

Review

Integrating Ecological and Economic Approaches for Ecosystem Services and Biodiversity Conservation: Challenges and Opportunities

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Abstract

This narrative review examines how ecological and economic perspectives can be integrated to support ecosystem services management and biodiversity conservation. We synthesize core valuation approaches (accounting-based exchange values versus welfare-based measures), discuss their appropriate uses and limitations, and illustrate implications through selected cases in watershed protection, protected areas, and forest carbon. We then review design features of Payments for Ecosystem Services (PES) with attention to additionality, leakage, and equity, and distill lessons for policy mixes that combine market-based instruments with regulatory and informational tools. Finally, we outline opportunities and risks in applying artificial intelligence to ecological–economic analysis, emphasizing accuracy–energy trade-offs and responsible data practices. Across topics, we prioritize mechanism-focused interpretation, triangulate findings from representative studies, and highlight decision-relevant takeaways rather than comprehensive coverage. We conclude with practical recommendations for analysts and policymakers: align valuation method with decision context; pair PES with targeting and monitoring; embed price-based instruments in adaptive policy mixes; and adopt transparent, efficiency-aware analytic workflows—especially when using computationally intensive methods.

Keywords: ecosystem services; biodiversity conservation; economic valuation; payments for ecosystem services; cost–benefit analysis; artificial intelligence



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1. Introduction

The accelerating pace of global environmental change has exposed a structural misalignment between dominant twentieth-century growth paradigms and the biophysical limits of a finite planet. For much of the last century, mainstream economic analysis treated nature as an externality—implicitly assuming inexhaustible sources of inputs and bottomless sinks for wastes—thereby rendering the depreciation of natural capital invisible in economic accounts and encouraging its systematic overuse [1]. Ecological economics challenges this conceptual separation by positing that the economy is a subsystem of the ecosphere whose performance is ultimately constrained by the condition of natural capital stocks and the service flows they sustain [2]. This reframing moved from theory to policy through initiatives such as The Economics of Ecosystems and Biodiversity (TEEB), which quantified the social costs of biodiversity loss and ecosystem degradation and demonstrated

the inadequacy of conventional indicators like GDP when natural assets depreciate [3]. In parallel, the 2019 Global Assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) synthesized evidence of unprecedented declines in species and ecosystems driven by land- and sea-use change, overexploitation, climate change, pollution, and invasive species [4]. The cumulative message is clear: policies that ignore ecological limits are environmentally unsustainable and economically self-defeating over the long run [5].

A decision-oriented integration of ecology and economics requires concepts and metrics that connect biophysical change to human well-being. The ecosystem-services framework has become a widely used analytical language for this purpose, organizing nature's contributions into provisioning, regulating, supporting, and cultural services [6–8]. Beyond taxonomy, the framework traces how alterations in ecosystem structure and function propagate through service pathways to affect social and economic outcomes in ways that decision-makers can observe, compare, and manage [6–8]. Biodiversity is foundational in this architecture: variation within and among species underpins productivity, functional complementarity, and response diversity, thereby conferring resilience to shocks, including those intensified by climate change [7]. Casting ecosystems and biodiversity as natural capital embeds these insights within economic analysis, treating maintenance and restoration as investments that yield intertemporal returns and aligning environmental stewardship with sustainable development objectives that balance prosperity, ecological integrity, and social equity across generations [7,9]. This lens also clarifies that failure to maintain natural capital threatens the stability and distribution of ecosystem-service flows upon which economies and livelihoods depend [1,9]. In this review, we explicitly adopt a natural capital perspective to integrate ecological and economic considerations.

Despite growing conceptual convergence, persistent confusion in practice stems from the coexistence of distinct valuation traditions that serve different decision problems. Accounting-based exchange values, implemented in natural capital accounting consistent with the System of National Accounts, are designed for macro-tracking, balance-sheet compilation, and corporate disclosure; by construction, they emphasize observed or imputed market prices and exclude consumer surplus. In contrast, welfare-based measures—changes in consumer and producer surplus estimated using revealed-preference (e.g., travel cost, hedonic) or stated-preference approaches—are appropriate for project appraisal, cost–benefit analysis, and distributionally sensitive policy design. Conflating these perspectives can yield misleading inferences about benefits and costs, especially when accounting metrics are treated as if they captured welfare change, or when welfare measures are inserted into accounting aggregates [1,6–9]. The best practice is to match the method to decision context, to be explicit about what each metric captures and omits, and to communicate uncertainty using confidence intervals, sensitivity analysis, and scenario ranges. Where feasible, reporting both perspectives with clear labeling improves transparency and comparability across policy arenas, while avoiding double-counting and scope errors [6–9].

Policy design presents a complementary set of challenges and opportunities, because instruments intended to conserve biodiversity and secure ecosystem services operate in institutional environments characterized by heterogeneous incentives, information frictions, and equity concerns. Payments for Ecosystem Services (PES) exemplify this complexity: outcomes hinge on targeting high-risk or high-benefit areas, enforcing conditionality through credible monitoring and verification, setting payment levels that foster additionality without inducing excessive rents, and tracking who participates and who benefits [9]. Leakage across space or sectors and dynamic responses to incentives require explicit attention to counterfactuals and spillovers. More broadly, policy mixes that combine price-based

tools with regulatory guardrails and information instruments can mitigate the weaknesses of any single instrument and support adaptive management as ecological and economic conditions evolve. Designing such mixes requires clarity about objectives (e.g., thresholds versus marginal trade-offs), interactions among instruments, and mechanisms for periodic review and recalibration, particularly under uncertainty about ecological responses and behavioral adaptation [9]. These considerations argue for decision frameworks that are transparent about objectives, accountable for distributional effects, and capable of learning.

Rapid advances in data and computation create new possibilities for integrating ecological and economic analysis while introducing risks that must be managed. Remote sensing and machine learning can sharpen spatial targeting, improve predictions of land-use change and species distributions, and enable near-real-time monitoring of outcomes. Yet responsible practice requires attention to model interpretability, data provenance and licensing, and the computational and energy costs of analytic pipelines—considerations that are material for public agencies and conservation organizations operating under budget constraints [5,9]. In contexts where analytic choices have meaningful cost or environmental footprints, documenting these trade-offs is part of transparent and accountable decision support. Efficiency-aware workflows, appropriate baselines, and openness about uncertainty can ensure that computational innovation complements, rather than distorts, ecological–economic inference.

However, existing research remains siloed between ecology and economics, leaving an important gap in integrated approaches. Against this backdrop, the present article offers a narrative, decision-oriented synthesis of methods and practices at the ecology–economy interface. The aim is to clarify how valuation paradigms should be aligned with specific decision contexts; to distill design lessons from PES with attention to additionality, leakage, and equity; to translate these insights into pragmatic guidance for constructing policy mixes that combine price-based, regulatory, and informational tools; and to discuss opportunities and risks in applying data-intensive methods to ecological–economic problems [1–3,6–9]. The review selectively integrates relevant literature identified via database searches (e.g., Web of Science, Google Scholar) using keywords such as “ecosystem services valuation” and “biodiversity economics”, as well as influential reports. We focused on sources primarily from 2000 to 2025, selected for conceptual clarity, methodological representativeness, and policy relevance. This review is conducted as a narrative (non-systematic) review. Accordingly, we did not follow PRISMA guidelines or perform a formal systematic review or meta-analysis; instead, we triangulated multiple information sources and explicitly noted limitations to ensure rigor and transparency [10,11]. This review offers a novel synthesis that bridges ecological and economic perspectives in a unified analysis. It aligns with the scope of *Ecologies* by advancing ecological understanding with clear decision-support implications, and it fills a gap in the literature by integrating recent innovations (e.g., AI applications in conservation finance) into the discussion.

This review is intended to serve researchers, practitioners, and policymakers working to reconcile biodiversity conservation and human well-being under global change. The contribution aligns with the scope of *Ecologies* to advance ecological understanding with clear decision-support implications and is intended to serve researchers, practitioners, and policymakers. To sharpen our focus, we have now articulated the guiding research questions in the Introduction. For example, we explicitly ask: “How can ecological and economic valuation paradigms be aligned with specific decision contexts to improve decision-making for biodiversity conservation?” These questions highlight the gaps our review addresses and frame the subsequent analysis.

As shown in the conceptual framework (Figure 1), this review is structured around four key elements: aligning valuation methods with decision contexts, designing PES programs

effectively (with attention to additionality, leakage, and equity), building adaptive policy mixes that combine market-based and regulatory tools, and using data-intensive tools (like AI) responsibly. We have revised the manuscript to ensure that the narrative closely follows this framework.

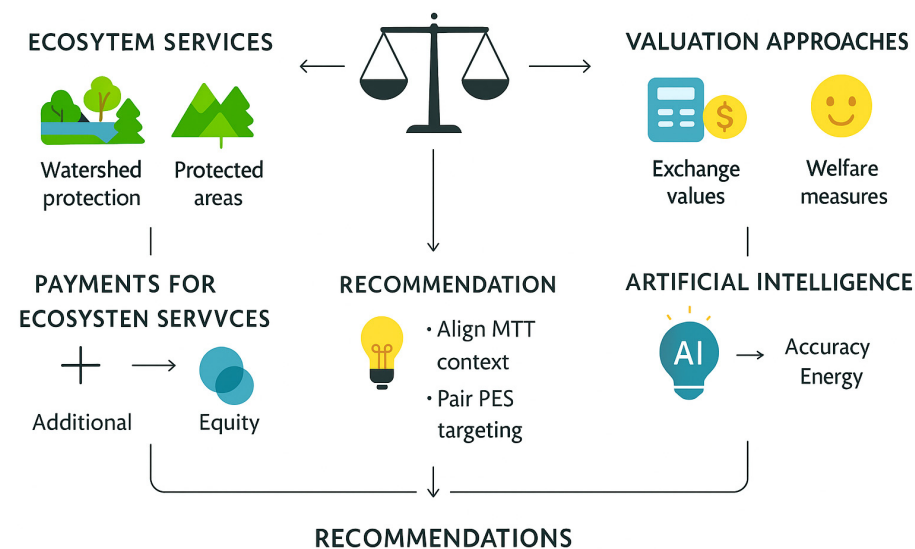


Figure 1. Overview of how ecosystem services, valuation (accounting vs. welfare), PES, and AI connect to inform policy recommendations.

2. Valuing Nature: An Economic Perspective on Ecosystem Services

2.1. Conceptualizing Ecosystem Services: Definitions, Classifications, and Significance

To systematically integrate the value of nature into economic decision-making, it is essential to have a clear and comprehensive framework for understanding what is being valued. The concept of ecosystem services provides this structure by categorizing the diverse benefits that flow from natural capital to human societies. These services are typically grouped into four main categories: provisioning, regulating, supporting, and cultural. Table 1 provides a detailed typology of these services, offering definitions and concrete examples that illustrate their direct and indirect contributions to human well-being [8].

Beyond service classes, the Total Economic Value (TEV) framework decomposes the full spectrum of values people derive from ecosystems, encompassing both market-mediated and non-market components [12]. TEV typically includes the following: (i) direct-use values (consumptive uses such as timber and fish; non-consumptive uses such as recreation and tourism); (ii) indirect-use values (benefits from ecological functions that support economic activity without being directly consumed, e.g., flood regulation, pollination, water purification); (iii) option values (the value of maintaining the possibility of future use, including prospective genetic resources); (iv) non-use values, commonly divided into bequest values (for future generations) and existence values (value from the mere existence of species or ecosystems). This decomposition is crucial because many regulating, cultural, and non-use components are public goods—non-excludable and non-rival—so they lack market prices and are systematically at risk of undervaluation and degradation in conventional accounts [13]. The central methodological challenge is therefore to adopt tools capable of capturing this plural set of values in a manner that is rigorous, transparent, and decision-relevant.

Table 1. A typology of ecosystem services [14].

Category	Definition	Examples
Provisioning	The material or energy outputs from ecosystems. These are the tangible products that can be directly consumed or used by people.	Food (crops, livestock, fisheries), fresh water, timber and fiber (cotton, wood), medicinal resources, biofuels.
Regulating	The benefits obtained from the regulation of ecosystem processes. These services often maintain environmental quality and stability.	Climate regulation (carbon sequestration), water purification, air quality regulation, flood and storm protection, erosion control, pollination, pest, and disease control.
Supporting	The underlying natural processes that are necessary to produce all other ecosystem services. Their impact on people is indirect and occurs over a long-time scale.	Nutrient cycling, soil formation, primary production (photosynthesis), water cycling, provision of habitat for species.
Cultural	The non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, recreation, and esthetic experiences.	Recreational opportunities (hiking, fishing, ecotourism), esthetic values (scenic landscapes), spiritual and religious values, educational opportunities, cultural heritage, sense of place.

2.2. Methodological Toolkit for Economic Valuation

Assigning monetary value to ecosystem services—especially those without market prices—is essential for cost–benefit analysis, budgeting, and policy appraisal, yet method choice must match decision purpose and inferential requirements [15,16]. Three families dominate: cost-based, revealed-preference, and stated-preference approaches. A concise map of these approaches is provided in Table 2.

Table 2. Economic Valuation Methods for Ecosystem Services [16].

Method Category	Specific Method	Underlying Principle	Primary Application (Service Types)	Key Strengths	Key Limitations
Cost-Based	Replacement Cost	Value is estimated as the cost of providing a human-made substitute for an ecosystem service.	Regulating (e.g., water filtration, flood control).	Intuitive and easily understood by policymakers; uses tangible cost data.	May over- or under-estimate value; assumes the substitute is equivalent and would be built.
Revealed Preference	Travel Cost Method (TCM)	Value is inferred from the time and money people spend to visit a natural site for recreation.	Cultural (Recreation).	Based on actual behavior, not hypothetical intentions; grounded in standard economic demand theory.	Cannot measure non-use values; requires complex data collection and statistical analysis.
Stated Preference	Contingent Valuation (CV)	A hypothetical market is created, and people are asked about their willingness-to-pay for a change in an ecosystem service.	All services, especially Cultural and Non-Use (Existence, Bequest).	Only method capable of estimating non-use values; highly flexible.	Subject to hypothetical bias; results can be sensitive to survey design and framing.
	Choice Experiment (CE)	People make choices between alternative scenarios with varying levels of ecosystem services and costs, revealing implicit values.	All services, especially when valuing multiple attributes and trade-offs.	Can value individual attributes of an ecosystem; statistically robust.	Cognitively demanding for respondents; subject to hypothetical bias.
Value Transfer	Benefit Transfer	Adapts value estimates from existing studies (“study sites”) to a new policy site.	All services.	Low cost and rapid assessment compared to primary studies.	Can be highly inaccurate if the study and policy sites are not sufficiently similar.

2.2.1. Cost-Based Methods

Replacement or avoided-cost approaches infer value from the least-cost human-engineered alternative that would realistically be adopted if the service were unavailable [17]. For example, wetland water purification may be valued using the cost of constructing and operating a treatment facility delivering equivalent quality and quantity. Validity hinges on technical equivalence and behavioral plausibility; otherwise, estimates risk over- or under-stating value [18]. Applied studies often focus on regulating services (e.g., filtration, flood control). As an illustration, cost-based accounting has been used to quantify the direct consumptive value of aquatic species for Indigenous communities, providing a baseline for evaluating water resource development impacts [19].

2.2.2. Revealed-Preference (RP) Methods

RP techniques infer willingness to pay (WTP) from observed behavior in related markets. The Travel Cost Method (TCM) is widely used to value recreation by treating travel expenditures and time as implicit prices; both zonal (ZTCM) and individual (ITCM) variants are employed, with the latter generally offering sharper identification at the expense of richer data needs [20]. Recent applications refine demand modeling and correct for multi-destination trips and substitution patterns, including studies of national parks that demonstrate persistent policy relevance [21].

2.2.3. Stated-Preference (SP) Methods

For many non-use and cultural services lacking observable market behavior, SP methods are indispensable. Contingent valuation (CV) elicits WTP for specified changes; choice experiments (CE) recover marginal WTP for attributes by analyzing choices among scenarios with varying attribute levels and costs [22]. Good practice emphasizes consequential framing, scope sensitivity, and treatment of preference heterogeneity; nonetheless, hypothetical bias and framing effects remain concerns that require careful instrument design and validation [23]. Beyond carbon quantity, CE has been used to uncover preferences for the attributes of conservation instruments—for example, Japanese SMEs' premia for locally generated forest carbon credits and for co-benefits such as local employment and SDG contributions [24].

2.2.4. Benefit Transfer and Non-Monetary Approaches

When primary studies are infeasible, benefit transfer adapts estimates from study sites to a policy site; accuracy depends critically on ecological and socio-economic similarity and on the quality of the underlying evidence [25,26]. Recognizing limits to monetization—especially for cultural services—non-monetary approaches (e.g., analysis of geo-tagged social media, participatory GIS, qualitative inquiry) can surface plural and place-based values that complement, not replace, monetary metrics [26,27].

A persistent source of confusion is the welfare versus accounting distinction. Welfare analysis (for project appraisal) seeks changes in social surplus, including consumer and producer surplus, whereas national accounting (e.g., SEEA-EA, consistent with the SNA) compiles exchange values derived from observed or imputed market transactions and explicitly excludes consumer surplus [27,28]. The two perspectives can yield starkly different magnitudes—e.g., a protected-area application reporting USD 1.62 million from a resource-rent (accounting-compatible) method versus USD 65.19 million from a travel-cost (welfare-based) estimate including consumer surplus [27,29]. Rather than a dilemma, this reflects different questions: “What is the exchange value consistent with accounts?” versus “What does the welfare change from a policy or environmental change?” The best practice

is to choose the metric that fits the decision, label it unambiguously, avoid cross-use without reconciliation, and disclose uncertainty.

2.3. Global Applications: Quantifying the Economic Value of Key Services

Applications across watersheds and forests illustrate the policy salience and methodological range of valuation studies [30].

2.3.1. Watershed Protection

Cities face rising treatment costs as land degradation degrades source waters; investing in conservation (e.g., reforestation, improved practices) can be cost-effective relative to gray infrastructure [31]. Rigorous appraisals couple biophysical models (e.g., sediment or nutrient loads) with economic valuation of welfare or cost changes. A valuation of the Upper American River Watershed (California) used benefit transfer, calibrated with local data, to estimate annual value exceeding USD 14.8 billion across eighteen ecosystem and geologic services, providing a common metric for comparing natural capital investments with built infrastructure [22]. Advanced hydrologic–ecosystem modeling (e.g., Hydro Geosphere) has also been used to isolate the marginal productivity of subsurface “green water,” with estimates showing substantial contributions to ecosystem services during drought and total annual values peaking above CAD 424 million in extreme years—evidence that hydrologic stores not directly visible in markets can be economically material [32]. These studies exemplify how integrated modeling, and valuation can reframe watershed restoration as an economically grounded investment rather than a purely environmental expense [31].

Payments for Ecosystem Services (PES) have become a critical tool for protecting watershed services. In Costa Rica, the PES program compensates landowners for forest conservation, which enhances water quality and reduces the need for costly gray infrastructure, such as water treatment plants. The economic value of these ecosystem services is significant, with estimates exceeding USD 14.8 billion annually across various regions [33]. However, a challenge is ensuring that payments are tied to actual environmental improvements. By integrating remote sensing and ground-based data, such as satellite imagery and water quality monitoring, PES programs can be more accurately assessed and adjusted. Additionally, cost–benefit analyses comparing nature-based solutions like reforestation to traditional infrastructure investments provide compelling evidence that PES is a cost-effective strategy for urban water supply challenges. This approach aligns well with broader environmental and economic goals, making it an attractive policy option for cities facing water scarcity [34].

2.3.2. Forest Carbon Sequestration

Forests regulate climate by sequestering and storing carbon; valuing this service informs mitigation policy and underpins crediting systems. National-scale assessments have employed avoided-damage and mitigation-cost approaches, such as valuing annual sequestration in Hungary at approximately €525 million [35]. Stated-preference studies reveal demand for attributes of credits as well as for carbon quantities: a 2024 experiment in Japan found SMEs willing to pay premia for locally generated credits and for projects delivering co-benefits such as employment and SDG contributions, implying the scope to enhance market value by bundling local benefits [36]. Technological advances, including high-resolution satellite imagery and convolutional neural networks, now enable scalable biomass and carbon-stock mapping (e.g., in Quito, Ecuador), strengthening measurement, reporting, and verification as well as supporting conservation finance and market design [37]. Together, these applications show that diverse valuation tools, when carefully matched to decision contexts and supported by robust biophysical evidence, can make the economic stakes of conservation legible to policymakers and investors.

Forest carbon sequestration plays an essential role in mitigating climate change, and PES is increasingly used to incentivize this service. In Hungary, the value of forest carbon sequestration is estimated at approximately EUR 525 million annually, demonstrating the significant economic benefits of forest conservation [38]. The integration of PES with carbon markets improves these programs' effectiveness. In Japan, small- and medium-sized enterprises (SMEs) are willing to pay premiums for carbon credits from local projects that provide additional benefits, such as job creation and contributions to the SDGs [24]. Advances in satellite imagery and AI-driven models, such as Convolutional Neural Networks (CNNs), have improved the precision of carbon stock measurements, enhancing monitoring and verification (MRV) processes for carbon sequestration [39]. Linking local development goals with forest carbon sequestration services ensures that PES can drive both environmental protection and sustainable economic growth [38].

3. The Economics of Biodiversity: From Costs of Loss to Incentives for Conservation

3.1. *The Dual Value of Biodiversity: Ecological Function and Economic Foundation*

Biodiversity is often treated as a peripheral environmental issue rather than a core economic concern. This is a category error. From an ecological–economic perspective, biodiversity has a dual value: it is the living machinery that enables ecological functions and the foundational asset base upon which natural capital-dependent economic activity ultimately rests [40]. Biodiversity is not merely one item in the ecosystem-services ledger; it is the infrastructure that underwrites the provision, stability, and resilience of nearly all services. Genetic diversity in crops buffers production against pests and climate stress; species diversity in forests regulates hydrological cycles and soil processes; and diversity across ecosystems creates habitat mosaics that sustain complex interactions and functions [7].

The economic significance of this functional role is substantial. More diverse systems tend to be more productive and stable, providing “natural insurance” that secures the supply of provisioning services—food, water, timber—under variable and increasingly volatile conditions [7]. Functional redundancy and response diversity allow ecosystems to absorb shocks and maintain performance when individual species fail, reducing variance in service flows and the costs of disruptions. In this light, biodiversity conservation is not a discretionary amenity to be pursued after growth; it is a strategic investment in preserving the productive capacity of the biosphere and, by extension, the long-run viability of human economies [41].

3.2. *Quantifying the Economic Consequences of Biodiversity Decline in Key Sectors*

The costs of biodiversity loss are already visible in sectoral balance sheets. Translating ecological degradation into economic terms clarifies the return on investment in conservation and the risks of inaction [42]. As illustrated in Figure 2, habitat-loss and fragmentation hotspots are heavily concentrated in tropical protected areas of South America and Africa, accentuating the sector-specific economic vulnerabilities discussed below [43].

The clustering of ecological degradation in these biodiversity hotspots implies that sectoral revenues—ranging from pollinator-dependent crops to reef-based tourism—are disproportionately exposed to localized habitat loss.

3.2.1. Agriculture

Crop production depends critically on biologically mediated services, notably animal pollination. A large share of global food crops relies on bees, butterflies, birds, and other pollinators, with estimated contributions of roughly USD 235–577 billion annually to global crop output [44]. Pollinator declines driven by habitat loss, pesticide exposure, and climate stress threaten yields, quality, and farm incomes. In the United States, honeybee

pollination services are valued at about USD 15 billion per year, with the Californian almond sector—entirely reliant on managed pollination—illustrating how ecological shocks can translate quickly into economic losses if biological substitutes fail [45]. Substituting manual pollination or other engineered responses is typically costlier and less effective, implying higher consumer prices and reduced food security [45].

3.2.2. Fisheries

Marine biodiversity underpins commercial fisheries and coastal livelihoods. Over-exploitation and habitat degradation erode stock productivity and ecosystem stability, with some assessments warning that continued trends risk widespread stock collapses within decades, with severe economic consequences for coastal economies [44,46]. The 71% decline in oceanic shark and ray populations since the 1970s exemplifies how losing apex and mesopredators disrupts food webs and cascades through ecosystems [47]. Coral reefs—nurseries for many commercial species and anchors of tourism—face compounding threats from warming, acidification, and local stressors; their degradation could entail losses on the order of up to USD 1 trillion per year by 2100 across fisheries, tourism, and coastal protection [48]. These patterns underscore that unsustainable harvest is not only ecologically harmful but also economically self-undermining [49].

3.2.3. Other Sectors

Forestry performance is sensitive to biotic diversity and structural complexity, which influence growth rates, disease resistance, and climate resilience; reduced diversity can lower productivity and raise risk [39]. Tourism, a major export for many countries, depends on biodiverse seascapes and landscapes—from reefs to protected areas—whose degradation diminishes recreational and esthetic value. At the system scale, the loss of regulating services (e.g., carbon storage) imposes diffuse but material costs. Deforestation and degradation reduce terrestrial carbon sinks and amplify climate damages, with estimates of climate-change costs from land-use change alone reaching into the trillions annually within the next decade. Taken together, these examples demonstrate that biodiversity is not a cost center but a high-value asset whose depreciation carries substantial macro- and microeconomic risks [50].

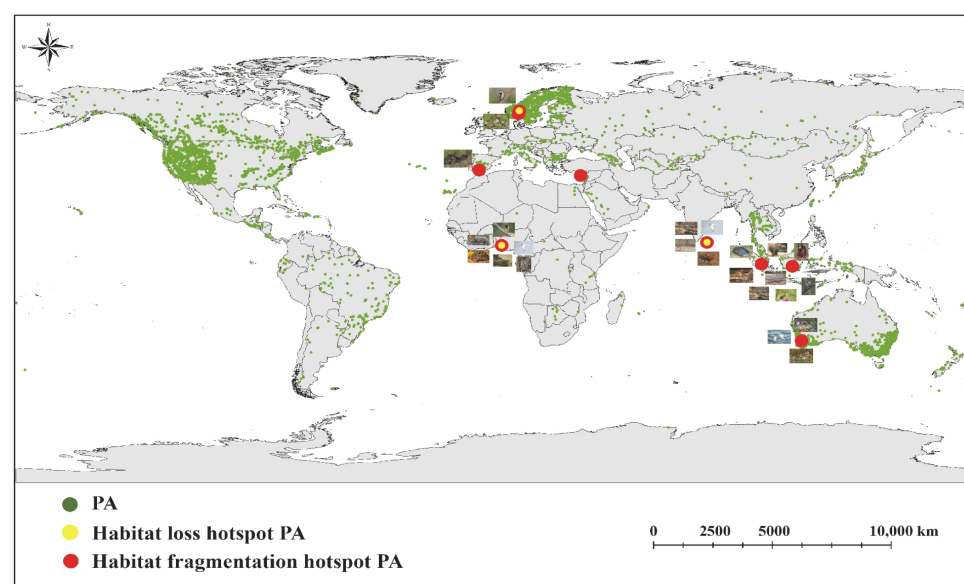


Figure 2. Global hotspots of habitat loss and fragmentation (2000–2020). Reproduced from Smith et al. [43]. Copyright 2024 Elsevier.

3.3. Economic Instruments for Conservation: Payments for Ecosystem Services (PES) and Innovative Finance

Recognizing value is necessary but not sufficient; mechanisms are required to translate value into incentives for conservation-compatible behavior [51].

Payments for Ecosystem Services (PES). PES are among the most prominent market-based instruments. In a canonical formulation, a PES scheme is a voluntary transaction in which a well-defined service (or service-securing land use) is purchased by at least one buyer from at least one provider if—and only if—provision is secured (conditionality). Implementations range from downstream users compensating upstream landholders for source-water protection to public or private payments for forest conservation to deliver carbon sequestration and biodiversity benefits. Global expenditures on PES have been estimated in the tens of billions of dollars annually [52].

Experience reveals both promise and pitfalls. Narrowly targeting a single service (e.g., carbon) can create new externalities, such as monoculture plantations that depress biodiversity or alter hydrology. Payments can crowd out intrinsic conservation motives if not carefully designed, weakening stewardship if payments cease. Efficiency objectives may conflict with equity, as cost-effectiveness can favor larger landholders with lower opportunity costs, excluding smaller or poorer participants. Finally, designing, monitoring, and enforcing conditional contracts entails transaction and monitoring costs that can erode net benefits [53].

Case: Costa Rica's PSA. Costa Rica's national program (PSA) has been a touchstone for both achievements and limitations. Established in 1997, PSA pays for four bundled services—carbon sequestration, biodiversity protection, water regulation, and scenic beauty—funded by fuel taxes and user fees (e.g., hydropower) [54,55]. Over time, the program has transferred more than USD 524 million to >18,000 families and enrolled >1.3 million hectares, supporting reforestation and agroforestry adoption and providing supplementary income. Yet additionality has been contested because PSA followed the 1996 Forestry Law that banned clearing of mature forests; many enrolled parcels faced low deforestation risk regardless, implying modest direct effects on deforestation rates in some evaluations. Equity concerns also arose early, with participation skewed toward larger, wealthier landholders better able to navigate administrative requirements. Institutional adaptations—such as an agroforestry (SAF) modality tailored to smallholders—were introduced to improve inclusion [56]. The broader lesson is that PES perform best as part of a hybrid governance model, anchored by clear regulatory baselines and evolving through adaptive design to balance ecological effectiveness with social equity [57].

Innovative biodiversity finance. Beyond traditional PES, emerging mechanisms aim to mobilize private capital at scale to close the biodiversity finance gap. Biodiversity credits/certificates monetize measurable positive outcomes (distinct from offsets that compensate damage), creating potential revenue streams for conservation and restoration. Blended finance structures use public or philanthropic funds to de-risk projects and crowd in private investment (e.g., guarantees for sustainable agriculture funds). Financing nature-based solutions (NbS)—actions that protect, manage, and restore ecosystems to address societal challenges while delivering biodiversity and well-being—seeks multiple benefits from single investments. These instruments are promising but immature. Achieving high integrity will require clear policy frameworks, robust governance, and credible, standardized methods for measuring, verifying, and attributing biodiversity outcomes, with safeguards for equity and transparency [58].

4. Bridging the Divide: Integrating Ecology and Economics in Policy and Governance

Integrating ecological and economic approaches requires bridging several fundamental gaps. Key pillars of this integration include establishing a common framework (e.g., treating ecosystems as natural capital to link ecology and economy), aligning economic incentives with ecological goals (for instance, Payments for Ecosystem Services and carbon markets), and strengthening governance mechanisms that foster synergy between conservation and development. In the following sections, we have expanded our discussion on these pillars and their interfaces in detail, underscoring the integration of ecological and economic approaches as a focal point of this review.

4.1. Designing Effective Eco-Economic Policy Instruments: Carbon Pricing and Green Taxation

Operationalizing ecological-economic principles require instruments that internalize environmental externalities while preserving incentives for efficient abatement and innovation. Carbon pricing is central to this architecture because it directly aligns private costs with the social costs of greenhouse-gas emissions. Two canonical modalities—carbon taxes and emissions trading systems (ETS)—embody distinct advantages and trade-offs (see Table 3) [59]. Yet recent evidence indicates that almost 60% of the CO₂ emitted by the world’s rivers derives from millennia-old carbon reservoirs, a flux that can be misidentified as fossil-fuel emissions in ¹⁴C-based inventories, thereby inflating apparent anthropogenic totals [33]. This adds an additional layer of uncertainty to baseline inventories, suggesting that price instruments might need wider safety margins or dynamic adjustment clauses.

Table 3. A Comparative Analysis of Carbon Pricing Mechanisms [59].

Feature	Carbon Tax	Cap-and-Trade (ETS)
Primary Control Variable	Price (tax rate per ton of CO ₂ e)	Quantity (total emissions cap)
Price Certainty	High (price is set by the government)	Low (price is determined by the market and can be volatile)
Emissions Certainty	Low (emissions reduction depends on economic response to the price)	High (total emissions are fixed by the cap)
Administrative Complexity	Relatively low (can be integrated into existing tax systems)	High (requires setting up a market, allocating allowances, and monitoring trades)
Revenue Generation	Predictable revenue stream for the government	Revenue can be generated if allowances are auctioned, but can be volatile
Vulnerability to Volatility	Less vulnerable to economic shocks (tax rate is stable)	Price of allowances can crash during economic downturns, reducing the incentive to abate
Key Political Challenge	Politically difficult to set a tax rate high enough to be effective	Allocation of free allowances can create windfall profits and political opposition

A carbon tax sets a statutory charge per metric ton of CO₂-equivalent emissions, thereby delivering price certainty to firms and households [60]. This predictability lowers planning risk and supports capital reallocation toward low-carbon technologies. Fiscal receipts can be recycled to finance green investment, reduce distortionary taxes (a “green tax shift”), or be rebated as equal dividends to address distributional concerns and political feasibility [53]. The principal limitation is quantity uncertainty: the realized emission reductions depend on behavioral responses to the price, which are uncertain ex ante and may vary with macroeconomic and technological conditions [61].

An ETS (cap-and-trade) fixes a total emissions quantity by issuing a finite number of tradable allowances over a compliance period [62]. Trading allocates abatement to actors with lower marginal costs, delivering cost-effectiveness under the cap. The strength of the ETS is environmental certainty at the aggregate level, but this comes with price uncertainty: allowance prices can be volatile owing to business cycles, fuel switching, policy expectations, and technology shocks [59,63]. Design features can mitigate these drawbacks. Hybrid architectures—such as auction price floors/ceilings, market-stability reserves, and allowance banking/borrowing—temper volatility while preserving the environmental integrity of the cap, thereby combining the salient strengths of price- and quantity-based approaches [60]. In practice, the “tax versus cap” debate is best understood as a choice over how to manage uncertainty—costs under a tax, quantities under a cap—rather than a binary assessment of instrument superiority [61].

4.2. *Synergies in Governance: Combining Market-Based and Command-and-Control Mechanisms*

Framing environmental policy as a dichotomy between market-based instruments (e.g., carbon pricing, PES) and command-and-control regulation (e.g., performance standards, technology mandates) obscures their complementarity in well-designed policy mixes. Market mechanisms require—and are constituted by—regulatory foundations: an ETS exists only because a public authority sets and enforces the cap; water-quality trading depends on legally binding total maximum loads and credible monitoring [64]. Conversely, targeted regulations can correct residual market failures that uniform prices do not fully address, such as innovation externalities (under-investment in R&D), network effects, or information asymmetries in consumer product markets [65].

High-ambition decarbonization and biodiversity goals typically demand coordinated policy packages. A broad carbon price provides economy-wide incentives; minimum performance standards prevent backsliding and address non-price barriers; disclosure and taxonomy rules lower transaction costs for green finance; and public procurement and concessional lending de-risk emerging technologies [65,66]. Internationally, the Paris Agreement (Article 6) reflects this integrated paradigm by enabling both market mechanisms (cooperative approaches and crediting) and non-market forms of cooperation (e.g., policy coordination, fiscal measures), recognizing that heterogeneous national circumstances and evolving technologies necessitate diverse instruments operating in concert. The governance challenge is therefore one of coherence: aligning objectives, timelines, and compliance systems so that instruments are mutually reinforcing rather than duplicative or contradictory [66].

4.3. *Policy in Practice: Global Case Studies of Integrated Ecological–Economic Governance*

Empirical experience from firms and jurisdictions illustrates how integrated policy and management can deliver both environmental and economic gains, clarifying design choices for scaling impact. AI-driven methods are increasingly being integrated into ecological–economic governance, with significant implications for ecosystem service valuation, PES design, and overall policy decision-making [67].

4.3.1. Corporate Practice

Leading firms increasingly embed sustainability within core operations, using data-driven management to capture efficiency gains and reduce risk exposure [68]. United Parcel Service’s ORION (On-Road Integrated Optimization and Navigation) deploys large-scale route optimization to reduce mileage and idling, reportedly saving ~10 million gallons of fuel and ~100,000 t CO₂ annually demonstrating how operational analytics translate directly into cost and emissions reductions [69]. IKEA’s IWAY supplier code integrates environmental and social criteria into procurement (e.g., water/waste management, worker

rights), improving supply-chain resilience and brand value while diffusing higher environmental standards across tiers. Airbus leverages additive manufacturing to reduce component weight, improving fuel efficiency over aircraft lifetimes; estimates attribute substantial avoided emissions to such weight savings on high-utilization platforms (e.g., the A320 family) [70]. These examples show how internal carbon-and-cost accounting, digital optimization, and supplier governance can function as micro-level complements to economy-wide pricing and standards.

4.3.2. Public Policy

Governments around the world are pairing economic instruments with social policy to achieve measurable environmental and economic outcomes. For example, British Columbia's carbon tax uses revenue recycling—such as lowering corporate taxes and providing targeted low-income credits—to mitigate the potential regressive effects while maintaining abatement incentives [71]. In Germany, the Coal Commission developed a just-transition process, incorporating worker retraining and regional development alongside a coal exit, aligning climate objectives with social equity [72]. Mexico's EcoCasa program uses green mortgages to stimulate energy-efficient housing, benefiting both the environment and low-income households.

AI tools can further enhance these policies by providing data-driven insights to improve targeting, distribution, and effectiveness. Machine learning models can optimize the design of PES programs by identifying regions that are most in need of environmental interventions, ensuring that resources are allocated efficiently. For example, AI models can predict the impact of various policy options, such as PES versus regulatory measures, to help governments make informed decisions on environmental resource allocation. Additionally, AI can enable real-time monitoring and adjustments to policies, ensuring that they remain effective as environmental conditions and socio-economic factors evolve.

4.3.3. The Role of AI in Ecological–Economic Integration

AI offers significant advantages in integrating ecological and economic approaches to governance. The use of machine learning and remote sensing enables policymakers to access more accurate and timely data for decision-making. However, integrating AI in policy decisions requires addressing key challenges, notably the trade-off between computational efficiency and model interpretability. While AI models can handle complex datasets and make predictions, they often operate as black boxes, making it difficult for policymakers to understand how decisions are made [73,74].

To ensure the responsible and effective use of AI in ecological–economic governance, explainable AI (XAI) techniques, such as SHAP (Shapley Additive Explanations) values and feature importance analysis, can be used to clarify the relationships between inputs and outputs. This transparency is essential for maintaining trust in AI-driven policy decisions. Moreover, integrating human expertise in ecology with AI models can improve the ecological validity of predictions and ensure that the models align with broader sustainability goals [75].

5. Charting a Path to Sustainability: A Unified Ecological and Economic Vision

5.1. Aligning with Global Agendas: The Role of Natural Capital in the Sustainable Development Goals (SDGs)

The 2030 Agenda articulates an integrated set of 17 Sustainable Development Goals (SDGs) that collectively define the principal dimensions of human well-being. An ecological–economic lens makes explicit that progress toward these goals is contingent on

the condition and stewardship of natural capital: the SDGs are not separable objectives but an interdependent system in which environmental sustainability constitutes a prerequisite for social and economic advancement [76]. Empirical syntheses have mapped these interdependencies, showing that at least 16 ecosystem services make material contributions to 41 targets across 12 SDGs [77]. Illustratively, SDG 2 (Zero Hunger) depends on provisioning services (food, fisheries) and regulating services (pollination, soil fertility); SDG 3 (Good Health and Well-Being) benefits from water and air purification, medicinal resources, and the psychological benefits of access to nature; SDG 6 (Clean Water and Sanitation) rests on hydrological services provided by forests, wetlands, and watersheds; and SDG 13 (Climate Action) relies on the carbon sequestration and storage functions of forests, oceans, and soils.

This evidence supports a causal chain: sustainable economic models that maintain natural capital secure the flows of ecosystem services, which in turn enable achievement of multiple SDG targets in tandem [77]. The policy implication is operational: ecosystem services should be treated as the biophysical linkage between economic activity and human well-being and therefore embedded in planning, budgeting, and appraisal—through natural capital accounting, ecosystem-service indicators in results frameworks, and routine use of environmental distributional analysis. Designing interventions around these linkages improves synergy (one investment advancing several targets) and cost-effectiveness (reducing the need for compensatory spending elsewhere). By contrast, an SDG strategy that neglects the natural capital base risks internal inconsistency and fragility—“building on sand”—as environmental degradation erodes the very capacities upon which social and economic goals depend [78].

5.2. Economic Paradigms for Sustainability: Green, Circular, and Low-Carbon Economies

Delivering the SDGs requires a transition away from linear, resource-depleting production–consumption patterns toward economic systems that respect biophysical limits while fostering inclusion and innovation [79]. Three overlapping paradigms provide complementary guidance.

The Green Economy, as defined by UNEP, is “low carbon, resource efficient and socially inclusive,” underpinned by principles of well-being, justice, planetary boundaries, efficiency and sufficiency, and good governance [80]. It reframes prosperity in terms of human, social, and natural capital, rather than financial aggregates alone, and orients policy toward maintaining the asset base that sustains well-being over time. Moreover, we have discussed these findings in a broader sustainability context and identified future research directions (e.g., exploring AI-integrated valuation and long-term policy monitoring) to further advance this field.

The Circular Economy operationalizes resource efficiency by challenging the “take–make–use–dispose” logic of linear systems. It emphasizes product and system design for durability, repair, reuse, remanufacturing, and high-quality recycling, keeping materials at their highest utility and value while minimizing virgin extraction and waste. In practice, the green economy provides the normative and strategic envelope (what to achieve and why), while the circular economy contributes design and operational principles (how to achieve it) [81–84].

The Low-Carbon Economy focuses on the specific imperative of greenhouse-gas mitigation. It is a necessary but not sufficient condition for sustainability: decarbonization must be complemented by sustainable management of water, soils, and biodiversity and by attention to equity and resilience. Conceptually, these paradigms are nested rather than competing: a low-carbon economy is a core component within green and circular frameworks, and circular strategies often enable decarbonization by reducing energy and material intensity [85]. Effective policy translates this nesting into instrument mixes—

prices, standards, innovation policy, green finance, and disclosure—that jointly pursue decoupling from environmental pressures while expanding opportunity sets.

5.3. *The Ecological Foundation of Sustainability: Resilience, Restoration, and Planetary Boundaries*

No economic paradigm can be sustainable unless it operates within the finite assimilative and regenerative capacities of the biosphere [86]. The planetary boundaries framework formalizes this constraint by identifying nine critical Earth-system processes and proposing quantitative thresholds consistent with a “safe operating space” for humanity—conditions broadly characteristic of the Holocene state in which complex societies flourished. A sustainable economy, by definition, must observe these limits in aggregate and over time, integrating them into targets, budgeting, and risk management [87].

Moving from avoidance to recovery is therefore essential. Ecological restoration—assisting the recovery of degraded ecosystems—rebuilds natural capital and delivers co-benefits: enhanced biodiversity, increased carbon sequestration and storage, improved water quality and regulation, and greater resilience of coupled human–natural systems to climate extremes [88]. Restoration should be planned as an intertemporal investment with measurable returns, embedded in landscape strategies that align conservation, production, and livelihood goals.

At the system level, resilience—the capacity to absorb disturbances while maintaining essential functions and structure—is the ecological foundation of sustainability. Biodiversity contributes to resilience via functional redundancy and response diversity, stabilizing service flows amid variability and shocks. A sustainable economy must mirror these properties: diversified portfolios of technologies and resources; adaptive governance with monitoring, learning, and revision clauses; and explicit recognition of dependence on life-support systems. Anchoring economic transformation in resilience, restoration, and planetary boundaries provides a coherent bridge between ecological science and policy design, ensuring that progress toward the SDGs is both feasible within Earth-system limits and durable in the face of uncertainty and change [89–91].

5.4. *Long-Term Implications: Ecological–Economic Integration in the Face of Global Change*

As the world grapples with the accelerating impacts of climate change, the long-term success of ecological-economic integration will increasingly depend on adapting economic systems to evolving environmental conditions. Future climate scenarios predict more frequent and severe weather events, shifting ecosystems, and fluctuating resource availability, which will directly affect ecosystem services such as water regulation, crop production, and carbon sequestration [37,92].

To effectively manage these changes, ecological economics will need to evolve by incorporating adaptive models that consider the unpredictability of future environmental shifts. Long-term sustainability requires integrating dynamic environmental risk assessments and developing policies that enhance the resilience of ecosystems and the economies dependent on them [93].

Moreover, the rise of emerging technologies like geoengineering and synthetic biology will pose new challenges and opportunities for ecological–economic integration. Geoengineering techniques, such as carbon capture and solar radiation management, could offer temporary solutions to climate issues but may also disrupt ecological balance and ecosystem services. Similarly, synthetic biology holds the potential to create new organisms that could support ecosystem functions, but these innovations also present risks related to biodiversity and ecological stability [94,95].

Incorporating these technologies into policy frameworks requires careful consideration of their long-term impacts on ecosystems and the potential unintended consequences for both natural and human systems. As ecological–economic integration evolves, the role

of ecological economics in assessing these technologies and guiding their responsible use will become more critical in ensuring that economic growth does not come at the cost of environmental and social well-being.

6. Frontiers and Headwinds: Challenges and Future Directions

6.1. Overcoming Interdisciplinary Barriers in Ecological Economics

Despite the clear imperative for integrating ecology and economics, the practical execution of truly interdisciplinary research remains a formidable challenge. The two fields have evolved with distinct theoretical foundations, methodologies, and academic cultures, creating significant barriers to collaboration. Research has shown that these barriers are not merely intellectual but are deeply embedded in the incentive structures of academia [96].

A primary obstacle is asymmetric information. Researchers in one discipline often lack the specialized knowledge to rigorously evaluate the methods and conclusions of the other. This raises the costs and lowers the rewards for engaging in interdisciplinary work, as researchers face greater difficulty in getting their work published in top-tier journals and recognized by tenure and promotion committees that are typically organized along disciplinary lines. This creates a powerful incentive for “disciplinary lock-in,” where even researchers who are willing to collaborate find it safer and more rewarding to remain within their specialized silos [97].

Furthermore, when faced with the inherent complexity of coupled social–ecological systems, research teams often retreat to a compartmentalized approach, dividing the problem along disciplinary lines and attempting to “reassemble” the pieces later [98]. This approach frequently fails to capture the emergent properties and feedback loops that are characteristic of such systems. Overcoming these challenges requires more than just goodwill; it demands the creation of new institutional structures that can support and reward interdisciplinary research. This includes developing shared terminologies, implementing adaptive research designs where ecologists and economists co-create research questions and protocols from the outset, and fostering journals and funding agencies with the expertise to properly review and value integrated research [98]. Without such institutional reforms, the gap between the recognized need for interdisciplinary research and its actual practice is likely to persist [99].

6.2. The Next Generation of Ecological–Economic Modeling and Data Integration

The future of ecological economics will be heavily influenced by advancements in modeling and data integration. A key goal is to develop more sophisticated integrated assessment models that can seamlessly link biophysical processes to economic outcomes and human well-being. Currently, many valuation studies rely on a fragmented process where the output of a biophysical model (e.g., tons of sediment retained by a forest, from a model like the Soil and Water Assessment Tool, SWAT, or InVEST) is used as an input into a separate economic valuation model [100]. Future models should aim to more dynamically couple these components, allowing for the analysis of feedback loops between human decisions and ecosystem responses [101].

A persistent challenge across all areas of ecological economics is the lack of high-quality, high-resolution data. This is a critical limitation in the evaluation of PES programs, where a lack of baseline data makes it difficult to assess additionality, and in the application of the benefit transfer method, where data limitations can lead to inaccurate value estimates. Future research must prioritize the collection of long-term ecological and socioeconomic data, particularly in data-poor regions of the Global South. The development of new biophysical models for services that are currently difficult to quantify is also a critical research frontier. Improving the precision and availability of data is fundamental to enhancing the credibility and policy relevance of ecological-economic analysis [102].

6.3. The Role of Artificial Intelligence: Opportunities and Pitfalls

Artificial Intelligence (AI) and machine learning (ML) are poised to revolutionize ecological-economic modeling, offering both unprecedented opportunities and significant new challenges. This emerging technology represents a double-edged sword for the field [103].

On one hand, AI offers powerful tools to overcome some of the field's most persistent problems. AI algorithms excel at analyzing vast, complex, and heterogeneous datasets (Big Data), identifying non-linear patterns and correlations that are often missed by traditional econometric and ecological models [104]. This capacity can dramatically improve the accuracy of forecasts, from predicting the economic impacts of climate change to modeling land-use change dynamics [104]. AI can integrate diverse data sources—such as satellite imagery, sensor data, economic statistics, and social media text—to create more holistic and dynamic models of coupled social–ecological systems [105]. To illustrate how multi-modal deep learning can be operationalized for monitoring, reporting, and verification (MRV), Figure 3 depicts the DeepBioFusion workflow proposed by Hanan et al. (2025) [106]. The pipeline fuses Sentinel-1 SAR and Sentinel-2 optical observations through parallel convolutional streams, followed by feature concatenation and gradient-boosted regression, ultimately delivering 10 m resolution above-ground biomass estimates with an error below $15 \text{ t} \cdot \text{ha}^{-1}$.

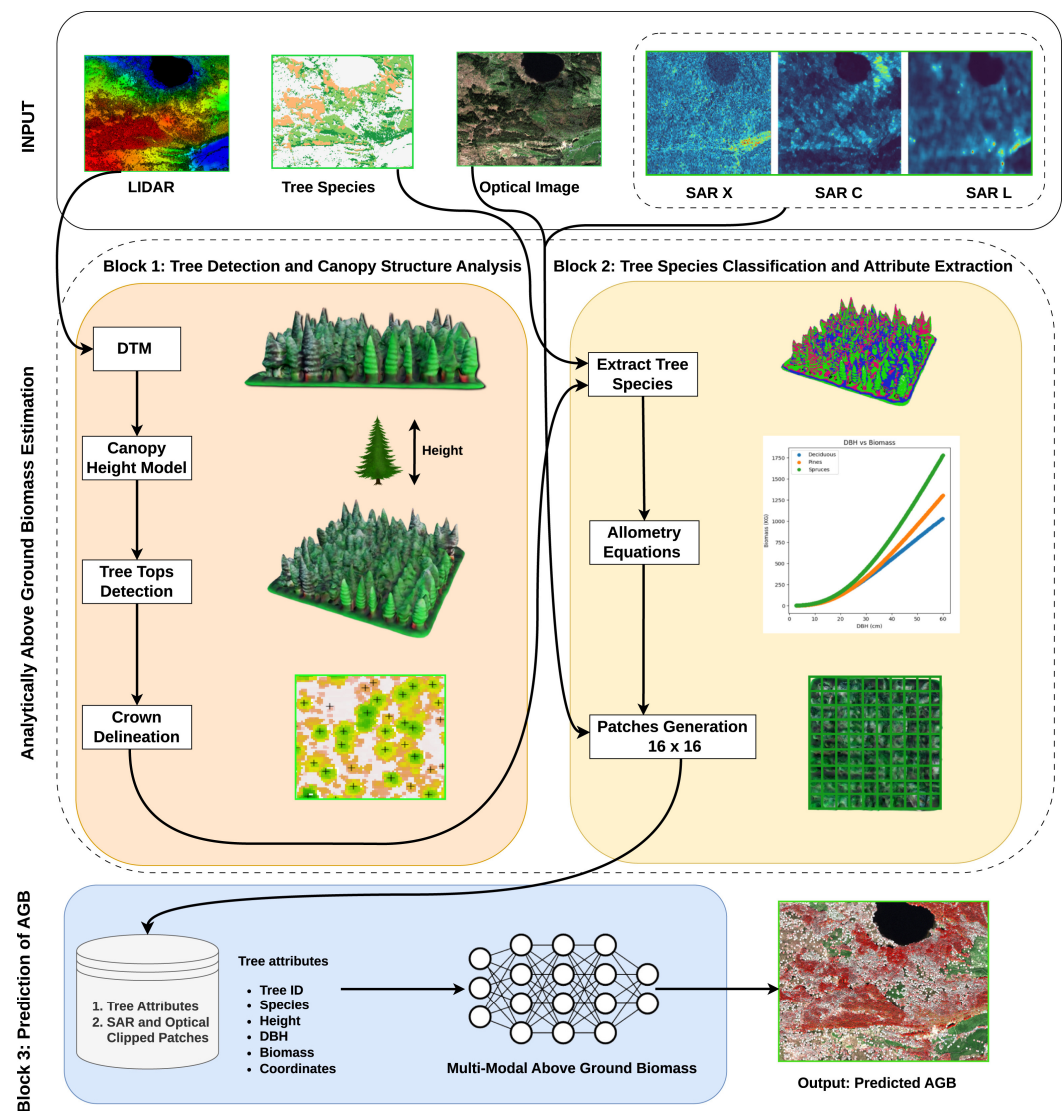


Figure 3. Workflow of the DeepBioFusion multi-modal deep-learning framework for above-ground biomass estimation [106]. Copyright 2025 Elsevier.

On the other hand, the rise of AI presents two profound challenges. The first is methodological. Many advanced AI models, particularly in deep learning, function as “black boxes.” While they may produce highly accurate predictions, their internal logic is often opaque, making it difficult to understand the causal mechanisms driving the results. This conflicts with a core goal of science, which is not just prediction but also explanation and mechanistic understanding. This creates a tension between the predictive power of AI and the explanatory goals of ecological and economic research.

The second challenge is a direct and deeply ironic environmental one. The computational power required to train and deploy large-scale AI models is immense. This process consumes staggering amounts of electricity and water for cooling data centers, contributing to increased carbon emissions and straining local resources [107]. The global electricity consumption of data centers, partly driven by AI, rose to 460 terawatt hours in 2022 [107]. This creates a paradox where a tool being developed to help solve sustainability challenges is itself becoming a significant driver of environmental pressure [108]. The future direction of the field will therefore involve a critical balancing act: harnessing the immense analytical power of AI while developing more transparent, explainable AI methods and mitigating the technology’s own substantial environmental footprint [109].

7. Conclusions: Synthesizing Insights and Charting the Path Forward

7.1. Recapitulation of Key Findings

Across the literature reviewed, a consistent message emerges: the persistent economic invisibility of nature within conventional accounts is a structural driver of degradation, and rectifying it is foundational to credible sustainability policy. Landmark initiatives—TEEB and the IPBES Global Assessment—have clarified that human well-being and prosperity are contingent on the condition of natural capital and the reliability of ecosystem-service flows, thereby underscoring the need to integrate ecological realities into core economic metrics and decisions. Methodologically, a mature valuation toolkit now exists, yet effective use requires matching metrics to decisions: welfare-oriented measures for project appraisal and distributional analysis versus accounting-compatible exchange values for national balance sheets and disclosure. Conflating these perspectives obscures trade-offs and can misguide policy; institutional pathways are therefore needed to channel valuation evidence into planning, budgeting, and regulation in a routine, transparent manner.

Experience with market-based conservation instruments, particularly Payments for Ecosystem Services, confirms their potential but also their dependence on context and institutional design. Evidence from Costa Rica’s PSA highlights that effectiveness and equity hinge on hybrid governance anchored in clear regulatory baselines and adaptive mechanisms to safeguard additionality, manage leakage, and broaden inclusion [46]. More broadly, a durable sustainability transition necessitates re-architecting economies along green, circular, and low-carbon lines that operate explicitly within planetary boundaries. Such reconfiguration is not merely technological; it requires overcoming institutional and cultural separations that perpetuate linear production–consumption patterns and impede cross-disciplinary problem solving [69,70].

7.2. Actionable Policy Recommendations for a Sustainable Future

For policymakers, three priorities follow. First, mainstream natural capital accounting—for example, SEEA-aligned frameworks—to reflect asset maintenance, depreciation, and restoration in national balance sheets and fiscal analysis, thereby improving the fidelity of macroeconomic signals beyond GDP [110]. Second, design hybrid, adaptive policy mixes that pair broad carbon pricing with targeted standards, innovation policy, and green finance, complemented by review clauses and distributional safeguards to address

unintended consequences and maintain legitimacy over time. Third, institutionalize science–policy interfaces—standing expert bodies, evidence registries, and valuation guidance—so ecological and economic evidence informs infrastructure planning, land-use allocation, and budget decisions in a timely and transparent fashion.

For the research community, priorities include bridging the theory–practice gap with decision-guidance on when and how to apply welfare versus accounting metrics; advancing coupled social–ecological integrated assessment capable of capturing feedback, thresholds, and heterogeneity; and developing transparent, explainable AI while measuring and reporting the environmental footprint of computational pipelines [111]. For business, adopting circular-economy operating models, investing in nature-based solutions as resilience assets and revenue opportunities (including carbon and emerging biodiversity credits), and integrating nature into corporate risk and dependency disclosures will strengthen long-run performance and align strategy with natural-capital maintenance [112]. Taken together, these actions offer a feasible pathway away from business as usual: by rendering nature’s value visible, creating durable incentives for conservation, and embedding planetary limits in policy architecture, societies can realign economic systems with the life-support functions on which they depend—advancing prosperity for people and planet alike.

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