

Economic Knowledge for Nature Preservation

An Epistemic Inquiry into Spatial Prioritisation and International Action

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Abstract

Biodiversity loss is accelerating worldwide, and economic research has increasingly turned to spatial prioritisation tools to guide restoration and conservation efforts. These methods, often based on cost–benefit and cost-effectiveness analyses, aim to identify areas where ecological gains can be maximised at minimal cost. Their results systematically highlight so-called developing countries or economically less productive regions as global priorities for restoration. This article conducts an epistemic inquiry into the assumptions underpinning such analyses and their implications for international ecological action. We identify three main limitations. First, prioritisation is constructed as the inverse of existing global inequalities, since economic and accounting cost data reflect wage gaps and disparities in value-added production. Second, the pixel-based framework overlooks the structural economic drivers of biodiversity decline, reducing transformative change to localised trade-offs. Third, the alleged objectivity of efficiency metrics excludes geopolitical and ontological complexities, neglecting questions of sovereignty, development trajectories, and plural relationships between societies and their environments. By interrogating the conceptual limits of techno-economic reasoning, this contribution argues for a new research agenda in economics. Such an agenda would situate biodiversity protection within the political economy of global value chains, financial dependencies, and distributive justice.

Keywords

Biodiversity, Spatial prioritisation, Cost–benefit analysis, Cost-effectiveness analysis, International governance

Introduction

Wild vertebrate populations declined by 73% between 1970 and 2020¹, and one million animal and plant species are threatened with extinction (IPBES 2019). More than 35% of wetlands have disappeared since 1970, and the destruction of natural habitats continues to accelerate. In order to

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¹ Living Planet Report 2024, WWF.

support international initiatives² for biodiversity restoration and, more broadly, nature protection, economic research seeks to identify the costs of land degradation and the benefits of ecological restoration, aiming both to demonstrate the positive value of large-scale ecological action and to organise its implementation (Nkonya et al., 2016; Giger et al., 2018; Mirzabaev & Wuepper 2023; Bodin et al., 2022). The assessment of the ecological and social benefits and costs of ecosystem restoration is intended to contribute to decision-making by cost-benefit analysis, cost-effectiveness analysis, and multi-criterion evaluation³.

An increasing number of economic studies are producing spatialized analyses to inform an effective distribution of land dedicated to biodiversity protection (Figure 1 and Figure 2). These analyses compare the ecological and socio-economic characteristics of various geographical areas in order to target environmental actions for greater ecological gain and at a lower cost. In other words, so-called cost-effective prioritisation maximises ecological gains and/or socio-economic-ecological benefits and minimises the costs of project implementation; the results allow the publication of maps highlighting the areas where it would be most effective to restore or conserve natural environments. Therefore, this method assumes that ecological actions are substitutable - or at least comparable - across different geographical areas at national, regional, or global scales.

To give an example of regional analysis, Alisher Mirzabaev et al. published in 2022 an empirical article - *Economic Efficiency and Targeting of the African Great Green Wall* - identifying the most economically efficient areas for the restoration of the Great Green Wall ecosystems⁴ (Figure 1). Other publications have used these methods globally (Figure 2). In 2020, Strassburg et al. published a world map of priority sites for ecological restoration by optimising three criteria – biodiversity gain, climate change mitigation and costs – across all terrestrial biomes and based on 1,200 scenarios (Box 1) (Figure 2 a). In 2024, economist Jonah Busch et al. published a cost-effectiveness prioritisation of two distinct ecological restoration techniques - natural regeneration and tree plantations - by integrating spatialized data on soil carbon storage on a global scale (Figure 2 b).

The findings of these spatialized analyses consistently indicate that biodiversity preservation is more cost-effective in southern countries or regions regarded as economically less developed. The available data and underlying assumptions (Box 1) mechanically frame cost-effective restoration of nature as the inverse of economic value creation. In other words, these analyses systematically suggest that the most economically rational strategy is to restore nature in areas where the economic returns from land use are the lowest.

This contribution questions the validity of such reasoning and the results it produces when used to inform international ecological action. We do not focus on the robustness of the data (Armsworth, 2014), a major limitation to the applicability of these methods, but rather on the more fundamental conceptual limitations that, in our view, underlie them. Beyond the issue of data availability, the complexity of both the drivers of biodiversity loss and the transformations required for an international economy that better integrates ecological imperatives calls for a different way of connecting economic knowledge production with the needs of public decision-making. Thus, our contribution examines the assumptions behind economic analyses of spatial prioritisation and their implications, organised into three main points, which are presented below and developed in detail throughout the article.

First, the recommendations for which areas to preserve tend to perpetuate existing economic inequalities. The cost data reflect differences in wages and in value-added production. Maximising ecological gains while minimising costs automatically leads to prioritising the ecological conservation of areas that are less integrated into the economic and trade system.

2 For example, the Kunming Montreal Agreement (2022), the United Nations Decade of Ecological Restoration (2021-2030), and the Bonn challenge.

3 This methodological framework also provides a basis for the construction of marginal biodiversity abatement cost curves to prioritize the spaces to be restored – from the least expensive to the most expensive per unit of ecological gain. This frontier of research in the economics of biodiversity is currently being debated. (cf. Keynote by Ben Groom (University of Exeter) at the first congress of the Latin American Association of Environmental and Resources Economists (LAERE) 2025.

4 The Great Green Wall is an African reforestation programme, whose historical route extends over the eleven countries of the Sahel zone, from Dakar to Djibouti.

Second, the methodological framework and the data do not take into account the causes – including the economic drivers – of natural habitat destruction. The definition of costs and the localised, pixel-by-pixel approach fall far short of capturing the full scope of efforts needed to curb biodiversity loss. They emphasise the restoration of natural environments, but only partially address the deeper causes of degradation. The efforts, measured in accounting or economic costs, are not conceived as part of a broader transformation of economic systems and value chains.

Third, the alleged positivity of these methods rejects the geopolitical and ontological complexity necessary to understand the compromises to be implemented in order to preserve non-human life. The restoration or repurposing of natural ecosystems is inherently tied to territorial development, a sovereign prerogative, a stake in conflict, and a forum for shaping societal relationships with their environment in its diversity. While economic analysis is not immediately intended to directly integrate these considerations, the question of how it can be linked to other forms of knowledge to guide the spatial distribution of ecological action must be explicitly addressed. At first glance, the information produced may seem useful, even though it neglects institutional and social contexts. Yet we argue that notions of costs and gains cannot be dissociated from the contexts in which they are deployed. Beyond costs and gains, defining a path to prosperity compatible with the preservation of natural environments can only be done through an integrated and multi-scalar reflection on the future of territories and their insertion into the international economy.

Using the example of spatial prioritisation methods, this contribution opens an epistemological inquiry into the role and limitations of techno-economic and instrumental analysis in informing international ecological action. The systemic nature of the necessary transformations and the lack of straightforward causal relationships warrant the examination of different epistemic viewpoints, tools, and methods. Building on the three limitations identified, this contribution seeks to outline the contours of a new economic research agenda on international action to safeguard biodiversity.

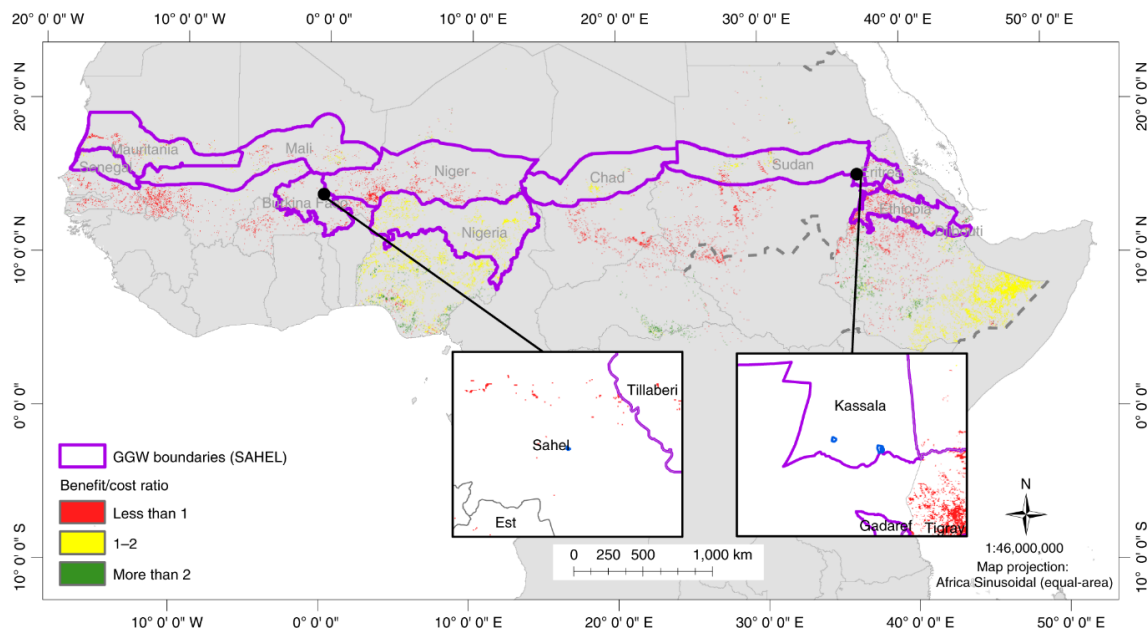


Figure 1: Cost-benefit ratio of land restoration in the eleven countries of the Great Green Wall.

Reading note: The map presents the projected benefit/cost ratios of future degraded land restoration activities in the Sahel between 2001 and 2018. Scenario 1 is based on a 10% discount rate and a planning horizon corresponding to the year of establishment of each restored biome.

Source: Mirzabaev et al., 2022.

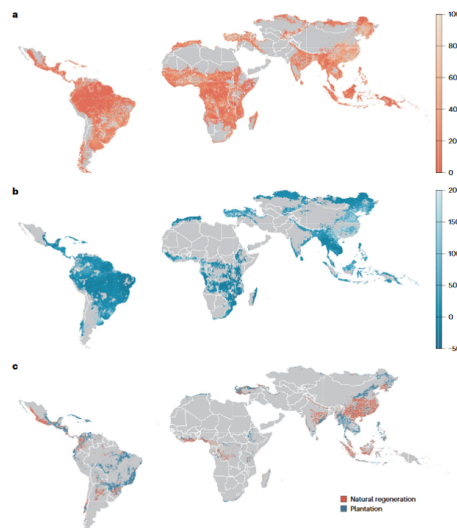


Figure 2a

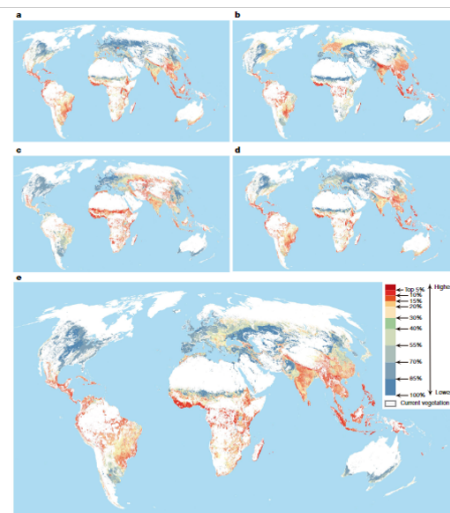


Figure 2b

Figure 2: Examples of cost-benefit and cost-effectiveness analyses with multi-criteria.

Source: Figure 2 a: Busch et al., 2024; Figure 2 b: Strassburg et al 2020.

Efficiency in Ecological Restoration: What World is protected?

The results of the spatialized cost-benefit and cost-effectiveness analyses systematically prioritize restoration and conservation policies in the so-called southern countries when conducted on a global scale (Figure 2), or in the poorest areas when applied at larger scales (Figure 1). Four factors mechanically produce these results.

First, accounting costs, the actual expenses incurred, are substantially lower in so-called developing countries than in developed countries (Bayraktarov, 2016). This is primarily due to the gap in labour costs, which constitute a major cost component of biodiversity projects (Giger et al., 2018; Su et al., 2021). In essence, these accounting costs are nothing more than the production costs of one unit of ecological restoration, with a significant wage gap between nations.

Second, opportunity costs mechanically follow economic value creation. They reflect the economic loss associated with implementing an ecological action (Box 1) and therefore increase with the profitability of the foregone activity. In other words, in the case of spatial prioritisation for ecological restoration, differences in opportunity cost reflect differences in income across land uses, and across land productivity when it comes to agricultural land (McAfee, 2012). At regional or global scales, estimated economic gains from land and labour are higher in countries considered more developed, resulting in proportionally higher opportunity costs. The notion of opportunity cost helps illustrate the fact that nature protection requires foregoing certain economic activities; however, the validity of comparing these costs across different geographical areas raises additional questions.

Third, when economists interpret ecological restoration as increasing nature's contribution to people or ecosystem services (Box 1), the greater the local dependence on these services, the higher the estimated socio-economic benefits of restoration⁵. However, assessed dependence on ecosystem services is, on average, higher in areas considered less developed⁶ (Whitehorn et al., 2019). This reflects limited infrastructure, the immediate role played by ecosystems in guaranteeing the conditions for survival, and the main types of employment - particularly agricultural or forestry - in these regions⁷.

Finally, potential ecological gains tend to be higher, or at least more predictable, in ecosystems that are less degraded or integrated into ecological corridors critical for ecosystem functioning and resilience⁸. Yet, such ecosystems are mainly located in areas considered to be less economically developed. The approximation of ecological restoration by an ecosystem change (Box 1) and its valuation through spatialized ecosystem services or carbon storage capacity structurally favour restoration in forested areas. In contrast, agricultural or urban areas, although generating pressures, entail higher costs for more uncertain ecological gains.

In other words, as it stands, cost-effective nature restoration is defined as the inverse of economic value creation, in particular through the lens of opportunity cost. Mechanistically, it is less costly and more effective to safeguard areas that have not already been degraded and altered by human activity by maintaining or intensifying the use of already economically productive areas. This also reflects the difficulty that economics researchers face in grasping the reality of integrated and multifunctional land use.

The recommendations derived from these spatialized analyses are in line with those of the conservationist approach to biodiversity - also known as the *half-earth* (Kok, 2022) or *spared land* (Kremen, 2015), "separate lands" - in the promotion of the strict separation of land uses⁹. Cost minimisation leads to prioritisation of the intensification of productive areas and the conservation of areas currently used for small-scale agriculture (McAfee, 2012). These results have been translated into policy recommendations in some economists' publications (Bateman & Balmford, 2023). This alleged economically efficient distribution reproduces, or rather is constructed as a mirror of, the spatial organisation of value-added production. Its own logic reinforces financial accumulation and ratifies existing economic inequalities between regions or nations. Implementation and opportunity costs are derived from market prices of land, labour, and commodities—particularly export commodities—and, even before considering restoration protocol effectiveness, these costs reflect disparities in purchasing power, wages, and living standards.

Implementing this efficient or optimal distribution encourages a reward by economically richer areas via compensation markets, guarantees, or payments for ecosystem services. The logic of separating productive and conserved spaces, when implemented, tends to make the "remaining" natural areas dependent on the payment of *Rent against development* (Karsenty, 2004). Carbon or biodiversity can then be considered as commodities, virtually exported¹⁰ to compensate for - i.e. to enable and maintain - a production process in industrialised regions¹¹. The lower production costs of a restored unit of biodiversity give rise to a form of ecological surplus value captured in low-wage

5 Ecological restoration is not always beneficial for vulnerable populations. The restoration of a wetland can improve certain water filtration or storage services, but can also promote the return of certain diseases (see Jeanne de Montalembert's work on malaria in protected areas). But the large-scale cost-benefit and cost-efficiency analyses we are discussing do not reflect these trade-offs to our knowledge.

6 See Harold Levrel's note «D'une économie de la biodiversité à une économie de la conservation de la biodiversité» on the links between assessment of ecosystem dependence and industrial equipment (Levrel, 2020). See also David Simpson "The ecosystem service framework: a critical assessment" (Simpson 2010)2008.

7 This dependence is static and does not compare benefits across different development trajectories. This point is treated in section 2.

8 However, some studies have shown a greater effectiveness of restoration in highly anthropized areas due to a consideration of the marginal ecological gain of restoration. These analyses do not include cost, and these results are discussed because of the risks of failure of ecological restoration in areas that are too degraded.

9 We will not deal here with the debates in ecology and conservation science on the validity of the conservationist approach. It is increasingly debated in a context of soil erosion, water pollution, resistance to pesticides and antibiotics, and the disappearance of insect populations that a strict geographical separation is ecologically viable.

10 The operation is similar to that of virtual water described in the work of John Anthony Allan (1998).

11 Depending on the regulatory framework (carbon neutrality, corporate social and environmental responsibility), these biodiversity or carbon commodities are an input to production to ensure compliance.

countries. In the case of an offset market, it is transferred through international exchange to more industrialised countries. More broadly, preventing further destruction of biotopes leads to freezing the status quo, that is, a hierarchical structure of economic development in exchange for guarantees, allowing us to make the analogy with the rationality of non-proliferation¹². This model of global distribution of ecological action raises questions, as Guillaume Blanc (2020) puts it, “*what world is protected?*” by these recommendations.

The Hidden Economic Drivers of Biodiversity decline

The under-representation of factors driving biodiversity loss - such as pollution, fragmentation of natural habitats, overexploitation, or invasive species - in spatial prioritisation analyses is an obstacle to their ability to inform ecological policy. Economic interests implicated in biodiversity loss are only marginally reflected by the cost estimates, and not at all by the environmental indicators used by these analyses (Spangenberg, 2007). Opportunity cost – defined by the cessation of an economic activity on a given plot (Box 1) – is insufficient to account for the transformative changes required to halt the loss of biodiversity, for two reasons detailed in this section: (1) the concentration of analyses and data at a highly local scale, and (2) the lack of connection between the need for ecological restoration and broader production systems.

The calculation of opportunity costs is micro-economic, conveying the idea that degradation occurs “at the plot” level and results from a trade-off between exploitation and protection of the land according to the perceived benefit (Giger et al., 2018). Spatialized analyses, by treating¹³ each pixel virtually independently – describing it by ecosystem type, management practices, a predefined associated cost (Box 1) – cannot provide a systematic or transformative view. The resulting map layers cannot take into account the structure of the agricultural system, its resilience, and its ability to meet domestic needs and/or export demands. What are the structures of jobs? What dietary changes are expected? Will a reduction in subsistence agriculture lead to inflationary pressures? Opportunity costs are a static indication, detached from development trajectory, national priorities, or the socio-economic vulnerabilities of the regions under consideration.

However, several studies have demonstrated the complexity of the socio-economic drivers of land use (Lambin et al., 2001; Lambin & Meyfroidt, 2010) and biodiversity loss (Spangenberg, 2007). For instance, empirical analyses highlight the links between the ecosystems destruction and global value chains and exports¹⁴ (Arto et al., 2022; Mittempergher et al., 2023; Hoang & Kanemoto, 2021; Moran & Kanemoto, 2017; Pendrill et al., 2019), and distinguish between “net exporters” or “net importers” of biodiversity - *i.e.* countries that degrade their natural environments primarily for the export of commodities, or those whose domestic demand is met by the exploitation of natural environments outside their borders (Lenzen et al., 2012). Specifically, the connection between the success of conservation programs and the modalities of integration into international trade has been studied, for instance, in Costa Rica (Jadin et al., 2016). In open economies with strong balance of payment constraints, international market trends shape the production of commodities – and, by extension, land use and biodiversity (Shandra et al., 2010; Althouse & Svartzman, 2022). Analogous to the low-carbon transition, halting nature loss requires a profound transformation of value chains, production and consumption models (Kok, 2022), and the political, economic, and financial institutions that structure them (Olk, 2024). I propose testable hypotheses that explain why countries that issue internationally acceptable currencies create net inflows of embodied labour, land, energy, raw materials, and carbon from countries whose currencies lack international acceptability: Countries with lower-ranking currencies face higher interest rates, which constrain their policy space, drive income outflows, and necessitate resource exports. Such countries also tend to have lower price levels (measured as the ratio between exchange rates and purchasing power parity rates). The depth of these socio-economic and institutional transformations, along with the associated

¹² This analogy is already used by political ecology regarding the non-proliferation of fossil fuels.

¹³ “Practically” here means that spatial analyses can take into account the pixels surrounding the pixel in question, for example to define ecological grids. This is the case of Strassburg et al. (2020).

¹⁴ Dasgupta dedicates one of the chapters of its review (2021) to the impact of international trade.

conflicts, cannot be reduced to a cost metric, even within an extended economic cost framework focused on well-being. This limitation echoes the conservationist assumptions that are underlying spatial prioritisation analyses - the separate earth or half earth mentioned earlier - which, in theory, do not require transformation of production systems¹⁵.

Responsibility for Ecological Action: Ontological and Geopolitical Complexities

Coordinating international action for biodiversity on a global scale involves “supra-economic” considerations, including ontological and geopolitical ones. Economic analyses on the effective prioritization of conservation areas assume that these considerations are second-order. Effectiveness is an objective criterion that determines the best spatial distribution, which is then adjusted and revised due to political compromises. We argue that an alternative articulation of economic reasoning with a normative and ethical framework for the protection of living species is necessary to guide decision-making in these complex governance contexts.

The very definition of costs and gains is contingent upon the socio-economic context. Their estimation requires a detailed understanding of the relationships between societies and their environment, followed by an integrated, dynamic and multi-scalar reflection on the future of spaces. When more closely embedded in context (Olivier de Sardan, 2021), at the crossroads between institutionalist analysis and the development of planning tools, at the scale of circumscribed territories, cost-effectiveness analyses can be tools to support decision-making (Claron et al., 2022). However, a techno-economic determination of costs and gains deprived of political, social and institutional content and abstracted from context cannot inform ecological action, even less at the international level.

The global distribution of ecological action and the trade-offs it entails engages the diverse ways of inhabiting the Earth, the plurality of relationships between human societies and their territories, and the interactions among these modes of existence, far beyond questions of economic and ecological efficiency. Implementing, making happen, effective biodiversity preservation on a global scale requires consideration of the plurality of ways of life, social organisation and relations with the living world (IPBES, 2019). “*The Earth cannot be reduced to a single global oikos*” (Ferdinand, 2022), and thus its management cannot be confined to a single *oikonomia*, a single regime of rules, or a single conception of efficiency. Once again, this example highlights the challenge for economic knowledge to address the plurality of contexts¹⁶ (Alves & Dutt, 2024)

The distribution of responsibility for ecological action among states or political entities is a geopolitical issue. Nature protection is closely linked to land use planning, an attribute of political sovereignty¹⁷ that is overlooked by concerns for globalized ecological-economic efficiency. The geopolitics of nature protection involves questions that are intrinsically economic, such as distributional issues related to access to development, prosperity and natural resources (Charbonnier, 2024). In practical terms, foregoing a form of economic development to establish ecological conservation or restoration within a territory can result in immediate and future losses of independence and bargaining power

15 However, the hypothesis of an intensification of economic activity deserves more economic analysis of its consequences in terms of employment, prices and capital concentration.

16 We can refer to recent developments in anthropological economics as a line of research. Building on Sraffian’s fundamental idea that the ultimate determinants of distribution are institutional rather than purely “economic,” anthropological economics aims to shed light on how political, social, and moral practices and ideas shape the distribution of surplus (Stanley, 2025) building on recent contributions from Cesaratto and Di Bucchianico, explores the possibilities offered by an ‘anthropological economics’. De L’Estoile has highlighted economic anthropology’s problematic tendency to self-define in opposition to the study of ‘modern’ economy, and the risks of depoliticisation engendered by a reliance on the category of the ‘economic’. As an alternative, he proposes an anthropology of *oikonomia* — the practices and imaginaries through which people ‘govern the house’ (*oikos*).

17 This same reason prevents the recognition of common but differentiated responsibility for biodiversity in international law (Tomoi et al., 2022) we reviewed existing relevant publications by quantifying and evaluating the responsibility of different countries under various categories (i.e., low-, middle-, and high-income: it is difficult to attribute the state of the landscapes of one territory to the influence of another space. Historically, the impact of European colonization on the natural environments of the Caribbean, Africa, Latin America and Asia has been widely demonstrated (Ferdinand, 2022; Haraway, 2015; Raja, 2022), as well as the persistence over time of these ecological degradations.

in international trade. In a fragmented international order, relying on the willingness of Western powers to pay for environmental protection seems precarious. This geographical distribution of responsibility for ecological action exemplifies what Amartya Sen describes as “an ethical problem with mechanical aspects and involving economic relations” (Sen, 2012, p. 83).

At the same time, these questions suggest another role for economics, in support of defining multilateral governance frameworks. Given the scale and complexity of the systemic transformations required, the absence of simple causality, other positions, tools, and methods must be explored. Economics can contribute to this international agenda—but only if it moves beyond optimizing a global ecological budget to inform the distributive dimensions of ecological policies¹⁸ (Myrdal, 1973). From a stewardship perspective, economics is then assigned a technical role, exploring the knowledge and know-how related to the allocation of resources and the production of economic goods (Sarr, 2016)

International Economics for Sustainability in a Plural and Fragmented World

Another economic research agenda to inform international action for biodiversity could be defined as follows: accept as a starting point the link between integration into global value chains, human needs, and nature loss. It would focus on mapping economic interests, conceive the geopolitical and geoeconomic consequences and tensions that rise from the transformations of production and consumption systems in order to anticipate them, and to propose instruments or regulations to cushion and distribute them¹⁹. In other words, economists can work on a different integration into the world economy of the different economic spaces, an integration that allows and engages ecological action adapted to their context, their socio-ecosystems, and the socio-economic vulnerabilities they face. This research agenda is based on the observation of the close link between economic dependencies and the conditions of ecological action: the bargaining power in international trade is a prerequisite, necessary, although not sufficient, for the ability to take care of one's own soil and territory.

As an example of existing work that can be connected to this research agenda, a strand of literature seeks to inform a sustainable integration into the world economy by examining the transformation of the international financial architecture so as to enhance green investment (Gallagher et al., 2023; 2024), mitigate macro-financial vulnerabilities associated with the green transition (Althouse et al., 2025) and improve solvency conditions (Volz et al., 2020; Zucker-Marques et al., 2025). Other strands of work focus on interdependencies and value chains through multi-region input-output analyses (Oppon et al., 2018), or even multi-scale and multi-region (Bachmann et al., 2015) to provide a more systemic mapping of ecological-economic relations. From a more normative perspective, this agenda also resonates with the literature on the economics of global reparations (Sylla et al., 2024).

This research agenda does not primarily depend on making the dynamics of non-human life visible or integrating them directly, as is generally proposed in efforts to ontological recast economics in response to biodiversity loss. Rather, its horizon remains oriented toward the classic objects of economic inquiry—namely, the distribution of value and access to development—while integrating the constraints imposed by natural resource use and environmental impacts, rather than towards the establishment of a bioeconomic science (Jean & Mouysset, 2022). It is therefore not a matter of inverting the ethical and economic order by asking economics, as a discipline, to interpret the needs of non-human entities, even if the underlying ethical frameworks acknowledge them. This does not imply, however, that the epistemological transformations required to rearticulate the production of economic knowledge within an ecological, ethical, and normative framework are any less ambitious.

18 “The environmental problem [...] is discussed as a global problem. But there is a distributional issue involved: who has the power over the resources? The disregard of this issue makes much of the now common brave and broad pronouncements utterly superficial and misleading, indeed meaningless. To give meaning, concreteness and relevance to our pronouncements on the global problem of resource depletion, we have to lay down as an assumption, needed for drawing our inferences, a definite condition in regard to the distributional issue.” (Myrdal, 1973).

19 The wording is taken from Pierre Charbonnier (2024, p. 241).

Box 1: Measuring the Economic Effectiveness of Ecosystem Restoration

The calculation of a differentiated economic efficiency of ecosystem restoration across geographical areas follows three steps: (1) the measurement of the costs of restoration, (2) the definition of efficiency criteria and the estimation of benefits, and (3) the net present value of restoration. This box details these steps, without claiming to exhaustively cover the methods present in the literature.

In the case of the spatialized analyses we focus on, each pixel is generally associated with a type of ecosystem that these steps successively allow to characterize it by a cost, an ecological potential and/or a benefit.

Step 1: Estimating Restoration Costs

Depending on the studies, restoration costs can include some or all of the following costs: acquisition, establishment, maintenance, transaction costs and opportunity costs (Iftekhhar et al., 2017; Mirzabaev & Wuepper, 2023). These costs cover both accounting and economic or socio-economic costs. The accounting cost corresponds to the actual expenses incurred (wages, equipment, etc.). The economic cost includes accounting costs but adds opportunity costs and implicit costs, up to and including the loss of welfare. The economic cost reflects a forward-looking vision aimed at optimal management. The scope of the relevant costs reflects different realities and varies across publications.

Accounting costs include acquisition, establishment and maintenance costs. Acquisition costs are the expenses incurred to acquire land for conservation or restoration. Establishment costs are those required to implement ecological restoration practices and technologies (site preparation, seeding, or planting). Maintenance costs refer to the recurring expenses incurred afterwards to maintain these plantations.

Between accounting costs and economic costs, there are transaction costs, which, depending on the theoretical approach, may or may not be accounted for (Coggan et al., 2010; Falconer & Saunders, 2002; McCann, 2013; Gonon et al., 2025). In accounting terms, transaction costs include expenses associated with identifying suitable sites for restoration, planning, negotiation, and program organization. In economic terms, following the work of Ronald Coase, transaction costs refer to the risks inherent in the transaction, hindering or slowing down exchanges on a market.

Opportunity costs are the loss of economic benefits from the previous use of the restored land. For example, if a reforestation program is implemented on agricultural land, the foregone farm income should be accounted for as opportunity costs in the economic analysis. In some cases, opportunity costs can account for up to 87% of total costs in these analyses (Strassburg et al., 2020).

The costs considered for ecological restoration vary across publications. Some analyses include only opportunity costs (Jakovac et al., 2020), while others exclude them (Bayraktarov et al., 2016). Some vary the costs according to ecosystems or biomes (Mirzabaev et al., 2022), others depending on the restoration method (passive regeneration, planting) regardless of the biome or ecosystem concerned (Brancalion et al., 2016). The costs associated with work, salaried employment or equivalent, are a significant part of the costs of establishment and maintenance, as highlighted in several meta-analyses (Su et al., 2021; van Kooten et al., 2004).

The spatialization of these costs requires the construction of cartographic layers from data on productivity and ecological characteristics. For instance, Strassburg et al. (2020) (Figure 2) mention in the appendices of their study, "We used each net present value [farm profit] to convert the maps of each crop's current productivity in each grid cell, from the quantity produced per area to the value of production per area. [...] We added the resulting maps to get the opportunity cost layer for agriculture.²⁰".

Step 2: Defining and Quantifying Benefits or Effectiveness

The benefits and costs of degradation are estimated by the sum of the changes in the Total Economic Value (VET), which represents the sum of the ecosystem services taken into account in the analysis, over a time interval such as:

$$C_{LULC} = \sum_i^k (\Delta a_1 \cdot p_1 - \Delta a_1 \cdot p_2)$$

Avec :

C_{LULC} : Ecosystem change through degradation or restoration

p_1 : VET of ecosystem 1

p_1 : VET of ecosystem 1

p_2 : VET of ecosystem 2

This step therefore requires that each geographic statistical unit (pixel) be identified by an ecosystem, and each type of ecosystem to a VET.

If then, there has been degradation²¹, and the cost is equivalent to the VET differential. Conversely, the increase in VET reflects the estimated gain in catering. This implies that restoration is equivalent to ecosystem change, for example, ecosystem 1 is a "tree savannah" and ecosystem 2 is a "forest". The VET differential is then integrated into the profit calculation (Step 3). $p_1 > p_2$

The measurement of the effectiveness (rather than benefits) works on a similar logic, but uses other criteria and metrics, allowing for less aggregated information or prohibiting certain equivalence statements. Ecological restoration is associated with benefits in terms of carbon sequestration and a biodiversity index, such as extinction risk (IUCN).

For carbon, a conventional method is to sample maps of current carbon stocks to obtain average carbon stock values of the remaining native vegetation, and then extrapolate these values to restorable areas in the same geographic area based on an ecosystem typology. These estimates of gains are therefore approximated by the typology (from one type of ecosystem to another), not by the ecological dynamics of the ecosystems considered. In other words, each type of ecosystem corresponds to a potential for sequestration, and restoration is equivalent to a change in the type of ecosystem.

20 "We used each NPV to convert the ref. maps of current productivity of each crop in each grid cell from produced quantity per area to production value per area. We assumed a 20% margin of profit to obtain the opportunity cost for each commodity, as a likely conservative (that is, high) estimate based on profit margins in the USA (non-small farms), some EU countries and Canada. We recognize this is a simplified assumption and that in reality profit margins vary greatly, in particular with farm sizes. We added the resulting maps to obtain the opportunity cost layer for agriculture." (Appendix)

21 Degradation costs in the economic sense are a total loss of economic value, they are not costs in the accounting sense of the term.

There are many indicators of biodiversity gains. For example, in Strassburg et al. (2020), IUCN Red List data on the high-altitude ranges and habitat preferences of each endangered species are reclassified to correspond to a simplified typology of ecosystems (which also determines carbon gains and costs). To estimate the potential benefits of restoration for biodiversity, the reduction in the risk of extinction of each species is quantified by the increase in its habitat area, i.e. an increase in the number of pixels associated with the relevant ecosystem.

Step 3: Assessing the Effectiveness of Ecological Restoration through Scenarios

The benefit of restoration is obtained by the Net Present Value (π_t) of land restoration in year t over the planning horizon T of the land user.

$$\pi_t^i = \frac{1}{\rho^t} \sum_{t=0}^T (PY_t^i + IV_t^i - lm_t^i - c_t^i)$$

With π_t^d $1 + r$, r is the land user's discount rate; Y_t the production of ecosystem services for direct use after land restoration (food, fodder, wood, non-timber forest products, etc.), these ecosystem services may include cultural or heritage dimensions depending on the analyses; P is the unit price of Y_t ; IV_t the value of ecosystem services of indirect use (e.g. carbon sequestration); lm_t the costs of land restoration; c_t the direct costs of production. The exponent i refers to the restored biome. Scenarios allow the discount rate and time horizons to be varied to match the choices and priorities of decision-makers. The difference compared to π_t^d without restoration gives the net profit of the restoration action.

Multi-criteria optimization can be done in several ways. In Strassburg et al. (2020), the proportion of an ecosystem type to be restored in each planning unit (i) is determined in order to maximise benefits (in terms of biodiversity and/or climate change mitigation) and/or minimise costs (opportunity and restoration costs).

$$\text{Max} \sum_i^{np} x_i \cdot \left(\frac{(w_b \cdot b_i + w_s \cdot s_i)}{c_i} \right)$$

with:

$x_i \in [0, IU]$: proportion of unit i to be restored

BI : biodiversity benefit (per \$/km²)

if : carbon benefit (tonnes per \$/km²)

CI : Total cost (opportunity + restoration) for Unit i (in \$/km²) w_b, w_s : weight attributed to biodiversity and climate

NP : Total number of planning units

The objective function is constrained by a maximum area to be restored, and a restorability constraint per unit $0 \leq x_i \leq u_i \forall i$, with u_i the maximum proportion of unit i that can be restored, and a restorability constraint per unit $0 \leq x_i \leq u_i \forall i$, with u_i the maximum proportion of unit i that can be restored (e.g. in the case of an urban area).

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