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Global biodiversity scenarios: what do they tell us for biodiversity-related socio-economic impacts?

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Abstract

This paper aims to review and compare existing global and quantitative biodiversity scenarios that could help to build a forward-looking assessment of the consequences of biodiversity loss. More broadly, it provides a literature review of existing biodiversity scenarios and models as well as an assessment of the path forward for research to developing scenarios for biodiversity related socio-economic impacts at each step of the process: from building narratives, quantifying the impacts and dependencies, assessing the uncertainty range on the results all the way from the ecosystem to the economic and financial asset.

We have several key findings. First, global and quantitative physical risk scenarios are almost absent; this is why we concentrate on transition scenarios of biodiversity. Second, we find that most ecological transition scenarios are built in accordance with the conservation goals of the Convention on Biological Diversity (CBD), even if future land allocation varies across studies. Third, the Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) to assess socio-economic and climate change trajectories do not entirely incorporate the spatial implications of their economic growth hypothesis. Fourth, we underline the need to incorporate the uncertainties inherent to these integrated models, as well as the functional uncertainty of biodiversity indicators, which measure only a tiny fraction of global biodiversity. Finally, we make recommendations shorter-term improvements for assessing socio-economic impacts.

Keywords: Biodiversity scenarios, Biodiversity-related socio-economic impacts, Ecological transition modeling.

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Highlights

- The Convention on Biological Diversity (CBD), which brings together 196 parties, has established the "Post-2020 Global Biodiversity Framework" to reverse biodiversity loss. This global agreement proposes 21 targets, including the extension of Protected Areas (PAs) to 30% of the earth's surface by 2030, to enable the recovery of natural ecosystems by 2050.

- These targets align with a desire to "live in harmony with nature" as proposed in the "Vision 2050" of the CBD.

- Biodiversity scenarios are a crucial aspect of the implementation of these targets as they help us understand the socio-economic consequences of their implementation.

Nevertheless, scenario-building processes need to be improved in the long term to analyze the interactions between biodiversity and the economy, but efforts must begin immediately.

- Indeed, **physical scenarios** assessing changes in biodiversity **are almost absent** from the literature. Further research is, therefore, urgently needed to understand better the temporal and spatial properties of regime shifts and tipping points in ecosystems.

- **None of the narratives of transition scenarios** identified in this literature review **address planetary boundaries, potential ecosystem regime shifts, or tipping points**. We thus recommend including the consequences of climate change and biodiversity loss in the Shared Socio-economic Pathways (SSPs).

- One solution **to identify sectors with potential innovation opportunities** regarding transition or physical shocks would be to combine the Integrated Assessment Models (IAMs) with the EE-MRIO tables. However, **a higher granularity of sectors and subsectors** in these models **is needed** for this analysis to be relevant.

- **Overall, the models need** to be better linked to understand and explain the essential relationships and feedback between the components of coupled economic and ecological systems. Indeed, **two damage feedback loops** need to be added to existing modeling exercises; they refer to the consequences of biodiversity and ecosystem losses on economic activity.

- Moreover, **the dynamics of biodiversity and Ecosystem Services (ESs) must feedback on the narratives.** Indeed, the exogeneity of some model variables (e.g., GDP and RCP) must be questioned and relativized in the narratives to highlight the interactions between the economy and biodiversity.

In the meantime and in the shorter term, the following steps could be adopted to analyze the socio-economic impacts emerging from the CBD “2050 vision”.

- **using the Environmental Sustainability Gap Analysis (ESGAP) framework to construct physical scenarios** to determine whether countries are moving toward or away from a safe operating space for the economy and therefore the risk of encountering a tipping point.
- adapting recent work **on transition risk analysis** for climate change **by comparing biodiversity-dependent and biodiversity-impacting sectors** in a given country with its equivalents in the same sector and in the same type of biome; and
- **multiply data collection, open publication, and distribution approaches**, including non-conventional ones, **to feed future models** while ensuring the reproducibility of analyses, their open quality control, and the respect of data rights.

Introduction and motivations

Human activity exacerbates the erosion of biodiversity on a global scale at a rate unprecedented in human history, although it represents the living fabric of our planet (Brondizio et al., 2019). Indeed, biodiversity refers to the variety of living organisms present in each terrestrial and aquatic ecosystem and their ecological complexes. It includes genetic diversity, diversity between species, diversity of ecosystems, and the interactions within and between each of these diversity dimensions.

The anthropic pressures on biodiversity occurs directly (e.g., through land-use change, natural resource use, pollution, introduction of invasive species, and climate change) and indirectly (e.g., through demography, economy, technology, and governance). Moreover, biodiversity decline has severe and often irreversible consequences for Ecosystem Services (ESs), i.e., contributions of ecosystems to human survival and quality of life. Given that industries depend on these services for production, the economic impacts caused by biodiversity loss can be at least as great as those generated by climate change, in addition to interacting with them and leading to compounded effects (Bradshaw et al., 2021; Section 1 Pörtner et al., 2021; Chenet et al., 2022). These economic impacts therefore may have the potential to threaten the entire financial system through the industries' portfolio of financial institutions.

As in the case of climate, one can distinguish between two types of biodiversity related financial risks. Physical risks on the one hand arise when biodiversity loss affect human capital and economic activity. These losses lead in a non-linear way to the loss of ESs. Industries that are highly dependent on them directly or indirectly through their value chain will be the most affected. For example, the agricultural sector relies highly on the pollination service, which determines a large proportion of crop yields and thus profits and jobs directly or indirectly related to this sector. On the opposite, physical opportunities could be identified by researching within these economic sectors with high dependencies, which practices allow to reduce the dependencies to ecosystem services or to maintain the flow of ecosystem services.

On the other hand, sources of transition risks include changes in policies, consumer preferences or behaviors, and changes in technologies to mitigate human activity's impact on biodiversity. The idea is to consider that firms with a significant negative impact on biodiversity have a higher chance of being affected by a biodiversity transition shock than a business with a low impact (i.e., more virtuous firms in the same or in different sectors). For example, regulating imported deforestation through imported products will limit businesses' ability to expand if they have strong deforestation footprint. Then, transition opportunities would be to identify within each sector with high biodiversity footprints, which one produces a lower pressure and could benefit from the transition in the future.

It is possible to approach biodiversity-related financial risks[1] statically.

- In the case of exposure to physical risks, one can analyze each type of industries' dependencies on ESs through their whole value chain. The idea is to combine Environmentally Extended Multiregional input-output (EE-MRIO) tables, such as EXIOBASE[2], with databases, such as ENCORE[3], providing the dependence rate of production processes on ESs. For instance, Svartzman et al. (2021) found that 42% of the value of securities held by French financial institutions comes from issuers highly or extremely dependent on at least one ES.

- For transition risks, one can explore industries' positive or negative impacts on biodiversity. One method that has been widely used is to combine EE-MRIO tables with the Global Biodiversity Score (GBS)[4] to measure the impact of a specific type of industry on ecosystem integrity. For example, once aggregated, the biodiversity footprint of Dutch financial institutions would be comparable to the loss of 58,000 km^2 of pristine nature, which is more than 1.7 times the terrestrial surface of the Netherlands (van Toor et al., 2020).

However, the advantages of dynamic and prospective approaches (through scenario assessments) to assess physical and transition industries' exposures are multiple. They are suitable for anticipating the emergence of risks that have never been observed, and they could highlight the interconnections of the different systems. They can take into account the adaptability of the society and the non-linearity of ecosystem dynamics, biodiversity loss, and its consequences (tipping points).

Scenarios are qualitative and/or quantitative representations of possible futures. In the case of biodiversity, they describe the evolution of multiple components of a system, e.g., of drivers of change in biodiversity (e.g., land-use changes), including alternative policy (e.g., Protected Areas -PAs- expansion) or management options (e.g., agroecology) to reduce biodiversity loss. Scenarios do not predict the future, as there is no consensus on future environmental and socio-economic trajectories; instead, they allow for the description of likely futures in situations of high uncertainty based on a set of assumptions (Brondizio et al., 2019). They will enable an understanding of local, regional, and global dynamics.

Scenarios required to assess transition risks/shocks are target-seeking and policy-screening scenarios (i.e., transition scenarios). Target-seeking scenarios identify one or more objectives, generally in terms of achievable targets, and then determine different pathways to achieve that outcome, such as scenarios aiming at reversing the biodiversity curve by 2050. Policy-screening scenarios allow ex-ante assessments to predict the effects of various interventions on environmental outcomes, such as scenarios testing

[1] In the rest of this paper when we use the term "biodiversity-related financial risks" or "risks" we mean both risk and opportunities as being the two sides of the same coin.

[2] The EE-MRIO EXIOBASE table offers information on the value chain (the value of the output produced, the value of intermediate consumption to produce it for each industry and region) of 163 industries in 49 world regions (189 countries).

[3] Exploring Natural Capital Opportunities, Risks, and Exposure (ENCORE) breaks down the industry's direct and indirect dependence on 21 ecosystem services by business process. It also provides the dependence of an industry's activities on ecosystem services; five low to very high scores are available.

[4] The Global Biodiversity Score (GBS) is a tool developed by CDC Biodiversity that enables companies and financial institutions to measure their biodiversity footprint. The tool provides an aggregated metric (in Mean Species Abundance km^2) to assess the level of ecosystem degradation attributed to companies. It distinguishes between permanent and dynamic impacts and takes into account the impacts on biodiversity along the entire upstream value chain.

multiple supply side (e.g., removing subsidies) and demand side (e.g., awareness campaign on water use) policies applied to a specific industry. Thus, both scenario types can simulate the impact of an "ecological transition" on biodiversity and on the whole economy.

Exploratory scenarios assess physical risks/shocks related to biodiversity degradation (i.e., physical scenarios). They examine a range of plausible futures given potential trajectories of biodiversity's direct and/or indirect drivers. They can thus assess economic or environmental responses to a shock related to a specific modification, change, or degradation of nature (e.g., drought caused by global warming).

The goal of this policy paper is to evaluate and improve existing scenario-building methods used to assess socio-economic impacts associated with biodiversity dynamics.

I – The Literature Review Methodology

We used three criteria to select the scenarios surveyed in this paper: the scenarios had to be (1) global, (2) quantitative, and (3) measuring impact on biodiversity.

Although qualitative scenarios provide a better understanding of the interactions between the different components of the system, as they are less constrained by modeling assumptions, they are not inherently sufficient to assess the dependencies and impacts of industries on biodiversity because they are more difficult to transform in quantitative assessment of socio-economic indicators.

We selected global scenarios because most of the economic assets held are part of a globalized economy through two dynamics: on the one hand global value chains and financial networks developed internationally implying strong interconnections between industries in different countries, and on the other one a geographical (and sectoral) diversification of industries' dependencies and impact on biodiversity. Therefore, working on local scenarios may quickly fail to cover all impacts and dependencies, and an aggregation of a multitude of local scenarios would considerably increase the complexity of the analysis. As this is an "emerging science", it seemed preferable to analyze the state of the science globally to examine, in a second step, the possibilities and limits of disaggregating the results of these scenarios at national (or even sub-national) levels.

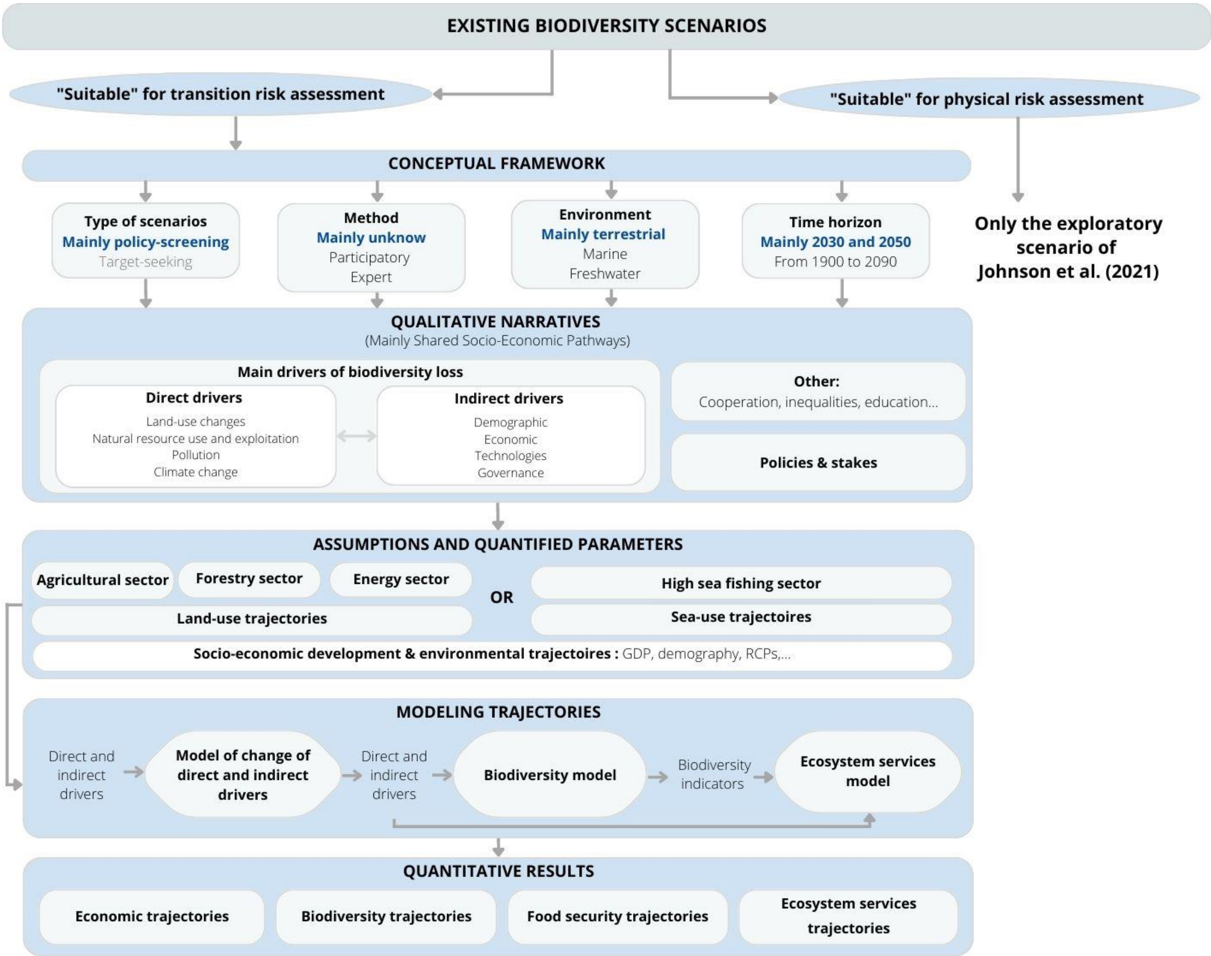
Finally, we excluded scenarios assessing only changes in biodiversity drivers (e.g., land-use changes). Instead, we chose scenarios quantifying input pressure into at least one interspecies indicator of biodiversity after the implementation of a transition scenario. Indeed, our focus is on measuring and comparing the impact of industries/sectors on biodiversity.

To identify these scenarios, we analyzed the Convention on Biological Diversity (CBD) report, "Global Biodiversity Outlook 5" (Hirsch et al., 2020), which describes two articles with quantitative biodiversity scenarios (which meet our criteria). We then explored the literature review of the main terrestrial, aquatic, and marine biodiversity scenarios from the IPBES (Brondizio et al., 2019) report. Among the most recent literature, we selected five articles: two applied to marine biodiversity and three to terrestrial and freshwater biodiversity.

Finally, we completed this panel of scenarios with further research and gathered in the end 8 studies and 78 quantitative scenarios on a global scale.

There is no universal methodology for developing global and quantified biodiversity scenarios. However, we have identified five main steps: (1) setting the conceptual framework, (2) constructing narratives, (3) quantifying parameters and assumptions, (4) quantifying scenarios through simulations of one or more models, and (5) analyzing the results. We thus organized this paper accordingly (see Figure 1).

Figure 1. Representation of existing biodiversity scenario development processes.



II – The Conceptual Framework

The conceptual framework refers to the setup by which the scenario is conceptualized. We identified four characteristics that could summarize this framework: the type of scenario, the methodology used to construct the scenario, the nature of the environment considered, and the time horizon for the scenario/ Table 1 synthetize the our findings for the selected scenarios.

Biodiversity scenarios are mainly policy-screening and target-seeking. It means that almost no physical scenarios exist at the global scale, i.e., scenarios of physical shocks that anticipate tipping point exceedances and possible regime shifts, as well as related changes in ESs at different geographical points in the world (Turner et al., 2020).

The only scenario in this literature review suitable to analyze physical shocks is the exploratory scenario of Johnson et al. (2021). It corresponds to a narrative where biodiversity tipping points are crossed, in this particular case where three arbitrarily chosen ESs (i.e., pollination, marine, and timber production) declining by an arbitrary magnitude.

Further research is thus urgently needed to address this knowledge gap and to pursue efforts to understand better the timing and spatial properties of regime shifts and ecosystem tipping points (in relation with climate changes scenarios).

Quantitative scenarios are mainly terrestrial, to the detriment of freshwater and marine environments (only one freshwater and two marine scenarios met our criteria), even if the biological diversity of marine habitats is potentially considerable and unknown (Appeltans et al., 2012). The lack of data on species distribution partly explain the poor knowledge of these ecosystems and thus leads to the absence of marine scenarios. Underrepresenting future trajectories of marine biodiversity and associated ESs, as well as policies for managing and conserving these ecosystems, tends to underestimate the impact of their degradation on socio-economic indicators. Indeed, the fisheries sector is highly dependent on the ES of fish production. Some regions, such as West African and Southeast Asian countries, particularly the Philippines and Indonesia, depend on fish as their primary food and livelihood source (Teh et al., 2017).

Physical shocks tend to emerge earlier than transition shocks, which depend mainly on policy announcements regarding conservation goals (INSPIRE & NGFS, 2022). Nevertheless, the impacts of such scenarios should address short- and medium-term as well as long-term effects on the economy and the environment. It is thus crucial to determine the appropriate time horizon for the different future trajectories.

The objectives and horizons of the selected scenarios are primarily aligned with those of the CBD, resulting in a high representation of projections for 2030 (i.e., target to halt biodiversity loss) and 2050 (i.e., target to start recording a net positive increase in biodiversity). There is no consensus on a suitable global target, unlike climate transition scenarios, which mainly use the target of 1.5 °C (or 2 °C) of global warming above pre-industrial levels.

Finally, the reviewed papers explore different possible narratives for each type of research question and are thus not limited to a single scenario, taking into account some level of uncertainty. As a result, the reviewed papers consider between 3 and 10 scenarios each.

Table 1. Overview of biodiversity scenarios articles selected for this literature review.

ARTICLE	NUMBER OF SCENA-RIOS	TYPE OF ANALYSIS	TYPE OF RISKS	TYPE OF SCENA-RIOS	MAIN ENVI-RONMENTS	TIME HORI-ZON
Kok et al. (2020)	5	Biophysical	Transition, physical	Target-seeking	Terrestrial, freshwater	2030, 2050, 2070
Johnson et al. (2021)	10	Economic	Transition, physical	Exploratory, pol-icy-screening, target-seeking	Terrestrial	2030
Leclère et al. (2020)	7	Biophysical	Transition	Target-seeking	Terrestrial	2050
Cheung et al. (2019)	4	Biophysi-cal, econo-mic	Transition	Policy-screening	Terrestrial	2030, 2050, 2090
Obersteiner et al. (2016)	42	Biophysical	Transition	Policy-screening	Terrestrial	2030, 2050
Costello et al. (2016)	3	Biophysi-cal, econo-mic	Transition	Policy-screening	Marine	From 1980 to 2050
Schipper et al. (2020)	3	Biophysical	Transition	Policy-screening	Terrestrial	2050
Pereira et al. (2020)	4	Biophysical	Transition, physical	Policy-screening	Terrestrial	From 1900 to 2050

III – The Development of Scenario Narratives

Once the conceptual framework is set, the next step is to design or determine scenario narratives (i.e., storylines); they describe the possible evolution of the world given a specified context. These narratives can be composed of qualitative socio-economic pathways, policies, technological changes, agent preferences, behavior shifts, and assumptions on natural resource conditions, i.e., changes in direct and indirect drivers of biodiversity loss.

Almost all of the authors in this literature review used Shared Socio-economic Pathway (SSP) narratives, sometimes complemented with other narratives. SSPs are composed of five qualitative scenarios describing possible socio-economic development trends (e.g., economic growth, demography, technology, and governance) worldwide (O'Neill et al., 2014, 2017; Riahi et al., 2017). They were created to define a common research framework on global warming issues and thus facilitate the production of integrated assessments. It is important to note that these narratives do not include explicitly climate (or biodiversity) policies nor the consequences of climate change (or biodiversity loss). Instead, they should be coupled with policies that may, for example, aim to achieve radiative forcing targets (van Vuuren et al., 2014) or biodiversity conservation goals.

These five specific narratives explore existing uncertainties regarding mitigation and adaptation policies associated with different climate and socio-economic futures. They thus describe the conditions that will make it more or less difficult for countries to manage a transition to a low-carbon economy rather than a nature positive transition. Original SSP narratives are available in O'Neill et al. (2017) and the land-use-related narratives in (Popp et al., 2017).

In the context of biodiversity scenarios, SSPs can provide storylines for the main indirect and direct drivers of biodiversity loss, except for introducing and spreading invasive species. Indeed, this pressure is always missing in the narratives, although it poses a significant threat to ecosystems and economies (Andersen, et al., 2004; Olson, 2006; Stohlgren & Schnase, 2006): notably through the agricultural sector (e.g., increase in pest control costs), the forestry sector (e.g., degradation of trees health) and the fish sector (e.g., extinction of native fish species).

Alternatively, two articles designed their own narratives, allowing for more specific inclusion of biodiversity dynamics and political stakes but losing comparison with other studies.

Cheung et al. (2019) developed three scenario narratives related to marine environments that complement the SSP1, SSP3, and SSP5 storylines, the most modeled pathways in the literature. This approach allows them to start from a homogenized conceptual framework widely used in the literature and add specificities related to the high-seas fishing sector, such as changes in agent consumption or marine biodiversity conservation policies.

Kok et al. (2020) constructed their storylines without qualitatively specifying the socio-economic contexts in which they are embedded. They thus developed two scenarios that describe different goals in terms of biodiversity conservation objectives. The first promotes a "land sparing" approach to protect the intrinsic values of nature, and the second has a "land sharing" vision where ESs play a central role in decision-making[5].

Overall, none of the narratives identified in this literature review discuss planetary boundaries, possible ecosystem regime shifts, or tipping points. The non-linear and finite aspect of the resources we use for our consumption and production should form an integral part of the storylines to better understand the different impacts of these phenomena on our society's stability and thus improve the quality and realism of the qualitative hypotheses. It therefore seems more desirable to integrate the consequences of climate change and biodiversity into the SSPs. The narratives also lack details in the policies and tools needed to leverage the socio-economic change needed at scale.

[5] While a land sharing system contains a patchwork of low-intensity agriculture containing natural features like ponds and hedgerows, rather than keeping agriculture and wilderness separate, a land sparing system requires substantial, separate areas of sustainably intensified agriculture and wildness.

IV – Key Assumptions and Quantified Parameters

Once a scenario narrative is complete, it can be transformed into a quantitative trajectory using models. Indeed, the storyline must be translated into a quantitative scenario, specifying values (constant or varying) for several model parameters. The model will also need other quantitative hypotheses to fix values of the parameters that do not belong to the specified scenario (this is also known as calibrating or estimating the model). However, moving from qualitative to quantitative scenarios often means that some dynamics are not measurable or not easily accounted for.

Almost all studies quantified Gross Domestic Product (GDP) and population trajectories (at least) from SSPs. Many of them also coupled the SSP assumptions with one or more Representative Concentration Pathways (RCPs) that describe future greenhouse gas (GHG) concentration for different climate scenarios until 2300 (van Vuuren et al., 2011).

A – The Gross Domestic Product (GDP) Quantification

The Organisation for Economic Co-operation and Development (OECD) approach for measuring GDP trends in the SSP trajectories is dominant. They opted for an augmented version of the Solow growth model, which does not include natural resources and land-use other than crude oil and natural gas as growth factors. Namely, if no land is available to expand agriculture and the land currently being farmed is too degraded, the country's long-run production and/or value-added will not be affected.

Moreover, their model assumes conditional convergence. It means that, from the first year of the projection, the GDP of least developed countries will increase more rapidly than those of developed countries, leading to convergence (catch-up effect). As a result, GDP growth trajectories are positive for every country at least until 2100 (both in total and per capita term) even though the scenario envisaged proposes a significant structural change (either an ecological transition or collapse of biodiversity) which should precisely affect long-term growth.

It is however likely that the dramatic changes in direct and indirect drivers of biodiversity loss and mitigation policies implied by the scenarios will result in a decrease in global GDP, or at least for some countries that fail to adapt to an ecological transition or experience an ecosystem collapse.

The only attempt to recast SSPs for exploring low, zero, and negative GDP growth by coupling biodiversity loss to economic growth, i.e., by incorporating the possibility of limited growth due to natural resource degradation, is that of Otero et al. (2020). However, these storylines have never been quantified.

B – An Overview of Possible Quantitative Policies and Trajectories per "Sectors"

On top of SSP trajectories, most authors added various pathways, political/behavior shifts, or collapse assumptions; they incorporated strategies for biodiversity conservation, ecosystem restoration, food security, or global warming mitigation. However, some authors did not necessarily couple SSP with biodiversity conservation policies and only looked at the impact of SSP on biodiversity (Schipper et al., 2020; Pereira et al., 2020). All these assumptions and quantified parameters are mostly embedded in the following sectors or areas of focus.

The agricultural sector

The agricultural sector is crucial in biodiversity scenario development because it affects biodiversity the most, notably by converting natural habitats to intensely managed systems and releasing pollutants: crops and livestock production occupy 50% of the global habitable land surface (excluding ice-covered land).

The trajectories attributed to this sector are mainly supply-side, and trajectories related to the agricultural sector productivity (e.g., crop yield, irrigation, and fertilizer efficiency) are the most widely modeled. Usually, crop productivity without additional inputs (i.e., fertilizer and waste) in developing countries is projected to converge to the level of developed countries, even if it will require a lot of investment and innovation. Crop productivity may also be constrained by climate change impact on soils (Rosenzweig et al., 2014), which is often not accounted for in the scenarios.

The authors also added policies to limit harmful subsidies or increase taxes on the agricultural sector. For example, Johnson et al. (2021) quantified the removal of all subsidies from the agricultural sector in favor of a system of lump-sum transfers to farmers, and Kok et al. (2020) quantified the introduction of a 10% import tax on all agricultural products by 2050. However, as agricultural products are internationally traded, those interventions necessitate a global implementation and, therefore, total cooperation between countries. However, SSP narratives do not propose the same degree of collaboration between countries.

Some demand-side policies are nevertheless modeled; they are primarily related to changes in food production, such as reducing food losses (from harvesting, processing, distribution, and final household consumption) and changes in the consumption of animal products. For example, Kok et al. (2020) and Leclère et al. (2020) simulated a 50% reduction in food loss and animal calorie consumption by 2050 based on current country trends.

Policies that target the agricultural sector are very broad and do not differentiate between the different agricultural practices that exist. We will see later that the concern is with models of direct and indirect drivers of change that are unable to provide accurate information on sectors and sub-sectors.

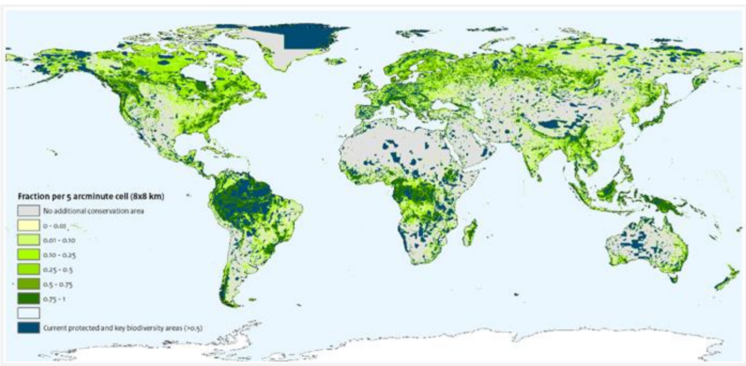
Land-use trajectories

A flagship measure of the CBD in the "Post-2020 Biodiversity Framework" is the protection and conservation of species habitats through the expansion of PAs and Other Effective area-based Conservation Measures (OECMs)[6] to protect at least 30% of the terrestrial surface by 2030. Currently, PAs and OECMs cover only 17% of the world's land and inland water surface but depending on the country, the proportion can vary from 1% to 50%[7].

Therefore, expanding PAs and OECMs is the most widely modeled biodiversity conservation policy. However, because no consensus exists globally on what percentage of land should be regulated and where, researchers make their own decision, guided by existing literature and desired outcomes.

Depending on the scenario, the assumptions range from 30% to 50% of terrestrial PA expansion, but their distribution differs widely. For example, we compare the 30% PA expansion policy of Kok et al. (2020) with the 40% expansion policy designed by Leclère et al. (2020), see Figure 2. We can see that the latter is "politically" easier to implement but not at all convincing from an ecological point of view. Indeed, the conservation effort shifted to the northern boreal zones and the desert zones of Australia and the Sahara in Africa, sparing, for example, the tropical forests of the Congo Basin, which represents a key zone in terms of biodiversity. Yet the CBD emphasizes the need to select PAs based on their importance for biodiversity and their contribution to people for conservation to be effective and equitable.

Figure 2. (A) Conservation areas for the Sharing the Planet scenario with the ambition to conserve 30% of the global land and freshwater area by 2050 (Kok et al., 2020); (B) Conservation zones for PA expansion policy with the ambition of conserving 40% of the land area by 2020 (Leclère et al., 2020).



A

[6] An Other Effective area-based Conservation Measure (OECM) represents a geographically defined area other than a PA, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socio–economic, and other locally relevant values." (Definition agreed at the 14th Conference of Parties of the CBD in 2018).

[7] Protected Planet. https://www.protectedplanet.net/en.

B

In addition, establishing an effective PA network is costly. It can include monitoring habitat health, enforcing regulations, and investing in research fees to prevent illegal activities in PAs, such as logging, poaching of protected animals, mining, and encroachment by human settlements and agriculture. Nevertheless, they offer economical and social benefits and mitigate the economic risks of climate change even if not all countries will have the capacity to capture them, particularly in terms of tourism development (Waldron et al., 2020).

Overall, Johnson et al. (2021) estimated that achieving the protection of 30% of the world's lands would require an average annual investment of about $115 billion until 2030. Still, if the benefit of avoided carbon emissions is included, it is reduced to $13 billion. The cost and benefits associated with the expansion of PAs are however rarely considered in the scenarios.

The type of protection envisaged in the PAs, such as whether or not human activities can be developed within them or what kind of activity is allowed (e.g., recreational and forestry), is not always clearly defined in the scenarios. However, these factors will potentially significantly impact the speed and magnitude of biodiversity degradation and economic outcomes.

The high-sea fishing sector and sea-use trajectories

The policies and trajectories implemented to improve marine biodiversity are diverse and creative. They focus, for example, on subsidies, ex-vessel fees, Marine PAs (MPAs), or fisheries management techniques shifts.

For example, Cheung et al. (2019) quantified and adjusted three SSP narratives notably by adapting trajectories on ex-vessel prices of marine species, subsidy changes, fishery operating and investment costs, and catchability rates. For all these scenarios, MPA expansion constraints of 0-50% are simulated by 2050, with a median target of 30% of the total high-seas area, and radiative forcing trajectories are defined (i.e., RCP 2.6 and RCP 8.5).

However, current MPAs only cover about 8.15%[8] of the oceans, so establishing 50% MPAs by 2050 will be challenging and will require a lot of monitoring and investment that is not accounted for in the scenarios. Moreover, as with terrestrial PAs, MPAs are likely to be costly

[8] Protected Planet. https://www.protectedplanet.net/en.

and generate co-benefits (e.g., tourism and coastal protection) that are not accounted for in the scenarios.

Globally, no article distinguishes between different fishing sectors (i.e., recreational, subsistence, and commercial) and types of commercial fishing methods: whether an industry is fishing with nets (e.g., purse seine, trawling, and bottom trawl) or with line (e.g., longlines, pole, and line) or harvesting shellfish. Nevertheless, all these parameters will have different consequences in terms of biodiversity erosion and capacity to satisfy the growing seafood demand. Additionally, it does not allow for the differentiation of fishing activities and, therefore, the identification and valorization of techniques that are less destructive of marine ecosystems (i.e. identification of transition opportunities).

The forestry sector

Researchers explored measures to mitigate global warming by maintaining carbon storage through avoiding deforestation in the scenarios. These policies always assume full cooperation and coordination between countries. For instance, Johnson et al. (2021) identified two different trajectories depending on the scenario. In the former case, payment for forest carbon is made within each country by limiting the supply of land and compensating forest owners through increased land subsidies. In the second case, payment for forest carbon is realized by rich countries based on their historical GHG emissions, and payment is received by poorer countries based on avoided deforestation.

The energy sector

Only a few studies have set up trajectories targeting the energy sector. For instance, Obersteiner et al. (2016) simulated two different policies to achieve the 2°C global warming target by imposing either a moderate share of bioenergy and nuclear power or a high percentage of bioenergy and no nuclear power by 2030.

Contrary to the climate scenarios for which this sector is crucial, biodiversity is less impacted by a single industry. As a result, the studies integrate a few climate change mitigation and adaptation policies (e.g., through the forestry or the energy sector). We, therefore, recommend building a bridge between climate and biodiversity scenarios, especially to identify the potential for compounding and cascading impacts on the economy.

Nevertheless, scenarios focusing on biodiversity change allow us to understand which policy intervention will be the most effective in conserving biodiversity. Indeed, some measures to mitigate global warming do not produce "co-benefits" for biodiversity or even degrade it further and vice versa. For example, the expansion of hydropower plants, intensely simulated in climate scenarios, provides clean electricity with low GHG emissions, but at the same time, it degrades biodiversity (e.g., by fragmenting watercourses and disrupting certain biological cycles).

C – Collapse Assumptions

Johnson et al. (2021) designed the only exploratory physical scenario in the literature review. They designed a collapse of multiple ESs due to extreme environmental shocks. They simulated the effect of a 90% reduction in wild pollination on agricultural yields (i.e., the collapse of pollinator ESs) only for crops dependent on wild pollination.

Moreover, they designed a collapse of marine fisheries. As a result, they implemented a severe climate change scenario (RCP 8.5) to simulate drastic disruptions in fish migration that would result in a reduced total catch in terms of biomass, which registers as a technology-neutral productivity change in the fishing sector.

In addition, Johnson et al. (2021) modeled a sudden collapse in timber production. They assumed an 88% decrease in forest cover for all tropical regions and suggested a decline in the ability to expand forestry in humid tropical areas with a longer growth period.

V – Modeling Trajectories

Three main categories of models are commonly used to construct biodiversity scenarios. Some models assess how changes in indirect pressures (e.g., economy, technology, and demography) affect direct pressures (e.g., land-use change, climate change, and nitrogen deposition) of biodiversity loss and vice versa. Others model the magnitude of change of direct and indirect pressures on nature regarding biodiversity and ecosystem functioning. A final category of models assesses the consequences of natural changes on the well-being that people derive from nature and that contribute to a good quality of life, including ESs (Brondizio et al., 2019). One should never forget that no single set of scenarios and models is perfect for representing the future: they have inherent limitations that are more or less reasonable.

A – Models of Change of Direct and Indirect Drivers of Biodiversity Loss

Models of change of direct and indirect drivers of biodiversity loss project for multiple horizons, quantified parameters and assumptions on socio-economic, and environmental pressures. They are composed of many different models, which may provide spatial results (e.g., crop allocation) and/or aggregate indicators (e.g., food prices).

Two of the studies selected for this literature review, used an Integrated Assessment Model (IAM)[9] to describe quantitatively key processes in human and earth systems and their interactions. Indeed, Kok et al. (2020) and Schipper et al. (2020) used IMAGE[10], a computable

[9] When we speak of Integrated Assessment Models, we are referring to the category of "complex" IAMs, i.e., those that describe future development paths in terms of technology change, energy mode choice, land-use change or societal trends towards protecting or not protecting the biosphere, and that provide sectoral information on the processes being modeled (also known as "process-based models"). In addition, we refer to IAMs that determine global equilibria by assuming partial equilibria of the economy.

[10] The IMAGE model, created by the Netherlands Environmental Assessment Agency (PlanBureau voor de Leefomgeving - PBL), allows the simulation of future global dynamics between societies, biosphere, and atmosphere and their interactions until 2100. For each

general equilibrium model. IAMs were developed to anticipate the evolution of climate trajectories and related issues, which implies, among other things, that they were not designed to respond to research questions related to biodiversity.

In general, IAMs take as inputs GDP and demographic trajectories (typically from the quantification of SSPs), policy trajectories (e.g., RCP targets, specific policies for biodiversity concerns), and other options such as agents' preferences or technological changes. These inputs are then implemented into different modules to explore energy, land, climate systems, and the economy, among others. These modules are linked to assess some cascading effects, "co-benefits", and unintended consequences, tracing how choices in one domain affect the rest of the model. Finally, integrated models provide outputs on economic, biophysical, energy, and land-use trajectories.

Some authors only selected land modules (e.g., GLOBIOM, MAGNET) or dynamic global vegetation models (e.g., LPJ-GUESS, LPJ) to assess changes in indirect and direct drivers of biodiversity, which are included in the IAM modeling process. They provide similar insight as IAMs as they consider the same inputs and provide the same outputs; the main difference is their inability to be as comprehensive, i.e., to explore global, multi-sectoral dynamics and their interactions but typically provide more detailed results regarding land use and biodiversity outcomes.

IAMs and associated modules seek to know what structure of the economy (e.g., production, demand, and exports) will give them the socio-economic trajectories they desire (e.g., GDP, demography, and policy outcomes). For example, they take future GDP trajectories for granted no matter the modelled policies or the emissions projections. The main tool that allows them to distinguish between economic structure and ensuing economic or ecological outcomes is the variation of relative prices. This modeling process considerably impacts the analysis of an ecological transition, as the SSP projects positive GDP growths for all countries until 2100, even if a long-term structural change is modeled (i.e., an ecological transition or an ecosystem collapse).

Moreover, the consequences of SSP trajectories will depend on each model and the hypotheses made by its team of modelers. Indeed, not all IAMs/land modules have the same structure and make the same trade-offs: they differ in biochemical, biophysical, and socio-economic parameters. Land-use assumptions such as agricultural productivity, the environmental impact of food consumption, international trade, or land-based climate change mitigation policies are different between IAMs (Popp et al., 2017). Nevertheless, one should remember that proposing different alternatives explores the uncertainties of the scenarios and models.

Because these models are global and shaped for assessing climate aspects, they are severely lacking in accuracy at many levels, notably in sectors and sub-sectors impacting

of the 26 regions it covers, it can assess terrestrial dynamics for socio-economic indicators with a spatial scale of 0.5 x 0.5 degrees of latitude-longitude.

biodiversity. For example, GLOBIOM[11] only distinguishes between eighteen crops and seven animal products; it can differentiate between six land-uses (cropland, grassland, short-rotation plantations, managed forest, unmanaged forest, and other naturally vegetated lands) and four management systems (food crop, low-input rainfed, high-input rainfed, high-input irrigated). Thus, these classifications remain very general and do not easily allow for the targeting of activities and practices likely to be the most impacted and/or having the higher impact in the event of an ecosystem collapse or an ecological transition, such as identifying organic farming, agroforestry, natural farming, conservation agriculture or precision farming. The differentiation of practices within sectors will allow better identification of transition opportunities for pro-nature policies and avoid the risk of discriminatory policies towards a specific sector, such as limiting agricultural subsidies regardless of good or bad practices.

Overall, the main sectors represented are the energy, forestry, and agricultural sectors. Some activities are absent from the analysis, such as mining and quarrying, high-sea fishing, or the manufacturing sector, although they considerably impact biodiversity. In order to identify sectors with potential innovation opportunities (e.g., finding textile industries with low chemical release compared to other similar industries), one solution would be to combine IAMs with EE-MRIO tables. Still, a better granularity of sectors and subsectors is needed for this analysis to be relevant. We thus encourage efforts to improve sectors' representation in both models.

Alternatively, Johnson et al. (2021) opted for the "Global Trade Analysis Project" (GTAP) model, which is a multi-regional, multi-sectorial, and computable general equilibrium model. They combined it with agro-ecological-zones (GTAP-AEZ) to cover 137 regions. The main advantage of this model over IAMs is that it offers a broader sectorial disaggregation (57 commodities/sectors), which improves the possibility of linking biodiversity impacts with sectors/industries in the context of a transition impact assessment.

Moreover, IAMs and GTAP-AEZ models are only tailored to explore terrestrial or freshwater systems. Thus, it is not yet possible to use them to assess the impact of human activities, notably through the high-sea fishing sector, on marine ecosystems. In the absence of these models, Cheung et al. (2019) and Costello et al. (2016) have used bioeconomic models, i.e., models that capture both economic and biophysical dynamics.

Finally, an essential pressure on biodiversity erosion never taken into account by any models of change in direct or indirect factors of biodiversity loss is, as already noted for scenario narratives, the introduction and development of invasive species (some being diseases vectors and pandemic factors).

[11] GLOBIOM is a dynamic partial equilibrium model of the agricultural and forestry sector. It can be used alone or with the IAM MESSAGE to obtain computable general equilibria. It allocates land between production activities to maximize consumer and producer surplus by considering a dynamic set of demand, resources, technologies, and policies.

B – Biodiversity Models

Biodiversity models allow direct and indirect drivers of biodiversity loss to be translated into biodiversity impacts, measured through the biodiversity indicators they provide. The authors used various biodiversity models and indicators.

Some of them, such as Pereira et al. (2020), combined several models and indicators to assess the impact of a scenario on biodiversity, while others chose a single pair. The method will depend on the compatibility between the model and the biodiversity indicator. There is a trade-off here between using many scenarios and indicators to be more transparent about the uncertainties associated with modeling and choosing a limited number to explore more specific hypotheses related to biodiversity issues.

Biodiversity is multidimensional and cannot be summarized in a single indicator, unlike climate change with the proxy of CO2-equivalent emissions or concentration. Indeed, biodiversity is a large concept that includes diversity within species (genetic diversity), between species (species diversity), ecosystem diversity (ecological diversity), and the interactions within and between each of these three levels of diversity.

All the identified articles measure biodiversity between species, and some also measure ecosystem diversity, but none explore genetic diversity. However, genetic diversity is essential for analyzing the ability of species to adapt to future environmental changes. For example, climate change can alter genetic traits, sometimes affecting species' resilience. However, we must recognize that on a global scale, genetic data are scarce.

Half of the authors' predominant measure of biodiversity is the Mean Species Abundance (MSA). It is defined as the average abundance of indigenous species compared to their abundance in non-degraded ecosystems, i.e., undisturbed by human activity. The indicator ranges from zero to one, where one represents an undisturbed ecosystem and zero a completely degraded ecosystem, i.e., as rich in biodiversity as a parking lot. For example, the MSA of a pasture with livestock might be 60%, 10% for an ecosystem with intensive agriculture, and 5% for an urbanized area.

However, this indicator raises many questions about its interpretation. Indeed, when the MSA is worth 0.5, does it indicate 100% destruction on 50% of the territory or 50% destruction on 100% of the territory? Furthermore, the indicator is constructed from a meta-analysis, and the context of the studies likely influences the results. Unlike the similar Biodiversity Intactness Index (BII)[12], the MSA normalizes abundances to one, not more, which means that the undisturbed ecosystem is the richest in biodiversity, so adding new non-native species to the ecosystem does not increase biodiversity.

Obersteiner (2016) and Johnson et al. (2021) combined multiple biodiversity indicators into a single measure. This method offers the possibility of weighting biodiversity indicators

[12] The Biodiversity Intactness Index (BII) measures the average abundance of species relative to their reference populations in a given geographic area.

differently. However, there is a risk of double counting the same biodiversity measure, and its interpretation is not obvious.

Moreover, indicators over-represent mammal and bird species. Indeed, around 35% of the indicators treated by the authors take into account wild mammals, although they represent only 0.001% of the total biomass. Then, the most represented taxa are birds, plants, and amphibians, while they represent 0.0003%, 81.82%, and 0.018% of the total biomass, respectively. Nevertheless, all papers that used a mammal biodiversity indicator also used one that incorporated plants and birds.

Finally, biodiversity models and, therefore, indicators do not consider the same pressures, which will affect the results for a determined location. For example, the BII only includes pressures from land-use, demography, and fragmentation, so the indicator may be very high in an area where hunting is the only significant threat to biodiversity.

C – Details on Ecosystem Service (ES) Models

Only three studies analyzed the evolution of some ESs resulting from their transition scenarios with ESs models. Kok et al. (2020) primarily used the GLOBIO-ES[13] model, Johnson et al. (2021) used InVEST[14], and Pereira et al. (2020) used these two models. These are the most represented ES models at the global scale; they used outputs from the two first types of models (i.e., models of change of direct and indirect drivers of biodiversity loss and biodiversity models). Alternatively, models of change of direct and indirect drivers may directly provide proxies for ES assessments. For example, IMAGE gives total crop production in calories per year, a measure of food provisioning ESs.

The main problem with existing ES models is that they do not incorporate possible tipping points and regime shifts in their analysis. In addition, models do not (or hardly) consider the interconnections between the different ESs; they mainly analyze each service separately (Agudelo et al., 2020). The main reason is that data on the link between land-use and landscape characteristics and ESs are scarce and fragmented. Nevertheless, some ESs, such as pollination, are much better documented than others.

Moreover, the modeling of regulatory ESs predominates over provisioning services, and cultural and supporting services are completely absent.

Overall, models must be better linked to understand and explain essential relationships and feedback between components of coupled economic-ecological systems. Indeed two damage feedback loops are missing from existing modeling exercises. The first one corresponds to the consequences of biodiversity loss on economic activity and hence on

[13] GLOBIO-ES is a complementary model to GLOBIO that calculates the status, trends, and possible future scenarios of ESs at the global level. It allows for the analysis of 8 cultural, material, or regulatory ESs. It takes as spatially explicit input data: direct pressures (i.e., land-use and management, and climate change), indirect pressures (e.g., revenues and food demand), and ecosystem properties (e.g., relief, soil properties, and climate variables).

[14] InVEST is a suite of models that can map 21 ESs and assign a monetary value to them through a production function. It uses maps as a source of information but also as a result. The model is quite complex and requires very precise data, which implies that at the global scale it is difficult, if not impossible, to use all its components.

countries' economic growth. As a result, the biodiversity model does not influence the model of change in direct and indirect drivers of biodiversity loss. It means that if a scenario projects the extinction of all species on earth, GDP will continue to grow for all countries worldwide. The second arrow represents the same mechanism, but this time for the loss of ESs.

Furthermore, the dynamics of biodiversity and ESs must feed back into the narratives. Thus, the exogeneity of model variables (e.g., GDP and RCP) must be questioned and put into perspective in the narratives to highlight better the interactions between the economy and biodiversity.

VI – The Evaluation of the Results

Biodiversity outcomes

Unsurprisingly, all scenarios that modeled a baseline trajectory only found declining biodiversity indicators but not in the same proportion.

For example, in the business-as-usual scenario of Leclère et al. (2020), terrestrial biodiversity intactness indicators (MSA or BII) declines on average by only 0.89% from 2010 to 2050 and by 5% from 2010 to 2100. Nevertheless, Kok et al. (2020) anticipate a much faster loss of MSA, as their terrestrial MSA declined by about 4.7% by 2050. At the marine scale, Cheung et al. (2019) find a loss of MSA of 7-20% by 2050 and 15-55% by 2100 depending on the RCP trajectories.

Some scenarios envisage futures that allow biodiversity regeneration at the cost of extremely ambitious policies. In Kok et al. (2020), two scenarios reverse the biodiversity decline while achieving the Sustainable Development Goal (SDG) 2 "Zero Hunger" and limit global warming to 2°C by 2050 for the Living Planet Index (LPI)[15] indicator and by 2030 for the MSA. As already said, these scenarios require ambitious policies regarding biodiversity conservation, climate change mitigation, and food security, including expanding PAs to 30% or 50% of the planet's terrestrial surface. The most ambitious scenario of Leclère et al. (2020), which includes various demand side, supply side, and 40% PA expansion policies, achieves biodiversity regeneration as early as 2050 for the LPI (for all the models used). However, with this scenario, MSA trends become positive only by 2075 (on model average). The only model that does not predict the recovery of MSAs is IMAGE, even by 2100.

Overall, scenarios are not optimistic in terms of biodiversity regeneration. The most ambitious scenarios of Schipper et al. (2020) and Pereira et al. (2020), i.e., based on the very optimistic SSP1, do not achieve positive MSA dynamics or species richness[16] trajectories by 2050. At the high-sea fishing sector level, only a 50% expansion of MPAs in a SSP1 scenario of

[15] The Living Planet Index measures changes in terrestrial species populations relative to a specific year (i.e., 1970).

[16] Species richness is a measure of the biodiversity of all or part of an ecosystem; it refers to the number of species within a given area.

Cheung et al. (2019) coupled with an RCP2.6 trajectory, clearly out of reach with current policies, envision a positive MSA change for 2100.

Food security outcomes

Kok et al. (2020) are the only ones to have analyzed a food security indicator at the regional scale. Sub-Saharan Africa and South Asia remain the most critical regions for all their scenarios.

All studies show a trade-off between ambitious conservation measures and improving food security. For instance, Obersteiner et al. (2016) found a positive and significant correlation between food prices and their environmental index (including a biodiversity indicator) for 2030. That is, the most effective conservation policies lead to higher prices.

When Kok et al. (2020) project their scenario only incorporating biodiversity conservation measures, food insecurity risks are reduced, but not to the same extent as in the baseline scenario. As land available for agriculture becomes scarcer, as a transition to agroecology takes place or as agricultural intensification is implemented, prices will increase and access to food will be restricted.

However, if additional measures are implemented in the conservation scenarios, such as reducing meat consumption or food waste, food security loss can be compensated for (Kok et al., 2020). Indeed, these measures will reduce the demand for food and food prices compared to the baseline scenario and thus improve food security.

Ecosystem service (ES) outcomes

In the reference scenario of Kok et al. (2020), material ESs (food and feed production) improved from 2015 to 2070 with the expansion of agricultural land. Inversely, in Johnson et al. (2021), material ESs (marine and timber production) decrease from 2030 onwards.

Most of the authors found that the carbon sequestration service for regulating ESs will vastly decrease. Nevertheless, according to Johnson et al. (2021), the ES of pollination increases in the baseline scenario, whereas in Kok et al. (2020) it starts decreasing by 2070.

In Pereira et al. (2020) and Kok et al. (2020), material services will improve for any SSP or conservation scenario by 2050 or 2070. In addition, Kok et al. (2020) found an increase in terrestrial regulating services in both of their conservation scenarios, except for the carbon sequestration service, which only improves if additional measures to mitigate climate change are added. Pereira et al. (2020) found the same results except for the nitrogen retention service, which is projected to decrease for all their scenarios, and the carbon sequestration service, which increases slightly in all of their scenarios (including SSP5).

Economic outcomes

Only three studies provide an analysis of the economic trajectories of their scenarios, either in terms of profit of a specific sector, or in terms of GDP at the global level or disaggregated by countries or groups of countries according to their income.

In the baseline scenario of Johnson et al. (2021), the decline in the ecosystem services analyzed (i.e., timber production, marine production, and pollination), under the business-as-usual trajectory, will lead to a drop of $90-225 billion in global GDP in 2030, depending on whether or not climate-related costs are taken into account. Nearly all of the worldwide population in 2030 will live in countries that lose in terms of GDP if climate change damages are included, and the most significant impacts of GDP per capita are found in poor countries. Furthermore, all policy-screening scenarios allow for an increase in GDP while conserving natural ecosystems. The most ambitious policy will increase global GDP by $150 billion in 2030.

On the other hand, in the exploratory scenario of Johnson et al. (2021), the collapse of the ecosystem services of pollination, timber, and fish production will lead to a decrease in GDP on a global scale of only 2.3% (-$2.7 trillion) between 2021 and 2030 compared to the baseline (suffered mainly by the poorest countries). Regionally, Sub-Saharan Africa will experience the most significant declines, including Madagascar and Angola–Democratic Republic of the Congo, which is projected to experience a 20% decline in GDP, mainly due to the collapse of timber production. The second most affected region is South Asia (notably Bangladesh and Pakistan), with a 6.5% loss of GDP caused mainly by the decline in pollination.

Cheung et al. (2019) found that the SSP1 scenario leads to the lowest contribution, on average, of income generation from the high-sea fishing sector. Indeed, fishing costs will increase by 50% for all countries by 2050 with rising fossil fuel prices and declining subsidies. In SSP3, as fishing effort increases beyond the economically optimal levels, the total cost of fishing increases, and profits will decrease, especially for the poorest countries. In SSP5, a decline in profit is expected because the fishing effort will raise the total cost of fishing in all income group countries. In conclusion, fishing has a chance of being or remaining marginally profitable by 2100 only in rich countries in the SSP1 or SSP5 scenarios, but in the SSP5 scenario, fishing is only profitable because subsidies offset the high cost of fishing.

According to Costello et al. (2026), applying sound management reforms to the world's fisheries could generate an additional benefit of $53 billion by 2050. The countries that will benefit most from these management reforms are China, Indonesia, India, Japan, the Philippines, Thailand, Malaysia, the Republic of Korea, Vietnam, and Taiwan.

Model comparison

In general, results are very different among studies even if similar hypotheses and indicators are set: It is very likely that the parameterization of the models dramatically influences the results . Indeed, the baseline scenario of Leclère et al. (2020) projects, on model average, a slight decrease in relative prices of crops (not dedicated to energy) between 2010 and 2050.

Nevertheless, there are considerable differences between the models for the same scenario; for example, IMAGE prices increase by about 10%, and GLOBIOM and MAgPIE decrease by about 10%.

It is, therefore, advisable to project the same scenarios through multiple models (Ferrier et al., 2016) to improve the robustness of projected trajectories. Depending on the differences in policies and contexts, it is essential to diversify the types of scenarios and models to find the most appropriate approach and use different spatial and temporal scales. Uncertainties inherent in scenarios and models must be clearly assessed and communicated to avoid the propagation of false results (either optimistic or pessimistic). These uncertainties can have various origins, such as the use of erroneous or insufficient data, the lack of understanding of ecological processes, or the poor predictability of the system.

Conclusion

As of today, there are no comprehensive and ready to use scenarios designed to assess industries'/countries' transition and physical impact exposure related to biodiversity changes. Current biodiversity transition scenarios, do not allow for visualizing precise socio-economic trajectories, while physical scenarios are almost completely absent from the landscape. Indeed, transition scenarios allow assessing the impacts of different human pressures on land, aquatic ecosystems, vegetation, and species, but not necessarily on all industries and sectors.

Therefore, it is essential to improve the precision and linkages between models. This is a long-term objective as it will require re-designing large-scale model, efforts must hence start today. In addition, we recommend working simultaneously on transition and physical assessments to improve the coherence of scenarios and the understanding of biophysical trajectories.

In the meantime and in the shorter term, the following steps could be adopted to analyze the socio-economic impacts emerging from the CBD "2050 vision". These three steps are intended for all entities likely to build biodiversity scenarios at national and international levels. It includes ministries of economy and finance to better target policies that can improve biodiversity, financial institutions/regulators to perform biodiversity stress tests, and the academic sphere to enhance our understanding of the interconnection between economic and biophysical dynamics.

1-/ The first step for building physical scenarios will be to build data to characterize ecosystems from a biophysical point of view. Several methods exist, such as the Environmental Sustainability Gap (ESGAP) (Usubiaga-Liaño & Ekins, 2021a, 2021b) framework. Indeed, ESGAP was developed for European countries and is being tested in other regions (ISPONRE & UCL, 2021; NEMA & UCL, 2022; WWF, 2020). The latest developments in Europe have led to the establishment of the Strong Environmental Sustainability Progress Index (SESPI), which shows whether countries are moving towards or away from good environmental state standards (Usubiaga-Liaño & Ekins, 2022). SESPI aggregate 19 indicators of critical environmental functions. Each of these sub-indicators makes it possible to know whether, within the framework of current trends and under a targeted time horizon, the critical environmental functions are approaching or moving away from a safe operating space for the economy and therefore the risk of encountering a tipping point.

Without predicting the tipping point, this methodology indicates whether an economy is moving towards or away from the probability where these regime shifts are more likely to occur. This method also allows to reflect the non-substitutability between the different types of capital (i.e., natural, social, and economic) as well as the finiteness of the planet's natural resources and the constraints that these limits pose to economic growth. Thus, ESGAP adopts a strong sustainability vision to preserve a "critical natural capital" to be transmitted to future generations.

2-/ To conduct transition assessments, examining the spatial distribution (as accurately as possible) of threatened ecosystems and socio-economic interconnections is necessary. It will then allow the development of prospective (possibly qualitative) scenarios for changes in practices, ecosystem protection, and restoration.

Thus, one solution would be to adapt recent work on the analysis of transition risks for climate change (Espagne et al., 2021) to the case of biodiversity. This alternative would consist of comparing the sectors dependent on and impacting biodiversity in a given country with its equivalents such as the same sector in the same type of biome (using IUCN classification). The aim is to identify potential innovation opportunities to reduce dependence or impact on biodiversity under roughly equivalent ecological conditions.

3-/ Multiply data collection, open publication and distribution approaches including non-conventional ones such as satellite data, machine learning of land register, tax or household and business surveys to feed future models while ensuring the reproducibility of analyses, their open quality control and the respect of data rights.

Finally, the three approaches proposed above will help to improve the relevance of the models and make them more accurate of these data. Invest in the long-term will nourish the short-term.

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List of Acronyms and Abbreviation

BII Biodiversity Intactness Index
CBD Convention on Biological Diversity
EE-MRIO Environmentally Extended Multiregional input-output
ENCORE Exploring Natural Capital Opportunities, Risks, and Exposure
ES Ecosystem Service
GDP Gross Domestic Product
GHG Greenhouse Gas
GTAP Global Trade Analysis Project
GTAP-AEZ Global Trade Analysis Project Agro-Ecological-Zones
IAM Integrated Assessment Models
LPI Living Planet Index
MPA Marine Protected Area
MSA Mean Species Abundance
OECD Organisation for Economic Co-operation and Development
PA Protected Area
RCP Representative Concentration Pathway
SDG Sustainable Development Goal
SSP Shared Socio-economic Pathwa

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