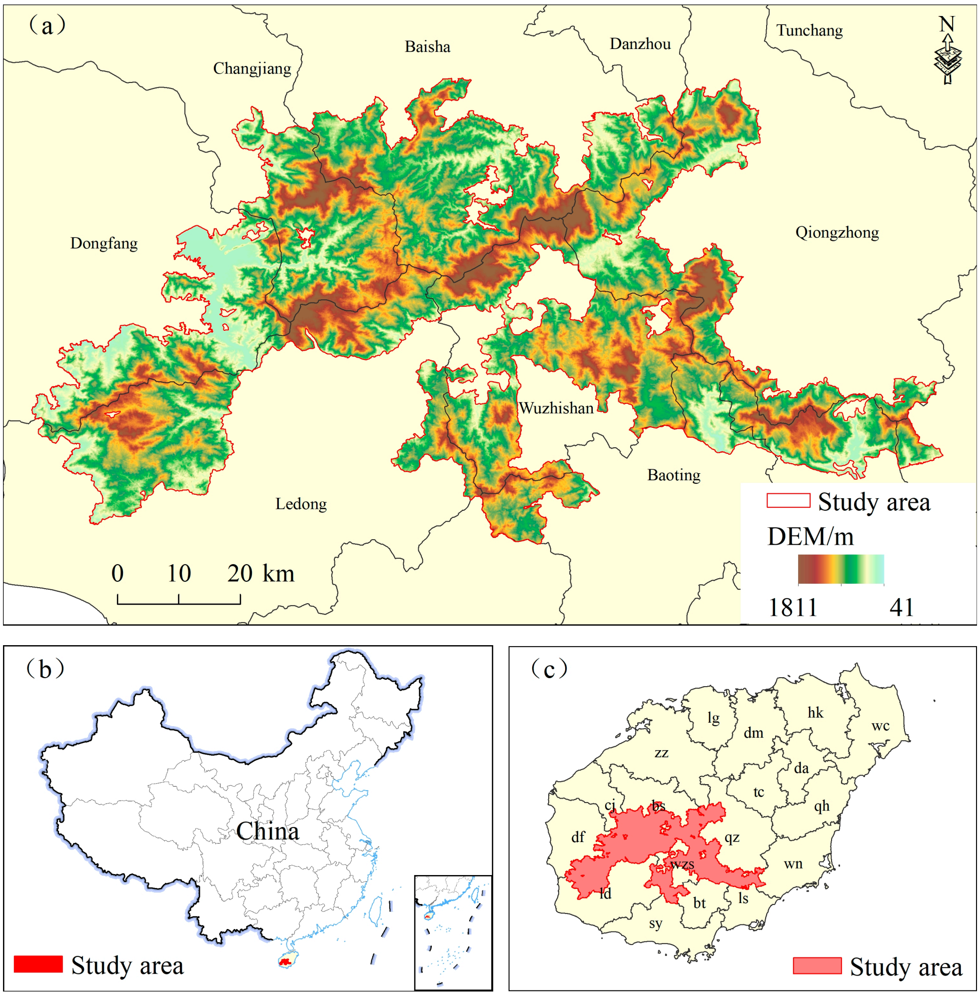

Figure 1. The DEM of the study area (**a**); the location of the study area in China (**b**); the location of the study area on Hainan Island (**c**).

2.2. *Accounting Framework and Method of RES Evaluation*

HTRNP has the highest peak and is perceived as the "Hainan ridge" and "Water Tower" on Hainan Island, with the headstream of three main rivers, i.e., Changhua River, Nandu River, and Wanquan River. Meanwhile, it is also regarded as the "Green Lung" and "Natural air-conditioner". Thus, we selected five related and highly recognized indicators, namely, water conservation (WC), soil retention (SR), carbon sequestration (CS), oxygen release (OR), and climate regulation (CR), to assess RESs in terms of biophysical quantity and monetary value. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was developed by Stanford University, the Nature Conservancy (TNC), and the World Wildlife Fund (WWF), providing a crucial underpinning to decision- and policy-making [7]. At present, this model is particularly prominent on account of its simplicity, ease of data acquisition, flexible parameter adjustment, and spatially expressible results [49,50]. Due to limitations imposed by landforms and strict conservation regulations, it is hard to obtain localized data for HTRNP. Therefore, the assessment of biophysical quantities of goods is realized by using a combination of ArcGIS 10.1 and the InVEST 3.5 model, and the assessment of monetary value is realized by applying certain mainstream methods in economics, such as Market Prices and the Surrogate Market. The calculation equations and models are shown in Table 1.

Table 1. Indicators and calculation models of RESs.

Indicator	Biophysical Quantity Accounting Method	Monetary Value Accounting Method
Water conservation (WC)	$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \cdot P_x$ Y_{xj} is the annual water yield depth of rasterx and land-use type j; AET_{xj} is the average annual evapotranspiration of raster x and land-use type j; P_x is the average annual precipitation of raster x.	$V_w = Q_w \times P_w$ V_w is the total value of water conservation; Q_w is the amount of water conservation; and P_w is the investment price of building unit reservoir capacity, with P_w = 9.67 CNY/m^3.
Soil retention (SR)	$Q = RKLS - USLE$ $USLE = R \times K \times LS \times C \times P$ Q is the biophysical quantity of soil retention; $RKLS$ is the average annual potential erosion; $USLE$ is the average annual soil erosion; R is the rainfall erosivity factor; K is the soil erodibility factor; LS is the topography factor, which is mainly determined by the slope gradient and the slope length; C is the vegetation cover and management factor; and P is the soil and water conservation measure factor.	① Maintaining soil fertility $Va = USLE \times (C_N \times \frac{P1}{R1} + C_P \times \frac{P1}{R2} + C_K \times \frac{P2}{R3} + C_O \times P_3)$ V_a is the value of maintaining soil nutrients; C_N is the content of nitrogen in the soil; C_P is the content of phosphorus in the soil; C_K is the content of potassium in the soil; C_O is the content of organic matter in the soil; P_1 is the price of Diammonium Phosphate (DAP), with P_1 = 3895 CNY/t; R_1 is the nitrogen content of DAP; R_2 is the phosphorus content of DAP; P_2 is the price of potassium chloride (KCl), with P_2 = 3300 CNY/t; R_3 is the potassium content of KCl; and P_3 is the price of organic matter, with P_3 = 2180 CNY/t. ② Reducing sedimentation $V_b = \lambda \times USLE \times Cr/\rho$ V_b is the value of mitigating sedimentation; λ is the coefficient of sedimentation, generally taking a value of 24%; C_r is the cost of the reservoir project, with Cr = 9.67 CNY/t; and ρ is the soil capacity weight.
Carbon sequestration (CS)	$Q_c = S \times NPP \times 1.63 \times \frac{12}{44}$ Qc is the biophysical quantity of carbon sequestration; NPP is net primary productivity; and S is the ecosystem area.	$V_c = Q_c \times P_c$ V_c is the value of carbon sequestration; Q_c is the total amount of carbon sequestration; and P_c is the price per unit of sequestered carbon, with P_c = 28 CNY/t.
Oxygen release (OR)	$Q_o = S \times NPP \times 1.19$ Q_o is the biophysical quantity of oxygen release; NPP is net primary productivity; and S is the ecosystem area.	$V_o = Q_o \times P_o$ V_o is the value of oxygen released from the ecosystem; Q_o is the total amount of oxygen released from the ecosystem; and P_o is the price per unit of oxygen released, with P_o = 10 CNY/t.
Climate regulation(CR)	① Vegetation transpiration: $E_{pp} = \sum_i^3 GPP \times S_i \times d/(3600 \times R)$ E_{pp} is the biophysical quantity of vegetation transpiration; GPP is the heat consumption of transpiration per unit area of different ecosystems; S_i is the area of the *type-i* ecosystem; R is the air-conditioning energy efficiency ratio; d is the number of days the air-conditioner opens; and i is the ecosystem type (i.e., forest, scrub, grassland). ② Water surface evaporation: $E_{we} = E_q \times q \times 10^3/3600 + Eq \times \gamma$ E_{we} is the biophysical quantity of water surface evaporation; E_q is the water surface evaporation per unit; q is the latent heat of volatilization; and γ is the electricity consumption of a humidifier required to convert 1 m^3 water into vapor.	$V_{cr} = V_{PP} + V_{we}$ $V_{PP} = E_{pp} \times P$ $V_{we} = E_{we} \times P$ V_{cr} is the total value of ecosystem climate regulation; V_{pp} is the value of ecosystem vegetation transpiration; V_{we} is the value of ecosystem water surface evapotranspiration; and P is the price of electricity, with P = 0.63 CNY/kW·h.

2.3. Research Method

2.3.1. RESs of Different LULC Types

LULC is one of the most influential determiners of RESs. We calculated the total value of RESs and intensity of RESs per unit according to different LULC types and conducted spatial analysis accordingly [51,52]. The calculation equations are as follows:

$$T_{rsi} = \sum_{j=1}^{n} A_{ij} \times C_i \tag{1}$$

$$\overline{V}_{rsi} = \frac{T_{rsi}}{C_i} \tag{2}$$

Here, T_{rsi} is the total RES value of the i-th ecosystem type, CNY; A_{ij} represents the per-unit value of the j-th RES type and the i-th ecosystem type, CNY/km^2; $\overline{V}_{rsi}$ is per-unit value of the i-th ecosystem type, CNY; C_i represents the area of the i-th ecosystem type, km^2; and j = 1, 2, 3, ...n represents the RES type.

2.3.2. Land-Use Transfer Matrix

A land-use transfer matrix represents changes in LULC based on the category and area of a certain piece of land in different periods. The land-use transfer matrix can reflect the land area of a certain region at a certain time and clearly expresses the area's data during transformation and its direction (Table 2). Thus, this study reflects land-use changes in 2030 and 2050 by using a land-use transfer matrix.

Table 2. A sample of a land-use transition matrix.

		T_2				**P_{i+}**	**Decreased**
		A_1	**A_2**	...	**A_n**		
T_1	A_1	P_{11}	P_{12}	...	P_{1n}	P_{1+}	P_{1+}–P_{11}
	A_2	P_{21}	P_{22}	...	P_{2n}	P_{2+}	P_{2+}–P_2
	...	...	...	...	...	...	...
	A_m	P_{m1}	P_{m2}	...	P_{mn}	P_{m+}	P_{m+}–P_{mn}
P_{+j}		P_{+1}	P_{+2}	...	P_{+n}	1	
Increased		P_{+1}–P_{11}	P_{+2}–P_{22}	...	P_{+n}–P_{nn}		

2.3.3. Linear Programming Equation

A linear programming equation, generally consisting of an objective function and a set of constraints, can be applied to solutions to optimization problems for the best production. The objective function is designed to maximize profits or minimize inputs. The constraint set is the set of decision variables. It is usually defined as follows:

$$\max(\min)Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n \tag{3}$$

$$\text{s.t.} \begin{cases} a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \le b_1 \\ a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n \le b2 \\ \ldots\ldots \\ a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n \le b_m \\ x_1 \ge 0, x_2 \ge 0, \ldots, x_n \ge 0 \end{cases} \tag{4}$$

Here, Z represents the numeric value of the objective function, c_i represents the coefficient of a decision variable in the objective function, x_i represents the value of the decision variable, and b_i represents the right-sided coefficient of the constraint.

3. Results

3.1. RES Value

Using ArcGIS and the InVEST model, we obtained the biophysical quantities of RESs in HTRNP. By means of valuation methods such as Market Prices and the Surrogate Market, we estimated the monetary value of RESs in HTRNP. By adding up all numeric values, we obtained CNY 2090.67 $\times$ 10^8 as the total RES value of HTRNP in 2020. As a proportion of RESs, CR holds the highest value, accounting for 61.40%; WC and SR also have relatively high proportions, accounting for 20.21% and 15.74%, respectively. The value of CS and OR is the lowest, accounting for 2.84% of the total value. In general, RESs in HTRNP in the eastern and central areas are higher than those in the western area. However, different RESs reveal different spatial distribution patterns. For example, WC has "high value in the east and low in the west"; SR has "high value in central and low in surrounding areas"; CS and OR has "high value in central and low in surrounding areas"; and CR has "higher value in the west than other areas" (Figure 2).

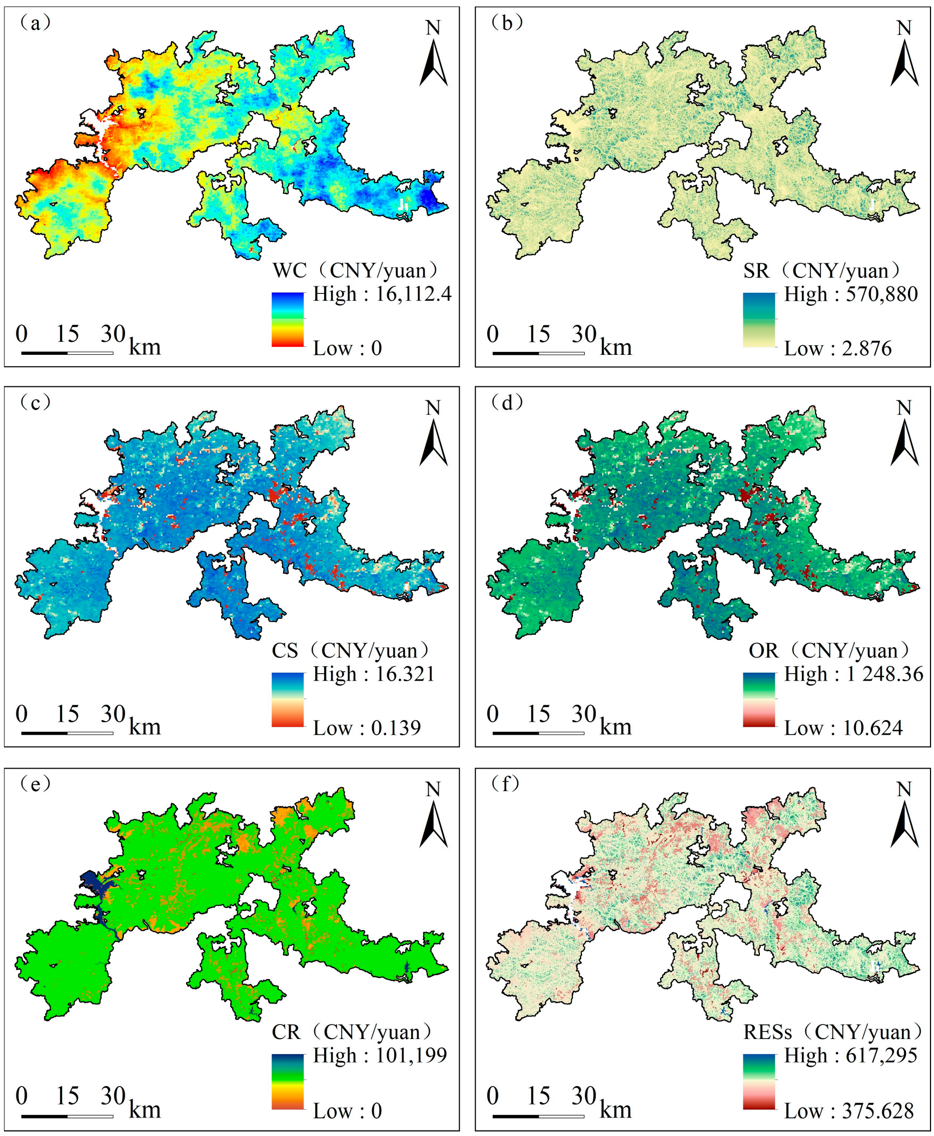

Figure 2. The value of water conservation (**a**), soil retention (**b**), carbon sequestration (**c**), oxygen release (**d**), climate regulation (**e**), and regulating services (**f**) in Hainan Tropical Rainforest National Park.

3.2. Value Distribution of Different Ecosystems

HTRNP mainly includes five ecosystems, namely, forest, grassland, wetland, farmland, and settlement. The area of the forest ecosystem accounts for 96.02%, with natural forest at 76.94% and planted forest at 19.08%. The other ecosystems only make up 3.98%, as wetland, grassland, farmland, and settlement account for 2.66%, 0.33%, 0.55%, and 0.44%, respectively (Figure 3).

Ecosystem			**Area (km^2)**	**Proportion of area (%)**	**Values of RESs (×10^8 yuan)**	**Proportion of values (%)**	**Variables**
Forest Ecosystem	Natural Forest	Montane Rainforest	621.44	14.56	402.55	19.25	x1
		Lowland Rainforest	1161.86	27.22	621.2	29.71	x2
		Lowland Secondary	1279.67	29.98	644.72	30.84	x3
		Deciduous Monsoon Forest	135.87	3.18	65.66	3.14	x4
		Tropical Coniferous	43.41	1.02	21.43	1.02	x5
		Tropical Cloud Forest	31.51	0.74	14.25	0.68	x6
		Shrubbery	10.23	0.24	3.68	0.18	x7
	Planted Forest	Rubber Forest	233.06	5.46	67.1	3.21	x8
		Timber Forest	426.57	9.99	131.58	6.29	x9
		Economic Forest	154.74	3.63	46.14	2.21	x10
Grassland			14.11	0.33	2.76	0.13	x11
Wetland			113.63	2.66	65.22	3.12	x12
Farmland			23.68	0.55	2.68	0.13	x13
Traditional settlement			18.76	0.44	1.74	0.08	x14
Total			4268.54	100	2090.71	100	

Figure 3. Ecosystem types, areas, and their RES value. The color bar represents the proportion of values.

In terms of RESs' total value, forest holds the highest value. The RES value of natural forest is CNY 1773.49 $\times$ 10^8, accounting for 84.82%, including lowland secondary rainforests (30.84%), lowland rainforests (29.71%), montane rainforests (19.25%), deciduous monsoon rainforests (3.14%), etc. The RES value of planted forest is CNY 244.82 $\times$ 10^8, making up 11.71%, in which the proportions of timber forest, rubber forest, and economic forest are 6.29%, 3.21%, and 2.21%, respectively. The RES value of wetland is also relatively high, totaling CNY 65.22 $\times$ 10^8, accounting for 3.12%, while that of farmland and settlement is lower than 1% (Figure 3).

In terms of RES value per unit area, natural forest holds the highest value, of which montane rainforest, lowland rainforest, and lowland secondary rainforest are valued at 0.648 $\times$ 10^8 CNY/km^2, 0.535 $\times$ 10^8 CNY/km^2, and 0.504 $\times$ 10^8 CNY/km^2, respectively. Right after natural forest is the wetland ecosystem with a value of 0.574 $\times$ 10^8 CNY/km^2. The RES value per unit area of planted forest is also less than half of the natural forest value due to differences in species composition and stand structure. In addition, the RES value of farmland and settlement is also relatively low, ranging from 0.093 to 0.113 × 10^8 CNY/km^2, which is less than 20% of the montane rainforest value (Figure 4).

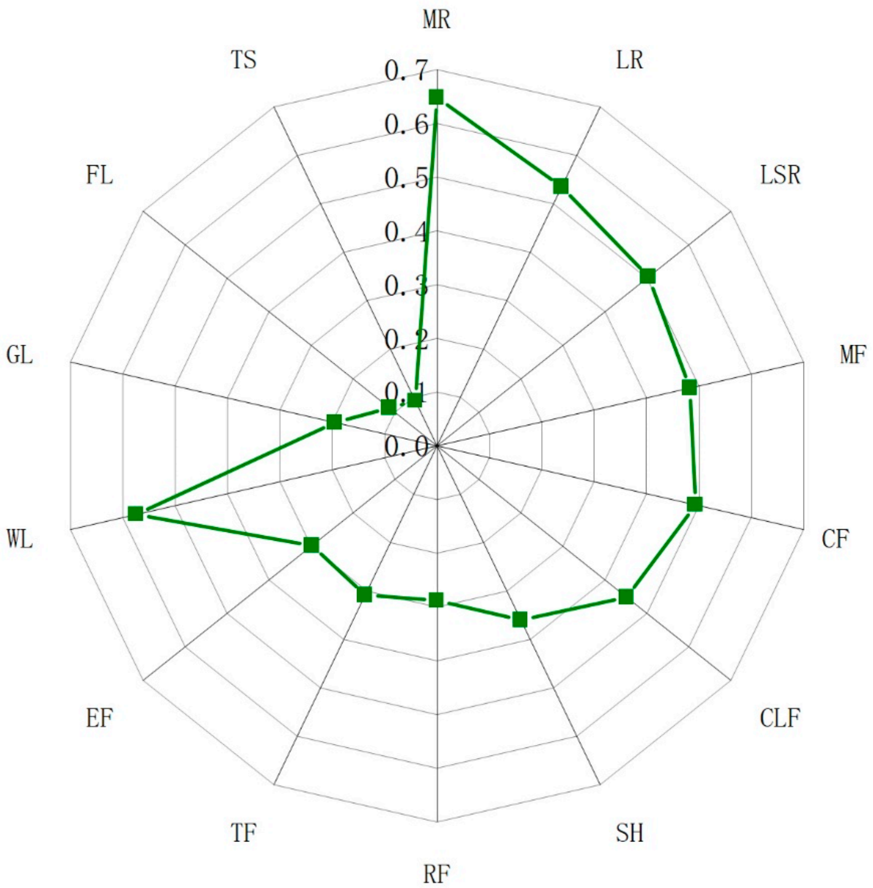

Figure 4. Value of RESs per unit area of different ecosystem types (unit: ×10^8 CNY/km^2). Notes: montane rainforest (MR), lowland rainforest (LR), lowland secondary rainforest (LSR), deciduous monsoon forest (MF), tropical coniferous forest (CF), tropical cloud forest (CLF), shrubbery (SH), rubber forest (RF), timber forest (TF), economic forest (EF), grassland (GL), wetland (WL), farmland (FL), traditional settlement (TS).

3.3. Scenario Setting and Simulation Prediction

3.3.1. Construction of Objective Function

To satisfy the need to construct a linear programming model and realize the objective of maximizing RES value, an objective function equation, given LULC types and their corresponding value per unit area, was established as follows:

$$\begin{gathered}\text{Max}: Z = 0.648x_1 + 0.535x_2 + 0.504x_3 + 0.483x_4 + 0.494x_5 + \\ 0.452x_6 + 0.360x_7 + 0.288x_8 + 0.308x_9 + 0.298x_{10} + 0.195x_{11} + \\ 0.574x_{12} + 0.113x_{13} + 0.093x_{14}\end{gathered} \tag{5}$$

3.3.2. Scenario Setting

According to the Pilot Program and Overall Planning for Hainan Tropical Rainforest National Park (2022–2030) and the objective of optimizing RESs, given natural conditions, socioeconomic development, land development intensity, and the possible eco-environment conservation level, both a short-term scenario (to 2030) and a long-term scenario (to 2050) were established to optimize LULC types and areas in HTRNP accordingly.

1. Based on constraints set by the *Overall Planning for HTRNP*, the short-term scenario assumes that the ecosystems in HTRNP will be gradually restored based on current

strict and efficient conservation and ecological restoration measures. Firstly, assuming that stringent protective and nature-restorative measures are taken toward primitive forests, rainforests, and monsoon rainforests, resulting in fewer anthropogenic impacts and positive succession in secondary forests, we suppose that 20% of the forest ecosystem will experience positive natural succession. Given the impact of annual precipitation, runoff, and human activities, this study sets a fluctuation range of 10% for wetland and grassland. Secondly, planted forests with 154.26 km^2 in the core area and economic forests with 358.85 km^2 in ecological corridors will be restored. Thirdly, according to national policies on ecological relocation and residents' willingness to access non-agricultural jobs, we suppose that 20% of settlements and farmlands will be voluntarily returned to nature. In addition, a 10-hectare ecological relocation site in the core area will be rehabilitated. Therefore, the short-term constraint function is as follows:

$$\text{s.t.}(2030)\begin{cases} x_1 \geq 621.44 \\ x_2 \geq 1161.86 \\ 1023.74 \leq x_3 \leq 1279.67 \\ 108.7 \leq x_4 \leq 135.87 \\ 34.73 \leq x_5 \leq 43.41 \\ 25.21 \leq x_6 \leq 31.51 \\ 8.18 \leq x_7 \leq 10.23 \\ \sum_{i=1}^{7} x_i \geq 3283.99 \\ x_8 \leq 233.06 \\ x_9 \leq 426.57 \\ x_{10} \leq 154.74 \\ x_8 + x_9 + x_{10} = 301.26 \\ 12.70 \leq x_{11} \leq 15.21 \\ 102.27 \leq x_{12} \leq 124.99 \\ 18.94 \leq x_{13} \leq 23.68 \\ 15.01 \leq x_{14} \leq 18.76 \\ \sum_{i=1}^{14} x_i = 4268.54 \\ x_i \geq 0,\ i = 1,\ 2,\ \cdots, 14 \end{cases} \quad (6)$$

2. Based on the objective of optimizing RESs, we suppose that the integrity and authenticity of the rainforest ecosystem will be achieved step by step through artificial breeding and natural succession, and finally, problems related to the habitat segmentation of rare wild animals, such as *Nomascus hainanus*, will be solved. Firstly, forest ecosystems will be well preserved and recover and will all become montane or lowland rainforests [53]. Given natural factors and anthropogenic factors for the formation of grassland ecosystems, we suppose that 50% of grassland will be restored to natural forest. Secondly, despite the current weak self-sustaining and self-renewal capabilities, planted forests will all be well restored to natural forests through natural succession and artificial breeding. Thirdly, based on the gradually increased willingness of community residents to be employed in non-agricultural industries, plus incentive policies on ecological relocation, artificial landscape sites such as farmlands and settlements will all pull out of the national park and become forest ecosystems. Therefore, the long-term constraint function is as follows:

$$\text{s.t.}(2050)\begin{cases} x_1 \geq 621.44 \\ x_2 \geq 1161.86 \\ x_3 \leq 1279.67 \\ x_4 \leq 135.87 \\ x_5 \leq 43.41 \\ x_6 \leq 31.51 \\ x_7 \leq 10.23 \\ \sum_{i=1}^{7} x_i \geq 3283.99 \\ x_8 \leq 233.06 \\ x_9 \leq 426.57 \\ x_{10} \leq 154.74 \\ x_8 + x_9 + x_{10} \leq 814.37 \\ 7.06 \leq x_{11} \leq 14.11 \\ 102.27 \leq x_{12} \leq 124.99 \\ x_{13} \leq 23.68 \\ x_{14} \leq 18.76 \\ \sum_{i=1}^{14} x_i = 4268.54 \\ x_i \geq 0,\ i = 1,\ 2,\ \cdots,14 \end{cases} \tag{7}$$

3.3.3. Simulation Prediction

The area and value of all LULC types were obtained by simulation prediction through a linear programming model. In the short-term scenario, the area of montane rainforest, lowland rainforest, and lowland secondary rainforest will increase by 44.20 km^2, 255.93 km^2, and 278.44 km^2, respectively. The area of planted forest will be reduced by 513.11 km^2, and other ecosystems will also be adjusted accordingly (Figure 5). In this scenario, the value of RESs in HTRNP is CNY 2216.64 × 10^8, an increase of CNY 118.97 × 10^8 compared to 2020, with an increase rate of 5.67% (Table 3).

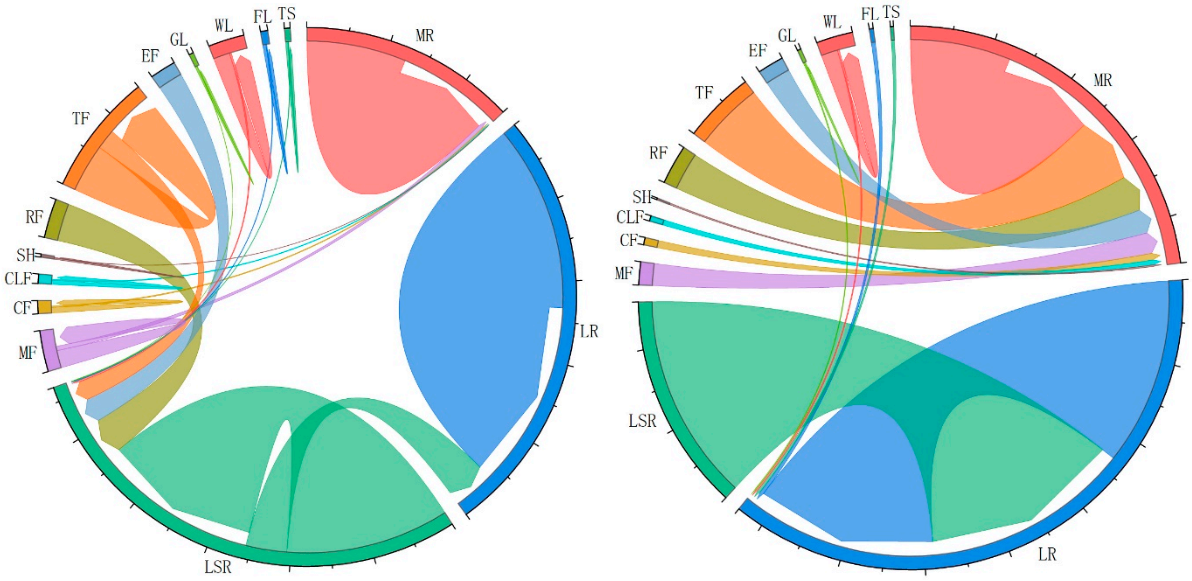

Figure 5. Chord diagram based on LULC in the short-term scenario (2030) and long-term scenario (2050). The abbreviations are the same as in Figure 4.

Table 3. Simulation prediction results for Hainan Tropical Rainforest National Park.

Ecosystem Types			Currency (2020)		Short-Term Scenario (2030)		Long-Term Scenario (2050)	
			Area (km^2)	Value ($\times 10^8$ CNY)	Area (km^2)	Value ($\times 10^8$ CNY)	Area (km^2)	Value ($\times 10^8$ CNY)
Forest Ecosystem	Natural Forest	Montane Rainforest	621.44	402.55	665.64	431.33	1656.83	1073.63
		Lowland Rainforest	1161.86	621.2	1417.79	758.52	2502.39	1338.78
		Lowland Secondary Rainforest	1279.67	644.72	1558.11	785.29	0	0
		Deciduous Monsoon Forest	135.87	65.66	108.7	52.5	0	0
		Tropical Coniferous Forest	43.41	21.43	34.73	17.16	0	0
		Tropical Cloud Forest	31.51	14.25	25.21	11.39	0	0
		Shrubbery	10.23	3.68	8.18	2.94	0	0
	Planted Forest	Rubber Forest	233.06	67.1	0	0	0	0
		Timber Forest	426.57	131.58	301.26	92.79	0	0
		Economic Forest	154.74	46.14	0	0	0	0
Grassland			14.11	2.76	12.7	2.48	7.06	1.37
Wetland			113.63	65.22	102.27	58.7	102.27	58.7
Farmland			23.68	2.68	18.94	2.14	0	0
Traditional settlement			18.76	1.74	15.01	1.4	0	0
Total			4268.54	2090.71	4268.54	2216.64	4268.54	2472.48

In the long-term scenario, the forest ecosystems will all be turned into montane rainforest (1656.83 km^2) and lowland rainforest (2502.39 km^2). The areas of grassland and wetland are 7.06 km^2 and 102.27 km^2, respectively. Ecosystems of planted forests and farmlands will all pull out of HTRNP (Figure 5). In this scenario, the value of RESs in HTRNP is CNY 2472.48 $\times$ 10^8, an increase of CNY 374.81 $\times$ 10^8 compared to 2020, with an increase rate of 17.87% (Table 3).

4. Discussion

4.1. RESs and Spatial Distribution

There are many and varied ways to estimate ecosystem services for human well-being, yet the monetary method is the most feasible and recognized approach for commodification, marketization, and policy-making [7]. This study reveals that the total value of RESs in HTRNP in 2020 was CNY 2090.67 $\times$ 10^8, which is close to the results of previous studies [54,55]. In terms of the RES composition, the CR value is the highest among all, accounting for 61.4%. Similar results can also be found in previous studies in other fields. For example, Costanza et al. (1997) valuated global CR at 684 USD/hm^2·a, accounting for 85% of the total ES value in the same period [56]; Ma et al. (2017) valuated RESs in China in 2015 and revealed that CR accounted for 43.6% of the total ES value [57]. In addition, this study reveals that the proportions of WC and SR are also relatively high, accounting for 20.21% and 15.47%, respectively, which further demonstrates that HTRNP is highly biologically diverse and of great importance as a key zone of biodiversity in the world. The proportion of CS only accounts for 2.84% for two possible reasons: firstly, when calculating the biophysical quantity of NPP, the high value of carbon storage in soil has not been taken consideration; secondly, the carbon emission trading price is set at 28 CNY/t based on Laws on Carbon Emission Trading Price while consulting the Technical Guide to GEP Accounting in Hainan Province, which may undermine the actual carbon emission transaction price. Undoubtedly, CS plays a key role in achieving carbon peaking and carbon neutrality in China, as HTRNP is one of the key carbon sequestration regions [58] and home to an immense rainforest, which is likely to expand in the future. Moreover, with the advantages of a long storage time and a large annually accumulated quantity, forest carbon storage is globally accepted as an economical, safe, and efficient sequestration measure and plays an important role in maintaining the global carbon balance and mitigating greenhouse gasses. It is suggested to pay more attention to soil carbon storage, establish appropriate models and select parameters in accordance with local conditions, improve the CS accounting method, and put more effort toward eco-space conservation in order to increase the stability of terrestrial ecosystem carbon storage.

In terms of spatial distribution, different indicators exhibit various spatial patterns. WC has "high value in the east and low in the west", which has been discussed in former studies [59]. SR has "high value in central and low in surrounding areas", which means that higher SR capability was found with steeper slopes in the central area of HTRNP. This is not consistent with a previous study [60], possibly for the following reasons: Firstly, the central area has been under strict protection for a long time, with higher rainforest coverage and a more complete layer structure of trees, shrubs, grasses, and vines. Therefore, the kinetic energy of precipitation can be effectively reduced by leaves, and soil and surface sediments are held by plant roots, which helps reduce rain wash and soil erosion [61]. CS and OR are characterized as "high value in central and low in surrounding areas". With the implementation of the "Returning Farmland to Forest Policy", farmlands and economic forests in central areas with high altitudes were first turned into natural rainforests, with more diverse thriving vegetation and higher-intensity carbon storage [62]. On the contrary, human activities, such as urbanization, traffic construction, and industrial development, are more frequent in the surrounding areas with low altitudes, and some areas were not officially included in HTRNP until 2019. CR has "higher value in the west than other areas". Hainan Island is located on the northern edge of the tropical region, belonging to the tropical monsoon climate and tropical oceanic climate zones. The average annual precipitation gradually decreases from east to west in HTRNP due to southeast monsoons and the block formed by the central mountainous areas of Wuzhishan, Limuling, and Bawangling [63]. The average annual precipitation in the eastern area reaches 2400 mm, while precipitation in western areas, such as Dongfang and Changjiang, is merely 1000 mm. Meanwhile, evaporation shows the opposite trend, where evaporation in the west is much higher than that in other areas. The combination of precipitation and evaporation forms the spatial pattern of CR.

4.2. Linear Programming and Simulation Prediction

LULC directly reflects the influence of human activities on the natural environment and exerts a direct impact on the spatial distribution of RES value [64]. The RES value and its spatial distribution vary among different land-use types [51], and the results of this study reveal that natural forests are valued from 0.36 to 0.648 $\times 10^8$ CNY/km^2. Different spatial RESs can even occur with the same land-use type if it has vegetation at different growth stages. For example, the per-unit value of lowland rainforest is higher than that of lowland secondary rainforest, at 0.535 and 0.504 $\times 10^8$ CNY/km^2, respectively. In addition, trees of different species, ages, and well-being levels also generate different spatial RESs [65]. Therefore, taking LULC as a constraint factor on RESs in HTRNP is of theoretical and practical significance and provides a reference for HTRNP's ecological planning and effective management in the future.

LULC reflects the joint influence of natural factors and human activities, and it is subject to climate conditions and regulations, as well as policies. Within the study period, climate conditions will not experience major fluctuations leading to ecosystem changes [66], and therefore, there will be no obstacles to positive ecosystem succession. In terms of policy planning, to satisfy the needs of socioeconomic development at an earlier stage, China approved the large-scale industrial logging of rainforests in the 1950s and established 11 large logging enterprises successively, such as Bawangling, Jianfengling, Diaoluoshan, Limushan, and so on. Meanwhile, the Hainan government also designated 12 million acres of primitive forests suitable for rubber plantation at that time and planted timber forests and economic forests as replacements. According to statistics, the primitive forest coverage rate in Hainan Island reached 35.4% in 1950 and had declined to 7.9% by 1990 [67]. After the 1990s, Hainan launched programs of Prohibition for Deforestation and Conservation of Natural Forest and started eight projects for "Greening Hainan Island" in 2011. The rainforest coverage rate had been restored to 19.17% by 2018. Since 2019, China has successively approved a series of planning and policies to transform HTRNP into a prohibited development zone; such policies include The Guiding Opinions on Establishing National Park-based Nature Reserve System, The Guiding Opinions on Overall Demarcation and Implementation of Three Control Line in National Spatial Planning, and Overall Planning for HTRNP. These policies focused on the overall conservation, systematic restoration, and comprehensive administration of rainforest resources, further promoting scientific conservation and the sustainable use of resources. To summarize, HTRNP has evolved from economy-centered development to systematic ecological conservation-centered development, which provides a policy foundation for RES-oriented spatial optimization.

4.3. Policy Implications

As the important means of balancing the economic input and ecological output, ESs are of great importance for formulating national protection laws, implementing protection measures, and allocating human and financial resources [68]. Since the HTRNP was officially selected as one of the first five national parks in 2021, the assessments of ESs have been gradually conducted from academia and government. In this paper, the total value of RESs in HTRNP is very high, but different indicators exhibit various spatial patterns, which provides the guideline of future eco-planning and managements. So, we suggest the overall protection but differentiated management of HTRNP in the future. On one hand, the RESs of HTRNP is up to CNY 2090.67 $\times$ 10^8, providing the monetized value to explore the path of transforming lucid waters and lush mountains into mountains of gold and silver for realization. Thus, it is necessary to implement the overall protection and systematical management for enhancing the eco-security pattern and sustainable socioeconomic development [38]. On the other hand, different LULC performed various value of RESs. For example, rubber plantations led to a significant decline in landscape connectivity, with significant negative impacts on RESs [69,70]. So, for core areas of HTRNP, it is recommended to restrict human activities to maintain succession of natural ecosystem. For the skylight and boundary areas of HTRNP, the planted and economic forests will be restored to natural forests by combining natural restoration and artificial nurturing measures. This will help to enhance the connectivity and integrity of forestland and grassland, hence, to obtain higher value of RESs.

5. Conclusions and Prospects

5.1. Conclusions

In this study, taking HTRNP as an example, the value of RESs in 2020 was assessed via the InVEST model, and the RES value per unit was calculated for different LULC types. In addition, following the Overall Planning for HTRNP and the objective of optimizing RESs, the value of RESs in a short-term scenario (to 2030) and a long-term scenario (to 2050) was forecast via a linear programming model. The conclusions are as follows: (1) The RES value of HTRNP in 2020 was CNY 2090.67 $\times$ 10^8, with CR accounting for the largest proportion; the spatial distribution of RESs in the east and central areas is higher than that in the west, but different RES indicators have varied spatial distribution structures. (2) The natural forest ecosystem of HTRNP accounts for 76.94% of the total area but 84.82% of the total value of RESs. The value of RESs per unit area is ranked from highest to lowest as follows: montane rainforests > wetlands > lowland rainforests > lowland secondary rainforests > tropical coniferous forests > deciduous monsoon rainforests > tropical cloud forests > shrub forests > timber forests > economic forests > rubber forests > grasslands > farmlands > settlements. (3) In the short-term scenario, the value of RESs is CNY 2216.64 $\times$ 10^8, an increase of CNY 118.97 $\times$ 10^8 compared to 2020, with an increase rate of 5.67%. In the long-term scenario, the value of RESs is CNY 2472.48 $\times$ 10^8, an increase of CNY 374.81 $\times$ 10^8 compared to 2020, with an increase rate of 17.87%. In terms of the quantitative assessment and simulation prediction of the RES value, this study provides a basis for land-use adjustment, eco-environment conservation, and refined management of HTRNP and provides a new roadmap for the protection and management of other national parks.

5.2. Shortcomings and Prospects

Firstly, limited by landforms and strict conservation regulations, it is hard to obtain localized parameters for the InVEST model. Therefore, the valuation results of specific indicators differ significantly from those of previous studies. However, the framework and method proposed in this study will be of great importance as background data for the temporal–spatial comparison of RESs in the future. Meanwhile, it is encouraged to conduct successive monitoring and valuation to obtain necessary data for RESs in HTRNP.

Secondly, LULC prediction is a complicated process and is affected by climate change, human activities, land management policies, residents' willingness to relocate, and other major policies. More factors should be taken into consideration to obtain reliable and spatial LULC predictions based on current institutional reforms and multi-scenario analyses.

Thirdly, a linear programming model was applied to predict RESs in short-term and long-term scenarios, avoiding errors produced by the complicacy of models and the inaccuracy of parameters. However, the prediction was conducted based on values in 2020, which excludes any increases in RESs that have since occurred as ecosystems underwent positive succession. The spatial concepts should be incorporated to optimize the model to provide more effective policy guidance in the future.

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