

Editorial

Forest Ecosystem Services and Sustainable Management: From Assessment to Adaptive and Inclusive Action

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Forests sustain human societies through an interdependent portfolio of provisioning, regulating, cultural, and supporting services. They store carbon, regulate water and climate, conserve soil and biodiversity, provide timber and non-timber products, sustain livelihoods, and shape cultural identity and recreation. These benefits are not produced independently: management that enhances one service can reinforce, weaken, or redistribute others. Climate change, land-use pressure, biodiversity loss, and unequal access to forest benefits further complicate the task. Recent assessments of nature-based climate solutions in forests have emphasized that credible interventions require not only measurable climate benefits but also ecological integrity, durable outcomes, transparent accounting, and safeguards against adverse social and environmental effects [1]. Sustainable forest management must therefore move beyond maintaining forest area or maximizing a single output. It must clarify how ecosystem services are generated, where trade-offs and synergies arise, whose values and knowledge guide decisions, and which institutions and incentives can convert evidence into durable action.

This Special Issue, entitled “Forest Ecosystem Services and Sustainable Management”, was conceived to advance this transition from assessment to implementation. Its eight contributions examine forests and forest-dependent landscapes in South Korea, the Democratic Republic of the Congo, Laos, China, Italy, and Chile. Together, they span restored temperate forests, tropical Indigenous territories, rural land-use mosaics, mountain ecosystems, Mediterranean cork oak woodlands, mixed native forests, and a heavily visited national park. Their methods are equally diverse, including field inventories, structural equation modeling, surveys and social valuation, Indigenous and local knowledge assessment, spatial ecosystem-service modeling, geographic detector analysis, forest economic optimization, third-party certification, and unsupervised machine learning for functional zoning. Read together, the papers trace a progression from ecological mechanisms and economic decisions to spatial prioritization, stakeholder values, Indigenous knowledge, and accountable governance. This breadth demonstrates that forest ecosystem services are simultaneously biophysical processes, spatially differentiated benefits, socially perceived values, and outcomes shaped by institutions and economic choices.

At the stand level, the contribution by Kwak et al. shows why sustainable management must begin with the ecological mechanisms that generate services [2]. Drawing on 149 plots in early-stage forest restoration sites in South Korea, the study identifies stand structural diversity as the most consistent driver of aboveground biomass across coniferous and broadleaved forests. Importantly, the pathways differed by forest type: structural diversity



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and tree functional identity were more influential in coniferous stands, whereas species richness and climatic conditions had greater importance in broadleaved stands. These findings caution against applying a universal restoration prescription. Species richness alone was not a consistent predictor across forest types, particularly while communities were still assembling. Instead, species selection, functional traits, size differentiation, and the development of structurally complex stands should be matched to forest type and successional stage. Restoration monitoring should therefore extend beyond survival rates or canopy establishment to determine whether stand development ultimately supports carbon accumulation, resilience, habitat complexity, and other long-term functions. Because the sampled stands were no older than 10 years and the response variable was aboveground biomass, these broader outcomes remain priorities for long-term evaluation rather than effects directly demonstrated by the study.

The economic analysis of mixed native forests in southern Chile reaches a complementary conclusion from a different disciplinary perspective [3]. Moreno-García et al. integrate timber production and carbon sequestration into a Faustmann-based optimization framework for Roble-Raulí-Coigüe and evergreen forests. In the modeled scenarios, mixed-species configurations at moderate densities were generally more profitable than monocultures, while assigning an economic value to carbon increased land expectation values and extended optimal rotations. Ecological heterogeneity thus need not be treated solely as a conservation cost; under appropriate incentives, it can form part of a viable production strategy. Together, these studies show that ecological diversity and economic viability need not be opposing objectives. Yet the adoption of diverse forest structures by owners also depends on expected returns, rotation decisions, market access, and policy support. Sustainable management therefore requires ecological prescriptions and economic institutions to be designed together.

Three contributions demonstrate that ecosystem-service management must also be spatially explicit. In the Nanling Mountains, Zhang et al. document synergies and trade-offs among habitat quality, carbon storage, soil conservation, and water yield, together with marked differences between northern and southern slopes [4]. Habitat quality and soil conservation were generally synergistic, whereas habitat quality and water yield displayed important trade-offs. Temperature and economic activity were influential on both slopes, while slope gradient played an additional role on the southern slope. By treating the northern and southern slopes as distinct analytical units, the study illustrates a broader principle: spatial units for management should reflect ecological processes rather than merely administrative convenience.

Xu et al. reinforce this principle in the arid Chinese Altai Mountains [5]. Between 2000 and 2020, water and soil conservation increased, whereas carbon storage declined slightly and habitat quality followed a rise-then-fall pattern. Carbon storage and habitat quality were concentrated in mid-elevation forests and remained strongly synergistic, but the negative association between carbon storage and water conservation intensified. This water-carbon conflict is especially important for restoration and afforestation policy. Increasing tree cover or biomass in water-limited environments may enhance carbon storage while increasing evapotranspiration and reducing water availability. The authors therefore recommend avoiding high-density afforestation in water-sensitive zones, optimizing stand structure at mid-elevations, and protecting hydrological functions at higher elevations. Such findings challenge the assumption that more trees everywhere necessarily deliver more ecosystem services.

The Jirisan National Park study by Kim et al. brings spatial differentiation directly into protected-area management [6]. By combining five ecosystem-service indicators with topographic conditions and proximity to roads and trails, the authors use a Self-Organizing

Map (SOM) to delineate seven functional spatial types. High-altitude areas near major trails were characterized by strong visitor pressure and mismatches among regulating services, whereas interior forest areas maintained high multifunctionality and evenness. Low-altitude facility-dense and disturbance-adjacent zones showed relatively low habitat quality or service imbalance. This approach moves beyond boundary-oriented zoning by identifying where ecological value, service supply, and human pressure coincide or conflict. It also provides a practical basis for differentiated interventions, including visitor-use management, habitat-connectivity restoration, restoration-oriented management of disturbed zones, and protection of multifunctional core areas. Across the Nanling, Altai, and Jirisan studies, the shared message is that ecosystem-service averages conceal the locations where management choices matter most. Effective decisions require maps of service bundles, trade-offs, pressures, and beneficiaries, followed by locally tailored action and monitoring.

Biophysical assessment, however, does not by itself determine what society will protect or manage. The contribution from rural Laos by Lee and Rhee demonstrates systematic differences between community and expert priorities across bamboo forests, rice paddies, and teak plantations [7]. Local communities emphasized tangible provisioning and cultural services linked to daily life, whereas experts placed greater weight on less visible regulating and habitat services. The study also identified distinct perceived land use-specific bundles: bamboo forests were associated with raw materials and freshwater, rice paddies with food and medicine, and teak plantations with timber, bioenergy, and several regulating functions. These patterns reveal why technically sound plans may encounter resistance when they disregard locally experienced benefits. They also show why a landscape portfolio is preferable to a single-objective strategy: different land uses were perceived to provide complementary services, but their value depended on stakeholder priorities as well as ecological supply. Participatory co-management, ecosystem-service literacy, and culturally appropriate dialog are therefore not supplementary communication activities; they are integral components of the management system.

Kasoki et al. deepen this argument through their study of the Mbuti and Efe peoples in the Okapi Wildlife Reserve landscape in the Democratic Republic of the Congo [8]. Customary taboos, restrictions, livelihood practices, and species knowledge operate as *de facto* ecological regulations, even amid rapid socio-cultural change. At the same time, biodiversity decline, changing tools and livelihoods, sedentarization, weakening intergenerational knowledge transmission, and growing dependence on the monetary economy create new vulnerabilities. The study demonstrates that Indigenous knowledge is neither a static cultural remnant nor merely anecdotal information. It is a structured and adaptive system that helps identify and interpret environmental change, regulates resource use, and supports cultural and ecological resilience. Sustainable management of the reserve should therefore recognize Indigenous institutions, rights, aspirations, and environmental knowledge within formal co-management arrangements.

This conclusion is consistent with recent evidence from Amazonian forests showing that community-led surveillance can protect a functional area far larger than the directly managed area generating income, while the associated monitoring costs may still be borne by low-income local households [9]. The implication for forest ecosystem-service policy is twofold. First, participation must entail genuine authority, not only consultation after objectives have already been set. Second, payment for ecosystem services, conservation finance, and related incentive schemes should recognize the broader territorial benefits generated by local stewardship and distribute costs and benefits fairly. Without secure rights, credible benefit sharing, and support for knowledge transmission, governance arrangements may rely on local contributions while leaving communities to bear disproportionate implementation costs.

The case of the municipal cork oak forest of Alà dei Sardi in Sardinia illustrates how these principles can be institutionalized [10]. Seddaiu et al. document the first known case of a publicly owned municipal cork oak forest attaining an advanced level of Forest Stewardship Council certification encompassing Forest Management and Chain of Custody certification, together with verification of impacts on five ecosystem services. Territorial planning, public administration, stakeholder engagement, forest inventory, and voluntary certification were linked to biodiversity conservation, carbon sequestration and storage, water protection, soil conservation, and recreational services. The significance of this case lies not simply in certification as a label, but in the operational architecture behind it: explicit objectives, spatial management units, evidence, monitoring, stakeholder procedures, traceability, and external accountability. Its transferability depends on administrative capacity, qualified personnel, financing, and adaptation to local legal and ecological contexts, but it demonstrates a route by which multifunctionality can become a documented management commitment rather than a broad aspiration.

Taken together, the eight contributions suggest five closely related directions for research and practice. Sustainable forest management should first be portfolio-based, explicitly considering multiple ecosystem services rather than treating carbon, timber, water, biodiversity, recreation, or livelihoods in isolation. Second, it should be place-specific and differentiated by forest type, successional stage, elevation, slope, land use, and disturbance context, because the same intervention can produce different outcomes across space and time. Third, it should combine biophysical measurement with social valuation, Indigenous and local knowledge, and economic analysis. No single evidence system is sufficient: models can identify potential service supply, field data can reveal ecological mechanisms, and stakeholder knowledge can identify dependence, legitimacy, and change that remote observations may miss. Fourth, management should be adaptive and accountable, with baselines, indicators, participatory monitoring, transparent reporting, and feedback mechanisms that allow interventions to change as forests, climate, markets, and social priorities change. Fifth, incentives and institutions should align those who finance, manage, use, and benefit from forests. Carbon payments, certification, public planning, and conservation finance can support better management, but their design must address context, accountability, and distribution. For forest carbon interventions in particular, additionality, durability, leakage, and social safeguards require credible treatment [1], while local rights and fair benefit sharing remain central to participatory governance [8,9].

The resulting research agenda is equally integrative. Longitudinal studies are needed to connect short-term changes in biomass, structure, water, habitat, and livelihoods with long-term resilience. Spatial models should increasingly incorporate climate and disturbance scenarios, including drought, wildfire, pests, land-use change, and shifting recreational demand. Social valuation should be linked to measured ecosystem-service supply so that ecological provision, perceived importance, access, and realized benefit can be distinguished. Governance research should move beyond documenting participation to evaluating which combinations of rights, rules, monitoring, incentives, and administrative capacity produce durable and equitable outcomes. Economic models should incorporate a broader set of services and risks, including non-timber products, avoided degradation, biodiversity, hydrological effects, monitoring costs, permanence, and uncertainty. Finally, advances in remote sensing, artificial intelligence, and spatial optimization should be combined with field observations and local knowledge rather than replacing them. The central challenge is not simply to generate more precise maps or valuations, but to build decision processes capable of using diverse evidence responsibly.

This Special Issue shows that the science of forest ecosystem services is moving from identifying and valuing benefits toward designing actionable, place-based management systems. Its contributions do not point to one universally optimal forest structure, land use, zoning rule, or governance model. Instead, they demonstrate that sustainability emerges when management is fitted to ecological mechanisms, spatial heterogeneity, stakeholder values, institutional capacity, and economic realities. The overarching lesson is that assessment is necessary but insufficient: information becomes consequential only when it is connected to explicit objectives, inclusive deliberation, spatial prioritization, incentives, monitoring, and accountability. Forests can simultaneously support climate mitigation, biodiversity, water security, livelihoods, cultural continuity, recreation, and production, but these outcomes require deliberate choices, transparent treatment of trade-offs, and sustained learning. The next step is to connect these elements across scales so that ecosystem-service knowledge changes decisions on the ground.

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