



*Research article*

## **Biodiversity and ecosystem service assessment in terrestrial habitats**

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**Abstract:** Terrestrial ecosystems represent some of the most extensive and human-influenced systems on Earth, playing a fundamental role in maintaining biodiversity, regulating ecological processes, and providing vital services to human societies. Assessing biodiversity and ecosystem services in terrestrial habitats is essential for understanding ecological dynamics, supporting conservation, and informing sustainable land-use policies. In this paper, we explored the theoretical underpinnings of biodiversity-ecosystem service relationships, reviewed methodological approaches for mapping and assessment, and presented selected case studies from Europe, South America, and Asia. The case studies highlighted the use of integrated frameworks such as the Mapping and Assessment of Ecosystems and their Services (MAES), expert-based ecosystem service supply matrices, and spatial modeling techniques. By examining how biodiversity loss and land-use changes affect service delivery, we demonstrated the importance of linking ecological knowledge with socioeconomic needs. We argue that advancing interdisciplinary, spatially explicit approaches to ecosystem assessment is critical for addressing global challenges such as climate change, habitat degradation, and sustainable development.

**Keywords:** biodiversity; terrestrial ecosystems; MAES; ecosystem condition; land-use change; nature-based solutions; spatial modeling

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### **1. Introduction**

Terrestrial ecosystems refer to land-based habitats such as forests, grasslands, shrublands, agricultural landscapes, and inland wetlands, excluding marine and coastal waters. These ecosystems host most of the world's species diversity and provide essential functions for human well-being [1]. They regulate global biogeochemical cycles, influence climate dynamics, and provide indispensable

ecosystem services ranging from carbon sequestration and nutrient cycling to food, raw materials, and recreation. Beyond provisioning and regulating services, terrestrial habitats also provide cultural, spiritual, and aesthetic values, shaping human identities and societies across the globe [2].

Yet, these ecosystems are under escalating pressure. Human-driven land-use change, intensification of agriculture, deforestation, infrastructure expansion, and urbanization have dramatically altered terrestrial landscapes [3]. Climate change further exacerbates these pressures, shifting species distributions, altering phenological patterns, and intensifying disturbance regimes such as wildfires and droughts [4]. As a result, terrestrial biodiversity faces critical declines, with species extinctions accelerating and ecological functions being impaired [5].

Biodiversity plays a fundamental role in the maintenance of ecosystem processes and the delivery of services. Rich and functionally diverse communities are more resilient to disturbances, support higher productivity, and provide a broader range of services [6]. Thus, biodiversity is not only an environmental indicator but also a key determinant of human well-being. Understanding and quantifying the links between biodiversity and ecosystem services has become a central scientific and policy challenge.

In Europe, the Mapping and Assessment of Ecosystems and their Services (MAES) initiative has been instrumental in establishing standardized approaches for monitoring ecosystem condition and services across member states [7]. Similarly, at the global scale, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has advanced the conceptual and methodological frameworks linking biodiversity, ecosystem services, and human well-being, highlighting the importance of nature's contributions to people [8]. These frameworks provide the foundation for integrating ecological assessments into environmental management, conservation planning, and sustainable development strategies.

Despite progress, significant gaps remain. Assessments are often limited by insufficient data, methodological inconsistencies, and the challenge of integrating ecological complexity with socioeconomic dimensions [9]. Furthermore, terrestrial ecosystems vary greatly in their structure, dynamics, and service provision across spatial and temporal scales, requiring flexible and context-specific approaches. Our purpose of this paper is threefold:

1. To present the theoretical foundations linking biodiversity to ecosystem service delivery in terrestrial systems.
2. To review methodological approaches for biodiversity and ecosystem service assessment, including mapping techniques, modeling, and valuation frameworks.
3. To illustrate these approaches with case studies from Europe, South America, and Asia, highlighting the opportunities and challenges of ecosystem service assessments in practice.

By combining theory, methodology, and empirical evidence, we emphasize the importance of biodiversity and ecosystem services as cornerstones of sustainable land-use management and climate adaptation strategies. Ultimately, advancing integrated, interdisciplinary approaches will be crucial for reversing biodiversity loss, safeguarding ecosystem functions, and aligning ecological sustainability with human development goals.

Our overarching aim of this narrative review is to synthesize how biodiversity underpins the delivery of ecosystem services in terrestrial ecosystems. Specifically, we integrate:

- (i) Theoretical perspectives on biodiversity–ecosystem service relationships.
- (ii) Methodological approaches for mapping and assessing services.
- (iii) Representative case studies illustrating ecological and policy applications across continents.

## 2. Theoretical background

### 2.1. Biodiversity as the foundation of ecosystem services

Biodiversity underpins ecosystem services through multiple, interlinked dimensions, i.e., genetic, species, functional, and habitat/ecosystem diversity, which operate at different spatial and temporal scales to support provisioning, regulating, supporting, and cultural services. At the genetic level, intraspecific variation enhances population adaptability and resistance to pests, diseases, and climatic stress, directly sustaining provisioning services such as crop yield stability and livestock health [10]. At the species level, greater species richness and community composition influence processes such as pollination and biological control: For example, diverse pollinator assemblages increase fruit and seed set across many crops, while predator diversity contributes to natural pest regulation [11,12]. Functional diversity, the variety and complementarity of species traits, is particularly important for supporting and regulating services because species with complementary traits (e.g., root depth, phenology, and decomposition rates) enhance nutrient cycling, soil formation, water regulation, and carbon storage, and confer resilience to environmental change [13–15]. Habitat and ecosystem diversity (landscape heterogeneity, mosaic structure) further determine spatial flows of services and underpin many cultural services by providing recreation, sense of place, and spiritual values [8,16]. Importantly, the biodiversity–service relationship is context-dependent and non-linear: Increases in species richness can produce diminishing marginal returns for some services, while losses of keystone or functionally unique species may produce disproportionate declines in service delivery [6,17]. Together, these lines of evidence indicate that conserving multiple facets of biodiversity, such as genetic, species, functional and habitat diversity, is essential to maintain the full spectrum of ecosystem services, sustain resilience under land-use change and climate pressures, and support human well-being [1,5].

### 2.2. Categories of ecosystem services

The Millennium Ecosystem Assessment [2] provided a widely adopted classification of ecosystem services into four major categories:

1. Provisioning services: Material outputs such as food, fresh water, timber, and medicinal resources.
2. Regulating services: Processes that maintain environmental stability, including climate regulation, water purification, and pollination.
3. Cultural services: Non-material benefits such as recreation, aesthetic values, and spiritual enrichment.
4. Supporting services: Underlying processes like soil formation and nutrient cycling that enable all other services.

Building upon MEA, the IPBES framework introduced the concept of nature's contributions to people (NCP), emphasizing the interlinkages between ecosystems, cultural contexts, and human well-being [5]. This evolution highlights the multidimensional and socio-ecological nature of ecosystem service assessments.

### 2.3. Ecosystem service frameworks and assessment approaches

Several frameworks have been developed to conceptualize and operationalize the links between biodiversity and services. The cascade model [18] is a prominent example, illustrating how biodiversity and ecosystem functions translate into services, which then generate human benefits and values. This model has informed policy-driven initiatives such as the EU's MAES framework, which integrates ecological indicators, spatial mapping, and socioeconomic valuation [7].

Assessment approaches can be grouped into three major categories:

1. Biophysical assessments, using ecological indicators (e.g., species richness, biomass, and land cover).
2. Economic assessments, assigning monetary values to services [19,20].
3. Sociocultural assessments, capturing local knowledge, perceptions, and non-monetary values [21].

Increasingly, integrated approaches combine these dimensions to provide a holistic understanding of ecosystem services and their role in sustainability [9].

### 2.4. Policy and conservation implications

The recognition of biodiversity–ecosystem service linkages has transformed conservation from a purely species- or habitat-oriented approach into a broader socio-ecological paradigm. This shift aligns ecological science with the United Nations Sustainable Development Goals (SDGs), particularly those relating to climate action, life on land, and sustainable resource use. By embedding ecosystem services into policy frameworks, governments and stakeholders can design land-use strategies that maximize ecological and social co-benefits while mitigating trade-offs [22].

Overall, the theoretical background highlights biodiversity as both a regulator of ecological processes and a determinant of human well-being. Ecosystem service frameworks provide essential tools for translating ecological complexity into actionable knowledge, enabling evidence-based conservation and sustainable land management.

## 3. Methodological approaches

A narrative review approach was adopted to synthesize theoretical and empirical evidence. A structured literature search was conducted in Google Scholar and Scopus using English-language keywords related to biodiversity, ecosystem services, terrestrial ecosystems, and spatial assessment (e.g., “ecosystem services mapping”, “terrestrial biodiversity”, “MAES”, and “nature's contributions to people”).

Inclusion criteria included peer-reviewed articles, landmark reports (MAES, IPBES), and case studies in terrestrial ecosystems (2000–2025). Exclusion criteria included marine ecosystems, grey literature, and non-English sources.

### 3.1. Mapping and classification of terrestrial ecosystems

Evidence was synthesized using thematic grouping, focusing on biodiversity–service linkages, assessment tools, and regional applications. The narrative review format is suitable for integrating

multidisciplinary knowledge and policy-relevant perspectives. The first step in assessing biodiversity and ecosystem services is the spatial delineation and classification of terrestrial ecosystems. Mapping typically combines remote sensing, Geographic Information Systems (GIS), and field surveys to identify habitat types and land cover classes [23]. High-resolution satellite imagery and LiDAR have been increasingly used to capture vegetation structure, canopy cover, and landscape fragmentation [24].

In Europe, the EUNIS habitat classification system and the CORINE Land Cover database provide standardized frameworks for ecosystem mapping, while globally the IPBES and MAES initiatives encourage harmonized ecosystem typologies [7]. Accurate ecosystem classification ensures comparability across regions and supports integration into policy and conservation planning.

### 3.2. Biodiversity assessment

Biodiversity in terrestrial ecosystems is commonly evaluated at three levels:

- Genetic diversity, using molecular markers and population genetics.
- Species diversity, often measured by species richness, abundance, or diversity indices (e.g., Shannon, Simpson).
- Community and habitat diversity, reflecting vegetation structure, functional traits, and habitat heterogeneity [25].

Long-term ecological monitoring programs, such as the European Long-Term Ecosystem Research (LTER) network, provide baseline data on biodiversity dynamics. Increasingly, functional and phylogenetic diversity metrics are applied to link species composition with ecosystem processes and services [26].

### 3.3. Ecosystem service assessment frameworks

Ecosystem service assessments employ a combination of biophysical, economic, and sociocultural approaches.

- Biophysical methods quantify services using ecological indicators and models. For example, carbon sequestration is estimated through biomass and soil organic carbon measurements, while pollination is assessed using insect diversity and visitation rates [12].
- Economic valuation assigns monetary values to services using techniques such as market pricing, contingent valuation, and avoided cost methods [20]. These approaches help integrate ecosystem services into cost–benefit analyses for policy and planning.
- Sociocultural assessments employ participatory mapping, surveys, and interviews to capture cultural, recreational, and spiritual values often overlooked in biophysical models [21].

The cascade model [18] remains a widely applied conceptual tool, linking ecosystem structures and processes to services and human benefits.

### 3.4. Spatial modeling and integrated tools

Recent advances in spatial modeling enable integrated assessment of biodiversity and ecosystem services across multiple scales. Such models enable researchers and policymakers to quantify service provision, evaluate trade-offs, and explore alternative management scenarios under varying environmental conditions.

Among the most widely used tools, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) provides a suite of spatially explicit models to quantify services such as water yield, carbon storage, habitat quality, and pollination [27]. Its modular design enables users to simulate land-use and land-cover change scenarios and to assess the potential trade-offs between ecological conservation and socioeconomic development.

Artificial Intelligence for Ecosystem Services (ARIES) applies probabilistic and semantic-modeling approaches based on Bayesian networks to estimate spatial flows of ecosystem services from areas of supply to areas of demand [28]. It integrates heterogeneous ecological, social, and economic data, providing context-specific results adaptable to data-rich and data-scarce regions.

ESTIMAP, developed within the MAES framework, represents a GIS-based modeling tool for the spatial assessment of multiple ecosystem services across Europe, including pollination, recreation, and water regulation [29].

In addition, other globally recognized tools complement these approaches by addressing different dimensions of ecosystem service assessment. Social Values for Ecosystem Services (SolVES) focuses on the sociocultural valuation of ecosystems, mapping the perceived importance of ecosystem services based on public value surveys and spatial interpolation techniques [30]. This tool highlights the non-material and cultural dimensions of human–nature relationships that are often overlooked in biophysical or economic assessments.

Co\$ting Nature is a web-based decision-support system that combines global datasets on land cover, biodiversity, carbon, and hydrology to evaluate ecosystem service provision, beneficiaries, and threats [31]. It supports conservation prioritization and sustainable land-use planning by enabling scenario analysis under varying management and policy options.

Together, these tools provide complementary perspectives on ecosystem service assessment. InVEST and ARIES emphasize biophysical and economic quantification, SolVES highlights sociocultural values, and Co\$ting Nature integrates multiple service dimensions at global scales. Their combined application enhances the robustness, transparency, and policy relevance of biodiversity and ecosystem service (BES) evaluations.

### *3.5. Challenges and limitations*

Moreover, emerging machine learning and deep learning methods, such as species distribution modeling using neural networks, show promise for improving predictive capacity and spatial resolution in biodiversity assessments [32]. Despite significant methodological progress, several challenges persist. Data scarcity, particularly in biodiversity-rich but poorly monitored regions, limits the accuracy of assessments. Scale mismatches between ecological processes and socio-political boundaries complicate policy implementation [9]. Additionally, trade-offs between ecosystem services, such as agricultural intensification increasing food provision while reducing pollination or soil quality, require multi-criteria approaches.

Overall, methodological advances in mapping, monitoring, and modeling have significantly improved the capacity to assess terrestrial biodiversity and ecosystem services. Nevertheless, integrated approaches that combine ecological, economic, and sociocultural dimensions remain essential for producing actionable knowledge for decision-makers.

## 4. Case studies

The three regions, Southern Europe (Spain), South America (Amazon Basin), and South Asia (Himalayan region), were selected because they represent highly contrasting biogeographical, socio-economic, and climatic contexts, providing a balanced and comparative perspective on how BES relationships manifest across global terrestrial systems.

The Mediterranean region of Europe exemplifies temperate and semi-arid ecosystems experiencing strong anthropogenic pressures such as land abandonment, agricultural intensification, and urban expansion. It offers insights into the dynamics of biodiversity–service trade-offs in multifunctional landscapes with long human management histories.

The Amazon Basin in South America represents one of the world’s most critical humid tropical ecosystems, characterized by exceptional biodiversity, carbon storage capacity, and sensitivity to deforestation and climate change. Its inclusion provides a global reference point for understanding how large-scale land-use conversion impacts carbon sequestration and hydrological regulation.

The Himalayan region in Asia reflects mountainous and high-altitude ecosystems, where biodiversity underpins provisioning and cultural services essential for local livelihoods. These ecosystems highlight the socio-ecological interdependence between biodiversity conservation and community well-being under conditions of environmental and economic vulnerability.

Collectively, these three regions capture a spectrum of terrestrial ecosystem types and socio-environmental gradients, from Mediterranean drylands to tropical rainforests and mountain systems, offering a representative cross-section of the world’s major biomes. This selection ensures that the analysis reflects not only ecological diversity but also differences in governance, cultural values, and land-use pressures, thereby enhancing the global relevance and comparability of the findings.

### 4.1. Europe: Mediterranean forest ecosystem services in Spain

The Mediterranean basin is a global biodiversity hotspot, but its ecosystems face severe threats from climate change, land abandonment, and urbanization. Researchers conducting a study in Catalonia, Spain, applied the InVEST model to assess forest ecosystem services such as carbon storage, soil retention, and water regulation [33]. Their results showed that areas with high biodiversity often coincided with high levels of service provision, but also highlighted trade-offs; for example, increased timber harvesting reduced carbon storage and habitat quality. This case illustrates the need for multi-criteria decision frameworks to balance conservation and economic development in Mediterranean landscapes.

### 4.2. South America: Amazonian deforestation and carbon sequestration

The Amazon rainforest, the world’s largest terrestrial carbon sink, has experienced unprecedented deforestation due to agriculture and logging. Fearnside [34] demonstrated that land-use conversion drastically reduces carbon sequestration capacity while disrupting hydrological cycles. Biodiversity loss further undermines ecosystem resilience, making forests more vulnerable to fires and droughts. Ecosystem service assessments in the Amazon have influenced national policies and international climate agreements, emphasizing the forest’s global importance for carbon regulation and climate stability. This case underscores the role of biodiversity in maintaining ecosystem functions under large-scale disturbance regimes.

### 4.3. Asia: Himalayan ecosystem services and livelihoods

In the Indian Himalayas, terrestrial ecosystems provide critical services such as water regulation, soil fertility, and non-timber forest products (NTFPs), which sustain rural livelihoods. Pandit et al. [35] conducted participatory assessments combining ecological surveys and community-based valuation methods to evaluate provisioning and cultural services. Findings revealed that local communities highly valued cultural and spiritual dimensions, often overlooked in purely biophysical assessments. However, increasing pressure from tourism and land-use change threatens biodiversity and ecosystem service provisions. This case demonstrates the importance of integrating sociocultural perspectives into ecosystem service frameworks, especially in indigenous and rural contexts.

### 4.4. Cross-Case insights

Across these regions, common themes emerge (Table 1):

- Biodiversity–service synergies: High biodiversity areas often provide multiple services, enhancing resilience.
- Trade-offs: Intensification of provisioning services (e.g., timber, agriculture) often reduces regulating or cultural services.
- Policy relevance: Ecosystem service assessments directly inform climate policies (Amazon), land-use planning (Mediterranean), and community development (Himalayas).
- Methodological integration: The most effective studies combined ecological monitoring, spatial modeling, and participatory approaches, highlighting the value of interdisciplinarity.

**Table 1.** Cross-case comparative insights.

Theme	Europe (Spain)	South America (Amazon)	Asia (Himalayas)	Synthesis insight
Biodiversity–service Link	High biodiversity = multiple regulating services	Biodiversity underpins global carbon storage	Biodiversity supports cultural and provisioning services	Biodiversity universally enhances resilience and multi-service provision.
Trade-offs	Timber vs. carbon and habitat	Agriculture vs. carbon and biodiversity	Tourism vs. cultural and ecological integrity	Trade-offs occur across provisioning vs. regulating/cultural services.
Methods	Spatial models + field surveys	Remote sensing + ecological modelling	Participatory + ecological surveys	Mixed-methods approaches yield most comprehensive insights.
Policy impact	EU land-use planning	Climate negotiations, REDD + programs	Community forestry and rural policy	BES assessments are critical for local, regional, and global policy.

## 5. Discussion

The case studies from Europe, South America, and Asia demonstrate the versatility and importance of BES assessments across terrestrial contexts (Table 2). Despite ecological, cultural, and

socio-economic differences, several key patterns emerge. Table 2 provides a synthesized overview of the key characteristics, methods, and major findings of each case study, serving as a visual bridge between the regional analyses (Section 4) and the cross-case discussion presented below.

**Table 2.** Overview of case studies.

Region	Ecosystem type	Methods used	Key services assessed	Major findings
Europe (Spain)	Mediterranean forests	InVEST modelling, GIS, biodiversity surveys	Carbon storage, soil retention, water regulation	Biodiversity hotspots align with high service provision; trade-offs with timber harvesting.
South America (Amazon)	Tropical rainforest	Remote sensing, carbon models, climate data	Carbon sequestration, hydrological regulation	Deforestation reduces carbon storage and resilience; global climate policy relevance.
Asia (Himalayas)	Mountain forests and agroecosystems	Participatory mapping, surveys, ecological monitoring	Provisioning (NTFPs), cultural, water regulation	Strong cultural values; biodiversity critical to livelihoods; threats from tourism/land use.

First, synergies between biodiversity and ecosystem services are evident in all cases. In Mediterranean forests, high biodiversity coincided with enhanced regulating services such as carbon storage and soil retention. Similarly, the Amazon's unparalleled biodiversity underpins global climate regulation. In the Himalayas, biodiversity supports not only provisioning services but also deeply valued cultural services. These findings affirm that biodiversity is not merely an ecological attribute but a functional driver of service provision [6].

Second, the studies highlight trade-offs that emerge from land-use change and resource exploitation. In Spain, timber harvesting conflicted with carbon storage and habitat quality. In the Amazon, agricultural expansion provided short-term economic benefits at the expense of biodiversity and long-term ecological stability. Such trade-offs are consistent with global findings that provisioning services often increase at the cost of regulating and cultural services [5].

Third, the importance of methodological integration becomes clear. Biophysical models (e.g., InVEST), economic valuation, and participatory approaches complement one another. For instance, participatory assessments in the Himalayas captured cultural dimensions that would have been missed by remote sensing alone. The most effective BES assessments are thus interdisciplinary, combining ecological, economic, and sociocultural perspectives.

Finally, these cases underscore the policy relevance of BES assessments. Results from the Amazon influence climate negotiations; Mediterranean studies inform EU land-use planning; and Himalayan assessments support community forestry initiatives. These examples demonstrate how BES assessments bridge science and policy, guiding conservation and sustainable development.

## 6. Conclusion

This review advances our knowledge and practice in BES assessment by demonstrating several key contributions:

(a) Biodiversity consistently enhances multi-service provisions across terrestrial systems, supporting the view that ecological integrity is the foundation of human well-being. Evidence from Mediterranean, tropical, and mountain ecosystems reveals that species- and functionally-rich communities sustain multiple provisioning, regulating, and cultural services simultaneously, thereby reinforcing ecosystem resilience under climate and land-use pressures.

(b) Integrated assessment tools and frameworks, including biophysical, economic, and sociocultural approaches, enable a more comprehensive understanding of ecosystem dynamics and support evidence-based decision-making. The synthesis presented here highlights the value of combining spatial models (e.g., InVEST and ARIES), participatory mapping, and valuation methods to capture the full spectrum of ecosystem benefits. Such interdisciplinary integration strengthens the scientific foundations of ecosystem-based planning and policy.

(c) Spatially explicit and adaptive governance mechanisms are essential for addressing ecosystem service trade-offs and mitigating biodiversity loss. By demonstrating how regional assessments inform land-use, conservation, and climate adaptation policies, this study underscores the critical importance of linking spatial data and ecological knowledge to real-world management frameworks

Collectively, these findings emphasize the urgent need to embed ecosystem service assessments within land-use policy, climate strategies, and nature-based solutions, in direct alignment with the United Nations Sustainable Development Goals (SDGs), particularly Goals 13 (Climate Action), 15 (Life on Land), and 11 (Sustainable Cities and Communities).

In the future, researchers should prioritize the establishment of long-term monitoring systems to track biodiversity–service interactions through time, the co-development of valuation frameworks with local communities to ensure social legitimacy, and the deeper integration of biodiversity indicators into service modeling frameworks. Such advances will foster more equitable, data-driven, and sustainable management of terrestrial ecosystems worldwide.

Our findings contribute to advancing current knowledge by demonstrating the interdependence between biodiversity and multiple ecosystem services across contrasting terrestrial systems. Scientifically, the paper provides an integrative framework combining ecological, socio-economic, and spatial perspectives. Practically, it offers insights for policymakers and planners aiming to align biodiversity conservation with sustainable land-use strategies. By emphasizing interdisciplinary assessment methods, this work bridges science, policy, and practice in the pursuit of global sustainability goals.

Ultimately, advancing interdisciplinary, multi-scale BES assessments is essential for aligning biodiversity conservation with the global sustainability agenda and the UN Sustainable Development Goals.

### **Use of AI tools declaration**

The author declares he has not used Artificial Intelligence (AI) tools in the creation of this article.

### **Conflict of interest**

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

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