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Integrating techno-economic analysis into restoration ecology: bridging ecological outcomes with financial feasibility

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Restoration ecology has become a critical discipline for addressing biodiversity loss, climate change, and ecosystem degradation. Yet, many restoration initiatives struggle to scale due to uncertain financial feasibility and limited integration of economic analysis into ecological planning. Techno-economic analysis (TEA), widely applied in energy and industrial systems, offers a structured framework for evaluating restoration interventions by combining technical performance metrics with cost-effectiveness and life-cycle economics. In this integrative review, I examine the role of TEA in restoration ecology to bridge ecological outcomes with financial viability. Drawing on examples from the literature of forest restoration, peatland rewetting, blue carbon ecosystems, and urban green infrastructure, the analysis reveals that TEA is particularly effective for optimizing high-capital, active restoration interventions, though less distinct in passive regeneration contexts. This review illustrates that while TEA enhances the transparency, comparability, and scalability of restoration projects, it also presents significant governance challenges, including regional data disparities, the risk of "carbon tunnel vision," and ethical concerns regarding the commodification of nature. I argue that integrating TEA into restoration ecology can strengthen investment decisions and support Payments for Ecosystem Services (PES) schemes, provided it is coupled with robust safeguards to ensure equitable outcomes. Ultimately, by systematically linking ecological and economic dimensions, TEA provides a powerful decision-support tool for designing resilient strategies capable of meeting the dual imperatives of conservation and climate adaptation.

KEYWORDS

ecological economics, ecosystem restoration, ecosystem services, environmental policy, nature-based solutions, restoration finance, techno-economic analysis

Highlights

- TEA bridges ecological science with financial feasibility for restoration
- Analysis reveals TEA is most effective for high-capital active restoration
- Binding laws like the EU Nature Restoration Law drive demand for TEA tools
- Unregulated TEA risks "carbon tunnel vision" and social exclusion
- Governance safeguards are essential to prevent the commodification of nature

1 Introduction

Restoration ecology faces urgent challenges in scaling up to meet global biodiversity and climate goals. Industrialization, unsustainable agriculture, and urban expansion have driven habitat loss and weakened ecosystem integrity, while pollution and invasive species further disrupt native systems (Schoonjans and Luttik, 2014; Meli et al., 2014). The Convention on Biological Diversity warns that nearly 1 million species risk extinction due to habitat degradation (Bayraktarov et al., 2019). Critical ecosystems such as peatlands and wetlands, vital for biodiversity and climate regulation, have suffered extensive damage, requiring adaptive strategies that account for dynamic conditions and climate projections (Gaffney et al., 2023; Ritson et al., 2025).

Biodiversity loss erodes genetic and functional diversity essential for resilience (Bayraktarov et al., 2020), while climate change further complicates restoration outcomes through altered hydrological regimes and extreme events (Budiharta et al., 2016; Basconi et al., 2019). Strategic interventions such as wetland restoration can reinstate ecological functions vital for pollination, soil fertility, and water purification (Kingsford et al., 2016). Yet many projects fail to achieve long-term success because ecological goals are rarely aligned with financial feasibility, underscoring the need for integrated approaches that combine ecological rigor with economic sustainability.

Techno-economic analysis (TEA) provides such a framework by linking ecological indicators with financial metrics to strengthen investment cases, support financing mechanisms like green bonds (Dondisch and Montanez, 2023), and ensure equitable socio-economic benefits (Carter et al., 2024). Historically, restoration initiatives overlooked financial viability, leading to failures in achieving ecological and economic objectives (Iftekhar et al., 2016). Calls for decision-support tools that evaluate ecological outcomes alongside economic sustainability highlight TEA's potential to fill this gap (Naidoo and Ricketts, 2006; Bodin et al., 2021).

Originating in energy systems analysis during the 1970s oil crises, TEA linked technical feasibility with economic variables (Saadha et al., 2025; Shoeb and Shafiullah, 2018). It has since evolved to include ecological dimensions, bridging environmental outcomes with financial realities (Li et al., 2020; Calvo et al., 2021; Maltby, 2022). Applications in renewable energy demonstrated its ability to combine environmental benefits with financial metrics (Hobbs and Harris, 2001; Wei et al., 2022; Haq et al., 2023; Padovezi et al., 2022). More recently, TEA has been adapted to restoration contexts, from reforestation and coral cultivation to coastal and agroecological systems (Lwanga, 2003; Xin et al., 2024; Ma et al., 2024; Sacco et al., 2021).

Despite promising applications, systematic use of TEA in restoration remains limited compared to energy, agriculture, and waste management, where it has optimized biorefineries, biofuels, and recycling (Biddy et al., 2016; Meramo et al., 2022; Mosalpuri et al., 2023). Scholars argue that broader adoption could improve project viability, scalability, and stakeholder support (Kang et al., 2023; Peng et al., 2022). This paper critically examines TEA's role in restoration ecology with three objectives: (1) explore potential applications drawing lessons from energy, agriculture, and waste management; (2) evaluate benefits in strengthening restoration planning, resource allocation, and stakeholder engagement; and (3) identify the methodological limitations, ethical risks, and governance challenges of applying TEA in ecological contexts. By bridging ecological outcomes with financial feasibility, TEA emerges as a vital decision-support tool for advancing restoration strategies that are both environmentally effective and economically sustainable.

Unlike previous reviews that examine restoration economics within specific ecosystem silos or rely on static valuation methods like Cost–Benefit Analysis, this paper provides the first comprehensive synthesis of TEA across diverse biomes, ranging from tropical forests and peatlands to blue carbon and urban infrastructure. By analyzing these distinct applications through a unified framework, I demonstrate that TEA is not merely a financial accounting tool, but a generative process-engineering instrument capable of operationalizing global restoration mandates. This review fills a critical gap in the literature by showing how TEA serves as the "transmission mechanism" that translates abstract ecological ambition into bankable, technically feasible projects.

2 Methodology and conceptual framework

2.1 Review methodology

This study adopts an integrative review approach (Whittemore and Knafl, 2005), which allows for the synthesis of diverse literature streams, specifically TEA and restoration ecology, to generate new conceptual frameworks. Unlike a systematic review, which focuses on aggregating empirical data to answer a narrow question, an integrative review is appropriate here as it permits the combination of experimental ecological data, economic modeling methodologies, and policy frameworks to provide a holistic understanding of TEA's potential.

Literature was identified using databases including Web of Science, Scopus, and Google Scholar, targeting the intersection of 'techno-economic analysis,' 'ecosystem restoration,' and 'financial feasibility.' The review prioritized literature published between 2010 and 2025 that offered transferable lessons from energy and industrial sectors to ecological contexts, aiming to construct a unified decision-support framework (Figure 1).

2.2 The TEA framework

TEA links ecological outcomes with financial feasibility by combining technical performance metrics with economic evaluation. System-dynamics modeling helps assess trade-offs (Crookes et al., 2013), while high restoration costs underscore the need for long-term cost-effectiveness analysis (Birch et al., 2010). Financial tools such as Net Present Value (NPV) clarify returns by balancing upfront expenditures with ecological and economic benefits (Cheng, 2025; Gasparinetti et al., 2022). Aligning biodiversity viability and ecosystem functionality with financial metrics supports more effective resource allocation (Martin and Lyons, 2018), and recent work stresses coupling ecological indicators with financial calculations to advance eco-resilient practices (Elias et al., 2024; Wei et al., 2022).

Adapting TEA to restoration ecology requires translating indicators such as species survival, carbon sequestration, and water quality into measurable economic variables. This strengthens investment cases and helps prioritize actions by integrating ecological conditions with

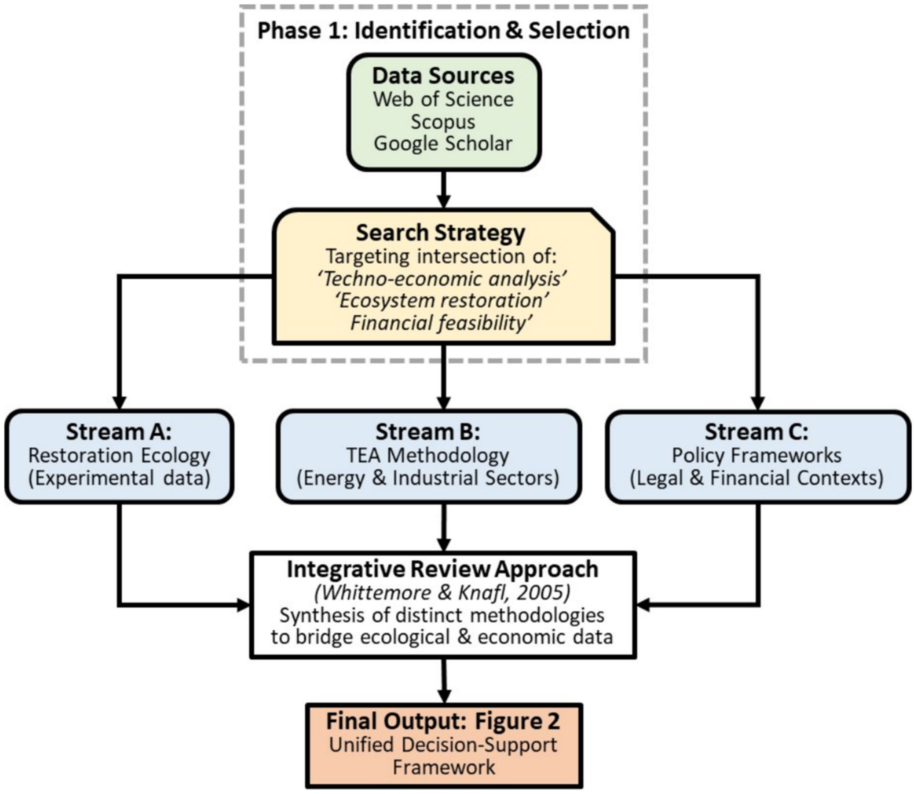

FIGURE 1
Methodological flowchart of the integrative review process.

financial costs (Adame et al., 2014; Liu et al., 2023). Frameworks that merge ecological metrics with financial assessments maximize ecological outcomes and economic viability (Groot et al., 2013), while sustainability metrics ensure long-term community and ecosystem benefits (Brancalion et al., 2019; Elias et al., 2024). Although valuing non-market ecosystem services remains challenging, contingent valuation and benefit transfer techniques offer pathways for assessing services such as water purification and carbon sequestration (Chen et al., 2023).

2.3 Comparative positioning: TEA vs. CBA, LCA, and ESV

While TEA shares data requirements with Cost–Benefit Analysis (CBA), Life Cycle Assessment (LCA), and Ecosystem Service Valuation (ESV), it remains analytically distinct in its granularity and directionality. Traditional tools are typically evaluative and retrospective, assessing a fixed restoration design to determine its net value or environmental footprint. For instance, CBA emphasizes financial efficiency but often undervalues biodiversity and resilience (Acuña et al., 2013). LCA evaluates environmental impacts across a project's lifecycle, offering sustainability insights but lacking financial feasibility integration (Vega et al., 2020). Similarly, ESV quantifies ecological benefits to strengthen stakeholder support but often struggles to translate these values into actionable technical planning (Wainger et al., 2017).

In contrast to these static assessments, TEA is generative and iterative. As summarized in Table 1, TEA functions as a process-engineering tool that links technical parameters such as seedling density, hydrological flow rates, or machinery fuel consumption directly to costs. This integrative capacity allows practitioners to identify specific "hotspots" of cost inefficiency and optimize the design before implementation (Gómez-Baggethun and Ruíz-Pérez, 2011). If a project appears unfeasible, TEA does not merely reject it; it triggers a feedback loop to re-engineer the technical specifications to achieve viability (Wang et al., 2023).

Crucially, TEA provides a distinct decision-making advantage by transforming these otherwise fragmented analytical outputs into a single, scenario-based framework. This elevates TEA from a mere aggregation of existing tools to a strategic decision-support system, changing the decision-making outcome from a binary "go/no-go" verdict to a "how-to" optimization process capable of guiding investment and policy design under real-world constraints.

Figure 2 presents TEA as the core analytical framework in restoration planning, positioned at the center of three established assessment methods: CBA, LCA, and ESV. The diagram shows directional linkages indicating how TEA draws from each method: CBA contributes financial efficiency metrics, LCA provides lifecycle environmental impact insights, and ESV supplies economic valuation of ecosystem services. By integrating these distinct inputs, TEA produces combined ecological-economic indicators that allow planners to compare restoration scenarios, quantify trade-offs, and evaluate feasibility under real-world constraints. The diagram emphasizes TEA's role as a unifying methodology that consolidates diverse data streams into a coherent structure, enabling stakeholders and policymakers to assess restoration options in terms of both ecological outcomes and financial viability. In doing so, TEA supports transparent

TABLE 1 Comparative analysis of decision-support frameworks in restoration ecology.

Methodology	Primary question	Key inputs	Analytical distinctness	Decision-making outcome
Cost–Benefit Analysis (CBA)	Is this project socially or financially profitable?	Market prices, discount rates, ES valuations.	Macro-level valuation: Aggregates total costs vs. total benefits of a *fixed* design.	Binary: Fund the project or reject it based on Net Present Value (NPV).
Life Cycle Assessment (LCA)	What is the environmental burden?	Energy inputs, material flows, emission factors.	Impact accounting: Tracks physical flows (carbon, water) from cradle to grave.	Selection: Choose Material A over Material B to minimize footprint.
Ecosystem Services Valuation (ESV)	What is nature worth?	Biophysical data, willingness-to-pay surveys.	Monetization: Translates non-market ecological functions into currency.	Justification: Provides the "Benefit" data for CBA.
Techno-Economic Analysis (TEA)	How do we engineer this to be viable?	Process parameters (e.g., flow rates, equipment capacity) + Unit costs.	Process optimization: Links *technical design* variables directly to financial performance.	Iterative optimization: "Change the technical design (e.g., reduce planting density by 10%) to make the project viable."

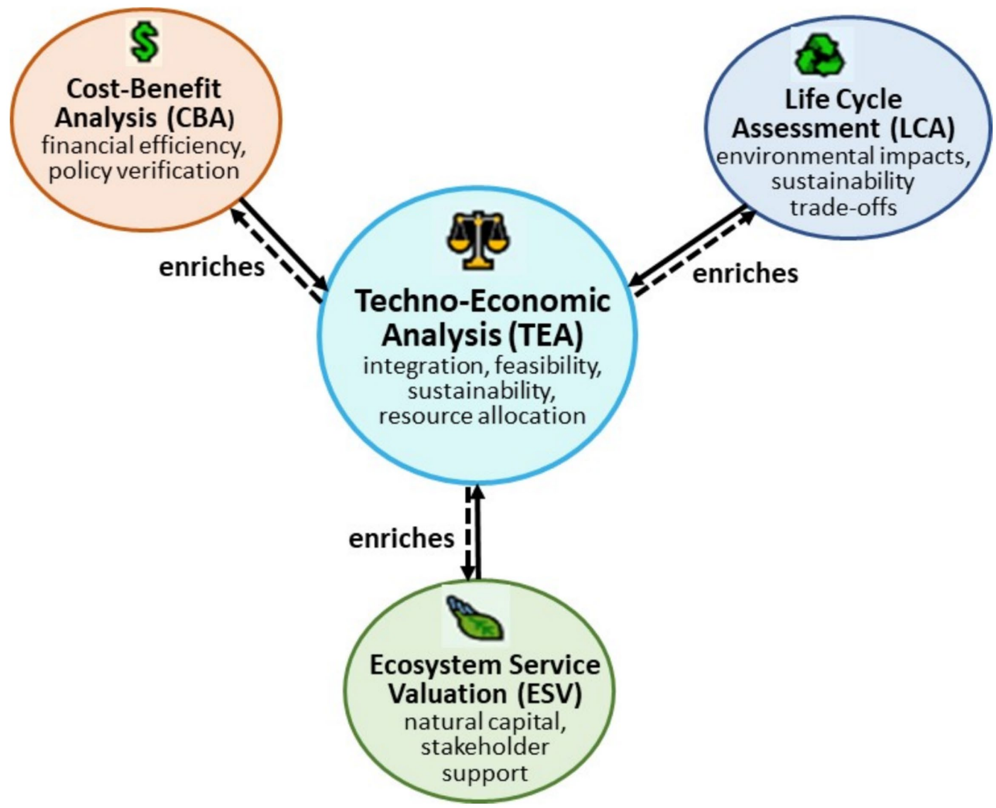

FIGURE 2
Conceptual framework of techno-economic analysis as an integrative decision-support system in restoration ecology.

decision-making, strengthens policy alignment, and guides the development of restoration strategies that are environmentally effective, economically resilient, and scalable across contexts.

3 Applications of TEA in restoration ecology

TEA is highly adaptable, linking ecological outcomes with financial feasibility across forests, wetlands and peatlands, blue-carbon systems, agroecological landscapes, and urban restoration. By integrating ecological indicators into financial models, TEA helps decision-makers balance ecological effectiveness, economic sustainability, and social impact.

3.1 Forest restoration

Forest restoration often weighs active planting against Assisted Natural Regeneration (ANR). TEA helps assess trade-offs between the

TABLE 2 Comparative evaluation of forest restoration strategies, active planting, assisted natural regeneration (ANR), and hybrid approaches.

Aspect	Active restoration (native species planting)	Assisted natural regeneration (ANR, passive restoration)	Hybrid approaches
Description	Planting native species, often in high-density mixed-species plantations; requires site preparation and ongoing management.	Relies on natural recovery processes with minimal intervention (e.g., weed removal, site protection).	Combines planting with ANR to optimize ecological and socio-economic outcomes.
Ecological outcomes	Accelerates biodiversity recovery; increases species richness in early stages; re-establishes ecological functions in severely degraded landscapes.	Higher success rates in biodiversity recovery and vegetation structure; ecosystem service recovery up to 91%; carbon sequestration rates equal or surpass planted forests.	Accelerates early species richness while allowing ecosystems to develop complexity over time; enhances resilience.
Economic outcomes	Resource-intensive; costs up to US$8,000 per hectare over 3 years; requires long-term maintenance.	Up to ten times less expensive than active planting; minimal capital investment; cost-effective resource allocation.	Balances costs and benefits; integrates livelihood opportunities with ecological gains.
Key limitations	High financial costs; dependent on sustained funding and management; less cost-effective compared to ANR.	Effectiveness depends on site-specific conditions (soil, disturbance, seed dispersal); slower initial species richness.	Requires context-specific tailoring; dependent on community engagement and local knowledge.
Representative studies	César et al. (2018), Vieira et al. (2021), Soterroni et al. (2023)	Crouzeilles et al. (2017), Brancalion et al. (2019), Shimamoto et al. (2018), Williams et al. (2024), Méndez-Toribio et al. (2021)	Souza et al. (2016), Meli et al. (2017), Carvajal et al. (2025)

high upfront costs of planting, often exceeding US$8,000 per hectare (César et al., 2018; Osuri et al., 2021), and the far lower cost of ANR, which can be up to 10 times cheaper (Brancalion et al., 2019). ANR frequently delivers stronger biodiversity recovery and vegetation structure (Crouzeilles et al., 2017; Williams et al., 2024), though outcomes depend on soil conditions, disturbance regimes, and seed dispersal (Méndez-Toribio et al., 2021).

Hybrid models blend planting with ANR to boost early species richness and long-term resilience (Souza et al., 2016; Vieira et al., 2021; Meli et al., 2017). TEA clarifies when active planting is necessary for severely degraded sites (Soterroni et al., 2023) and when ANR or hybrid approaches offer more sustainable results, integrating ecological dynamics with socio-economic factors such as landowner incentives and community engagement (Tavares et al., 2024; Carvajal et al., 2025).

As summarized in Table 2, TEA highlights the ecological, economic, and socio-economic trade-offs among active planting, ANR, and hybrid approaches, enabling context-specific restoration decisions. Figure 3 further illustrates how TEA integrates these strategies into a hybrid framework, balancing immediate canopy cover with long-term resilience and cost-effectiveness.

3.2 Wetland and peatland restoration

Wetland and peatland restoration play a key role in climate mitigation due to their carbon sequestration capacity. TEA assesses hydrological interventions such as ditch blocking and rewetting, which enhance soil moisture and carbon storage (Schimelpfenig et al., 2013; Waddington et al., 2010). Financial viability often relies on carbon markets, where restored peatlands generate tradable credits from verified emissions reductions (Swindles et al., 2025; Tarigan et al., 2021). Peatland restoration is generally more cost-effective than mineral soil sequestration (Leifeld and Menichetti, 2018), though uncertainties persist around methane emissions and land-use pressures (Hemes et al., 2018; Oikawa et al., 2017). Beyond carbon, wetlands deliver flood regulation, water purification, and biodiversity benefits, which TEA incorporates into financial models to capture full ecological and economic returns. Adaptive governance and community engagement further support long-term viability (Wu et al., 2025; Jeethu and Kaladevi, 2025).

Wetland and peatland restoration increasingly use TEA to link ecological processes with financial feasibility by monetizing key ecosystem services. Carbon sequestration is commonly valued by converting annual greenhouse gas abatement (tCO_2e) into revenue using voluntary market prices, improving NPV by treating carbon income as a negative operating cost (Zerbe et al., 2013; Valach et al., 2021). Flood regulation and water purification are incorporated through avoided-cost methods, where restored wetlands substitute for grey infrastructure, often yielding avoided damages that exceed initial restoration costs (Fluet-Chouinard et al., 2023). Additional services, such as protection of vulnerable peat carbon stocks (Page et al., 2011), nutrient removal via emergent vegetation (Jordan et al., 2003), and biodiversity gains that enhance resilience (Hoffmann et al., 2017; Novita et al., 2022), further strengthen economic justification. Persistent challenges include ecological variability, climate-driven uncertainty, and land-use legacies that shape restoration outcomes (Erwin, 2008). Ultimately, TEA shows that monetizing ecosystem services can justify restoration investments, while long-term success depends on aligning interventions with local conditions and community engagement (Basu et al., 2024).

3.3 Blue carbon ecosystems

Mangroves, seagrasses, and salt marshes offer exceptional carbon storage, with mangrove restoration projects exceeding 1,000 Mg C ha^{-1} when accounting for above- and below-ground biomass (Perera and Amarasinghe, 2021). TEA links these ecological gains with financial incentives through mechanisms such as Payments for Ecosystem

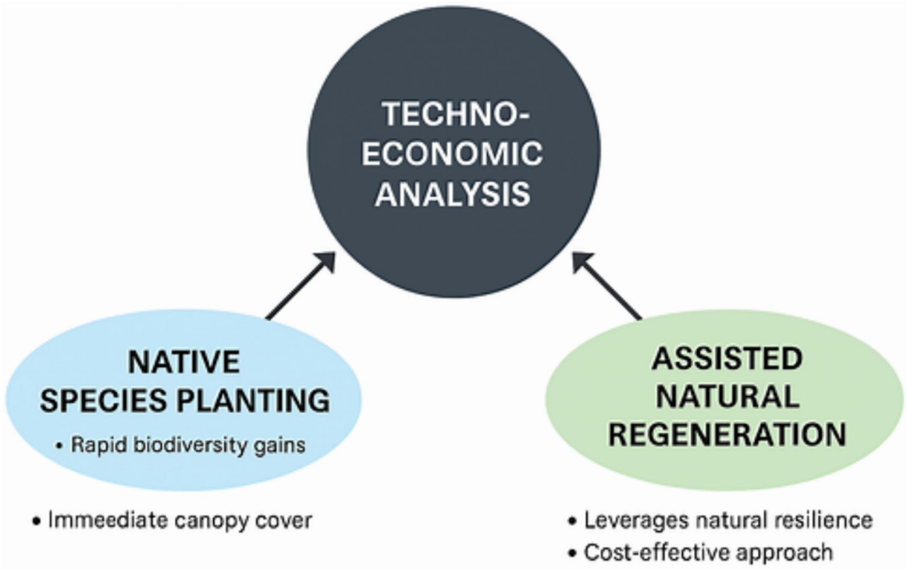

FIGURE 3
Conceptual framework illustrating a hybrid strategy that integrates native species planting with assisted natural regeneration (ANR) under the guidance of TEA.

Services (PES) and voluntary carbon markets (Taillardat et al., 2020). While high upfront costs and delayed returns challenge implementation, TEA helps balance ecological resilience with economic viability, guiding investment decisions and policy alignment.

3.4 Agroecological landscapes

Agroecological landscapes sit at the interface of agriculture and ecological restoration, and TEA provides a useful framework for assessing the financial and ecological performance of practices such as agroforestry, conservation agriculture, and regenerative farming. Agroforestry systems, including silvopasture and agrisilviculture enhance biomass, soil organic matter, and carbon sequestration (Sharma et al., 2025), while complementary practices like cover cropping and improved fallows strengthen soil fertility and reduce dependence on chemical inputs (Marques et al., 2022; Fahad et al., 2022). TEA quantifies the economic returns of these interventions, supporting restoration strategies that are both scientifically robust and financially viable (Ngulube et al., 2024). By incorporating biodiversity gains and ecosystem resilience into financial models, TEA enables holistic cost–benefit analyses of carbon farming and regenerative agriculture, which improve soil fertility, water retention, and erosion control (Ghosh et al., 2024; Shukla et al., 2025; Olarewaju et al., 2025).

3.5 Urban ecological restoration

Urban ecological restoration demonstrates TEA's value in assessing green infrastructure for stormwater management, heat mitigation, and biodiversity gains. Lifecycle cost assessments show that green roofs, permeable pavements, and constructed wetlands provide long-term ecological and economic benefits (Basconi et al., 2019; Budiharta et al., 2016). TEA helps clarify trade-offs between high upfront capital costs and long-term savings from flood regulation, water purification, and reduced infrastructure damage. By linking ecological outcomes with financial feasibility, TEA supports municipal planning and policy alignment, ensuring that urban restoration strategies remain cost-effective and resilient. Community engagement and equitable benefit distribution further strengthen the socio-economic sustainability of urban projects (Carter et al., 2024; Bodin et al., 2021).

3.6 Cross-ecosystem synthesis: conditions for TEA effectiveness

The effectiveness of TEA varies widely across ecosystems, with its strongest performance occurring in high-capital expenditure (CapEx) restoration projects. In engineered interventions, such as peatland rewetting, industrial-site grassland reconstruction, and urban green infrastructure, technical inputs like machinery hours and material volumes dominate overall costs, making TEA a valuable optimization tool. Studies show that TEA can identify designs that balance ecological gains with financial feasibility, as demonstrated by Csonka et al. (2023), who found that grassland reconstruction in industrial settings increased biodiversity while reducing installation and maintenance costs. Similar benefits are evident in urban green infrastructure, where TEA helps integrate ecological performance with fiscal constraints (Silva et al., 2017). In these contexts, TEA provides clear decision-support value by quantifying trade-offs and improving the predictability of ecological and financial outcomes.

In contrast, TEA is far less effective in passive or low-intervention restoration, where natural regeneration dominates and biological variability is high. These systems exhibit unpredictable recovery trajectories shaped by external ecological pressures, making economic modeling difficult and reducing TEA's decision-making utility (Greet et al., 2019). The literature also highlights a broader tension between financial optimization and ecological resilience: TEA frameworks that emphasize short-term economic returns may inadvertently promote simplified or monoculture systems, undermining long-term biodiversity and stability (Rohr et al., 2018; Sedmák et al., 2020). Financial incentives can even steer restoration toward ecologically suboptimal landscapes (Török et al., 2017), while decisions that ignore ecological constraints risk negative feedback loops that compromise restoration integrity (Standish et al., 2012; Lamb et al., 2005). These findings underscore the need for TEA frameworks that incorporate ecological safeguards and multifunctional benefits, ensuring that restoration strategies remain both economically viable and ecologically robust across diverse ecosystem types.

4 Empirical evidence and examples of TEA in restoration ecology

This section draws on empirical evidence from forests, wetlands, peatlands, blue carbon systems, agroecological landscapes, and urban green infrastructure to show how TEA functions in practice. Across these contexts, TEA helps clarify trade-offs, strengthen investment cases, and support policy alignment by integrating ecological indicators with financial metrics. Together, the examples reveal key opportunities and challenges and provide a foundation for advancing TEA as a decision-support framework for restoration ecology.

4.1 Forest restoration in Latin America

Forests in Latin America provide a key testing ground for TEA, particularly in comparing active planting with ANR. Evidence from Brazil and Mexico shows ANR can cut costs by up to 90% while achieving comparable biodiversity outcomes (Brancalion et al., 2019; Crouzeilles et al., 2017). Active planting remains necessary in severely degraded areas, but TEA helps identify when hybrid approaches offer the best balance of ecological recovery and financial sustainability (Souza et al., 2016; Vieira et al., 2021). These findings highlight TEA's value in tailoring restoration strategies to site conditions and socio-economic contexts.

4.2 Peatland restoration in Southeast Asia

Peatland restoration in Southeast Asia illustrates TEA's value in assessing hydrological interventions and their financial viability through carbon credit markets. Rewetting projects in Indonesia and Malaysia show that restoring peat hydrology reduces greenhouse gas emission while generating tradable credits, often outperforming mineral soil sequestration in cost-effectiveness (Swindles et al., 2025; Tarigan et al., 2021; Leifeld and Menichetti, 2018). Uncertainties linked to methane emissions and land-use pressures remain significant (Hemes et al., 2018; Oikawa et al., 2017), but TEA incorporates these risks into financial models to ensure investments remain viable under variable ecological conditions.

4.3 Blue carbon ecosystems in South Asia

In South Asia, TEA helps clarify how mangrove and seagrass restoration link ecological resilience to carbon market incentives. Mangrove projects in Sri Lanka and India report carbon stocks exceeding 1,000 Mg C ha^{-1} (Perera and Amarasinghe, 2021), with PES and voluntary carbon markets providing key revenue streams (Taillardat et al., 2020). TEA highlights trade-offs between high upfront costs and long-term returns, guiding investment decisions and policy frameworks that emphasize community participation and equitable benefit distribution.

4.4 Agroecological landscapes in Africa

In African agroecological landscapes, TEA helps evaluate how agroforestry and regenerative agriculture combine biodiversity gains with economic returns. Projects in Kenya and Uganda show that practices such as silvopasture and cover cropping improve soil fertility, biodiversity, and carbon sequestration while reducing chemical inputs (Marques et al., 2022; Ngulube et al., 2024). TEA models indicate these interventions generate positive net present values when ecosystem services are monetized, reinforcing the case for carbon farming and PES schemes (Avasiloaiei et al., 2023; Ghosh et al., 2024).

4.5 Urban green infrastructure in Europe and North America

Urban restoration projects in Europe and North America show TEA's value for municipal planning, where lifecycle cost assessments reveal long-term savings and ecological gains. Green roofs, permeable pavements and similar interventions help TEA evaluate upfront capital costs against downstream benefits in stormwater management, heat mitigation, and infrastructure resilience (Basconi et al., 2019; Budiharta et al., 2016). TEA clarifies trade-offs between immediate expenditures and long-term savings, supporting policies that integrate ecological restoration into urban development strategies and emphasize equitable, community-aligned planning (Carter et al., 2024; Bodin et al., 2021).

4.6 TEA's cross-system contributions to restoration planning

Across the examples reviewed, TEA consistently demonstrates adaptability across ecological contexts by clarifying when interventions are cost-effective, when hybrid approaches yield superior outcomes, and how financial tools such as carbon credits and PES schemes strengthen restoration financing. Table 3 synthesizes costs, benefits, and outcomes across projects, underscoring TEA's value as a unifying framework for restoration ecology.

4.7 Lessons learned

Across forest, wetland, coastal, agroecological, and urban systems, TEA consistently highlights the need to tailor restoration strategies to ecological conditions and socio-economic contexts. Evidence shows that Assisted Natural Regeneration can be substantially more cost-effective than active planting, while severely degraded landscapes still require resource-intensive or hybrid approaches (Brancalion et al., 2019; Soterroni et al., 2023; Vieira et al., 2021; Meli et al., 2017). TEA also strengthens stakeholder engagement by clarifying trade-offs and long-term benefits, helping build trust among landowners, policymakers, and local communities (Osuri et al., 2021; Tavares et al., 2024). Studies in agroecological and urban settings further emphasize the importance of participatory governance and equitable benefit distribution for sustaining restoration outcomes (Carter et al., 2024; Bodin et al., 2021).

Financing mechanisms emerge as another central lesson, with TEA demonstrating how carbon credits, green bonds, and PES can mobilize long-term investment when ecological outcomes are linked to financial incentives (Swindles et al., 2025; Tarigan et al., 2021; Taillardat et al., 2020). Yet variability in sequestration rates and market volatility require adaptive TEA models that incorporate ecological uncertainty (Leifeld and Menichetti, 2018; Hemes et al., 2018; Oikawa et al., 2017). Robust data and continuous monitoring remain essential, particularly given challenges in valuing non-market ecosystem services and the influence of hydrological variability on restoration success (Chen et al., 2023; Valach et al., 2021; Wu et al., 2025). Finally, TEA's application across forest, wetland, coastal, agroecological, and urban systems demonstrates its potential as a cross-sector integrative framework, enhancing comparability and supporting policy alignment toward global restoration commitments (Kang et al., 2023; Peng et al., 2022).

5 Evaluating techno-economic analysis in restoration ecology

This section reviews TEA's role in restoration ecology by outlining its strengths, limitations, policy applications, and future directions. TEA links ecological outcomes with financial feasibility, improving transparency and comparability while still facing challenges such as data gaps, ecological uncertainty, and monetization issues. It also supports policy tools, including investment strategies, PES, carbon markets, and blended finance, and highlights emerging opportunities involving digital technologies, AI, and participatory approaches. Overall, TEA is presented as a practical decision-support tool and an evolving framework suited to the complex demands of modern restoration.

5.1 Strengths of TEA

TEA strengthens restoration planning by providing a structured framework for assessing cost-effectiveness and guiding resource allocation. Because restoration involves substantial financial investment, TEA supports informed decision-making and helps prioritize actions that deliver the greatest ecological return. Birch et al. (2010) note that billions of dollars are invested in restoration globally, highlighting the need for rigorous financial evaluation. By quantifying the economic value of ecosystem services, TEA also identifies investment strategies that align with conservation objectives, as illustrated in applications such as Gourevitch et al. (2016).

Transparency: Transparency is a core strength of TEA, providing a structure for clarifying methodologies, assumptions, and expected outcomes. This openness builds trust and accountability, ensuring restoration decisions are evidence-based and clearly communicated. However, this benefit is conditional; transparency depends entirely on the rigorous disclosure of underlying assumptions, which is not always practiced. Without clear reporting of key parameters, TEA models risk becoming "black box" exercises that obscure rather than clarify decision-making. When applied correctly, transparent frameworks such as HaBREM improve assessment of restoration needs and strengthen stakeholder engagement (Baker et al., 2020), while monitoring systems for forest landscape restoration clarify expected impacts and measurable results, reinforcing accountability and confidence (Elias et al., 2024). Overall, transparency enhances TEA's utility by making the decision-making process explicit and accessible, provided that full assumption disclosure is enforced.

Comparability: TEA strengthens comparability across projects by using standardized metrics such as cost-effectiveness measures,

TABLE 3 Comparative synthesis of restoration examples applying TEA.

Context	Costs	Benefits	Outcomes	Representative references
Forest (Brazil, Mexico)	Active planting up to US$8,000/ha; ANR up to 90% cheaper	Biodiversity recovery; carbon sequestration	ANR often more cost-effective; hybrid approaches optimize resilience	Brancalion et al. (2019), Crouzeilles et al. (2017), Souza et al. (2016)
Peatlands (Indonesia, Malaysia)	Moderate rewetting costs; carbon credit revenues offset expenses	Reduced GHG emissions; carbon storage	Cost-effective compared to mineral soils; methane risks remain	Swindles et al. (2025), Tarigan et al. (2021), Leifeld and Menichetti (2018)
Blue carbon (Sri Lanka, India)	High upfront planting costs	Carbon storage >1,000 Mg C ha^{-1}; PES revenues	Long-term ecological and financial returns	Perera and Amarasinghe (2021), Taillardat et al. (2020)
Agroecological (Kenya, Uganda)	Variable; lower input costs in regenerative systems	Soil fertility; biodiversity; carbon sequestration	Positive NPV when ecosystem services monetized	Marques et al. (2022), Ngulube et al. (2024), Ghosh et al. (2024)
Urban (Europe, North America)	High upfront capital costs	Stormwater management; heat mitigation; infrastructure resilience	Lifecycle savings outweigh initial investments	Basconi et al. (2019), Budiharta et al. (2016), Carter et al. (2024)

TABLE 4 Key strengths and lessons from TEA applications across forest, wetland, coastal, agroecological, and urban restoration contexts.

Theme	Insight	Representative references
Transparency and stakeholder governance	Transparency clarifies assumptions and trade-offs, strengthening trust, participatory governance, and long-term sustainability across restoration contexts.	Baker et al. (2020), Elias et al. (2024), Osuri et al. (2021), Tavares et al. (2024), Carter et al. (2024), Bodin et al. (2021)
Comparability, scalability and context specificity	Standardized metrics (cost-effectiveness, LCoE, NPV) enable cross-project comparison and help determine when ANR, planting, or hybrid approaches are most cost-effective and scalable.	Birch et al. (2010), Pombo-Romero (2022), Fernandes et al. (2025), Brancalion et al. (2019), Soterroni et al. (2023), Vieira et al. (2021), Meli et al. (2017)
Financing mechanisms and market integration	TEA links ecological outcomes with financial incentives (carbon credits, PES, green bonds), but requires adaptive models to account for sequestration variability and market volatility.	Swindles et al. (2025), Tarigan et al. (2021), Taillardat et al. (2020), Leifeld and Menichetti (2018), Hemes et al. (2018), Oikawa et al. (2017)
Data, monitoring and adaptive management	TEA depends on reliable ecological and economic indicators; adaptive monitoring ensures viability under changing ecological and financial conditions.	Chen et al. (2023), Valach et al. (2021), Li et al. (2023), Wu et al. (2025)
Integration across sectors and ecological-economic metrics	TEA unifies ecological and economic metrics across forest, wetland, coastal, agroecological, and urban systems, enhancing policy alignment and holistic evaluation.	Kang et al. (2023), Peng et al. (2022), Elias et al. (2024), Ngulube et al. (2024), Sobhani et al. (2021), Gourevitch et al. (2016)

Levelized Cost of Energy (LCoE), and Net Present Value (NPV). These benchmarks enable consistent evaluations of restoration outcomes and support strategic prioritization, even under limited funding (Pombo-Romero, 2022; Fernandes et al., 2025). Standardized approaches also help identify scalable best practices and improve resource allocation. By facilitating cross-regional learning, TEA supports the adaptation and replication of restoration strategies across diverse ecological and socio-economic contexts (Birch et al., 2010).

Integration of ecological and economic metrics: TEA's key advantage is its ability to merge ecological and economic metrics into a single evaluation framework, ensuring restoration projects are both ecologically viable and financially sustainable. Evidence shows that projects grounded in strong ecological-economic alignment are more likely to secure funding and long-term support (Elias et al., 2024). Integrative applications, such as combining LCA with TEA, demonstrate synergies between energy production, ecosystem resilience, and economic feasibility (Ngulube et al., 2024). Additional approaches, including assessments of habitat integrity alongside economic indicators, further highlight TEA's capacity to capture the multifaceted impacts of restoration practices (Sobhani et al., 2021). Collectively, these studies position TEA as a critical tool for advancing restoration strategies that deliver meaningful ecological outcomes while remaining economically sustainable.

The integration of insights from diverse restoration contexts reveals that TEA's methodological strengths, transparency, comparability, and the integration of ecological and economic metrics directly shape the practical lessons emerging from field applications. By synthesizing these dimensions, Table 4 highlights how TEA not only clarifies cost-effectiveness and ecological trade-offs but also strengthens governance, financing strategies, monitoring frameworks, and cross-sector alignment. This consolidated view demonstrates how TEA functions as both an analytical tool and a strategic framework, guiding restoration practitioners toward interventions that are ecologically grounded, financially viable, and socially legitimate.

5.2 Limitations of TEA

While TEA provides a structured framework for linking ecological restoration with financial feasibility, its effectiveness is constrained by persistent limitations that extend beyond technical challenges. These limitations fall broadly into three categories, data gaps and regional disparities, uncertainty in ecological outcomes, and monetization and ethical challenges, each of which highlights the need for improved methodologies, interdisciplinary approaches, and justice-oriented frameworks to enhance TEA's reliability and equity in restoration ecology.

Data gaps and regional disparities: TEA depends on robust ecological and economic data, yet restoration projects often face incomplete, inconsistent, or geographically biased datasets. Restoration costs vary widely across ecosystems and degradation levels, making standardized financial benchmarks difficult to establish (Liu et al., 2023). Limited long-term monitoring and inconsistent reporting further restrict cross-project comparison (Han et al., 2025; Bodin et al., 2021). These gaps deepen global inequities, as TEA disproportionately reflects data-rich regions in the Global North while overlooking the ecological realities and socio-economic conditions of data-poor regions in the Global South (Blignaut and Aronson, 2008; Rodríguez-Labajos and Alier, 2013). Incomplete knowledge of key ecological processes, such as species dispersal, can also render TEA evaluations contextually irrelevant (Driscoll et al., 2014). Participatory and community-based monitoring can help incorporate local conditions and perspectives (Moore et al., 2022), yet data limitations continue to skew financial assessments, marginalize underrepresented regions, and weaken TEA's comparability across restoration contexts.

Uncertainty in ecological outcomes: Despite better data, uncertainty remains a major challenge for TEA. Restoration occurs in dynamic ecosystems where responses vary widely and are shaped by shifting climatic conditions (Kareksela et al., 2013; Rohal et al., 2019). Context-specific factors, such as soil quality, disturbance regimes, hydrological variability, and species interactions, make forecasting biodiversity recovery and ecosystem services difficult. These uncertainties increase risk in cost–benefit analyses and weaken confidence in TEA outputs, especially when models assume predictable ecological trajectories. Societal expectations add further complexity that standard TEA may not fully capture (Martin and Lyons, 2018). Addressing these challenges requires adaptive management approaches that integrate ecological theory, socio-economic perspectives, and flexible decision-support tools capable of adjusting to new information and under changing environmental conditions.

Monetization and ethical challenges: Valuing non-market ecosystem services such as biodiversity conservation, cultural heritage, and recreation remains a major challenge for TEA. Conventional cost–benefit analyses often miss intangible or relational values, leading to underestimated restoration outcomes (Shwiff et al., 2012; Wainger et al., 2017) and discouraging investment when broader ecological and social benefits are overlooked (Yu et al., 2023; Aronson et al., 2020). Ethical concerns also arise when nature is over-monetized, reducing complex ecosystems to commodities and incentivizing profit-driven restoration at the expense of ecological integrity and cultural meaning (Gómez-Baggethun and Ruíz-Pérez, 2011). These approaches risk marginalizing Indigenous and local communities whose relationships with ecosystems extend beyond financial valuation (Chaudhari, 2025). While multi-criteria decision analysis offers a more holistic way to assess ecosystem services (Saarikoski et al., 2016), it cannot fully resolve disparities in willingness-to-pay across socio-economic groups (Spash and Hanley, 1995; Chen and Jim, 2010). Justice-based frameworks argue for shifting away from market-centric valuation toward approaches that prioritize social sustainability, cultural continuity, and equitable benefit distribution (Seeland et al., 2024). Together, these challenges underscore the need for TEA to move beyond purely economic metrics and adopt more pluralistic, community-centered perspectives.

As summarized in Table 5, TEA's limitations in restoration ecology can be grouped into three primary categories: data gaps and regional disparities, uncertainty in ecological outcomes, and monetization and ethical challenges. Each category underscores constraints that affect TEA's reliability, equity, and practical relevance, reinforcing the need for interdisciplinary approaches that integrate ecological theory, socio-economic perspectives, cultural values, and justice-based principles. Together, these limitations introduce significant policy risk, as decisions based on incomplete, uncertain, or undervalued information can lead to misaligned incentives, inequitable outcomes, ineffective regulatory design, and reduced confidence in restoration governance.

5.3 Policy relevance

The integration of TEA into restoration ecology is increasingly recognized as essential for shaping effective environmental policies and guiding investment strategies. This importance has grown as restoration shifts from voluntary practice to legally mandated obligations, exemplified by England's Biodiversity Net Gain requirement of at least a 10% biodiversity increase (Cliquet et al., 2021; Blignaut et al., 2014), the EU Nature Restoration Law's binding ecosystem recovery targets (Perissi, 2025), restoration provisions in the U.S. Infrastructure Investment and Jobs Act (Farrell et al., 2021), and Brazil's Forest Code requiring landowners to restore degraded legal reserves (Cliquet et al., 2021). These statutory frameworks heighten the need for analytical tools that evaluate ecological effectiveness alongside financial feasibility, reinforcing the role of cost–benefit analysis in sustainable project design (Galatowitsch, 2022). Persistent gaps in monitoring and evaluation further underscore the need for stronger legal structures to support successful restoration outcomes (Chaves et al., 2015). Collectively, these developments demonstrate how TEA has become indispensable for bridging ecological science with policy implementation, particularly where compliance, accountability, and economic justification are central to restoration governance (Wainaina et al., 2020).

Within the framework of the UN Decade on Ecosystem Restoration (2021–2030), TEA enables policymakers to align biodiversity and climate objectives with financial feasibility, ensuring

TABLE 5 Summary of limitations in applying TEA to restoration ecology, with supporting references.

Limitation	Description	Key implications	Representative references
Data gaps and regional disparities	Incomplete, inconsistent, or geographically biased ecological and economic data; limited long-term monitoring; lack of standardized reporting frameworks; structural inequities between data-rich Global North regions and data-poor Global South regions.	Skewed financial assessments, weak comparability across projects, marginalization of underrepresented regions, reduced reliability of TEA outputs, and risk of context-inappropriate restoration decisions.	Rohal et al. (2019), Liu et al. (2023), Han et al. (2025), Bodin et al. (2021), Driscoll et al. (2014), Moore et al. (2022), Blignaut and Aronson (2008), Rodríguez-Labajos and Alier (2013)
Uncertainty in ecological outcomes	Dynamic ecosystems respond variably to restoration interventions; outcomes shaped by climate variability, disturbance regimes, species interactions, and socio-ecological expectations.	Complicates forecasting of ecological recovery, increases risk in cost–benefit analyses, reduces confidence in TEA outputs, and challenges long-term planning under changing environmental conditions.	Kareksela et al. (2013), Rohal et al. (2019), Moore et al. (2022), Martin and Lyons (2018)
Monetization and ethical challenges	Difficulty valuing non-market ecosystem services; risk of over-monetizing nature; commodification of biodiversity; exclusion of cultural, relational, and Indigenous values; disparities in willingness-to-pay across socio-economic groups.	Risks undervaluing restoration projects, discourages investment, overlooks broader ecological and social benefits, reinforces environmental injustice, and may misalign restoration priorities with community values.	Shwiff et al. (2012), Wainger et al. (2017), Yu et al. (2023), Aronson et al. (2020), Saarikoski et al. (2016), Gómez-Baggethun and Ruíz-Pérez (2011), Chaudhari (2025), Spash and Hanley (1995), Chen and Jim (2010), Seeland et al. (2024)

efficient resource allocation (Su et al., 2021; Fischer et al., 2021; Liu et al., 2023). PES exemplify this alignment by compensating stakeholders for conserving and restoring ecosystem services, with success dependent on rigorous evaluation of ecological and economic benefits (Comín et al., 2018). Prioritizing sites that maximize multiple ecosystem services enhances both ecological outcomes and economic viability (Bodin et al., 2021), while standardized cost–benefit frameworks can incentivize sustainable land use practices (Birch et al., 2010).

Carbon markets further illustrate TEA's policy relevance by linking ecosystem services valuation to carbon offset investments. Evidence shows that well-planned restoration can generate financial returns through enhanced carbon storage and water quality improvements (Blignaut et al., 2014; Lu et al., 2018). These mechanisms highlight TEA's role in bridging ecological goals with financial instruments, paving the way for blended finance models that leverage public and private resources to scale restoration initiatives (Ahir and Mahida, 2025; Shi, 2025).

However, the reliance on these market-based mechanisms raises significant governance and equity challenges that TEA must address. A critical risk lies in "carbon tunnel vision," where TEA models optimize exclusively for the most monetizable variable, typically carbon sequestration, at the expense of broader ecological integrity. This can create perverse incentives to select fast-growing monocultures over diverse native species, undermining long-term resilience (Sedmák et al., 2020). Furthermore, high-fidelity TEA models often require technical data and capacity unavailable to smallholders or community-led groups. If policy support is strictly tied to "bankable" TEA outputs, it risks excluding local stakeholders in favor of large-scale commercial developers, thereby deepening inequality.

To mitigate these risks, TEA must be paired with governance safeguards that prioritize social equity and biodiversity over financial efficiency. Stakeholder participation strengthens policy legitimacy and ensures alignment with local needs (Maniraho et al., 2023; Zhao et al., 2023). Under these ethical constraints, TEA offers strong analytics for forecasting trade-offs and tailoring strategies to local contexts (Crookes et al., 2013; Tian et al., 2016). Carbon pricing and blended finance can enhance project viability but require careful attention to equity and ecological integrity (Jia et al., 2025; Cheong, 2025). The socio-economic benefits of restoration, such as employment and livelihood support further highlight TEA's role in reducing inequalities and strengthening community resilience (Liu et al., 2022b).

By embedding TEA into investment strategies, PES schemes, carbon markets, and blended finance, while strictly adhering to governance safeguards, restoration policies can catalyze resilient ecosystems that deliver long-term ecological services while advancing ambitious conservation and climate goals (Wyborn et al., 2012; Birch et al., 2010). Table 6 summarizes TEA's policy relevance across these four mechanisms, while Figure 4 provides a conceptual diagram that synthesizes their interconnections. Together, they emphasize TEA's integrative role in bridging ecological science with economic strategy, thereby supporting the design of effective and adaptive restoration policies.

5.4 Future directions

Future directions for integrating TEA into restoration ecology center on the convergence of digital tools, artificial intelligence (AI), and participatory frameworks to balance ecological outcomes with financial feasibility. These innovations enable dynamic data collection, predictive modeling, and stakeholder co-creation, strengthening transparency, inclusivity, and resilience. Together, they position TEA as an adaptive framework capable of responding to the accelerating complexities of climate change and ecological degradation.

TABLE 6 Summary of TEA's policy relevance across mechanisms.

Mechanism	Description	Key implications	References
Statutory and regulatory frameworks	Legally binding mandates requiring measurable biodiversity gains, ecosystem recovery targets, and restoration obligations across jurisdictions (e.g., BNG, EU Nature Restoration Law, U. S. IIJA, Brazil's Forest Code).	Drives demand for TEA to ensure compliance, evaluate ecological and financial feasibility, support cost–benefit analysis, and strengthen monitoring and evaluation systems.	Cliquet et al. (2021), Blignaut et al. (2014), Farrell et al. (2021), Galatowitsch (2022), Chaves et al. (2015), Wainaina et al. (2020)
Investment strategies	Mobilizes public-private partnerships and financial instruments (e.g., green bonds, ESG investments) to support restoration at scale.	Aligns biodiversity and climate goals with financial feasibility, ensuring efficient resource allocation and long-term investment planning.	Su et al. (2021), Fischer et al. (2021), Liu et al. (2023), Ahir and Mahida (2025), Shi (2025)
Payments for ecosystem services (PES)	Compensates stakeholders for conserving and restoring ecosystem services using ecological and economic evaluations.	Promotes equity and sustainable land use while enhancing ecological outcomes and financial viability through standardized cost–benefit approaches.	Comín et al. (2018), Bodin et al. (2021), Birch et al. (2010)
Carbon markets	Links restoration outcomes to carbon offset and monetizes ecosystem services such as carbon storage and water quality improvements.	Provides financial incentives for restoration, improves project viability, and requires safeguards to maintain ecological integrity and equity.	Blignaut et al. (2014), Lu et al. (2018), Jia et al. (2025), Cheong (2025)
Blended finance	Combines public and private capital through risk-sharing mechanisms to scale restoration initiatives.	Attracts private investment, accelerates restoration, and integrates risk modeling into financial planning to ensure long-term sustainability.	Wyborn et al. (2012), Zhao et al. (2023), Maniraho et al. (2023)

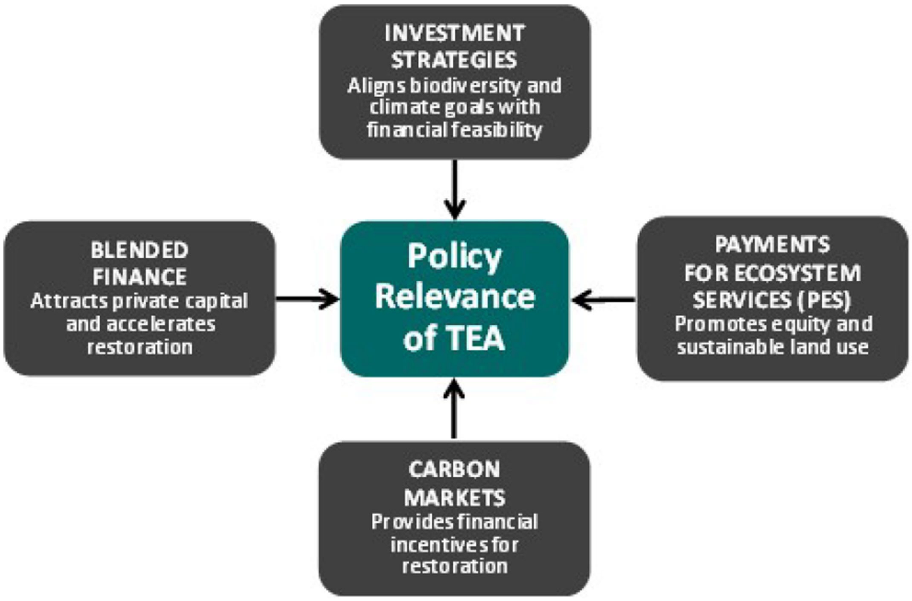

FIGURE 4
Conceptual diagram illustrating the policy relevance of TEA in restoration ecology.

Digital tools and ecological monitoring: Digital innovations, including real-time monitoring, geospatial intelligence, and digital twin technologies, are transforming ecological assessments by enabling dynamic data collection, adaptive management, and stakeholder co-creation (Kazanskaia, 2025; Lăzăroiu et al., 2024; Zhao et al., 2025b). User-friendly digital platforms enhance transparency and inclusivity, helping bridge gaps between scientists and local communities. Participatory evaluation methods further strengthen engagement, ensuring that restoration efforts reflect diverse ecological and social perspectives (Prajapati et al., 2025; Vişan and Mone, 2023; Loftus et al., 2024).

Artificial intelligence and predictive modeling: AI applications strengthens TEA by managing large datasets, automating analysis, and generating predictive models that respond to ecological uncertainty. These capabilities improve restoration planning, resource allocation, and long-term resilience (Ray et al., 2025; Vallabhu et al., 2025). Advanced tools such as predictive analytics and multi-objective optimization help balance biodiversity gains with economic feasibility (Patil et al., 2025; Shan et al., 2025). AI can also simulate ecological outcomes across scenarios, offering clear insights into trade-offs and risks. Community-focused approaches empahsize equitable access and the inclusion of marginalized voices to ensure AI-driven TEA remains socially responsive (Rizun et al., 2025).

Participatory TEA frameworks: Participatory TEA approaches help ensure restoration remains socially grounded and context-specific. Stakeholder involvement promotes transparency, integrates socio-economic dimensions, and incorporates local knowledge into culturally appropriate and ecologically effective designs (Zahraini, 2025; Olimov, 2025; Sebunya and Gichuki, 2024). Inclusive, accountable governance models support more sustainable outcomes, while hybrid approaches that combine AI, digital platforms, and participatory methods strengthen both ecological and financial viability (Long et al., 2025; Pawar and Gaikwad, 2025; Shah, 2025). These frameworks underscore the importance of equitable benefit sharing and community ownership in restoration efforts.

Digital tools, AI, and participatory frameworks position TEA as a dynamic, adaptive approach to restoration ecology. Integrating technological innovation with inclusive governance can make TEA more transparent, socially resilient, and economically sustainable. These pathways strengthen ecological outcomes while keeping restoration financially viable and socially legitimate under growing climate pressures. As summarized in Table 7, three future directions, digital tools, AI, and participatory TEA frameworks advance restoration through greater transparency, inclusivity, and resilience.

6 Conclusion

This review provides the first comprehensive synthesis of Techno-Economic Analysis (TEA) applications across diverse ecosystems, demonstrating its unique capacity to operationalize global restoration mandates by grounding ecological ambition in financial reality. By integrating ecological indicators with economic metrics, TEA transforms restoration from a theoretical ideal into a quantified engineering process, enabling practitioners to design restoration strategies that are both scientifically rigorous and financially bankable.

The analysis reveals that TEA is particularly effective in high-capital, active restoration projects, such as peatland rewetting and urban green infrastructure, where technical optimization can significantly improve return on investment. However, its application in passive restoration requires careful adaptation to account for high biological uncertainty and lower financial inputs. Crucially, TEA serves as a vital bridge for policy, validating the economic rationale for mechanisms like Payments for Ecosystem Services (PES) and biodiversity credits.

TABLE 7 Future directions for integrating TEA into restoration ecology.

Pathway	Description	Key contributions	Representative references
Digital tools	Innovations such as real-time monitoring, geospatial intelligence, and digital twin technologies.	Enable dynamic data collection, adaptive management, and stakeholder co-creation of restoration strategies.	Kazanskaia (2025), Lăzăroiu et al. (2024), Zhao et al. (2025b)
Artificial intelligence (AI)	Applications for managing large datasets, automating analysis, and predictive modeling.	Improve planning, resource allocation, and resilience by adapting to ecological uncertainties.	Ray et al. (2025), Vallabhu et al. (2025), Patil et al. (2025), Shan et al. (2025), Rizun et al. (2025)
Participatory TEA frameworks	Stakeholder involvement and governance models emphasizing inclusivity and accountability.	Promote transparency, integrate socio-economic dimensions, and ensure culturally relevant, equitable restoration outcomes.	Prajapati et al. (2025), Vişan and Mone (2023), Loftus et al. (2024), Zahraini (2025), Olimov (2025), Sebunya and Gichuki (2024), Long et al. (2025), Pawar and Gaikwad (2025), Shah (2025)

Yet, this potential comes with significant caveats. As highlighted in this review, TEA is constrained not only by data gaps and regional disparities that currently privilege the Global North but also by normative risks. The reliance on market-based valuation introduces the danger of "carbon tunnel vision," where financial optimization for sequestration may compromise broader biodiversity goals or marginalize local community values. Therefore, TEA should not be viewed as a passive calculator but as a powerful decision-support tool that requires robust governance side-boards to prevent the commodification of nature.

Looking ahead, the evolution of TEA lies in the convergence of digital innovation and justice-based frameworks. While tools like AI and remote sensing promise to bridge data gaps, they must be deployed within governance models that prioritize equity and social safeguards. Ultimately, when grounded in interdisciplinary collaboration and ethical oversight, TEA offers the necessary transmission mechanism to scale restoration from local pilots to the global levels required to meet the climate and biodiversity challenges of the coming decade.

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