

Biodiversity and Ecosystem Services Assessment Indicators and Methods Postprint

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Abstract

Assessing, simulating, and predicting the status and trends of global biodiversity and ecosystem services and their impacts on human well-being constitute important tasks in current biodiversity and ecosystem services research. Indicators and data, models and scenarios are crucial tools for advancing theoretical development and methodological integration in biodiversity and ecosystem services assessment research. However, comprehensive comparative studies on indicator systems and technical methods for biodiversity and ecosystem services assessment are currently relatively scarce. Therefore, this study systematically reviews the latest advances in conceptual frameworks, assessment indicators, and various assessment models and methods for biodiversity and ecosystem services evaluation. The biodiversity-ecosystem function-ecosystem services-human well-being cascade framework represents a highly logical framework for biodiversity and ecosystem services assessment. Existing assessment indicator systems and model methods still face numerous problems and challenges, making it difficult to fully reveal the formation and impact mechanisms of ecosystem services, the interconnections and functional mechanisms among services, and to effectively guide ecosystem services management and decision-making. Nevertheless, these assessment indicators and methods can provide important entry points for constructing a framework for integrated biodiversity and ecosystem services modeling research. Based on this, the core components of integrated biodiversity and ecosystem services modeling research are proposed: i) Objective: to identify scientific questions to be addressed based on scenario analysis of integrated natural-social characteristics, and to produce ecosystem services management and decision-making solutions; ii) Content: comprehensive analysis of scale, types of ecosystem services, hierarchical structure of biodiversity, interrelationships among components, driving factors, and multi-source data; iii) Methodology: to conduct comparative and uncertainty analyses of existing various models and model combinations, and to establish an integrated mapping model library for biodiversity and ecosystem services that meets regional

practical needs. On this basis, it is recommended that China should promptly develop a standardized indicator system and integrated assessment modeling system suitable for regional characteristics, conduct comprehensive assessments of biodiversity and ecosystem services regularly, grasp the changing trends of biodiversity and ecosystem services, and enhance China's international status and discourse power in the field of biodiversity and ecosystem services research.

Full Text

Preamble

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Indicator Systems and Methods for Evaluating Biodiversity and Ecosystem Services

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Abstract

Evaluating, simulating, and predicting the status and trends of global biodiversity and ecosystem services, as well as their impacts on human well-being, represent primary research goals in the field of biodiversity and ecosystem services. Indicators, data, models, and scenarios serve as major tools for theoretical development and methodological integration in biodiversity and ecosystem services assessment. However, comprehensive comparative studies of indicator systems and assessment methods remain relatively scarce. This paper systematically reviews recent advances in conceptual frameworks, assessment indicators, and various models and methods for evaluating biodiversity and ecosystem services. The biodiversity-ecosystem function-ecosystem services-human well-being cascade framework offers a highly logical structure for assessment. Nevertheless, existing indicator systems and methods face significant problems and challenges: they are ineffective for elucidating the mechanisms underlying ecosystem service formation and impacts, identifying internal connections and functional mechanisms among services, or providing guidance for ecosystem service management and policy-making. Despite these limitations, current indicators and methods provide important entry points for constructing integrated assessment models. Through comprehensive analysis and comparison of existing indicators and methods, we propose several core elements for integrated model development: (i) **Objectives**—determining scientific questions and developing ecosystem service management and decision-making schemes through scenario analysis based on

fundamental characteristics of nature-society interactions; (ii) **Content**—comprehensive analysis of scales, service types, hierarchical nature of biodiversity, component relationships, drivers, and multi-source data; and (iii) **Methods**—conducting comparative and uncertainty analyses of various models and model combinations to establish a comprehensive mapping model base suited to regional needs. Accordingly, we recommend that China should urgently develop standardized indicator systems and integrated assessment models tailored to its regional characteristics, enabling periodic evaluation, simulation, and prediction of biodiversity and ecosystem services status and trends, thereby enhancing China's international position and discourse power in this field.

Keywords: ecosystem; framework; indicator system; integrated assessment model

1 Conceptual Frameworks for Biodiversity and Ecosystem Services Assessment

In biodiversity and ecosystem services assessment, conceptual frameworks guide design and implementation, simplify relationships between humans and nature, organize assessment structures, and clarify fundamental scientific assumptions. Various organizations have constructed and refined conceptual frameworks linking ecosystem structure, services, and values, viewing ecosystem services as bridges between ecosystems and economic systems [2-6]. De Groot et al. [3] emphasized that ecosystem services derive from ecosystem functions that satisfy human needs, linking ecosystem services and human welfare. Haines-Young and Potschin [6] built upon De Groot et al.'s framework [3] to propose a cascade framework highlighting how biophysical structures support ecosystem services. The Millennium Ecosystem Assessment [7] developed a conceptual framework centered on ecosystem services and human well-being, using it to assess global and regional ecosystem service losses and their welfare impacts. The UK National Ecosystem Assessment framework focuses on connections between human well-being and the environment, exploring drivers of ecosystem and service changes across spatiotemporal scales and their interactions and impacts. The Spanish ecosystem assessment framework examines cascade relationships among ecosystems, ecosystem functions, human well-being, and values. The IPBES framework, built upon the Spanish national framework, emphasizes interactions among biodiversity, ecosystem services, their drivers, and human well-being across different knowledge systems, stressing the framework's role in guiding research to explore ecosystem service formation mechanisms and linkages among services [1,8]. The CICES (Common International Classification of Ecosystem Services) cascade framework also builds on the Spanish framework, highlighting biodiversity's role within it.

Despite these frameworks, no consensus exists on biodiversity's precise position and role in linking ecosystem functions and services. However, core theoretical

content and logical relationships can be summarized as: (1) biodiversity supports ecosystem structure, function, and services; (2) biodiversity determines the magnitude and stability of ecosystem processes; (3) ecosystem structures and processes interact to form ecosystem functions; and (4) ecosystem services represent both the products of ecosystem functions and their value in creating human well-being. Framework application remains in its early stages and requires further improvement.

2 Assessment Indicators for Biodiversity and Ecosystem Services

Indicators are essential tools for reflecting the status and trends of biodiversity and ecosystem services and for monitoring and communicating policy objectives and progress. The core of indicator development is establishing causal relationships among various biodiversity and ecosystem service indicators to build comprehensive, practical assessment systems [9]. The cascade framework (biodiversity → ecosystem function → ecosystem services) provides the foundation for indicator development. While biodiversity assessment underpins ecosystem service evaluation, the ultimate focus is on ecosystem services themselves. Biodiversity indicators should be selected based on direct linkages to services, as biodiversity determines the magnitude and stability of ecosystem processes and functions. However, biodiversity and ecosystem functions are multidimensional, representing different properties and meanings. For specific types and indicators, particular relationships may exist—such as positive correlations between species richness and pollination, negative correlations between wetland area and water quality, or between stand density and biomass/freshwater supply. Yet research has not validated all relationships between biodiversity and ecosystem function indicators due to data limitations, leaving most understanding at the conceptual level.

Ecosystem functions form the basis for ecosystem services, while services represent direct benefits to human well-being and another manifestation of value in human society. The core of ecosystem service indicator development lies in screening and constructing indicators of ecosystem functions that directly benefit human welfare. Functions and services do not have one-to-one correspondence—each service may derive from multiple functions, though their relative importance varies. For example, food provision in provisioning services results from combined effects of soil formation (supporting function), climate regulation (regulating function), and genetic resources (provisioning function). Air quality regulation in regulating services emerges from gas regulation, waste treatment/absorption, and plant barrier effects. Ecosystem function indicators representing specific services are typically diverse and may have non-linear relationships with service indicators. Current research has only theoretically explored relationships between ecological processes and services for certain cases. Strengthening the theoretical foundation of these relationships and developing reliable methods—such as mechanistic or semi-mechanistic models—to accurately

simulate and predict service status and change represents a key priority.

3 Assessment Methods for Biodiversity and Ecosystem Services

Analyzing the components of biodiversity, ecosystem structure, processes, functions, services, and values within assessment frameworks requires exploring relationships between ecological processes and services, biodiversity-service interactions and their drivers, and service linkages under different driver scenarios. Statistical methods primarily fall into three categories: observational data analysis, meta-analysis, and model simulation.

3.1 Statistical Analysis Based on Observational Data

Statistical analysis of observational data identifies ecosystem processes and quantifies relationships with uncertain measurement factors. Applications in biodiversity and ecosystem services assessment include: (1) using probability theory to estimate how well sample sets capture original data distribution characteristics [11]; (2) combining with biophysical models to determine mathematical functions between ecosystem attributes and final services, quantifying spatiotemporal trade-offs and marginal responses to ecological changes [11-12]; (3) conducting correlation analyses to test biodiversity-service relationships [11]; and (4) employing cluster and redundancy analyses to rank and classify complex service and impact factor datasets, transforming multi-service studies into analyses of several typical relationships and enabling management unit clustering based on service supply characteristics [13-15]. These methods are suitable for comprehensive analysis of multi-source data in assessment frameworks, constructing ecosystem service production functions, testing biodiversity-service correlations, and quantifying service trade-offs.

3.2 Meta-Analysis

Meta-analysis has become increasingly common in biodiversity and ecosystem services assessment. Its advantage lies in consistently collecting and synthesizing data from numerous sampling sites. Meta-analysis has examined driver impacts, particularly land-use change effects on biodiversity and food provision services, and linked individual statistical results to ecosystem models [11]. However, due to limited large-scale, multi-site data and case studies, meta-analysis has not yet been applied to explore relationships between biodiversity and services or service associations under different driver scenarios.

3.3 Simulation Models

Models primarily assess, simulate, and predict drivers affecting biodiversity and ecosystems, their impacts, and how biodiversity and ecosystem changes affect services and their values [1]. We categorize models into driver scenario models, biodiversity and ecosystem models, and ecosystem service models.

3.3.1 Driver Scenario Models Driver scenario models include direct and indirect driver models. Direct driver models simulate future land-use change, fishing, and water resource use under different scenarios, using empirical statistics, process-based dynamic models (e.g., CLUE-S, WaterGAP, IMAGE, EwE), or Earth system models. Indirect driver models explore how decision scenarios affect ecosystem conditions and human welfare, using dynamic system models and integrated models (e.g., general equilibrium models GREEN, GTAP) for macroeconomic policy comparison. In practice, Verbürg et al. [16] used CLUE-S to simulate European land demand and land-use patterns under scenarios of economic globalization and continental marketization. However, coarse spatial resolution and lack of regional driver information limit regional predictions. Downscaling methods can compensate but require further evaluation of uncertainties in quantitative assessment and downscaling processes [17].

3.3.2 Biodiversity and Ecosystem Models Biodiversity models focus on species, populations, and communities. Species/population-level models include species distribution models, relationship network models, and biogeographic models. Community-level models include community distribution models and species-trait approaches. System-level models comprise biophysical models (e.g., IMAGE) and integrated assessment models. These models assess habitat loss/fragmentation impacts on extinction [18-21], climate change effects on species distribution patterns [22-23], and global change impacts on vegetation geography [24]. Limitations include simplified assumptions, lack of unified performance metrics, and insufficient cross-method validation [24-26], resulting in less robust simulations of driver impacts on biodiversity. Ecosystem models include biogeochemical cycle models and hydrological process models. Biogeochemical models simulate ecosystem responses to atmospheric CO₂ doubling and climate change, using empirical models (e.g., Miami), process models (e.g., CENTURY, DNDC), and dynamic vegetation models (e.g., IBIS, LPJ-DGVM). Hydrological models simulate climate change impacts on water resources, including conceptual watershed models (e.g., SACRAMENTO, TANK), distributed models (e.g., TOPMODEL, SWAT), and high-resolution global models. Despite improved simulation capabilities through computer advances, issues with model structure, parameterization, cross-scale problems, and data scarcity limit global application [28-29]. Ecosystem models lack biodiversity-process relationship simulations, and integrated assessment models combining biodiversity, ecosystem processes, and driver scenarios require further development.

3.3.3 Ecosystem Service Assessment Models Ecosystem service models include supply, demand, and valuation models. Supply models simulate potential service provision using biophysical approaches. Demand models simulate service consumption relative to supply, typically using administrative or planning units. Valuation models assess diverse values: biophysical, cultural/social, public health, and holistic values.

Supply simulation methods include field data, proxy indicators, expert scoring,

correlation analysis, and regression models. Demand simulation uses socioeconomic statistics and biophysical models. Valuation methods include direct market pricing and benefit transfer. Recent progress includes: (1) models like InVEST and ARIES that integrate national/regional environmental, economic, and social data with expert knowledge, simplifying algorithms and employing spatial modeling and GIS for global application [30-31]; (2) models like EnviroAtlas and EPM that combine ground survey data with stakeholder preferences to construct scenarios for regional management [31-32]; (3) models like EcoMetrix and ESi that quantify marginal responses of services to ecological changes [31]; and (4) models like MIMES and InVEST that simulate spatiotemporal service evolution and trade-offs under different driver scenarios [31,35], with some incorporating biodiversity modules (e.g., GLOBIO, EcoAIM, InVEST). However, limitations remain: applicability is restricted, uncertainty analysis methods are often unspecified, functions and services remain difficult to distinguish (risking double-counting), most models only simulate supply, and comprehensive models integrating demand, beneficiary preferences, and human welfare links need development. Cross-validation is insufficient, and cultural service simulation remains limited.

[FIGURE:1] The main ecosystem service assessment models

4 Integrated Model Framework for Biodiversity and Ecosystem Services Assessment

Although quantitative methods cannot directly output management and decision-making schemes, they provide important principles for integrated assessment. Model selection should match specific evaluation objectives and decision contexts. Integrated models must consider: (1) ecological processes underlying service generation, biodiversity-service relationships, and service linkages under different driver scenarios; (2) spatiotemporal scaling issues of biodiversity and services and how different biodiversity levels affect services across scales; and (3) cascade relationships among biodiversity, ecosystem functions, and services.

Core components of integrated model research include: (i) **Objectives**—scientific questions addressed, such as optimal land-use allocation [36-37]; (ii) **Content**—hierarchical biodiversity structure, ecosystem service types, component relationships, multi-source data synthesis, and applicable scales; and (iii) **Methods**—comparative and uncertainty analyses of existing models and combinations to establish a comprehensive mapping model base suited to regional needs.

A flowchart for building a synthetic evaluation model of biodiversity and ecosystem services

B: Biodiversity; ES: Ecosystem services

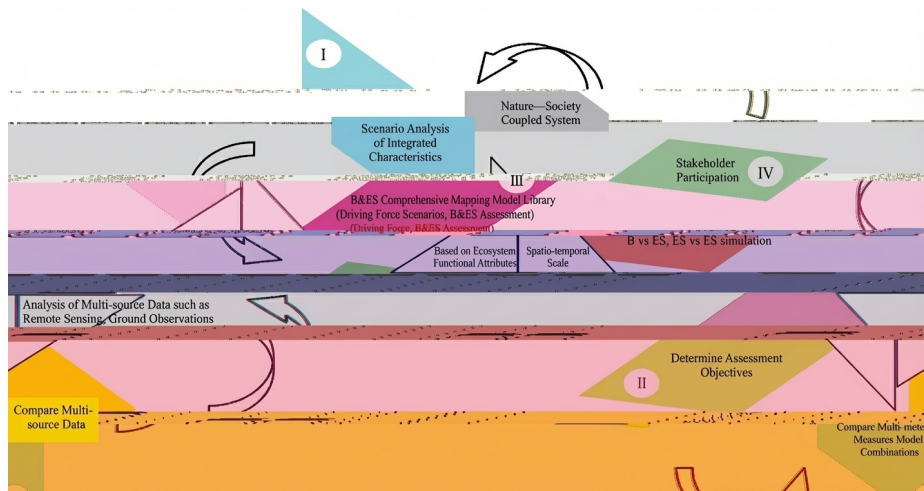


Figure 1: Figure 2

5 Research Outlook

Biodiversity and ecosystem services assessment is crucial for ecosystem management and decision-making. Indicators, data, models, and scenarios are important tools for theoretical and methodological integration. Current indicators have advanced research on cascade framework components, but data limitations and non-linear relationships among components prevent validation of all biodiversity-function and function-service relationships. Ecological and technical challenges—including scarce data, cross-scale issues, model structure/parameterization differences, and lack of unified performance metrics and cross-validation—prevent full quantification of component relationships and driver associations. Integrated assessment models combining biodiversity, ecosystem processes, and driver scenarios are lacking, hindering systematic analysis of driver impacts on biodiversity and ecosystem services.

Developing standardized indicator systems and integrated assessment models should be prioritized. Based on validated component relationships, further comparative analysis and synthesis of existing models should establish comprehensive indicator systems and mapping model libraries. China should urgently develop standardized systems and integrated models suited to its regional characteristics, enabling periodic assessment and simulation of biodiversity and ecosystem services trends to enhance its international standing in this field.

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