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Research Progress on the Valuation of Forest Ecosystem

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Abstract

Forest ecosystems play a pivotal role within the global ecological framework, significantly contributing to the maintenance of Earth's ecological balance and the sustainable development of human society. To clarify the current evaluation system of forest ecosystem service values, this study retrieves relevant literature from the Web of Science Core Collection and the CNKI CSSCI/CSCD journal databases using keywords such as "forest ecosystem services," "value assessment," and "accounting methods." It systematically reviews the progress in domestic and international research from three perspectives: the fundamental concepts of forest ecosystem services, value assessment methodologies, and practical applications of value accounting, aiming to promote theoretical refinement and practical implementation of forest ecosystem services. This paper provides a comprehensive summary of commonly used methods for valuing eight key forest ecosystem services, including water conservation, soil retention, carbon sequestration and oxygen release, Nutrient accumulation, environmental purification, forest protection, biodiversity conservation, and landscape recreation. Findings indicate that the direct economic value of forest products such as timber, flowers, and fruits is primarily assessed using the market price method, while the indirect economic values of services like water conservation and soil retention are quantified by integrating big data and modeling to evaluate ecosystem service physical quantities, followed by calculations employing the shadow engineering approach, replacement cost method, and equivalent factor method. Although the methodological framework and evaluation indicators for forest ecosystem service valuation in China are continually being enriched and refined, numerous shortcomings persist. Future efforts should focus on optimizing measurement techniques and technical tools, enhancing data acquisition capabilities, and improving the comprehensiveness and scientific rigor of ecosystem service function assessments. These advancements will provide theoretical and methodological references for promoting rational allocation of forest resources, facilitating the value transformation of ecological products, and strengthening the protection and sustainable management of forest ecosystems.

Keywords

Forest Ecosystem, Ecosystem Services, Value Assessment, Indicator System

1. Introduction

Ecosystem services refer to the environmental conditions generated and sustained by ecosystem structures, processes, and functions, which directly or indirectly contribute to human well-being. These services constitute the material foundation and essential environmental prerequisites for the survival and development of human societies. Their dynamics are closely linked to regional ecological security patterns and the capacity for sustainable socioeconomic development. Quantifying ecosystem services provides a critical foundation for natural resource asset accounting, implementing ecological compensation mechanisms, and formulating green development strategies. Ecosystem service valuation establishes a measurable linkage between natural capital and human needs, contributing not only to the scientific understanding of spatiotemporal variations in ecosystem functions but also offering practical guidance for regional development strategies, spatial planning adjustments, and the selection of sustainable development pathways.

Since the 1990s, escalating global challenges such as ecological degradation, biodiversity loss, and climate change have spurred the establishment and refinement of ecosystem service research frameworks. In a landmark 1997 study, Costanza *et al.* systematically estimated the annual global value of ecosystem services at approximately US$33 trillion, bringing ecological service valuation into policy discussions worldwide. Subsequently, extensive scholarly efforts have been devoted to classifying diverse ecosystem services, developing quantification techniques, and refining valuation methodologies. As the most extensive, structurally complex, and functionally integrated terrestrial ecosystem type, forests cover approximately one-third of the global land area and remain a central focus of ecosystem service research. Their capabilities in carbon sequestration, oxygen release, water conservation, climate regulation, and biodiversity preservation constitute vital components of Earth’s life-support systems, exerting significant influence on regional and global ecological security.

2. Overview of Domestic and International Research

2.1. International Research Progress

In the international arena, early assessments of forest ecosystem service value primarily focused on economically quantifiable benefits that can be directly reflected through market transactions, with particular emphasis on the monetization of timber and non-timber forest products [1] [2]. By the 1990s, this field of research entered a phase of rapid development, during which scholars dedicated themselves to constructing systematic theoretical frameworks and continuously refining evaluation methodologies. Fisher *et al.* proposed a theoretical framework that links ecosystem service classification systems with specific decision-making contexts, highlighting that classification approaches should be aligned with evaluation objectives, thereby establishing a methodological foundation for the subsequent development of contextualized assessment models [3]. Building on this work, De Groot *et al.* developed an integrated analytical framework that combines ecological functions, service provision, and value accounting, facilitating the practical application of assessment outcomes in spatial planning and sustainable management of natural resources [4]. In 2014, updated global ecosystem service valuation results by Costanza *et al.* indicated that the total global value reached approximately 125 trillion U.S. dollars in 2011, reflecting a nearly fourfold increase compared to the 1997 estimate [1]. This study further quantified the annual value loss attributable to land-use and land-cover changes, thereby revealing the substantial impacts of human activities on natural capital stocks. In recent years, there has been growing international attention to the interplay and feedback mechanisms between ecosystem services and multiple driving factors, such as climate change, land use transformation, and socioeconomic development. At the level of technical methodologies, the evaluation approaches have evolved from early dependence on field-based fixed-site observation and ground-level sampling toward an integrated technical framework incorporating multi-source remote sensing data, geographic information systems (GIS), ecological process modeling, and big-data analytics [5] [6]. These methodological advancements have not only deepened the understanding of the formation mechanisms, spatial differentiation patterns, and dynamic evolution laws of ecosystem services, but also provided more accurate and systematic scientific foundations for managing ecological assets, demarcating ecological conservation redlines, and designing sustainable development policies.

2.2. Progress in Domestic Research

Research on the valuation of forest ecosystem services in China commenced at the beginning of the 21st century and has advanced rapidly in response to the growing national demands for ecological conservation and construction. Xie Gaodi and his team pioneered a value assessment framework based on the equivalent factor of services per unit area, providing theoretical support and parameter standards for quantifying the service values of various ecosystems in China [7]. The research led by Zhao Tongqian *et al.* focused on the critical roles of forests in climate regulation and water conservation, indicating that forests contribute over 60% to these two pivotal regulatory services, thereby highlighting the strategic importance of forests in safeguarding national ecological security [8]. The theoretical framework and practical guidelines for Gross Ecosystem Product (GEP) accounting, developed under the leadership of Ouyang Zhiyun *et al.*, comprehensively assess the diverse products and service values that ecosystems provide for regional socioeconomic development. This work reveals the fundamental supporting role of ecological capital in economic and social development and offers a feasible pathway for integrating ecological benefits into the evaluation system of socioeconomic development, referred to as green GDP accounting [9].

Moreover, Xie Gaodi team innovatively advanced a spatially explicit assessment model based on the unit area value equivalent factor, which effectively addresses the challenge of quantifying spatial heterogeneity in ecosystem service values across different regions and ecosystem types. This improvement significantly enhances the accuracy and practical applicability of the assessment outcomes [10]. In 2016, Cui Yaqin and colleagues conducted a comprehensive multi-service value assessment of the forest ecosystem in Shanxi Province. By integrating both physical quantity and monetary valuation methods, their study demonstrated a high level of maturity in the integrated application of regional-scale evaluation techniques in China [11]. Using a meta-regression model, Wu Zijing *et al.* estimated the total value of China's forest ecosystem services in 2010 to be 26.26 trillion yuan. Among various service types, the values were ranked as follows: water conservation > biodiversity conservation > carbon sequestration and oxygen release > soil retention > air purification > forest products > forest recreation > nutrient accumulation [12]. In Sichuan Province, systematic efforts to promote the development of "forest reservoirs, grain reserves, financial reservoirs, and carbon sinks" have yielded remarkable results. The ecological service value of the province's forest ecosystems exceeds 2 trillion yuan, with a total water conservation capacity of 89 billion tons and an average annual carbon storage of 70 million tons. Additionally, forest-derived food production reached 15 million tons with an output value of 180 billion yuan, while eco-tourism and health retreats generated combined revenues exceeding 220 billion yuan [13]. Liu Jinghong *et al.* employed the shadow engineering approach to assess the water conservation service value in the middle and upper reaches of the Hun River from 2000 to 2019. Their findings indicate that upstream areas with higher forest coverage exhibit significantly greater per-unit-area water conservation value compared to downstream regions [14]. Similarly, Zhu Qing and colleagues applied methods such as market valuation and shadow engineering to demonstrate the positive impact of vegetation restoration on soil conservation across the Loess Plateau [15].

Currently, the rapid advancement of earth observation technologies and the continuous improvement of ecological monitoring networks have led to an increasingly rich repository of available remote sensing data, ground-based monitoring resources, and ecological process experiment data. Simultaneously, the widespread application of comprehensive assessment modeling frameworks—such as InVEST, ARIES, and SolVES—along with various econometric and ecological methodologies, has established a robust data foundation, theoretical support, and technical capability for the refined quantification and dynamic evaluation of forest ecosystem service values in China [16] [17].

3. Forest Ecosystem Service Functions

Forest ecosystem service functions refer to the diverse benefits provided by forest ecosystems and their ecological processes to support human survival and development. These functions are typically categorized into eight fundamental types: water conservation, soil retention, carbon sequestration and oxygen release, nutrient accumulation, environmental purification, forest protection, biodiversity conservation, as well as landscape recreation and ecological culture. These interconnected and synergistic functions collectively sustain regional and even global ecological balance and promote sustainable development [18].

3.1. Water Conservation Function

Forest ecosystems exert significant influence on hydrological processes through their multi-layered structure. The canopy layer intercepts precipitation, delaying direct rainfall impact on the ground surface. The litter layer demonstrates substantial water absorption and retention capacity, effectively reducing surface runoff velocity. Forest soils, facilitated by root system activities and organic matter accumulation, develop a porous structure that markedly enhances infiltration capacity and water storage potential. These synergistic mechanisms collectively contribute to peak flood reduction, delayed runoff generation, groundwater recharge, and the regulated seasonal distribution of river discharge through stored water release during dry periods.

3.2. Soil Conservation Function

Forests contribute to soil conservation primarily through soil stabilization and fertility preservation. The root systems of trees mechanically reinforce the soil matrix, enhancing its resistance to erosion. The canopy and litter layers effectively attenuate the kinetic energy of raindrop impact, thereby reducing surface runoff-induced soil scouring. Furthermore, decomposed litter transformed into humus by microbial activity improves soil aggregate structure, increases porosity and stability, and facilitates nutrient cycling. These processes collectively mitigate soil nutrient loss and sustain land productivity.

3.3. Carbon Sequestration and Oxygen Release Function

As the largest carbon reservoir in terrestrial ecosystems, forests absorb atmospheric carbon dioxide through photosynthesis, converting it into organic carbon stored in plant biomass and soil, while simultaneously releasing oxygen. This process establishes forests as critical “carbon sinks,” playing a pivotal role in mitigating the accumulation of global greenhouse gases and addressing climate change. Additionally, transpiration from forest vegetation helps regulate local climate conditions by increasing air humidity and reducing ambient temperatures, thereby alleviating the urban heat island effect.

3.4. Nutrient Accumulation Function

This function primarily refers to the total stock of essential nutrient elements—

such as nitrogen, phosphorus, and potassium—retained within forest ecosystems. These nutrients are stored in plant tissues, the litter layer, and the soil reservoir. Through biogeochemical cycling, they circulate and undergo transformations within the system, thereby supporting tree growth and maintaining the stability of material cycles in the ecosystem.

3.5. Environmental Purification Function

Forests can remove particulate matter (PM2.5, PM10) from the atmosphere through mechanisms such as foliar adsorption and stomatal absorption, while also absorbing gaseous pollutants including sulfur dioxide, nitrogen oxides, and ozone. Additionally, forests release negative air ions, which offer health benefits. Forest vegetation and its associated soil systems also contribute to water purification by intercepting, filtering, adsorbing, and degrading contaminants. These processes reduce the concentration of suspended solids, nutrients, and heavy metals in surface runoff, thereby improving the quality of downstream water bodies.

3.6. Forest Protection Functions

The shelterbelt system effectively reduces wind speed and mitigates wind erosion hazards. For instance, farmland shelterbelts can lower wind speeds by 30% - 50%, thereby protecting crops and soil. In wind–sand regions, tree root systems stabilize moving sand and inhibit sand dune migration. In mountainous areas, forests enhance slope stability through the anchoring effect of their roots, reducing the risk of geological disasters such as landslides and debris flows.

3.7. Species and Resource Conservation Functions

Forest ecosystems serve as crucial repositories for biodiversity, providing habitats and breeding grounds for over 80% of terrestrial plant and animal species worldwide. Their complex hierarchical structure and diverse habitat types create varied ecological niches, facilitating species coexistence and gene flow. Forests play an indispensable role in conserving rare and endangered species, maintaining population genetic diversity, and preserving ecological balance.

3.8. Landscape Recreation and Eco-Cultural Functions

Forest areas such as forest parks and nature reserves offer the public spaces to connect with nature, engage in ecotourism, and participate in recreational activities. Activities like hiking, birdwatching, and forest bathing not only promote public physical and mental well-being but also foster societal recognition of ecological conservation. Furthermore, as sources of inspiration and educational platforms, forests carry rich ecological-cultural significance and play a vital role in nature education, scientific research and monitoring, and cultural heritage preservation.

4. Research on the Valuation of Forest Ecosystem Services

Valuing forest ecosystem services serves as a critical foundation for quantifying their ecological benefits and supporting eco-compensation decision-making. This assessment not only scientifically reveals the crucial contributions of forests in maintaining ecological security and ensuring the sustainable utilization of resources, but also provides robust theoretical underpinnings and data support for formulating regional ecological conservation policies and determining eco-compensation standards.

The value composition primarily falls into direct economic value and indirect economic value. Direct economic value is predominantly derived from the economic worth of forest products recorded in forestry statistical yearbooks, such as timber, forest fruits, and other tangible outputs. These products exhibit distinct market economic attributes and can be directly calculated based on market prices.

In contrast, the evaluation of indirect economic value is more complex, requiring the synthesis of data from field measurements, long-term stationary observations, and literature to quantify the physical magnitude of various ecosystem service functions. Subsequently, monetary conversion is performed utilizing methods such as the shadow project approach, replacement cost method, and equivalent value factor method.

This paper systematically summarizes the evaluation indicators and commonly used methods for assessing eight forest ecosystem service values: water source conservation, soil conservation, carbon sequestration and oxygen release, nutrient accumulation, environmental purification, forest protection, biodiversity conservation, landscape recreation, and ecological services (**Table 1**).

Table 1. Methods for valuation of forest ecosystem services.

Ecosystem service	Evaluation indicators	Appraisal procedure
Water source conservation	adjust water volume, purify water quality	market price method, shadow engineering method
Soil conservation	soil consolidation, fertilizer conservation	market price method, substitute cost method
Carbon fixation and oxygen release	carbon fixation, oxygen release	carbon tax law, afforestation cost method, market price method, substitute cost method
Nutrient accumulation function	nutrient retention capacity, soil nutrient content	substitute cost method, shadow engineering method
Environmental purification	absorption of sulfur dioxide, dust retention	alternative engineering method, shadow price method
Forest protection	windbreak and sand fixation, disaster prevention and earthquake mitigation	alternative engineering method
Biodiversity conservation	species conservation, forest products	market price method, substitute cost method, value equivalence method, conditional value method
Landscape Recreation and Ecological Culture	forest recreation, nature education, wellness therapy	travel expense method, pleasure pricing method, conditional value method

4.1. Valuation Methodology for Water Conservation

The assessment of water conservation value is typically conducted using either the direct market pricing method or the shadow engineering approach [19]. The former evaluates the value based on actual market transaction prices generated by water conservation activities, while the latter indirectly quantifies the value by estimating the cost of constructing an artificial reservoir with equivalent water storage capacity. The unit reservoir storage cost can be referenced from technical standards outlined in the "Technical Specification for Ecological Benefit Assessment of Forestry Ecological Engineering" and the "Specification for Quantifying Forest Ecosystem Service Functions". According to available data, the unit storage cost of reservoir projects in China is approximately 6.11 CNY per cubic meter [20]. The total water conservation value is calculated as the product of the total water conservation volume and the unit storage cost.

4.2. Valuation Methodology for Soil Conservation Services

The economic value of soil conservation services is primarily reflected in two aspects: sediment deposition reduction and soil nutrient retention. The value of sediment reduction is assessed by estimating the dredging costs required to prevent siltation in infrastructures such as rivers and reservoirs. The value of soil nutrient conservation refers to the economic worth of nitrogen, phosphorus, potassium, and other nutrients preserved by ecosystems during soil fixation processes, which is typically quantified based on market prices of chemical fertilizers and soil nutrient content [21]. Furthermore, comprehensive evaluation of soil conservation value necessitates integration of parameters such as soil erosion modulus and nutrient loss rate [22]. The valuation formula is as follows:

$$SV_x = SV_{xs} + SV_{xn} \qquad \text{Expression (1)}$$

$$SV_{xs} = SDR_x \times A_s / \rho \times V_s \qquad \text{Expression (2)}$$

$$SV_{xn} = SDR_x \times C_{sn} \times V_n \qquad \text{Expression (3)}$$

In the given equation, the soil conservation value (SV_x) is comprised of the sediment retention value (SV_{xs}) and the soil nutrient preservation value (SV_{xn}), with the latter encompassing nitrogen, phosphorus, and potassium. Specifically, SDR_x represents the soil conservation amount (t); ρ denotes the soil bulk density (t/m^3); As is the estimation coefficient for sediment retention reduction; V_s and V_n indicate the unit prices for sediment reduction and soil nutrient preservation, respectively; C_{sn} refers to the soil nutrient content, where n includes nitrogen (n), phosphorus (p), and potassium (K).

4.3. Accounting Methodology for Carbon Sequestration and Oxygen Release Value

The economic valuation of carbon sequestration and oxygen release by ecosystems is typically grounded in the fundamental principles of vegetation photosynthesis [23]. The specific accounting procedure involves two sequential steps: First, the total amounts of carbon dioxide absorbed and oxygen released by vegetation per unit time are calculated based on the photosynthesis reaction equation. Subsequently, by integrating relevant economic parameters, these ecological functions are quantified into monetary terms. According to the photosynthesis equation, for each molecule of CO_2 assimilated by plants, one molecule of O_2 is released. In terms of mass conversion, sequestering 1 g of carbon is equivalent to absorbing 3.67 g of CO_2 while releasing approximately 2.67 g of O_2. This stoichiometric relationship provides a scientific basis for converting ecological functions into measurable physical quantities.

In the specific accounting of carbon sink service value, commonly adopted methodologies include the carbon tax method, afforestation cost method, market value method, and cost-benefit analysis [24]. Among these, the carbon tax method and afforestation cost method are widely applied in domestic and international studies owing to their data accessibility and operational maturity. The carbon tax method estimates the monetary cost of fixed CO_2 based on the carbon emission tax rate established by governmental authorities. Under Sweden's carbon tax standard, a rate of $150 per ton of CO_2 is levied, equivalent to approximately 934.26 RMB at current exchange rates. The afforestation cost method, on the other hand, estimates the cost required to sequester a unit of carbon during artificial afforestation processes. Reference data can be sourced from the "Cost-Benefit Analysis of Carbon Sequestration in Afforestation and Reforestation Projects Across Chinese Provinces," which indicates that the average carbon sequestration cost in China is approximately 1152.77 RMB per ton of carbon [25].

The valuation of oxygen release primarily employs either the replacement cost method or the market value method. The replacement cost method estimates the economic value of the oxygen release function of ecosystems by calculating the cost required to artificially produce an equivalent amount of oxygen. Currently, the cost of industrial oxygen production is widely adopted as a reference both domestically and internationally. According to recent industrial gas market reports, the average comprehensive market price of liquid oxygen in China is approximately 460 RMB per ton. This method assumes that, in the absence of oxygen supply from natural ecosystems, humanity would need to produce oxygen through industrial means, resulting in corresponding economic expenditures.

4.4. Nutrient Accumulation Function Value Accounting Method

The valuation of the nutrient accumulation function in ecosystems primarily quantifies the processes of input, output, storage, and cycling of nutrients between biotic communities and abiotic environments. The core framework for assessing nutrient accumulation is based on the principle of nutrient balance, expressed as: Nutrient accumulation = Total nutrient input – Total nutrient output. Input pathways include atmospheric deposition, biological nitrogen fixation, precipitation, litterfall return, and anthropogenic fertilization. Output pathways encompass runoff leaching, gaseous volatilization, harvesting, and nutrient losses due to disturbances such as wildfires or pest outbreaks. The economic value of nutrient retention attributable to forest ecosystems is typically estimated using the replacement cost method and shadow project approach, which are derived from market prices of chemical fertilizers and the nutrient composition of soils.

4.5. Methods for Valuating Environmental Purification Services

The economic assessment of ecosystem services related to environmental purification mainly adopts two approaches: the substitution engineering method and the shadow price method [26]. The substitution engineering method simulates the scenario where, without natural purification capacity, society would need to invest in engineering projects or equipment to achieve equivalent environmental purification effects—such as constructing wastewater treatment plants to process an equivalent volume of sewage or installing dust removal devices to reduce particulate matter concentrations in the air. The shadow price method is applied to environmental services that lack market transactions, estimating their implicit value through theoretical modeling. For instance, when evaluating the purification effect of forests on sulfur dioxide (SO_2), the common practice involves multiplying the total annual SO_2 absorption by forests by the marginal cost of industrial desulfurization in the local area. The limestone-gypsum wet flue gas desulfurization method, being a mainstream industrial desulfurization technology, has a comprehensive operating cost of approximately 640 RMB per ton of SO_2, which is often used as a benchmark for calculating the purification value of SO_2.

4.6. Valuation Methodology for Forest Protection Services

The economic valuation of forest protection functions within ecosystems predominantly employs the substitute engineering approach. This methodology operates on the premise that, in the absence of natural forest protection services, the construction and maintenance costs of artificial infrastructures required to achieve equivalent protective effects can serve as a quantitative basis for assessing forest protection value [27]. For instance, when evaluating the water conservation value of forests, reference may be made to the costs associated with constructing reservoir projects of comparable water retention capacity; similarly, the soil stabilization and nutrient retention functions can be quantified by simulating expenditures for erecting retaining walls or implementing soil remediation initiatives. The applicability of this approach hinges on the availability of engineering parameters and cost data, while also necessitating consideration of spatial scales and temporal dynamics that may influence valuation outcomes.

4.7. Biodiversity Conservation Value Assessment Methodology

The evaluation of biodiversity conservation value in ecosystems is a systematic process that identifies and quantifies-in monetary or non-monetary terms-he ecological functions, economic potential, social significance, and cultural connotations embodied by biodiversity, which includes species diversity, genetic diversity, and ecosystem diversity [28]. The total value of biodiversity often substantially exceeds its direct economic output and encompasses three major categories: direct use value, indirect use value, and non-use value.

Direct use value is primarily reflected in marketable biological resources, such as timber, medicinal plants, fish, and other non-timber forest products. This is commonly assessed using the market value method, whereby valuation is based on actual market transaction prices and quantities.

Indirect use value pertains to biodiversity's regulatory functions, including climate regulation, environmental purification, and the maintenance of ecological balance. As most of these services are not traded in markets, methods such as the replacement cost method, damage cost avoided method, or ecosystem service value equivalent method are frequently employed. For example, the value of water purification provided by natural wetlands can be estimated by referencing the construction cost of artificial wetlands.

Non-use value includes existence value, bequest value, and option value, among others. Its assessment is relatively complex and often relies on stated preference techniques such as the contingent valuation method (CVM) or choice experiments. The contingent valuation method involves designing standardized questionnaires to survey the public's maximum willingness to pay for the conservation of a specific species, genetic resource, or ecosystem, thereby deriving its non-market value. The implementation of this method requires careful attention to the scientific design of questionnaires and the correction of cognitive biases among respondents.

4.8. Assessment Methods for Landscape Recreation and Eco-Cultural Values

The assessment of landscape recreation and eco-cultural values in ecosystems aims to systematically quantify the cultural and spiritual services—such as leisure and recreation, nature-based education, spiritual experiences, health and wellness therapy—that ecosystems provide to humans. Common assessment approaches are generally categorized into monetary evaluation and non-monetary description [29]. Because these services are typically not directly reflected through market transactions, non-market valuation techniques are often required.

Among these methods, the Travel Cost Method (TCM) is one of the most widely applied. Its core rationale is to construct a recreation demand function by analyzing tourists' actual expenditures—including travel, accommodation, entrance fees, and other associated costs—for visiting a specific natural area (such as a national park, nature reserve, or scenic spot), thereby inferring the area's recreation economic value. In addition, the Hedonic Pricing Method can indirectly assess landscape values by examining the contribution of natural landscape attributes to real estate prices. For the non-use value component within cultural services, the Contingent Valuation Method can also be employed to provide estimates.

5. Limitations and Future Prospects

5.1. Limitations

The quantification of forest ecosystem service value represents a critical issue at the intersection of ecological economics and resource management, which continues to present challenges both theoretically and practically.

First, there exist substantial limitations in data collection and processing. Key experimental parameters typically require field-based sampling, which is not only costly but also constrained by terrain and topography, making it difficult to achieve extensive and continuous dynamic monitoring. While remote sensing technology offers periodic and wide-coverage observational data, its spatial and spectral resolution remains inadequate for capturing fine-scale parameters such as understory vegetation structure and species composition [30]. Moreover, data post-processing is prone to errors, which may compromise the reliability and spatial consistency of assessment outcomes. Future efforts should focus on advancing multi-source remote sensing collaborative inversion techniques (e.g., MODIS and Sentinel) to establish more robust ecological parameter monitoring systems, while developing error propagation analysis models to enhance the spatiotemporal accuracy and robustness of evaluations [31].

Second, interactions and functional overlaps among ecosystem services are pervasive, with inherent ambiguity in their boundaries. For instance, it is often difficult to clearly distinguish between carbon sequestration as part of the carbon absorption function and that occurring during nutrient cycling. Such coupling of functions may lead to double-counting of service values, resulting in overestimation of the total ecosystem value and undermining the scientific credibility and policy relevance of assessments [32]. Moving forward, it is essential to clarify causal relationships and contribution weights among services based on intrinsic ecological processes, identify dominant service flows and redundant indicators, and focus on key service types while eliminating clearly overlapping components. These steps will improve the logical coherence and regional comparability of evaluation outcomes.

Thirdly, the applicability of different valuation methods varies across regions with distinct socio-economic contexts. For traded services such as timber production or water provision, market value methods are heavily influenced by local price fluctuations, policy subsidies, and trade conditions, which often compromise the consistency of cross-regional comparisons. In measuring intangible values like cultural and regulatory services, non-market valuation methods—such as the contingent valuation method or travel cost method—rely on respondents' willingness to pay. This reliance tends to lead to substantial valuation discrepancies for the same ecosystem services between developed and less-developed areas, thereby complicating the aggregation and comparability of results at national or global scales. Moving forward, enhancing the comparability across scales and the policy relevance of assessment outcomes could be achieved through the establishment of internationally standardized evaluation parameters (e.g., shadow prices, social discount rates), the promotion of cross-national data-sharing mechanisms, or the development of regionally calibrated adjustment coefficient systems.

5.2. Frontier Technology Integration Directions

By integrating AI, big data, and model fusion, evaluation methods are advancing toward high precision, dynamic monitoring, and spatial representation. For instance: high-resolution remote sensing data are used to achieve land cover classification and dynamic monitoring of net primary productivity (NPP); ground-based observations, statistical yearbooks, FAO yield data, and administrative boundary data are integrated to construct spatiotemporal databases; the InVEST model is coupled with GIS to quantify changes in ecosystem service values over multi-year scales; and, accounting for income growth and increasing biodiversity scarcity, the present value of future ecosystem services is appropriately adjusted upward to more accurately reflect their long-term value.

Overall, by translating ecological functions into quantifiable economic indicators, the valuation of forest ecosystem services helps enhance societal recognition of natural capital stocks and provides scientific support for designing ecological compensation mechanisms, territorial spatial planning, and green development strategies. With deeper interdisciplinary methodological integration and the growing application of remote sensing, artificial intelligence, and big data technologies, continuous advancements are anticipated in evaluation accuracy, ecological mechanism interpretation, and decision-support capabilities in the future.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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