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Estimation of the Value of Forest Ecosystem Services in Pudacuo National Park, China

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Abstract: Forest ecosystems play an important role in maintaining the stability of the biosphere and improving the ecological environment. The valuation of forest ecosystem services provides data to support the implementation of forest ecosystem conservation and the development of ecological-compensation standards. We used multiple sources of data, such as remote-sensing and ground data, and we employed the methods of substitute market, shadow project, and contingent valuation. We valued the forest ecosystem services of Pudacuo National Park in Shangri-La, China, which consisted of six functions: soil conservation, forest nutrient retention, water conservation, carbon fixation and oxygen released, forest health care, and atmospheric environmental purification. The results showed that: the value of forest ecological services in Pudacuo National Park was 4.49×10^9 yuan·a^{-1}, with higher values of carbon fixation and oxygen released, water conservation, and forest health care, in the following order: carbon fixation and oxygen released (3.85×10^9 yuan·a^{-1}), water conservation (3.40×10^8 yuan·a^{-1}), forest health care (1.44×10^8 yuan·a^{-1}), soil conservation (1.15×10^8 yuan·a^{-1}), forest nutrient retention (3.29×10^7 yuan·a^{-1}), and atmosphere environmental purification (1.17×10^7 yuan·a^{-1}). In addition, the value of services per stand and unit area is discussed, and the results of the study will inform the government's ecological-compensation criteria in high-quality environmental areas.

Keywords: forest ecosystem; Pudacuo National Park; Shangri-La; the value of ecosystem services

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1. Introduction

Ecosystem services are natural environmental conditions and utilities of human survival that are necessary over the course of the development of ecosystems. They not only provide products and livelihoods for humans, but also maintain the life-support systems on which humans depend while supporting the transmission of material, energy, and information flows in the biosphere [1]. Forests are an important component of terrestrial ecosystems and play an irreplaceable role in providing diverse ecosystem services and products for society and the planet's life-support systems by providing biodiversity, carbon sequestration, water, and wood [2–4]. Consequently, forest ecosystem services are closely related to human well-being and constitute an important part of the global total economic value.

Since the 1990s, research on ecosystem services has evolved and become a hotspot for scholars worldwide. Studies on forest-ecosystem-service functions have mainly focused on the valuation of individual services and case studies, with the methods mainly being the travel-value method and the willingness-to-pay method [5]. In 1997, Constanza, an American scholar, made the first assessment of the value of global ecosystem services. In the assessment, scholars, represented by Constanza, have classified forest ecosystems into two types: tropical forests and temperate/boreal forests, and have estimated the value of ecosystem services for 13 and 9 indicators, respectively, with the value of ecosystem services for the two forest types being USD 3.81×10^{12}/a and USD 8.94×10^{9}/a, respectively [6–9]. Although Constanza's method and results have been widely debated and criticized by many ecologists and economists, they have provided a reference method for valuing forest ecosystem services and have promoted the research and application of the valuation of forest ecosystem services and their values in large regions.

In 1983, the Chinese Forestry Society conducted a study on the comprehensive benefits of forests. In 1984, the Environmental Protection Institute of Jilin Province adopted the Japanese forest-ecological-benefits accounting method to calculate four of the seven ecological values of the Changbai Mountain forests, and the results amounted to RMB 9.2 billion. In 1988, Li Jinchang led a study on the ecological benefits of forests, including those of forest resources. In the 1990s, the concept of ecosystem services was introduced to China, but at that time, the research was mainly focused on the introduction of foreign research results and the exploration of basic theories. In 1999, Ouyang [10] and other scholars were the first to estimate the value of terrestrial ecosystem services in China, mainly forests and grasslands, in terms of organic matter, the maintenance of the atmospheric CO_2 and O_2 balance, nutrient cycling and storage, soil and water conservation, water conservation, and the purification of environmental pollution by ecosystems. Since then, assessments of forest ecosystem services at different scales have been carried out based on national forest inventory data. For instance, Jiang [11] (1999), Zhao [5] (2004), and Yu [7] (2005) estimated the value of forest ecosystem services in China to be CNY 9.39×10^{10}, CNY 1.41×10^{12}, and CNY 3.06×10^{12}, respectively.

The assessment of the value of forest ecosystem services in nature reserves, mainly national parks, has gradually become an important part of realizing the unification of the ecological, social, and economic benefits within the system [12–14]. Pudacuo National Park is located in the Three Parallel Rivers World Heritage Site in northwest Yunnan, which is the center of differentiation of new endemic species in the northern hemisphere, and one of the 34 biodiversity hotspots in the world [15]. In addition, Northwest Yunnan is a typical remote area inhabited by ethnic minorities, and while conservation efforts are increasing, they are also limiting the traditional livelihoods of the local people and the economic development of the region. The forest-ecosystem-service functions in Yunnan Province have been studied from different regions, scales, and types [16–18], but the contribution of individual forest stands and the distribution of ecological values in the ecosystem-service values of forests in Pudacuo National Park are still unclear and need further study.

The Chinese government issued two versions of industry and national standards for valuing forest ecosystem services in 2008 [19] and 2020 [20]. There are 8 functions in the 2008 standard, which contains 14 indicators, and 9 functions in the 2020 standard, which contains 18 indicators. Due to the high status of the National Park itself, the vegetation within the park has varying levels of protection, and timber income is generated through the cutting of trees; the functional indicator of the forest product supply for the 9 functions in 2020 is not applicable in Pudacuo National Park. The national park is located in southwest China, where the forest cover is dense and there is no soil erosion or soil sanding, and the function of wind and sand control is generally not suitable for application in the forest-ecosystem-service value-assessment system in southern China. Species are abundant and widespread in the National Park, and we have some knowledge of the categories of treasured and endangered tree species, but not much about their numbers. After conducting some preliminary surveys, we found that we could not obtain convincing results, and we finally deliberated not to include this indicator in the assessment system.

Remote-sensing technology has been widely used in various regional-scale ecological-environment-assessment studies in recent years due to its advantages of large-scale, multiscale, and highly time-effective acquisition [21,22]. Remote-sensing technology has been applied in the fields of ecological and environmental monitoring and groundcover-information extraction, and it is currently the most important source of ecological and environmental information. Furthermore, remote-sensing information and other supporting natural and historical information are complementary, and their effective combination can bring more objective and richer information to ecological-assessment studies [23,24]. The use of remote-sensing technology combined with traditional working methods to process the image data of the study area and extract the data of each index needed for evaluation greatly saves time and effort in data collection and collation, while using scientific calculation methods in the process of the comprehensive evaluation of multisource information reduces the calculation volume while ensuring the correctness and accuracy of the calculation results, greatly improves the timeliness of the evaluation results, and provides technical support for the ecological environment [25].

This study takes the national standard *Specifications for Assessment of Forest Ecosystem Services (GB/T 38582-2020)* [20] as the standard, and it integrates remote-sensing data, ground-survey data, social public data, and literature data. Six assessment functions, namely, soil conservation, forest nutrient conservation, water conservation, carbon fixation and oxygen release, atmospheric environmental purification, and forest health care, were selected to discuss the value of the forest ecosystem services in Pudacuo National Park in 2020. The aim was to translate the forest-ecosystem-service functions of the forest ecosystems in Pudacuo National Park into perceived monetary values. The results could provide theoretical support for scientific ecological assessments of nature reserves, such as national parks, and can also provide a basis for the government's criteria for ecological compensation in areas with high-quality environments.

2. Materials and Methods

2.1. Overview of the Study Area

Shangri-La Pudacuo National Park is located in Shangri-La County, Diqing Tibetan Autonomous Prefecture, Yunnan Province, China, between 27°43′~28°04′ N and 99°54′~100°12′ E. It is approximately 25 km from Shangri-La County, Diqing Tibetan Autonomous Prefecture, Yunnan Province, and is part of the Diqing Plateau on the southeastern edge of the Qinghai–Tibet Plateau in the northern section of the high mountain-valley region of the Hengduan Mountains, with a total area of 6.02×10^4 hm^2 and an altitude of 2339~4547 m (Figure 1). Shangri-La County has a plateau monsoon climate, with an average annual temperature of 6.1 °C and average annual precipitation of 626.0 mm [26]. The vegetation in the park is distributed between 2300 and 4600 m above sea level and is located in the southeast of the alpine vegetation zone of the Qinghai–Tibet Plateau, bordering the subtropical evergreen broad-leaved-forest zone, which is a zone of transition from the subtropical evergreen broad-leaved-forest zone to the alpine vegetation zone of the Qinghai–Tibet Plateau [27]. The native representative vegetation of Shangri-La is Abies georgei (*Abies georgei*), Quercus pannosa (*Quercus pannosa*), Pinus yunnanensis (*Pinus yunnanensis*), Pinus densata (*Pinus densata*), Larix potaninii var. macrocarpa (*Larix potaninii* var. *macrocarpa*), etc. [28].

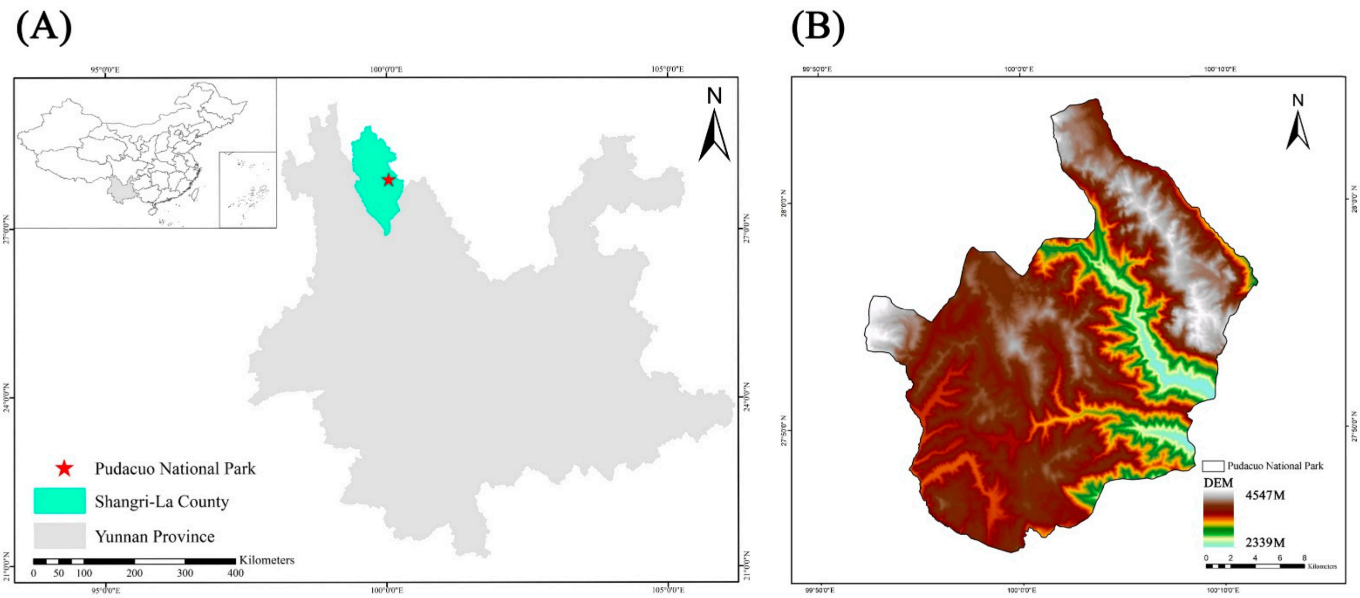

Figure 1. Map showing the location of the study area. (**A**) Location of Pudacuo National Park in China and (**B**) Elevation map of Pudacuo National Park.

2.2. Data Sources and Preprocessing

This study used four types (Table 1) of data to evaluate the value of forest ecosystem services in Pudacuo National Park.

Table 1. Data sources for evaluating the value of forest ecosystem services in Pudacuo National Park.

Name of Data	Unit	Source of Data
Soil-erosion modulus on wooded and unwooded land in forest stands	$t \cdot hm^{-2} \cdot a^{-1}$	Reference [29]
The soil in forest stands contains N, P, K, and organic matter	%	2021 *Report on the Comprehensive Scientific Study of Shangri-La's Pudacuo National Park*, Reference [30].
Elemental N, P, and K contents of forest	%	References [31,32]
Net productivity of forest stands	$t \cdot hm^{-2} \cdot a^{-1}$	Reference [33]
Precipitation outside the forest	$mm \cdot a^{-1}$	Reference [31]
Evapotranspiration from forest stands	$mm \cdot a^{-1}$	Reference [31]
Rapid surface runoff from forest stands	$mm \cdot a^{-1}$	Reference [34]
Carbon sequestration in forest soils	$t \cdot hm^{-2} \cdot a^{-1}$	Reference [35]
Amount of sulfur dioxide, fluoride, and nitrogen oxides absorbed by forest stands	$kg \cdot hm^{-2} \cdot a^{-1}$	Reference [36]
Negative-oxygen-ion concentration in forest stands	$pcs \cdot cm^{-3}$	Reference [37]
Forest-stand height	m	2021 *Report on the Comprehensive Scientific Study of Shangri-La's Pudacuo National Park*
Negative-oxygen-ion life	min	Reference [19]
Dust-holding capacity	$t \cdot hm^{-2} \cdot a^{-1}$	References [36,38]
Soil consolidation prices	$yuan \cdot m^{-3}$	Reference [19]. The price of soil consolidation instead of the cost of excavating and transporting a unit volume of soil is RMB 12.6 yuan/m^3.

Table 1. *Cont.*

Name of Data	Unit	Source of Data
Soil capacity	g·cm^{-3}	Reference [39]
Diammonium phosphate fertilizer prices Potassium chloride fertilizer prices Organic-matter fertilizer prices	yuan·t^{-1} yuan·t^{-1} yuan·t^{-1}	*National Price List of Agricultural Production Materials*, published by the Price Monitoring Centre of the National Development and Reform Commission of China in January–December 2020.
Nitrogen content of diammonium phosphate fertilizer Phosphorus content of diammonium phosphate fertilizer Potassium chloride fertilizer with the potassium content	% % %	Reference [40]
Water-transaction costs, water-purification costs	yuan·m^{-3}	Water-resource-transaction costs, water-purification costs, instead of reservoir-construction-unit reservoir-capacity investment costs (compensation for land demolition and relocation, construction costs, maintenance costs, etc.), *China Water Resources Yearbook 1993–1999*, *China Statistical Abstract 2019*.
Negative-oxygen-ion generation costs	yuan·pcs^{-1}	Reference [9]
Sulfur dioxide, fluoride, nitrogen oxides, and stagnant dust clean-up costs	yuan·kg^{-1}	*Notice on the Implementation Plan for the Adjustment of the Sewage Charge Levy Standard*, issued by the Yunnan Provincial Department of Environmental Protection, Reference [9].
Solid carbon prices	yuan·t^{-1}	International carbon tax law. 2020 USD:RMB, exchange rate of 1:6.86, Swedish carbon-tax rate: USD 129.7/t, equivalent to RMB 889.74/t
Oxygen prices	yuan·t^{-1}	*Oxygen Market Annual Report 2019–2020*. The price of oxygen was RMB 594.8/t.
The value of forest tourism and leisure industries, and forest rehabilitation and healing industries	yuan·a^{-1}	Courtesy of Pudacuo National Park Authority

2.2.1. Data Sources

(1) Remote-sensing data. The vegetation-type data, soil data, and high-resolution satellite remote-sensing data of Shangri-La City in 2020 from the Institute of Geographical Sciences and Resources of the Chinese Academy of Sciences-Resources and Environmental Science and Data Centre (https://www.resdc.cn, accessed on 2 March 2021) were used as the remote-sensing data source, with a data resolution of 30 m. (2) Ground-survey data. As the interval between official forest-resource surveys conducted by the Chinese forestry department is five years, we applied the latest released data from the 2014–2016 Shangri-La County Forest Resources Type II Survey. The ground-survey results from the *Report on the Comprehensive Scientific Study of Shangri-La's Pudacuo National Park* were applied as the basic data for the forest-ecosystem-value assessment. (3) Social public data. Data on the social consumption index, price index, forest recreation, and other indicators were collected from relevant units. Other social public data were obtained from social public data published by authoritative institutions in China. (4) Literature data. Literature, such as journal papers and dissertations, were collected and applied to the analysis of the ecological data statistics of Pudacuo National Park.

2.2.2. Preprocessing

The remote-sensing data were radiometrically calibrated, atmospherically corrected, and geometrically calibrated and cropped using ENVI 5.3 software, and the projection coordinates were standardized to WGS-84. The vegetation and soils in the study area were classified according to the needs of the study. Through the field survey, the topography, vegetation, soil, and surface morphology of the study area were fully considered, and the

TM image interpretation marks of the dominant tree vegetation types and soil types were verified against the corresponding TM image features. A library of image features was established separately according to the image features, and the images were automatically classified with the supervised classification function of ENVI 5.3 software to obtain the classification results, and they were then reclassified in ArcGIS software according to the forest type to analyze the forest-resource area, topography, soil, and tree species of Pudacuo National Park to determine the assessment units. The ESTARFM spatiotemporal fusion algorithm was used to fuse satellite remote-sensing data with ground-based forest-resource Type II-survey vector data in image space and time, and to calculate the difference between the ground-survey results to form the required results. Social public data and literature data are mostly static data with slow update cycles and large statistical scales, which can be combined with remote-sensing data in forest-ecosystem-service assessment to complement each other and improve the formation of the assessment results. Static data mainly include annual statistical yearbooks and bulletins released by forestry, economic, and ecological environment departments, and only a few literature data refer to close years and slower changes. The statistical data were spatially correlated with the administrative-boundary vector data of Pudacuo National Park in ArcGIS to obtain the assessment results of the value of the forest ecosystem services. The assessment data were assessed using 2020 as the base year.

2.3. Assessment Methodology and Indicator Selection

Pudacuo National Park has always been subject to varying degrees of disturbance from both manmade and natural sources, which decreased after the establishment of the national park and the environmental-protection inspectors organized by China's National Department of Ecology and Environment in 2017. Therefore, in the construction of the indicator system, the influence of future disturbance factors is not considered. Combined with the characteristics of Pudacuo National Park, the undergrowth or forest-complex operation, and the small area of farmland, the estimated amount of crop production increased by its protective function is therefore small, and taking into account the high degree of forest protection in the national park, the supply of forest products cannot form a value. According to the *Specifications for Assessment of Forest Ecosystem Services (GB/T 38582-2020)* [20], six functions were selected: soil conservation, forest nutrient retention, water conservation, carbon fixation and oxygen release, atmospheric environmental purification, and forest health care. A total of 19 indicators included: soil consolidation; nitrogen-loss reduction; phosphorus-loss reduction; potassium-loss reduction; organic-matter-loss reduction; nitrogen sequestration; phosphorus sequestration; potassium sequestration; water-quantity regulation; water-quality purification; carbon sequestration by vegetation; soil carbon sequestration; oxygen release; negative-ion provision; SO_2 absorption; HF absorption; NO_x absorption; dust retention; forest recreation, and they were assessed using the contingent-valuation method, shadow-project method, and substitute-market-value method (Table 2). Using a distributed measurement method, Pudacuo National Park was used as the primary measurement unit, and the second measurement unit was formed by the forest-stand type based on the vegetation classification system and principles of China's vegetation [41] and Yunnan vegetation [42].

Table 2. Value evaluation and calculation model of forest ecosystems in Pudacuo National Park.

Service Features	Evaluation Indicators	Evaluation Methods	Functional-Volume-Calculation Formula	Value-Quantity-Calculation Formula
I	E_1	OC	$G_{Sc} = A \times (X_2 - X_1)$	$U_{SC} = G_{Sc} \times C_S / \rho$
	E_2	OC	$G_N = A \times N \times (X_2 - X_1)$	$U_{Nf} = G_N \times C_1 / R_1$
	E_3		$G_P = A \times P \times (X_2 - X_1)$	$U_{Lf} = G_P \times C_1 / R_2$
	E_4		$G_K = A \times K \times (X_2 - X_1)$	$U_{Kf} = G_K \times C_2 / R_3$
	E_5		$G_{Om} = A \times M \times (X_2 - X_1)$	$U_{Omf} = G_{Om} \times C_3$

Table 2. *Cont.*

Service Features	Evaluation Indicators	Evaluation Methods	Functional-Volume-Calculation Formula	Value-Quantity-Calculation Formula
II	F_1 F_2 F_2	SP	$G_{FN} = A \times N_{Nu} \times B_a$ $G_{FP} = A \times P_{Nu} \times B_a$ $G_{FK} = A \times K_{Nu} \times B_a$	$U_{FN} = G_{FN} \times C_1$ $U_{FP} = G_{FP} \times C_1$ $U_{FK} = G_{FK} \times C_2$
III	G_1 G_2	WB	$G_{Re} = 10A \times (P_{Wa} - E - C)$ $G_{Pu} = 10A \times (P_{Wa} - E - C)$	$U_{Re} = G_{Re} \times C_{Re}$ $U_{Pu} = G_{Pu} \times K_{Wa}$
IV	H_1 H_2 H_3	OC	$G_{Vcs} = 1.63R_C \times A \times B_a$ $G_{Scs} = A \times S_s$ $G_{Ox} = 1.19A \times B_a$	$U_{Vcs} = G_{Vcs} \times C_C$ $U_{Scs} = G_{Scs} \times C_C$ $U_{Ox} = G_{Ox} \times C_{Ox}$
V	I_1 I_2 I_3 I_4 I_5	SP	$G_{Ni} = 5.256 \times 10^{15} Q_{Ni} \times A/L$ $G_{SO_2} = Q_{SO_2} \times A$ $G_{HF} = Q_{HF} \times A$ $G_{NOx} = Q_{NOx} \times A$ $G_{Sd} = Q_{Sd} \times A$	$U_{Ni} = 5.256 \times 10^{15} \times A \times H \times K_{Ni} \times (Q_{Ni} - 600)/L$ $U_{SO_2} = G_{SO_2} \times K_{SO_2}$ $U_{HF} = G_{HF} \times K_{HF}$ $U_{NOx} = G_{NO_x} \times K_{NO_x}$ $U_{Sd} = C_{Sd} \times G_{Sd}$
VI	J_1	MV		$U_r = 0.8U_k$

Notes: I: soil conservation; II: forest nutrient retention; III: water conservation; VI: carbon fixation and oxygen released; V: atmosphere environmental purification; VI: forest health care; OC: substitute-market method; SP: shadow-project method; WB: contingent-valuation method; E_1: soil consolidation; E_2: reduction in nitrogen loss; E_3: reduction in phosphorus loss; E_4: reduction in potassium loss; E_5: reduction in organic-matter loss; F_1: nitrogen fixation; F_2: phosphorus fixation; F_2: potassium fixation; G_1: regulating water volume; G_2: water purification; H_1: vegetation carbon sequestration; H_2: soil carbon sequestration; H_3: release of oxygen; I_1: provides negative ions; I_2: absorption of SO_2; I_3: absorption of HF; I_4: absorption of NO_x; I_5: stagnant dust; J_1: forest health care; G_{Sc}: annual soil consolidation in forest stands; A: area of forest stands; X_2: soil-erosion modulus on unwooded land; X_1: soil-erosion modulus of forested land in forest stands; G_N: reduced N loss due to soil sequestration by forest stands; P_N: soil nitrogen content in forest stands; G_P: reduced phosphorus loss due to soil sequestration by forest stands; G_P: soil phosphorus content in forest stands; G_K: reduced potassium loss due to soil sequestration by forest stands; G_K: soil potassium content in forest stands; G_{Om}: reduced organic-matter loss due to soil sequestration by forest stands; G_{Om}: soil containing organic matter in forest stands; G_{FN}: annual nitrogen fixation in forest stands; N_{Nu}: elemental nitrogen content of forest; B_a: net productivity of forest stands; G_{FP}: annual phosphorus sequestration in forest stands; P_{Nu}: elemental phosphorus content of forest trees; G_{FK}: annual stand potassium sequestration; K_{Nu}: annual stand potassium content; G_{Re}: annual stand regulated water; P_{Wa}: extra forest precipitation; E: stand evapotranspiration; C: stand rapid surface runoff; G_{Pu}: annual stand purified water quality; G_{Vcs}: annual stand vegetation carbon sequestration; G_{Scs}: annual stand soil carbon sequestration; R_C: carbon content in carbon dioxide; S_S: stand carbon sequestration per unit area soil carbon sequestration per unit area of stand; G_{Ox}: annual oxygen release from the stand; G_{Ni}: annual number of negative oxygen ions provided by the stand; Q_{Ni}: concentration of negative oxygen ions in the stand; H: stand height; L: the negative-ion lifetime; G_{SO2}: annual sulfur dioxide uptake by the stand; Q_{SO2}: sulfur dioxide per unit area of stand; G_{HF}: annual fluoride uptake by the stand; Q_{HF}: fluoride uptake per unit area of stand; G_{NOX}: annual nitrogen oxide uptake by the stand; Q_{NOX}: nitrogen oxide uptake per unit area of the stand; G_{Sd}: annual stand dust retention; Q_{Sd}: stand dust retention per unit area of the stand; U_{Sc}: stand soil value; C_S: cost of excavating and transporting a unit volume of soil; ρ: soil capacity; U_{Nf}: stand fertilizer-retention value; U_{Pf}: stand fertility-retention value; U_{Kf}: stand fertility-retention value; U_{Omf}: stand fertilizer-retention value; C_1: price of diammonium phosphate fertilizer; R_1: the nitrogen content of diammonium phosphate; R_2: phosphorus content of diammonium phosphate; C_2: price of potassium chloride fertilizer; R_3: potassium content of potassium chloride fertilizer; C_3: price of organic matter; U_{FN}: stand nitrogen-retention price; U_{FP}: stand phosphorus-retention price; U_{FK}: stand potassium-retention price; U_{Re}: stand annual regulated water value; C_{Re}: market price of water resources; U_{Pu}: annual value of water purification in the stand; K_{Wa}: cost of water purification; U_{Vcs}: annual value of carbon sequestration in stand vegetation; C_C: price of carbon sequestration; U_{Scs}: annual value of soil carbon sequestration in the stand; U_{Ox}: annual value of oxygen release in the stand; C_{Ox}: price of oxygen; U_{Ni}: annual value of negative ions provided by the stand; K_{Ni}: cost of negative-ion production; U_{SO2}: value of annual sulfur dioxide absorption by forest stands; K_{SO2}: cost of sulfur dioxide treatment; U_{HF}: value of annual fluoride absorption by forest stands; K_{HF}: cost of fluoride treatment; U_{NOX}: value of annual nitrogen oxide absorption by forest stands; K_{NOX}: cost of nitrogen oxide treatment; U_{Sd}: value of annual dust retention by forest stands; K_{Sd}: cost of dust-retention treatment; U_r: value of annual forest recreation in the region; U_k: value of forestry tourism and leisure industry and forest rehabilitation and recreation industry in each administrative region; k: number of administrative regions; 0.8: number of tourists received by forest parks, and the tourism-output value created approximately 80% of the total scale of forest tourism in China.

3. Results

3.1. Characteristics of Different Forest-Stand Types

We surveyed the vegetation resources of Pudacuo National Park. The forest vegetation was classified, according to stand types, as sclerophyllous evergreen broad-leaved forest, deciduous broad-leaved forest, warm coniferous forest, temperate coniferous forest, scrub, and meadow (Table 3). The number, classification, and distribution of vegetation were obtained by statistical calculations of satellite-image data (Figure 2).

Table 3. The stand types of forest vegetation classifications of Pudacuo National Park.

Vegetation Type	Dominant Species
Sclerophyllous evergreen broad-leaved forest	*Quercus pannosa* Hand.-Mazz., *Quercus guyavifolia* H. Léveillé, *Quercus senescens* Hand.-Mazz., *Quercus aquifolioides* Rehd. et Wils.
Deciduous broad-leaved forest	*Betula platyphylla* Suk., *Betula albo-sinensis* Burkill, *Populus rotundifolia* var. *duclouxiana* (Dode) Gomb., *Acer sterculiaceum* subsp. *franchetii* (Pax) A. E. Murray, *Acer davidii* Franch., *Salix takasagoalpina* Koidz., *Hippophae rhamnoides* L. *Pinus yunnanensis* Franch.
Warm coniferous forest	*Pinus yunnanensis* Franch., *Pinus armandii* Franch., *Taxus yunnanensis* W.C.Cheng and L.K.Fu.
Temperate coniferous forest	*Tsuga dumosa* (D. Don) Eichler, *Pinus densata* Mast., *Abies ernestii* var. *salouenensis* (Borderes-Rey et Gaussen) Cheng et L. K. Fu, *Juniperus tibetica* Komarov, *Picea likiangensis* (Franch) Pritz, *Abies georgei* Orr, *Larix potaninii* var. *australis* A. Henry ex Handel-Mazzetti.
Scrub	*Rhododendron hippophaeoides* Balf. F. et W. W. Smith, *Rhododendron telmateium* Balf. F. et W. W. Smith, *Rhododendron alutaceum* Balf. F. et W. W. Smith, *Rhododendron rubiginosum* Franch., *Caragana franchetiana* Kom., *Juniperus squamata* Buchanan-Hamilton ex D. Don, *Spiraea myrtilloides* Rehd., *Berberis dictyophylla* Franch., *Daphne aurantiaca* Diels.
Meadow	*Carex atrata* L., *Rheum alexandrae* Batal., *Carex forrestii* Kukenth.

A statistical map of vegetation classification based on synthetic remote-sensing data for the year 2020 shows that the total forest area of Pudacuo National Park is 5.97×10^4 hm^2, among which temperate coniferous forest, warm coniferous forest, and meadow have higher distribution-area ratios, accounting for 28.00%, 26.36%, and 21.59%, respectively, while scrub and deciduous broad-leaved forest account for 1.96% and 6.98%, respectively, and sclerophyllous evergreen broad-leaved forest accounts for 14.30% of the total area. The vegetation types in Pudacuo National Park are dominated by coniferous forest.

3.2. The Value of Forest Ecosystem Services

The forest-ecosystem-service value of Pudacuo National Park was calculated by the forest-ecosystem-assessment model based on the forest vegetation classifications from remote-sensing data (Figure 2), forest-ecosystem-service value-assessment data (Table 1), and the calculation model of forest-ecosystem-value assessment (Table 2). The forest-ecosystem-service value of Pudacuo National Park was 4.49×10^9 yuan·a^{-1}, of which 1.15×10^8 yuan·a^{-1} was for soil conservation, 3.29×10^7 yuan·a^{-1} for forest nutrient retention, 3.40×10^8 yuan·a^{-1} for water conservation, 3.85×10^9 yuan·a^{-1} for carbon fixation and oxygen released, 1.17×10^7 yuan·a^{-1} for atmosphere environmental purification, and 1.44×10^8 yuan·a^{-1} for forest health care (Table 4). The value of the forest ecological services in Pudacuo National Park is equivalent to nearly three times the GDP of Shangri-La County in 2019 (1.53×10^9 yuan·a^{-1}). The value of forests lies in not only providing raw materials for human production and livelihoods, but also in their important ecological benefits. The value of forest ecosystem services in Pudacuo National Park is, in descending order, carbon fixation and oxygen release, water connotation, forest health care, soil conservation, forest nutrient retention, and atmospheric environmental purification. The main forest-ecosystem-service values of Pudacuo National Park are provided by the functions of carbon fixation and oxygen release, water connotation, and forest health care. This is consistent with the results obtained by Tang [39], who found that Yunnan's Ailaoshan National Nature Reserve is dominated by water connotation and forest health care, and Wang [36], who found that Henan's Jigongshan Nature Reserve is dominated by carbon fixation and oxygen release.

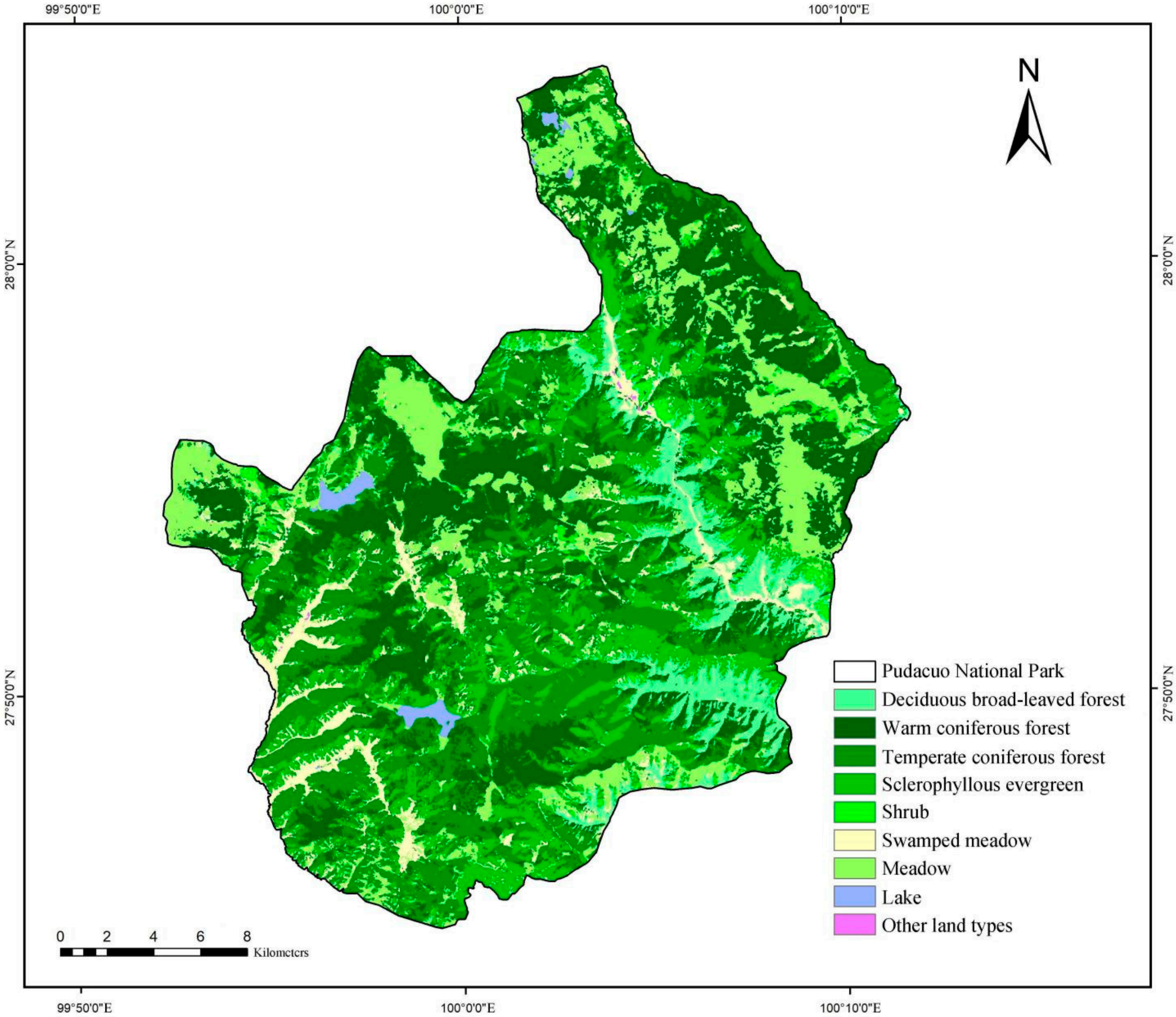

Figure 2. Vegetation distribution in Pudacuo National Park.

Table 4 shows that, among the ecosystem-service values of different forest types in Pudacuo National Park, temperate coniferous forest accounts for the largest proportion (49.00%), followed by warm coniferous forest (30.55%), and scrub accounts for the smallest proportion (less than 1%). The values of ecosystem services for different forest types in descending order is temperate coniferous forest, warm coniferous forest, sclerophyllous evergreen broad-leaved forest, deciduous broad-leaved forest, meadow, and scrub.

Figure 3 shows that, among the different forest types in Pudacuo National Park, the top three soil-conservation values are temperate coniferous forest, meadow, and warm coniferous forest; the top three forest-nutrient-retention values are temperate coniferous forest, warm coniferous forest, and meadow; the top three water-conservation values are temperate coniferous forest, warm coniferous forest, and meadow; the top three carbon-fixation and oxygen-released values are temperate coniferous forest, warm coniferous forest, and sclerophyllous evergreen broad-leaved forest; the top three atmospheric-environmental-purification values are temperate coniferous forest, warm coniferous forest, and sclerophyllous evergreen broad-leaved forest. The value of the temperate coniferous forest is high in all forest ecosystem services.

Table 4. Values of forest ecosystem services in Pudacuo National Park.

Type of Forest Stand	Value of Forest Ecosystem Services (10^6 yuan·a^{-1})					
	Soil Conservation	Forest Nutrient Retention	Water Conservation	Carbon Fixation and Oxygen Released	Atmosphere Environmental Purification	Forest Health Care
Deciduous broad-leaved forest	5.61	3.18	23.94	202.67	0.67	
Warm coniferous forest	20.70	7.91	90.38	1207.02	3.82	
Temperate coniferous forest	48.96	16.14	96.00	1967.39	4.40	
Sclerophyllous evergreen broad-leaved forest	11.42	0.96	49.03	387.33	1.40	
Scrub	2.20	0.85	6.71	26.83	0.13	
Meadow	26.20	3.86	74.04	61.88	1.24.	
Total	115.12	32.93	340.12	3853.15	11.67	144.44
Total value	4497.47					

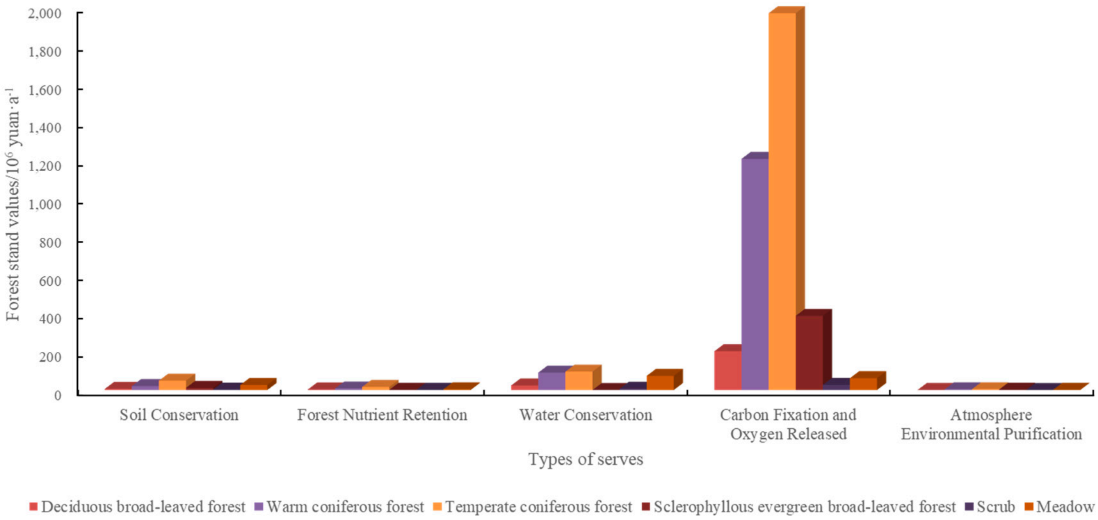

Figure 3. Stand value in different ecosystem-service functions of Pudacuo National Park.

3.3. Value of Ecosystem Services per Unit Area of Different Forest—Stand Types

According to the statistical results of the vegetation classification areas (Figure 2), the values of forest ecosystem services (Table 4), and the values of forest ecosystem services per unit area of different forest types in Pudacuo National Park, the temperate coniferous forest was the highest (1.27×10^5 yuan·hm^{-2}·a^{-1}), followed by warm coniferous forest (8.38×10^4 yuan·hm^{-2}·a^{-1}), deciduous broad-leaved forest (5.23×10^4 yuan·hm^{-2}·a^{-1}), sclerophyllous evergreen broad-leaved forest (5.62×10^4 yuan·hm^{-2}·a^{-1}), scrub (3.12×10^4 yuan·hm^{-2}·a^{-1}), and meadow (1.29×10^4 yuan·hm^{-2}·a^{-1}) (Table 5).

Table 5. Ecosystem-service value per unit area of different stand types in Pudacuo National Park.

Type of Forest Stand	Value of Forest Ecosystem Services per Unit Area (yuan·hm^{-2}·a^{-1})					
	Soil Conservation	Forest Nutrient Retention	Water Conservation	Carbon Fixation and Oxygen Released	Atmosphere Environmental Purification	Total
Deciduous broad-leaved forest	1336.09	756.69	5696.08	48,213.51	159.65	56,162.02
Warm coniferous forest	1305.02	499.13	5696.09	76,069.44	240.79	83,810.47
Temperate coniferous forest	2905.06	957.95	5696.09	116,725.20	261.16	126,545.46
Sclerophyllous evergreen broad-leaved forest	1327.15	111.97	5696.09	44,991.54	163.08	52,289.83
Scrub	1874.85	729.89	5696.12	22,775.98	114.00	31,190.84
Meadow	2015.97	297.57	5696.09	4760.54	95.84	12,866.01
Total	10,764.14	3353.20	34,176.56	313,536.21	1034.52	

Figure 4 shows that, among the different forest types in Pudacuo National Park, the top three soil-conservation forests in terms of unit area value are temperate coniferous forest, meadow, and scrub; the top three forest-nutrient-retention forests in terms of unit area value are temperate coniferous forest, deciduous broad-leaved forest, and scrub; the top three water-conservation forests in terms of unit area value are scrub, meadow, and sclerophyllous evergreen broad-leaved forest; the top three carbon-fixation and oxygen-released forests in terms of unit area value are temperate coniferous forest, warm coniferous forest, and deciduous broad-leaved forest; the top three atmosphere-environmental-purification forests in terms of unit area value are warm coniferous forests, warm coniferous forests, and deciduous broad-leaved forests. The value of the temperate coniferous forest is high in all forest-ecosystem-service functions. This is due to the large area covered by the temperate coniferous forest, and to the fact that the corresponding dominant species, such as alpine pine, long bush fir, and giant redbud fir, are light-loving, tolerant to dryness, barrenness, and cold, and have strong adaptability in harsh habitat conditions.

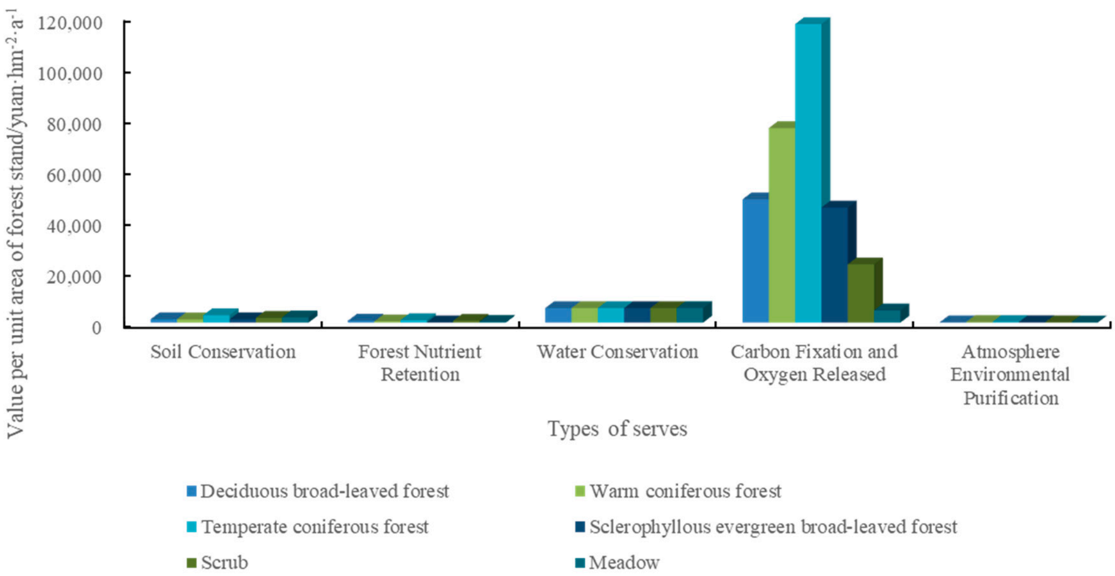

Figure 4. Value of stand per unit area in the ecosystem−service function of different stand types in Pudacuo National Park.

4. Discussion

4.1. Assessing the Value of Forest Ecosystem Services Using Multidisciplinary Cross-Sectional Research and Multisource Data

Most of the traditional studies on forest-ecosystem-service valuation are based on independent complete administrative regions and are mainly large-scale in scope, with few studies involving complex administrative regions and specific geographical units [43–46]. For example, Lan [43] selected Xinjiang province as a complete administrative area for forest ecosystem assessment, and Cui [44] assessed the value of forest ecosystem services in Shanxi province. In this study, the study area, Pudacuo National Park, covers three townships and six villages, and is not a complete administrative area. When assessing the amount of the forest ecosystem function, localized parameters are difficult to obtain, many data are not available in official statistics, and the officially published statistical yearbooks are only for fixed administrative areas. The relevant forest parameters need to be reintegrated for statistical purposes by fusing data from multiple sources. It is also necessary to disaggregate the statistics according to the different vegetation types. This makes it far more difficult to obtain basic data than for separate and complete administrative areas. This study used multisource-data fusion to integrate the forest parameters, which is consistent with Bo's [47] aim of fusing multisource data and integrating wetland data from the Ningxia Plain, and in terms of the results reflection, both resulted in higher-quality data results. Ma [48] used the remote-sensing processing software ENVI to image correct, enhance, and classify wetland types, and to improve the accuracy of the data, which is consistent with the results of this study.

The theory of forest-ecosystem-service value is an intersection of various disciplines, such as ecology, economics, resource science, and environmental science, and is an integrated and complex disciplinary system, while the technique of ecosystem-service-value assessment also involves different systems, such as fuzzy mathematics, computer technology, and geographic remote-sensing technology [49]. The existing research disciplines are isolated from each other, lack communication recognition, and lack a theoretical basis for the complex relationship between forest ecosystem functions and structures, ecological processes, and economic processes. Therefore, research on the value of forest ecosystem services and the selection of assessment methods should build a theoretical framework on an interdisciplinary basis so that the assessment results can more truly reflect the economic value of forest ecosystem services [50–52]. As forest ecosystem services are complex and multidimensional, suitable assessment data should be selected according to the different application scopes and constraints of various assessment data, and multisource-data-fusion techniques should be used to integrate all information data obtained from surveys and analyses into one so that the information data can be assessed in a unified manner and a unified information result can be obtained in the end. The aims are to integrate various data and information and to understand the characteristics and advantages of different data sources so as to avoid single data and produce better and richer results.

4.2. The Relationship between Forest Ecosystems and Ecological Compensation

The value of forest ecosystem services in Shangri-La Pudacuo National Park is significant, with carbon fixation and oxygen released, water conservation, and forest health care being the major ones. This is consistent with the results obtained by Tang [39], who found that the international-level nature reserves in Yunnan's Ailao Mountains are dominated by water connotation and forest health care, and Wang [36], who found that the Jigongshan Nature Reserve in Henan Province is dominated by carbon fixation and oxygen released. The value of forest ecosystem services in Shangri-La Pudacuo National Park was 4.49×10^9 yuan·a^{-1} in 2020, which was nearly three times the GDP of Shangri-La County (1.53×10^9 yuan·a^{-1}) in 2019. The value of forests not only provides raw materials for human production and livelihoods, but also has significant ecological benefits. The deciduous broad-leaved forest has the highest value of service functions per unit area and it covers a large area, and the corresponding dominant species of vegetation, such as alpine

pine, abies georgei, and larix potaninii var. macrocarpa, are light-loving, tolerant of dryness, barrenness, and cold, and have a strong capacity to adapt in harsh habitat conditions. As most of the forests in Pudacuo National Park are natural forests with a high degree of valorization, researchers have had difficulty studying the value of ecosystem services for different forest ages, and so this study did not consider the valuation of forest ecosystem services for the tertiary measurement unit.

Forest ecological compensation refers to relevant groups and individuals who have suffered certain damages to the ecological environment or enjoyed certain forest ecological benefits due to overexploitation and exploitation under the premise of lawfulness, and who pay a certain proportion of compensation funds to relevant government departments based on a reasonable determination of the ecological-damage value using market and administrative methods. Finally, the government department pays a certain amount of money to the party who has damaged or protected the forest ecological benefits. The government will then pay a certain amount of money to the party that damages the ecological benefits of the forest to compensate for its losses [53]. The essence of ecological compensation is that the beneficiaries or destroyers of ecological protection pay the main body of ecological protection, and so ecological compensation can be seen as a concrete practice of ecosystem-service valuation [54]. The value of ecosystem services based on market theory is a quantitative assessment of the costs and benefits of ecosystem services outside the market in monetary terms [55], which is then used as a basis for calculating the amount of the PES. The calculation results can accurately reflect the nonmarket value of ecosystem services and maximize ecological benefits based on which PES amount is theoretically the best compensation amount [56]. After the compensation amount is determined, the identification of the compensated area, and how to allocate the limited compensation funds fairly and reasonably, is another core and difficult point in establishing the ecological-compensation mechanism, and it is a fundamental and supporting study to determine whether an efficient and reasonable ecological-compensation mechanism can be established, which is of great importance to improving the ecological efficiency and financial efficiency of ecological compensation [57].

According to the survey, Pudacuo National Park completed two rounds of ecological compensation, from 2008 to 2012, and from 2013 to 2018. The relationship between the value of forest ecosystem services and forest ecological-compensation standards was not considered in either of the two completed rounds of ecological compensation, resulting in a decoupling between forest ecosystems and ecological compensation. Because foresters' returns from ecological protection are chronically low, they cannot even make up for the cost of stewardship. Therefore, exploring the establishment of an incentive and constraint mechanism that links the value of forest ecosystem services and the ecological-compensation standard, exploring the spatial and temporal variability of forest ecosystem patterns and ecosystem services, establishing an integrated model of the value of forest ecosystem services, and further exploring the effective coupling of forest ecological compensation and the value of ecosystem services are development directions for future research on how to establish ecological-compensation standards more scientifically. The study also found that, due to the single path of ecological compensation, the source of compensation funds is not stable, and there are still phenomena such as the delayed payment of compensation funds. Through the valuation of forest ecosystem services, we can help authorities and local governments implement precise policies to avoid the phenomenon of poverty return due to ecological protection in some high-quality ecological areas [56].

4.3. Analysis of Uncertainties

There is some subjectivity in the selection of indicators in this study's assessment work, and the data used are somewhat uncertain, making the assessment work somewhat controversial. The selection of indicators in this study considers the whole Pudacuo National Park and is not very specific to individual areas (e.g., the assessment framework only classifies vegetation into six categories, which may not be applicable to the vegetation in temperate areas and tropical areas, such as South Asian broad-leaved trees and tropical broad-leaved trees). At the same time, the spatial and temporal characteristics of the forest ecosystem integrity have a certain scale effect, and the use of data with different spatial resolutions may lead to a certain degree of variation in the study results. The spatial resolution of the data in this study is 30 m × 30 m. Although such data can be called high-resolution data, there are still cases, such as Quick Bird, where the accuracy can reach 2.44 m × 2.44 m. These can better show the spatial pattern of the forest ecosystem integrity and avoid bias in the assessment results due to ecosystem integrity. How to select representative and accurate indicators and data and consider the influence of potential disturbance factors on the forest ecosystem integrity is an important direction for future research for forest-ecosystem-integrity assessment.

5. Conclusions

Current research focuses on how to reasonably assess the value of the ecosystem services of forests at the small and medium scales. In this study, we found that the main vegetation type in Pudacuo National Park is coniferous forest. Coniferous forest, warm coniferous forest, and meadow have higher distribution-area ratios, accounting for 28.00%, 26.36%, and 21.59%, respectively, while scrub and deciduous broad-leaved forest account for 1.96% and 6.98%, respectively, and sclerophyllous evergreen broad-leaved forest accounts for 14.30% of the total area. The value of forest ecological services in Pudacuo National Park was 4.49×10^9 yuan·a^{-1}, with higher values of carbon fixation and oxygen released, water conservation, and forest health care, in the following order: carbon fixation and oxygen released (3.85×10^9 yuan·a^{-1}), water conservation (3.40×10^8 yuan·a^{-1}), forest health care (1.44×10^8 yuan·a^{-1}), soil conservation (1.15×10^8 yuan·a^{-1}), forest nutrient retention (3.29×10^7 yuan·a^{-1}), and atmosphere environmental purification (1.17×10^7 yuan·a^{-1}). The higher value of ecosystem services for different forest types in Pudacuo National Park was in coniferous forest, with the following order of magnitude: temperate coniferous forest (2.13×10^5 yuan·a^{-1}), warm coniferous forest (1.33×10^5 yuan·a^{-1}), sclerophyllous evergreen broad-leaved forest (4.50×10^4 yuan·a^{-1}), deciduous broad-leaved forest (2.36×10^4 yuan·a^{-1}), meadow (1.67×10^4 yuan·a^{-1}), and scrub (3.70×10^3 yuan·a^{-1}). The higher value of forest ecosystem services per unit area of different forest types in Pudacuo National Park was in coniferous forest, with the following order of value: temperate coniferous forest (13.65×10^4 yuan·hm^{-2}·a^{-1}), warm coniferous forest (8.38×10^4 yuan·hm^{-2}·a^{-1}), deciduous broad-leaved forest (5.62×10^4 yuan·hm^{-2}·a^{-1}), sclerophyllous evergreen broad-leaved forest (5.23×10^4 yuan·hm^{-2}·a^{-1}), scrub (3.12×10^4 yuan·hm^{-2}·a^{-1}), and meadow (1.29×10^4 yuan·hm^{-2}·a^{-1}).

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