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DECEMBER 2022
No. 266

Research papers

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Global biodiversity scenarios: what do they tell us for Biodiversity-Related Financial Risks?

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Abstract

The risks associated with biodiversity loss could have severe socio-economic and financial consequences, at least as large as those imposed by climate change, in addition to interacting with them. Because of the potential threat, they pose to financial stability, Biodiversity-Related Financial Risks (BRFRs) have recently captured the attention of the financial community. As with climate risks, central banks and financial authorities might have to conduct biodiversity risk stress tests and adjust their daily operations and regulatory tools to this new normal.

However, unless appropriate biodiversity scenarios are found to build a forward-looking assessment of the consequences of physical and transition shocks on industries and sectors, meaningful inclusion of Nature-Related Financial Risks (NRFRs) cannot see the light of day. This paper aims to review and compare existing quantitative biodiversity scenarios and models on a global scale that could help fulfill this role. It also offers an assessment of the path forward for research to developing scenarios for BRFRs 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.

The paper has several key findings. First, global and quantitative physical risk scenarios are almost absent; this is why it concentrates on transition scenarios of biodiversity. Second, most ecological transition scenarios are built in accordance with the Convention on Biological Diversity (CBD) goals, even if future land allocation varies across studies. Third, Shared Socio-economic Pathways (SSPs) do not assess the biophysical consequences of their economic growth hypothesis. Fourth, the paper highlights the need for central banks and supervisors to take into account the uncertainties inherent in both integrated models and biodiversity indicators. For the latter, the uncertainty results from measuring only a tiny fraction of global biodiversity. Finally, the study offers recommendations for central banks and financial authorities to improve their scenario selection in the shorter-term.

Keywords
Biodiversity scenarios; Biodiversity-related financial risks; Ecological transition modeling

Acknowledgments
We are grateful to the peer reviewers who provided invaluable input on a preliminary draft, including Benoit Faivre-Dupaigre (AFD), Hélène Soubelet (FRB), and Yoshihide Wada (IIASA). We would also like to acknowledge and thank Marcel Kok (PBL), Mathilde Salin (Banque de France) and Paul Hadji-Lazaro (AFD) for the multiple discussions we had with them on these topics. All remaining errors in the text are our own responsibility.

Original version
English

Introduction

Biological diversity is the living fabric of our planet. It refers to the variety of living organisms present in each terrestrial and aquatic ecosystem and the ecological complexes of which they are part; including diversity within species (i.e., genetic diversity), diversity between species (i.e., species diversity), and diversity of ecosystems (i.e., ecological diversity). The interactions within and between these three levels of diversity are another crucial component of biodiversity.

Human activity exacerbates the erosion of biodiversity both directly and indirectly. The main anthropogenic drivers[1] of biodiversity loss are land-use change, natural resource use, pollution, the introduction of invasive species, and climate change. In turn, indirect pressures related to demographic, socio-economic, technological, and governance trends in human societies influence these direct pressures. The human impact on biodiversity has severe and sometimes irreversible consequences for Ecosystem Services (ESs), which correspond to the contributions of ecosystems to human survival and quality of life. Four types of ESs are usually distinguished: supporting services (e.g., decomposition of organic matter that contributes to soil fertility), provisioning services (e.g., food products derived from plants, animals, and microorganisms), regulating services (e.g., trees and plants regulate the climate by storing greenhouse gases) and cultural services (e.g., recreation and ecotourism).

Recently, the the Network for Greening the Financial System (NGFS, a network of 114 central banks and financial supervisors) recognized that Biodiversity-Related Financial and socio-economic Risks (BRFRs), i.e. the risks related to collapse of biodiversity or related to a transition to an economy with low impacts on biodiversity, is to be considered as a major threat to financial stability (INSPIRE & NGFS, 2022). Given the difficulty of identifying a coherent biodiversity scenario that captures plausible financial shocks (Chenet et al., 2022), **this paper presents a literature review aiming to provide an overview of the scenarios useful for BRFR quantification.** It can thus inform the choice of central banks and financial authorities in their search for biodiversity scenarios. It can also contribute to improving macroeconomic models used to assess the risks associated with biodiversity loss, by raising methodological problems of existing attempts to scenarios quantification.

This paper is structured as follows. Section 1 introduces general concepts on BRFRs. Section 2 presents the general characterristics of global biodiversity scenarios as well as our approach to identify suitable scenarios for BRFR assessment. Section 3 is devoted to the comparison of these biodiversity scenarios and is structured according to the scenario development process (i.e., construction of qualitative narratives, quantification of hypotheses, trajectory modeling, analysis of results, and, if necessary, refining narratives or modeling

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[1] We will use the terms "driver" and "pressure" indifferently in this paper.

hypotheses) and proposes a critical analysis for each one. In section 4, we finally make several recommendations, achievable in the short- or long-term, for central banks and financial authorities to improve their scenario selection.

1. Biodiversity-Related Financial and socio-economic Risks (BRFRs)

1.1 Assessment of physical and transition risk related to biodiversity

The fast degradation of ESs, on which companies depend for their production, explains, in part, the growing interest of academic research and financial communities in BRFRs. These risks can be at least as large as those generated by climate change, in addition to interacting with them (Bradshaw et al., 2021; Section 1 Pörtner et al., 2021; Chenet et al., 2022). They have the potential to threaten the entire economy as well as the stability of financial systems (INSPIRE & NGFS, 2022). The conceptual framework developed to analyze these BRFRs follows the one designed for the case of climate change, distinguishing between physical and transition risks[2].

Physical risks generated by biodiversity loss arise when environmental changes affect human capital and economic activity, and thus indirectly, financial valuation. As biodiversity loss leads (in a non-linear way) to the loss of ESs, industries that are highly dependent on these ESs, directly or indirectly through their value chain, will be the most affected. For example, the agricultural sector is highly dependent on the pollination service, which alone determines a large proportion of crop yields and thus of profits and jobs.

The central bank of the Netherlands, De Nederlandsche Bank NV (DNB) was the first to conduct BRFRs assessment on a national scale (Van Toor et al., 2020). According to their study, 36% of the listed equity portfolios of financial institutions in the Netherlands are highly or very highly dependent on at least one ES. Other researchers have subsequently used all or part of this methodology to analyze BRFRs in Brazil, Europe, and Malaysia. Calice et al. (2021) find that 45% of Brazilian banks' total corporate loan portfolio is exposed to sectors that are highly or very highly dependent on one or more ESs. In France, 42% of the value of securities held by financial institutions comes from issuers highly or extremely dependent on at least one ES (Svartzman et al., 2021). In addition, Kedward (2021) find that 40% of the bonds held by the European Central Bank are highly or very highly dependent on ESs. The ESs on which the central bank's balance sheet assets are most dependent are those related to water, and the corresponding financial exposure amounts to 38.6 billion euros. According to the Malaysian central bank (BNM, 2022), 54% of the commercial loan portfolio of Malaysian banks is exposed to sectors that are highly dependent on ESs, particularly surface water (29%) and climate regulation (26%).

Sources of transition risk include changes in policy, consumer preferences or behavior, and changes in technology that aim at mitigating human activity's impact on biodiversity (INSPIRE & NGFS, 2022). These changes will affect industries that degrade ecosystems the most compared to more virtuous industries in the same sector. For example,

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[2] The Taskforce on Climate-related Financial Disclosures recommended this classification for climate change related financial risk (TCFD, 2017).

in April 2022, the European Commission accepted the registration of a citizens' initiative called "End The Slaughter Age", which proposes to remove all subsidies dedicated to the livestock sector in favor of ethical and ecological alternatives such as cellular agriculture or plant proteins[3].

In terms of transition risk exposure, the biodiversity footprint of Dutch financial institutions would be comparable to the loss of 58,000 km² of pristine nature, which is more than 1.7 times the terrestrial surface of the Netherlands (Van Toor et al., 2020). For the case of France, Svartzman et al. (2021) find that the biodiversity footprint of financial stocks is comparable to the artificialization of at least 130,000 km² of pristine nature, equivalent to the conversion of 24% of metropolitan France into a parking lot. Land-use change is the main factor explaining these results. In addition, the authors find that most industries' biodiversity footprint is caused by indirect activities (e.g., pollution generated by a supplier). In Brazil, 15% of the loan portfolio of banks is composed of companies that potentially operate in Protected Areas (PAs), 25% if areas likely to become PAs soon are added, and 38% if all high-priority areas for biodiversity conservation are included (Calice et al., 2021). As Brazil adopts biodiversity regulations and policies, as agents' preferences shift toward more sustainable consumption, and as litigation and reputational damages to industries emerge, companies and banks (if they fail to adapt) are likely to see losses.

1.2 The growing interest of the financial community in BRFRs

Nature-Related Financial Risks (NRFR) is a new term used by the financial community, particularly by the Taskforce on Nature-related Financial Disclosures (TNFD)[4] and the Network for Greening the Financial System (NGFS)[5]. It refers to risks related to climate change and other environmental disruptions in a single package, this study will concentrate on BRFRs. Indeed, it is only very recently that financial institutions have recognized biodiversity loss as a potential source of economic and financial risk and set up projects to develop a strategy to respond to them.

Since 2021, the NGFS has formed a working group that develops research-based approaches to help central banks and supervisors fulfill their mandates in light of biodiversity loss. In particular, it recommends assessing the degree of exposure of financial systems to BRFRs by conducting impact and dependence assessments and developing scenario analyses and biodiversity-related stress tests (INSPIRE & NGFS, 2022).

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[3] European Commission. https://ec.europa.eu/commission/presscorner/detail/fr/ip_22_2668

[4] The **Task Force on Nature-related Financial Disclosures (TNFD)** is a global working group of financial institutions, companies, and service providers. It develops and provides a common risk management and disclosure framework for organizations to report and respond to NRFRs, with the ultimate goal of directing global financial flows toward positive rather than negative outcomes for nature.

[5] **The Network for Greening the Financial System (NGFS)** is a voluntary initiative created on the occasion of the "One Planet Summit" launched in 2017 by the French President Emmanuel Macron, the United Nations, and the World Bank to identify and accelerate transformational initiatives and financing for climate, biodiversity and ocean solutions. The NGFS regroups 116 central banks and regulators worldwide.

Both NGFS and TNFD consider the double materiality approach to risks, which requires assessing not only how nature can impact an organization's immediate financial performance but also how the organization affects nature.

In addition to the growing interest of financial institutions in assessing BRFRs, financial authorities could systematize this assessment. For example, Article 29 of France's 2019 energy and climate law suggests the integration of BRFRs into the reporting practices of financial actors; it was the first country to make it mandatory. French banking regulators and insurers have also recognized that, like climate change, growing awareness of the risks posed by biodiversity loss could lead to increased regulation around this issue (ACPR et al., 2020).

More broadly, the concept of BRFR is rapidly emerging in the political and economic spheres (World Economic Forum, 2021). Policymakers (G7, 2021; OECD, 2019), civil society organizations (Finance Watch, 2022; WWF, 2020), the private sector (TNFD, 2021; SIF, 2021), and academia (Dasgupta, 2021; Kedward et al., 2020 and 2021) have all seized on the link between biodiversity loss and financial/economic instability caused by both the dependence of economic activities on degrading ESs and the likely growth of the activities that have the greatest impact on the biosphere.

1.3 Methodology of biodiversity-related stress test

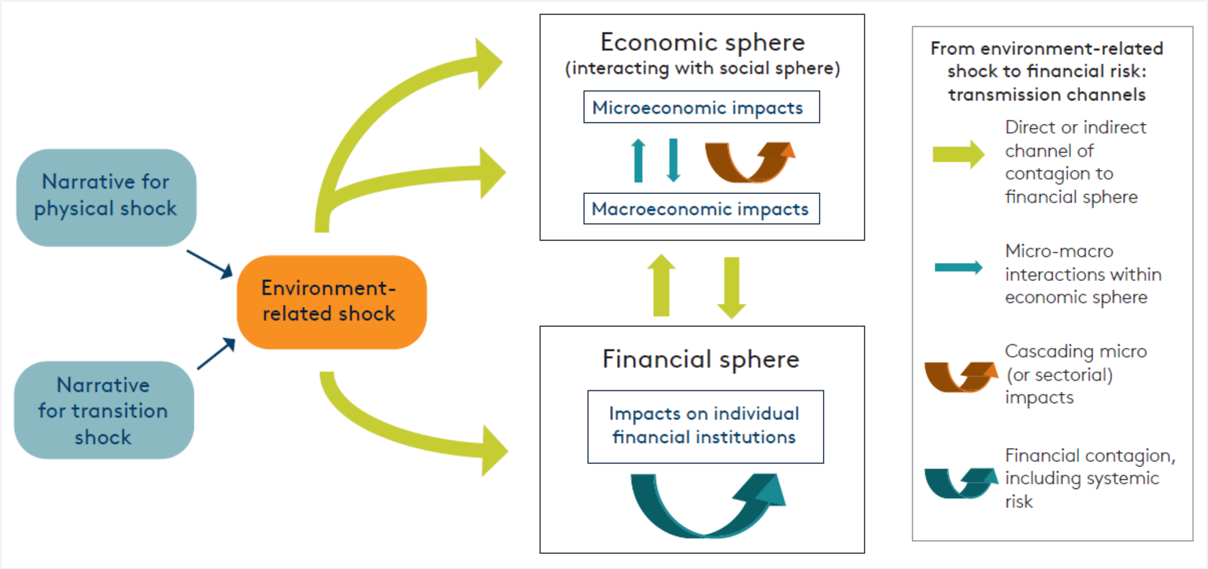
It is possible to approach BRFRs statically by analyzing industries or sectors' positive or negative impacts on biodiversity (i.e. exposure to transition risk) and dependencies on ESs (i.e. exposure to physical risk). Given their complexity and the many methodological challenges BRFRs raise, this method has been widely used, while ignoring the dynamics of ecosystems. Indeed, ecological processes are made up of complex non-linear dynamics, which sometimes lead to irreversible changes in ecosystems and to tipping points that are difficult to predict (Folke et al., 2004). For instance, if regulating and supporting ESs were to disappear, production would be impossible (Dasgupta, 2021). The destruction of natural capital must thus necessarily remain limited to its regeneration capacity to be sustainable in the long run.

In macroeconomic models, the value of ESs is often estimated in terms of their contribution to Gross Domestic Product (GDP) or output, leading to under evaluating their importance for economic activities. In developed countries, for example, agriculture does not account for a large share of GDP. Furthermore, it represents one of the sectors with the greatest impact on biodiversity loss. According to macroeconomic models, if ESs associated with this sector were to collapse partially or entirely, the effect on total GDP would hence be marginal. However, lack of agricultural product could lead to inflationary pressures or social unrest potentially disrupting the entire economy. Economic models thus need to consider the possibility that the ecosystem could be damaged to the extent that it affects related economic activities or could collapse altogether. Another major challenge is the impossibility of aggregating all aspects of biodiversity into a single measure that implies they are commensurable and comparable.

Assessing BRFRs dynamically and prospectively is essential, as regulators and financial actors need to anticipate the emergence of risks that have never been observed. Indeed, the future of biodiversity will depend on many factors, such as the actions of agents (e.g., consumption preferences), political strategies implemented (e.g., biodiversity conservation policies), or demographic changes (e.g., increasing population). In addition, pressures on biodiversity and their associated impacts evolve in a non-linear way. Regarding Climate-Related Financial Risks (CRFRs), central banks and financial authorities agree that it is impossible to simulate climate shocks using historical data (Batten et al., 2016; DG Treasury, 2017; TCFD, 2017; NGFS, 2019; Regelink et al., 2017). With a forward-looking approach, financial institutions expect to be able to understand and test the resilience of the companies, contained in their portfolio, the potential materialization of physical and transition risks, and the impact of these companies on key performance indices and their ability to adapt (Bolton et al., 2020).

Financial institutions use forward-looking scenario analysis in their stress testing to understand and anticipate CRFRs and the associated future economic costs. Three components are required to conduct these stress test (see Figure 1): (1) developing a scenario of the hazards or shocks that could translate into financial risks; (2) modeling the micro and/or macroeconomic consequences; and (3) modeling the impact of shocks on financial institutions.

Figure 1. An environmental stress test (from INSPIRE & NGFS, 2022). Shock narratives are used to model environmental effects and their direct and indirect effects on the economic and financial spheres



The first step thus is to define or identify one or more scenarios of hazards or shocks that could occur. It is complicated, however, to have a clear idea of the type of physical or transition shock that might emerge, notably because of the non-linearity of BRFRs. For example, because of increased external nutrient inputs (e.g., from agriculture), lakes can suddenly change from a biodiversity-rich state with clear, transparent water to an alternative, degraded state with cloudy water and lower species diversity: this is called eutrophication. In the eutrophic state, the water is degraded, invasive species (e.g., green algae in Brittany) can proliferate, and the abundance of fish decreases, which can have a substantial impact on tourism and fishing industries and all those who use the lake water.

In the meantime, biodiversity-related transition shocks could occur in the form of the introduction of specific policies to reduce biodiversity decline. Conservation policies, however, lack a target and metric comparable to the 1.5°C and tons of CO2-equivalent that are used for climate scenarios. For example, greenhouse gas (GHG) emissions contribute almost equally to global warming regardless of where they are emitted, while the impacts of biodiversity loss depend greatly on geographic location and ecosystem types. It is therefore not surprising that in the face of additional layers of uncertainty and non-linearity related to BRFR, the scientific literature aimed at proposing scenarios for analysing these risks face additional scientific challenges and limits in comparison with the CRFR.

2. A general presentation of biodiversity scenarios

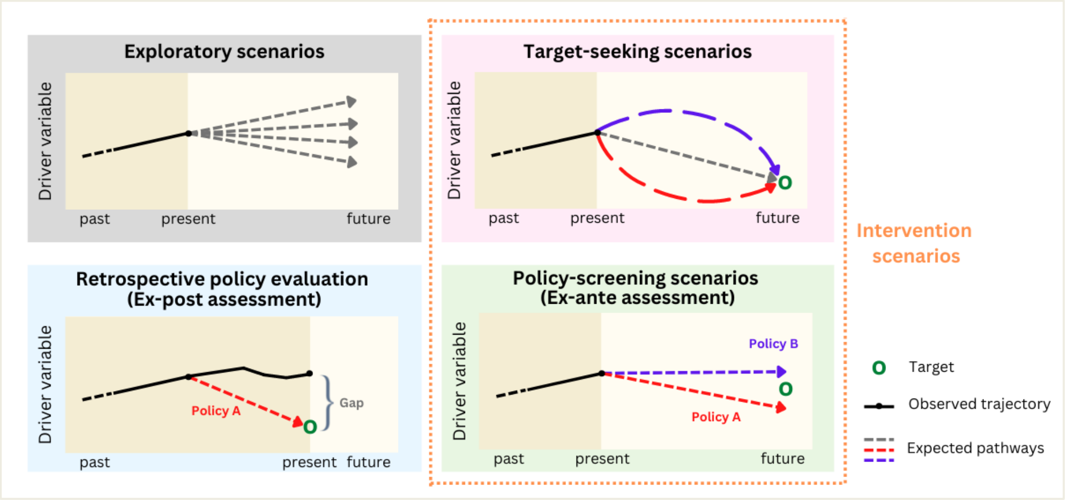
2.1 The different types of scenarios and models

Scenarios are qualitative and/or quantitative representations of possible futures. They describe the evolution of one or more biodiversity pressure factors (e.g., land-use changes) and policy and management options to modify their impacts (e.g., PAs expansion). 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). Scenarios can be used to understand local, regional, and global dynamics. While they cannot claim to represent everything, they guarantee internal consistency to support sound reasoning.

According to the IPBES (2016), three prominent families of scenarios can be distinguished (see Figure 2):

- **Exploratory scenarios** examine a range of plausible futures based on the potential trajectories of direct and/or indirect drivers of biodiversity loss.
- **Intervention scenarios** are used to evaluate policy or management options. They are composed of two subclasses: **target-seeking scenarios** and **policy-screening scenarios**. Target-seeking scenarios identify one or more objectives, either in terms of achievable targets or as an objective function to be maximized, and then determine different pathways to achieve that outcome. Policy-screening scenarios allow for ex-ante assessments to predict the effects of different interventions on environmental outcomes.
- **Retrospective policy evaluation scenarios** are used for ex-post evaluations, i.e., current assessments of past efforts to achieve policy objectives across all stages of the policy cycle and decision-making context.

Figure 2. The main types of scenarios that can be developed regarding the purpose of developers and users (adapted from Ferrier et al., 2016)



The scenario narrative can be designed by experts or through participatory methods. The so-called "expert" approach uses experts' opinions, knowledge, and judgment, i.e., individuals with experience in a particular dimension through their training, studies, and/or practices. It is among experts that the first assessments of climate damage functions were developed (Keen, 2021). The participatory approach is strongly recommended in some contexts for the development of biodiversity scenarios (Brondizio et al., 2019); it consists of promoting the use of local knowledge and including various stakeholders in the development of visions for the future, often through workshops. However, depending on the scale (e.g., global, regional, and national) considered, the effectiveness of this approach may vary. Indeed, on a global scale, the participatory approach is a challenge because the loss of biodiversity and natural resources are in principle, caused by very local problems. However, global scenarios are important because of the interconnection of ecological assets and drivers of changes.

Once a scenario narrative is complete, it can be transformed into a quantitative trajectory using models. 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). Different models can be used and coupled to quantify biodiversity scenarios. Some models assess how changes in indirect pressures (e.g., economy, technology and demography) affect direct pressures for nature (e.g., land-use change, climate change and nitrogen deposition). Others will model the magnitude of change of direct and indirect pressures on nature regarding biodiversity and ecosystem functioning. A final category of models will assess 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).

No single set of scenarios and models is perfect for representing the future: they have inherent limitations that are more or less manageable. The quality of the model can be assessed by comparing projections of the same scenario with independent data sets, i.e., those that have not been used for calibration or model building; a process also known as backtesting. It is, moreover, advisable to project the same scenario through multiple models to improve the robustness of projected trajectories (Ferrier et al., 2016). 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. Finally, uncertainties inherent in scenarios and models need to 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.

2.2 Existing biodiversity scenarios

To our knowledge, there are no comprehensive scenarios designed to assess the resilience of financial systems to specific physical or transition hazards or shocks related to biodiversity, making difficult to conduct biodiversity-related financial stress tests. Indeed, biodiversity scenarios, in their current state, do not allow for visualizing the risks incurred by the financial system through its portfolio of assets. **They permit assessing the impacts of different human pressures on land, aquatic ecosystems, vegetation, and species, but not necessarily the impact on industries and sectors of economic activity.**

In the absence of such scenarios, assessing transition and physical risks related to biodiversity could consist in identifying the assets most likely to be stranded or impaired in the event of an ecological transition or ecosystem degradation. For example in the case of climate, it is estimated that 60% of oil and gas reserves and 90% of coal reserves will remain unused if global warming is limited to 1.5 °C, the threshold set by the Paris Agreement (Welsby et al., 2021). In this case, many fossil resources will not be able to be burned, and fossil fuel infrastructure (e.g., pipelines and power plants) will no longer be used: resulting in losses before the end of their anticipated life (i.e. stranded assets).In terms of biodiversity risks, if governments were to suddenly decide to ban certain pesticides and herbicides that significantly degrade soil and surrounding biodiversity, industries in the sector may be left with stranded assets. However, unlike CRFR, no specific activity easily explains the vast majority of human-induced impacts on biodiversity (e.g., similar to sectors emitting GHGs through direct or indirect combustion of fossil fuel for climate change), making sectoral identification difficult. Nevertheless, quantitative scenarios provide a better understanding of changes in the indirect and direct determinants of biodiversity decline and their impacts on the environment. These scenarios mainly use biophysical models, although some explore socio-economic dynamics (see Chapter 3.4).

Furthermore, as stressed by the NGFS (INSPIRE & NGFS, 2022), cascading and second-round effects, as for CRFRs, will play an important role. Cascading effects imply that sectors or corporations can be indirectly affected by a shock through international supply chains (e.g., Cahen-Fourot et al., 2021; Godin & Hadji-Lazaro, 2022; Espagne et al. 2021) or through financial networks (e.g., Battiston et al., 2017). The combination of multidimensional impacts on biodiversity with multidimensional contagion or cascading effect makes the assessment of BRFRs particularly complex.

According to the IPBES (2019) literature review on global biodiversity scenarios, global target-seeking scenarios are the most widely used, followed by exploratory and policy-screening scenarios, and the participatory approach is the most common for building scenario narratives. Scenarios are mainly quantitative to the detriment of qualitative scenarios that allow for a better understanding of the interactions between different components of a system, as they are not constrained, in terms of assumptions, by modeling. There are mainly long projection scenarios with a strong representation of results for the 2050 and 2100 horizons. The agricultural and the forestry sectors are the most represented, followed by the energy and water sectors. The most widely modeled sustainable development goals (SDGs) are 2 (i.e., eradicate hunger) and 15 (i.e., preserve and restore terrestrial ecosystems) on the trade-off between food security and terrestrial biodiversity.

At the regional scale, biodiversity scenarios do not necessarily analyze the greatest pressures on biodiversity. Indeed, the most widely studied indirect drivers of pressure in scenarios are economics, and demography, while climate change and invasive alien species are the most represented direct drivers (Ferrier et al., 2016). Moreover, Titeux et al. (2016) analyzed 2,313 biodiversity scenario articles, at any scale, between 1990 and 2014 and estimated that 85.2% projected only climate change-related impacts, 4.1% related to land-use, and only 10.7% combined both pressure factors. The pressure factor that nevertheless has the most significant and imminent impact on terrestrial biodiversity is land-use change, not climate change: not integrating this factor in scenario analyses is equivalent to minimizing the risks to biodiversity. According to Titeux et al. (2016), in addition to underestimating land-use as a driver of biodiversity pressure, only some papers consider changes in how humans use and manage land. Indeed, land management regimes (e.g., whether grasslands are mowed or grazed) and land-use intensity (e.g., through timber harvesting or the use of fertilizers, pesticides, and irrigation in cultivated areas) are poorly represented or even completely absent in the scenarios.

Among global biodiversity scenarios, only a few are designed for freshwater and/or marine environments. For marine environments, scenarios primarily explore physical shocks to the fisheries sector through changes in fish catch numbers for different climate warming trajectories (Cheung et al., 2016 and 2017). Another area of great interest for these scenarios is identifying and assessing the impact of expanding Marine Protected Areas (MPAs) on fishing intensity or biodiversity (Halpern et al., 2010; Pompa et al., 2011).

2.3 Identification of biodiversity scenarios for the literature review

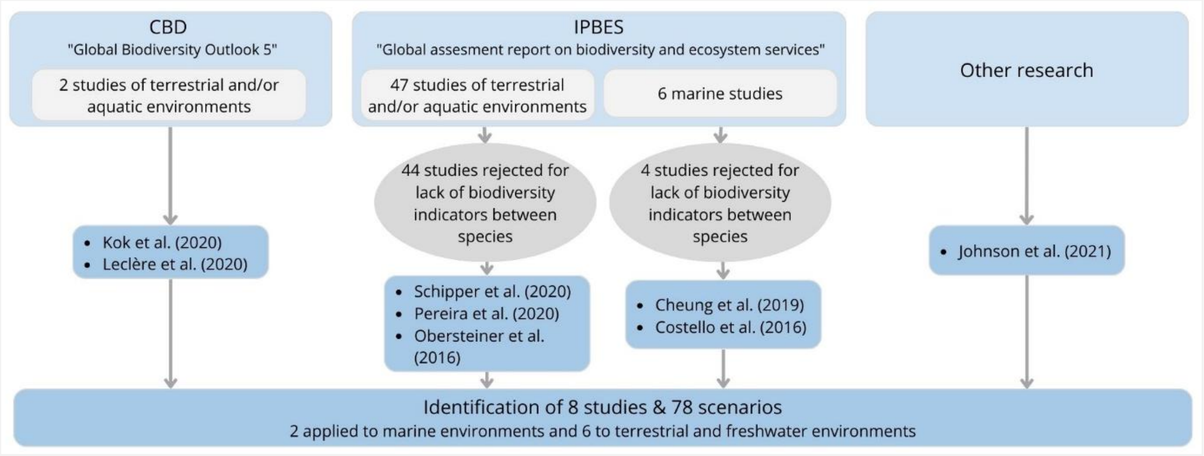
For the development of stress tests, central banks and financial institutions will need quantitative intervention scenarios (i.e., target-seeking and policy-screening scenarios) to assess biodiversity transition risks, and exploratory scenarios for analyzing physical shocks related to biodiversity degradation. Therefore, we selected a panel of quantitative biodiversity "transition" scenarios (Table 1) for assessing biodiversity transition shocks. These scenarios project biophysical and/or socio-economic dynamics to identify biodiversity changes under the transition assumption.

We found almost no global "physical" scenarios, i.e., scenarios of physical shocks that anticipate, *ceteris paribus* or assuming a climate scenario, the crossing of tipping point and possible regime shifts, as well as changes in ESs at different points in the world that would be linked to these regime shifts (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 proposes a narrative in which the tipping points of three arbitrarily chosen ESs are crossed (i.e. pollination, marine production and wood production) and decline by an arbitrary magnitude. Some scenarios, nevertheless, measure changes in ESs under an ecological transition assumption, which could help assessing which economic sectors or businesses would be affected if these changes were to occur. These analyzes are limited, as tipping points and regime shifts are not considered (see Chapter 3.4.3). Thus, most of the quantitative biodiversity scenarios explore transition shocks, with results that can be used for transition risk analyses (changes in biodiversity after the implementation of an ecological transition), and sometimes transition derived physical risk analyses (changes in ESs after the implementation of an ecological transition).

We selected only scenarios with global coverage because most of the economic assets held are part of a globalized economy through two dynamics: on the one hand, global value chains and international financial networks 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. The analysis conducted by the DNB and the Banque de France shows that many impacts and dependencies are imported or exported through globalized value chains. Working on local scenarios may, therefore, 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 in order to examine, in a second step, the possibilities and limits of working with disaggregated results of these scenarios at national (or even sub-national) levels, which are the usual levels at which financial regulators aggregate economic and financial data. It is implicitly accepted that these global scales are based on less sophisticated and precise scenarios than more localized ones. In this first approach, we have thus favored a criterion of completeness to the detriment of precise but not reproducible scenarios.

As represented in Figure 3, to identify these scenarios, we analyzed the Convention on Biological Diversity (CBD)[6] report, "Global Biodiversity Outlook 5" (Hirsch et al., 2020), which describes two articles with quantitative biodiversity scenarios with global coverage for achieving the CBD's "2050 Vision"[7]: Kok et al. (2020) and Leclère et al. (2020). We included them in the literature review since they have global coverage and propose several biodiversity indicators. Then we explored the IPBES (2019) literature review of the main terrestrial, aquatic, and marine biodiversity scenarios. The database contains 47 articles with quantitative and/or qualitative scenarios of global coverage. Among these studies, 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. We finally selected five articles from the IPBES report: 2 applied to marine biodiversity and 3 to terrestrial and freshwater realms.

Figure 3. Flowchart reporting the process of selecting global scale quantitative biodiversity scenarios articles



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

The articles selected for this review are therefore the result of a purposive sampling method adapted to our qualitative research but are neither the result of a systematic review nor the result of a meta-analysis of existing biodiversity scenarios.

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[6] The **Convention on Biological Diversity (CBD)** is a legally binding international treaty that was opened for signature on June 5, 1992, at the United Nations Conference on Environment and Development (also known as the "Earth Summit"). The 196 signatories commit to three main objectives: to conserve biological diversity, to use biological diversity sustainably, and to share the benefits arising from the use of genetic resources fairly and equitably.

[7] The "**2050 Vision**" is a world of "living in harmony with nature" by 2050, as established in the Strategic Plan for Biodiversity 2011-2020. This vision describes a world where "by 2050, biological diversity is valued, conserved, restored, and used wisely, sustaining ESs, maintaining a healthy planet, and providing essential benefits to all people".

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

ARTICLE	TYPE OF APPROACH	NUMBER OF SCENARIOS	TYPE OF ANALYSIS[8]	TYPE OF RISKS	TYPE OF SCENARIOS	MAIN ENVIRONMENTS	TIME HORIZON
Kok et al. (2020)	N/A	5	Biophysical	Transition, physical	Target-seeking	Terrestrial, freshwater	2030, 2050, 2070
Johnson et al. (2021)	N/A	10	Economic	Transition, physical	Exploratory, policy-screening, target-seeking	Terrestrial	2030
Leclère et al. (2020)	Expert	7	Biophysical	Transition	Target-seeking	Terrestrial	2050
Cheung et al. (2019)	Participatory	4	Biophysical, economic	Transition	Policy-screening	Marine	2030, 2050, 2090
Obersteiner et al. (2016)	N/A	42	Biophysical	Transition	Policy-screening	Terrestrial	2030, 2050
Costello et al. (2016)	N/A	3	Biophysical, economic	Transition	Policy-screening	Marine	From 1980 to 2050
Schipper et al. (2020)	N/A	3	Biophysical	Transition	Policy-screening	Terrestrial	2050
Pereira et al. (2020)	N/A	4	Biophysical	Transition, physical	Policy-screening	Terrestrial	From 1900 to 2050

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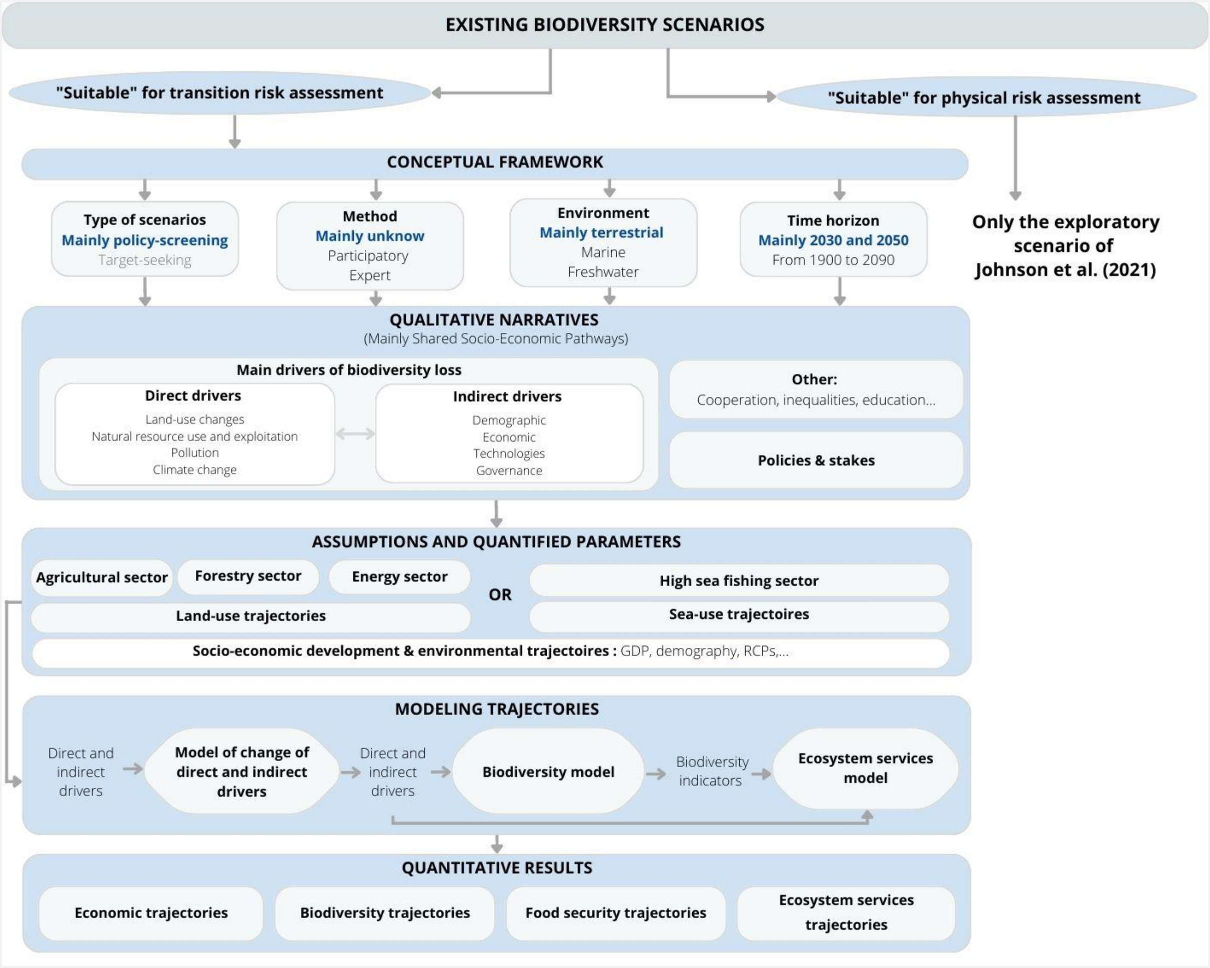
[8] The **type of analysis** refers to the results of the modeled scenarios: in some studies, only the biophysical dynamics resulting from the implementation of a scenario are explored, and in other studies, only economic trajectories are explained. However, it is important to dissociate the modeled trajectories from the results because a scenario may include, for example, GDP trajectories but not quantify the impact of the scenarios on these trajectories: this brings us back to the biophysical analysis category.

3. Comparison of quantitative biodiversity scenarios selected

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

Figure 4. Representation of existing biodiversity scenario development processes

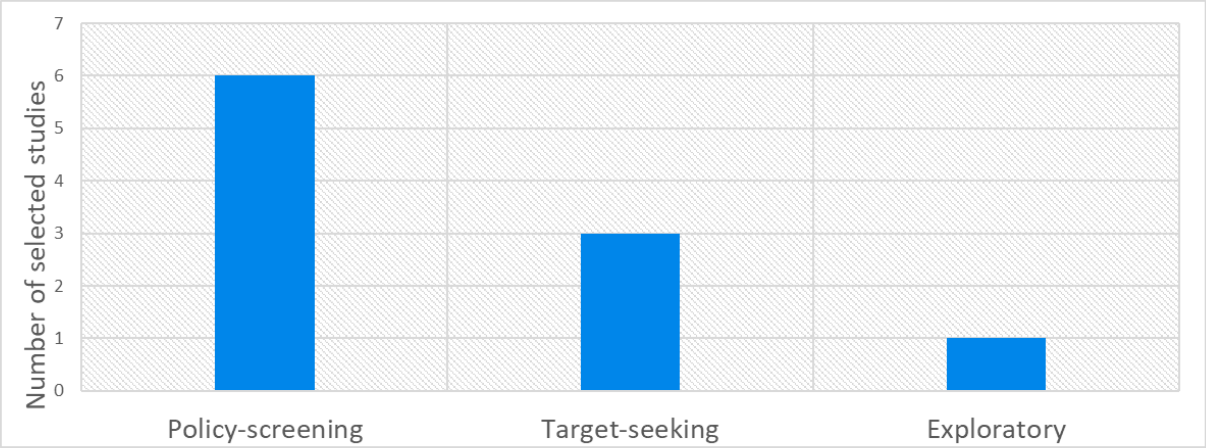


3.1 The conceptual framework

3.1.1. The type of scenarios

The first step in constructing a scenario is to define the research question (see Chapter 2.1). Policy-screening and target-seeking scenarios can simulate the impact of an "ecological transition" on biodiversity or the economy. In contrast, exploratory scenarios explore the responses of the economy or the environment to a shock related to a specific modification, change, or degradation of nature. Policy-screening scenarios are the most represented among the studies identified, followed by target-seeking and exploratory scenarios (see Figure 5).

Figure 5. Type of scenarios used in the articles identified, according to the IPBES (2016) classification. Some authors developed different types of scenarios in the same study



Target-seeking scenarios analyze the impact of a set of policies, agent behavior assumptions, or technologies to achieve one or more defined targets. To protect biodiversity, there is no consensus on the suitable target, unlike climate transition scenarios, which mainly use the target of 1.5 °C (or 2 °C) of global warming above pre-industrial levels. It is possible, however, to use the biodiversity targets defined in the new CBD framework. Indeed, the CBD has established a strategic plan, the "Post-2020 global biodiversity framework", which proposes 21 targets to be achieved, including expending PAs to 30% by 2030, to enable the recovery of natural ecosystems and "living in harmony with nature" by 2050. For example, Kok et al. (2020) analyzed how a set of policies could achieve the CBD "2050 Vision" while ensuring food security and meeting the 2°C global warming target. Johnson et al. (2021) explored how to reach the PA expansion target, and Leclère et al. (2020) added the dimension of feeding the growing population while meeting the Bonn Challenge of restoring 3.5 million km² of degraded and deforested landscapes by 2030 and more by 2050.

Policy-screening scenarios involve constructing a hypothetical narrative of transformative policies and changes, which are needed for analyzing BRFR transition shocks. The choice of shocks is infinite, and probably due to a lack of historical benchmarks for conservation policy and for the purpose of simplification, the policies associated with these scenarios sometimes lack realism about their feasibility and/or scientific basis. They allow, however, testing the efficiency of certain innovative actions in favor of biodiversity. For example, Costello et al. (2016) analyzed the impacts of contrasting management regimes on fish biomass and the fishing industry (representing 78% of global reported fish catch). One of their scenarios requires equalizing each capture rate to the Maximum Sustainable Yield (MSY), which is the largest amount of catch extractable from a fish stock in the long-term and, on average, under existing environmental conditions and without significantly affecting the reproductive process. This scenario is rather indicative, as it does not provide information on the implementation of these management regimes.

We identify only one scenario suitable to analyze physical shocks, the exploratory scenario of Johnson et al. (2021). It corresponds to a narrative where biodiversity tipping points are crossed. Indeed, they analyzed how the partial decline of three ESs (pollination, marine production, and timber production) would affect the economy. The study does not specify the nature of the shock that would lead to such degradation, probably because it is challenging to explain scientifically the causes, the likelihood of triggering the collapse or regime shift of ES and its magnitude (Turner et al., 2020).

For each type of research question, it is advisable to explore different possible narratives and thus not be limited to a single scenario because the future is unknown. For instance, Obersteiner et al. (2016) generated 42 scenarios by combining several policies with climate trajectories, see Table 1. The advantage of this method is uncertainty transparency; nevertheless, the main risk is losing the coherence of the stories behind the scenarios. The authors of this literature review developed between 3 and 10 scenarios in the other articles.

3.1.2. The method to construct scenarios

The identified articles were mainly written by research institutes, including the Netherlands Environmental Assessment Agency (PBL)[9], involved in Kok et al. (2020), Schipper et al. (2020), and to a lesser extent in Pereira et al. (2020), Obersteiner et al. (2016) and Leclère et al. (2020). Another research center widely represented in the selected studies is the International Institute for Applied Systems Analysis (IIASA)[10]. Some co-authors nevertheless are from non-governmental organizations such as WWF, BirdLife, Wildlife Conservation Society (Leclère et

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[9] The **Netherlands Environmental Assessment Agency (PlanBureau voor de Leefomgeving - PBL)** is the Dutch institute for strategic policy analysis in the fields of environment, nature, and spatial planning. It contributes to improving the quality of policy and administrative decisions by conducting prospective studies, analyses, and assessments.

[10] The **International Institute for Applied Systems Analysis (IIASA)** is an international research institute that advances systems analysis and applies its research methods to identify policy solutions to reduce the human footprint, improve the resilience of natural and socio-economic systems, and contribute to the achievement of the Sustainable Development Goals.

al., 2020), or the Environmental Defense Fund (Costello et al., 2016). Finally, we identified only one financial institution, the World Bank, which is the source of the Johnson et al. (2021) study.

The type of approach used to develop scenarios (participatory or expert approach) is rarely specified in the articles selected for this literature review. It does imply that scenarios were not developed with the participation of actors with diverse backgrounds, experiences, and knowledge, given the varied origins of the co-authors. Nevertheless, if no information is given in the article, we cannot know which authors participated in developing the scenario narrative. Only Cheung et al. (2019) expressed their choice in this matter; they opted for the participatory method. In a workshop, they brought 18 professionals with varied experiences: fisheries managers, marine ecologists, fisheries scientists, socio-ecological researchers, economists, marine geospatial scientists, high seas policy advisors, and fisheries policy and governance specialists. Participants were asked to describe their perceptions of future environmental, management, economic, governance, and social projections for high seas fisheries for three Shared Socio-economic Pathways (SSPs) (see Chapter 3.2) and policies dedicated to the sector. The authors used this information to build their scenarios. Participatory scenario analysis often reveals trade-offs and conflicts between different sectors and communities when identifying pathways to achieve MPA objectives (Daw et al., 2012). They are a good approach for mitigating uncertainties around future trajectories and simultaneously integrating different stakeholder priorities.

3.1.3. The environment

The scenarios surveyed are mainly terrestrial, to the detriment of freshwater and marine environments (see Figure 6) ; only one freshwater and two marine scenarios met our criteria (see Chapter 2.3). The biological diversity of marine environments, however, is potentially considerable, particularly in terms of species richness[11]: Marine scientists estimate that there are between 300,000 and 10 million marine species for only 150,000 to 274,000 known species (Appeltans et al., 2012). The lack of data on species distribution partly explains the poor knowledge of these ecosystems and thus leads to the absence of marine scenarios.

Although representing a biodiversity sink, marine environments are being degraded at an unprecedented rate: nearly 33% of reef-forming corals, sharks, and shark-related species, and more than 33% of marine mammals are threatened with extinction (Brondizio et al., 2019). Globally, direct exploitation of marine organisms (e.g., fishing activities) and land-/sea-use change over the past 50 years have caused the largest biodiversity decline and accelerated climate change driver (Brondizio et al., 2019). In addition, the loss of marine biodiversity weakens the ocean ecosystem and its ability to withstand disturbances, adapt to climate change, and play its role as a global ecological and climate regulator.

Underrepresenting the future trajectories of marine biodiversity and associated ESs, as well as the policies for managing and conserving these ecosystems, tends to underestimate the impact of their degradation on socio-economic indicators and, thus also on the financial

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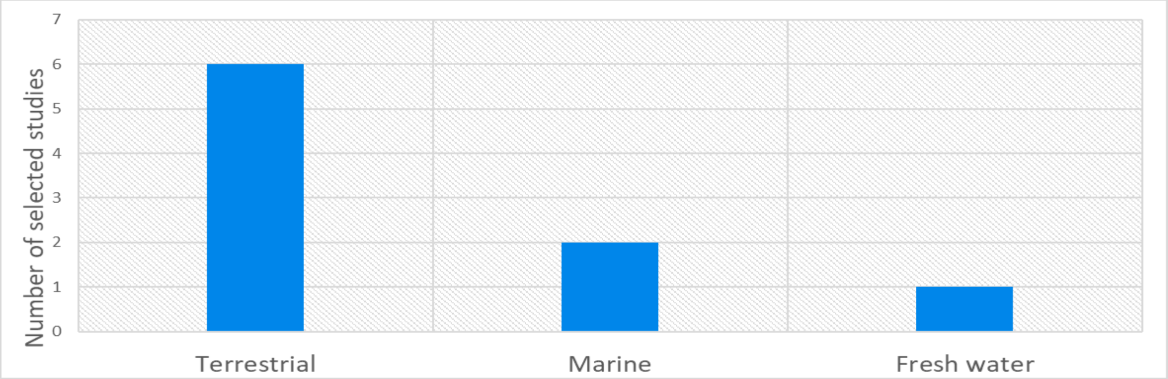
[11] **Species richness** is a measure of the biodiversity of all or part of an ecosystem; it refers to the number of species within a given area.

systems. Indeed, the fisheries sector highly depends on the ES of fish production, contributing to 0.5 to 2.5% of global GDP. Nevertheless, in some countries, such as Mauritania and Vietnam, the aquaculture and fisheries sector represents 10% of their GDP (Martini and Lindberg, 2013). Additionally, many nations depend on fish as their main food and livelihood source. The biggest nutritional reliance on fish and marine environments is seen in West African and Southeast Asian countries, particularly the Philippines and Indonesia (Teh et al., 2017).

The most comprehensive marine scenarios for analyzing the impact of possible future trajectories through conservation policies and socio-economic pathway variation with an assessment of environmental and socio-economic impacts are those of Cheung et al. (2019). The authors assessed the consequences of these trajectories for the high-sea fish sector. Also, through the fisheries sector, Costello et al. (2016) assessed the status, trends, and outcome of recovery policies for 4,713 fisheries worldwide.

Kok et al. (2020) evaluated the impact of ambitious biodiversity conservation policies on the integrity[12] of freshwater environments for two aquatic ESs: natural water purification measured by the reduction in the proportion of water bodies with excessive nutrient concentrations and lake health, which represents the proportion of lakes meeting the world health organization standards for harmful algal blooms.

Figure 6. Number of studies that have developed scenarios adapted to terrestrial, freshwater, and marine environments. Some studies have analyzed two different environments at the same time.



3.1.4. *The time horizon of scenario projections*

INSPIRE & NGFS (2022) estimate that BRFRs may emerge sooner than CRFRs, generally considered to be long-term. In addition, physical shocks tend to occur earlier than transition shocks, which depend on policy announcements regarding conservation targets whose effects are spread over time. It is thus important to choose the appropriate time horizon for the different future trajectories analyzed.

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[12] **Ecosystem integrity** is generally used to refer to the completeness and functionality of an ecosystem. When we use the term ecosystem integrity (or integrity), we refer to the completeness and functionality of an ecosystem and its ecological processes, particularly concerning its natural state.

Indeed, according to studies used for assessing biodiversity transition risks, the future horizons chosen are between the present and 2090, with a strong representation of projections for 2030 and 2050. Indeed scenario horizons are aligned with the CBD's "Post-2020 global biodiversity framework", which gives targets and time horizons for these two years: 2030 being the horizon target to halt biodiversity loss, and 2050 being the one to start recording a net positive increase (recovery) in biodiversity. Some articles, such as Kok et al. (2020) and Leclère et al. (2020), also assessed the impact of their scenarios for 2070 and 2090 respectively, which are horizons beyond the "2050 Vision". Moreover, Pereira et al. (2020) and Costello et al. (2016) also evaluated past trends in environmental and socio-economic trajectories since 1900 and 1980 respectively.

Some authors do not explain their time horizon choice (Costello et al., 2016; Schipper et al., 2020), and others aligned their scenarios with the Sustainable Development Goals (SDGs), which have a time horizon of 2030 (Cheung et al., 2019; Obersteiner et al., 2016). For example, Obersteiner et al. (2016) analyzed sets of policies that correspond to different SDG targets such as energy and climate policies (SDG 7 clean and affordable energy, SDG 13 measures to address climate change, and SDG 14 aquatic life), or biodiversity conservation policies (SDG 14 aquatic life and SDG 15 terrestrial life).

It should be noted that scenario assumptions have different time horizons than scenario projections. For example, Leclère et al. (2020) projected their scenarios to 2090, but some of their assumptions have a much closer time horizon. For example, one such assumption is a 50% linear total waste reduction by 2050. The time horizon of the assumptions is very important because a policy will not have the same impact if it is implemented in the short-, medium-, or long-term. Their choice has to deal with the fact that natural resource conservation policies are cheaper and simpler than restoration because they avoid potential tipping points and difficulties associated with regime shifts and maintain option values[13] by protecting ecosystems and species (Dasgupta, 2021).

Moreover, the magnitude of the pressures that have the greatest impact on biodiversity will be different in the future. Indeed, pollution and climate change are factors that could become more problematic in a few years than land and sea use changes (Millennium Ecosystem Assessment, 2005; Brondizio et al, 2019). Furthermore, if a policy aiming at reducing land-use pressure is implemented with too long a time horizon, the policy may not be adapted to the biodiversity issues of the future.

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[13] The **option value** reflects the willingness to pay to keep an alternative (an option) available for possible use in the future.

3.2 The scenario (qualitative) narratives

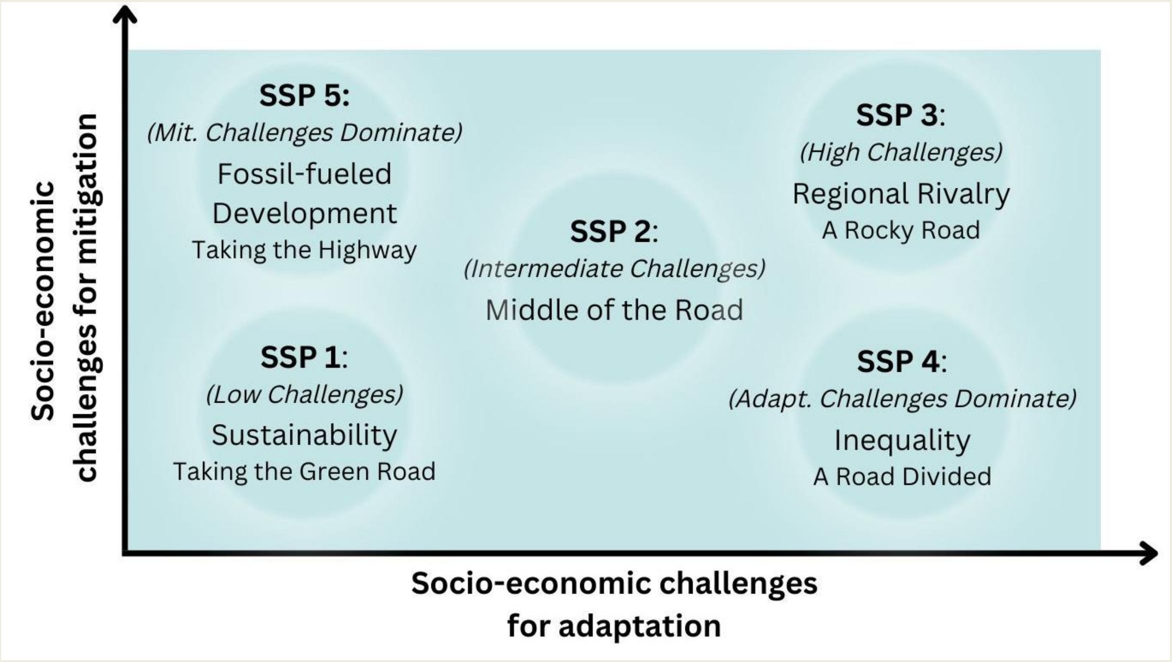
Once the conceptual framework is established, the next step is to create or select the scenario narratives (i.e., storylines); describing the possible evolution of the world given a specified context. These narratives can explore qualitative socio-economic pathways, policies, technological changes, agent 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, except Kok et al. (2020), Johnson et al. (2021), and Costello et al. (2016), who did not specify their choice. SSPs are qualitative scenarios that describe possible socio-economic development trends (e.g., GDP growth, demography, technology, and governance) (O'Neill et al., 2014 and 2017; Riahi et al., 2017). SSPs were created to define a common research framework on global warming issues and thus facilitate the production of integrated assessments based on combinations of climate model projections, socio-economic conditions, and assumptions about mitigation and adaptation policies. It is important to note that these narratives do not address either climate (or biodiversity) policies or the consequences of climate change (or biodiversity loss). These trajectories are intended to be coupled with policies that may, for example, aim to achieve radiative forcing targets (Vuuren et al., 2013) or ecosystem protection. Indeed, in the context of biodiversity scenario, they can provide storylines for the main drivers of indirect biodiversity loss (i.e., demography, economy, governance, and technology) and main direct drivers (i.e., land-use changes, natural resource use and exploitation, climate change, and pollution). For the latter, it is noted that the introduction of invasive species is always absent.

SSPs are composed of five specific narratives describing different worlds in terms of socio-economic development with a horizon of at least 2100. These trajectories explore uncertainties regarding mitigation and adaptation challenges associated with different climates 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 an ecological transition (see Figure 7).

SSPs were purposely constructed in odd numbers to avoid the risk of using one trajectory as a baseline (also known as "business-as-usual") (Kok et al., 2017). However, in light of user drift, the designers agreed on a "central" path, the SSP2, although it does not represent the most likely pathway (Fricko et al., 2017).Original SSP narratives are available in O'Neill et al. (2017) and the land-use-related narratives in (Popp et al., 2017), while a summary is available in the Appendix 1.

Figure 7. **SSPs mapped in the mitigation and adaptation challenge space (adapted from O'Neill et al., 2014)**



Most authors have relied solely on SSPs for their narrative, even though they do not incorporate the specifics of ecosystem dynamics due to their design for assessing climate change mitigation and adaptation challenges.

Alternatively, Cheung et al. (2019) developed three fisheries narratives that complement the SSP1, SSP3, and SSP5 storylines, most modeled in the literature. This approach allows them to start from a conceptual framework widely used in the literature and add specificities related to the high-sea fishing sector, such as changes in agent consumption or marine biodiversity protection policies (see Appendix 2 for more details).

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, while the second has a "land sharing" vision where ESs play a central role in decision-making (see Appendix 3 for more details)[14].

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[14] 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.

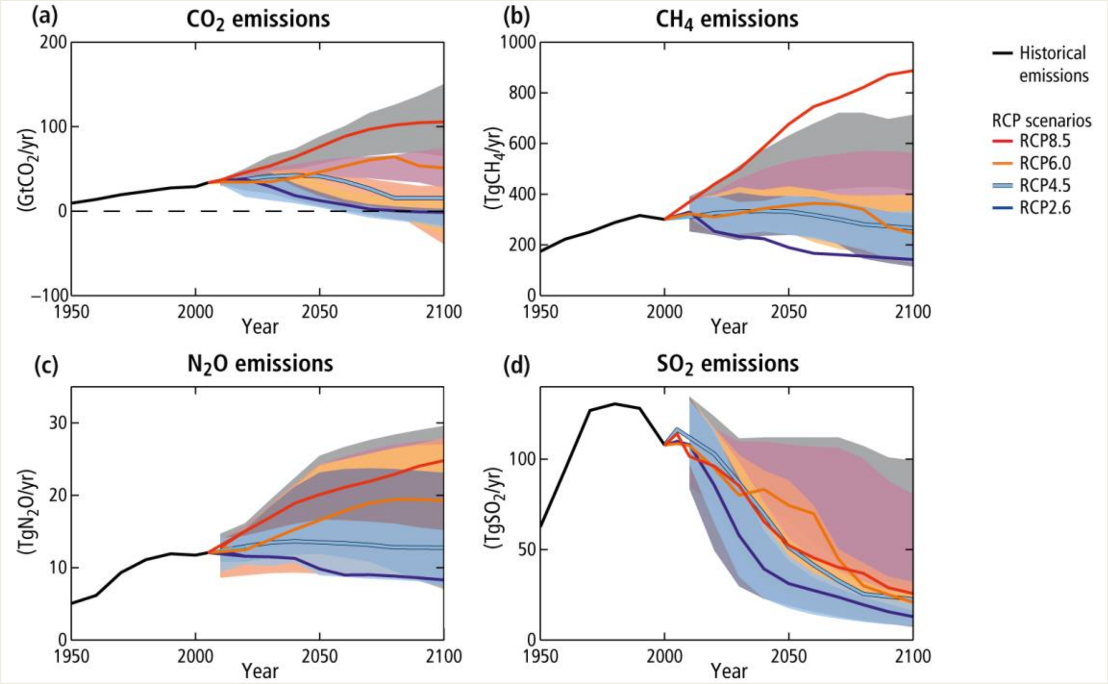
3.3 Assumptions and quantified parameters

3.3.1 Quantification of the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs)

Once a scenario narrative is complete, it can be transformed into quantitative trajectories using models. Indeed, the storyline is often translated into a quantitative scenario, specifying values 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. However, moving from qualitative to quantitative scenarios often means that some dynamics are not measurable or not easily accounted for.

Almost all studies used quantification of GDP and population trajectories (at least) from SSPs, with the exception of Costello et al. (2016). Many of them also coupled the SSP assumptions with one or more Representative Concentration Pathways (RCPs) that describe future GHG concentration for different climate scenarios until 2300 (Van Vuuren et al., 2011) (see Figure 8).

Figure 8. Emission scenarios and the resulting radiative forcing levels for the Representative Concentration Pathways. Panels a to d show the emissions of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and sulfur dioxide (SO2). (from Pachauri & Meyer, 2)



For the computation of GDP trajectories of SSP, the Organization for Economic Co-operation and Development (OECD), the Potsdam Institute for Climate Impact Research (PIK), and the IIASA have developed different methods[15]. The OECD approach, however, is the most widely used when extracting SSP data (see below). However, nothing prevents researchers from testing the sensitivity of their scenarios with the other computational methods.

GDP trajectories are assumed to be positive for every country even though the scenario envisaged proposes a major structural change (either an ecological transition or a collapse of biodiversity) which should impact long-term growth. Indeed, the OECD used the "ENV-Growth" model (Dellink et al., 2017) to attribute an economic growth path for each country per SSPs. It is an augmented version of the Solow growth model. It relies on several growth factors (e.g., physical capital, labor capital, and energy demand) but does not include natural resources and land-use other than crude oil and natural gas. It means, for example, that if no land is available to expand agriculture, the output and/or value added to the sector will not be impacted. The model is based on historical data from the OECD and the international monetary fund (from 2012 to 2017) and uses the assumption of conditional convergence. This means that from the first year of the projection, the GDPs of the least developed countries will increase more rapidly than those of the developed countries to converge towards the same values (catch-up effect). As a result, the GDPs of all countries will increase at least until 2100 (total and per capita), and the annual growth rate of aggregate GDP is expected to stagnate or decline for all SSPs from 2030 to 2100 (see Figure 9). It is likely, however, 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 the ecological transition or the biodiversity collapse.

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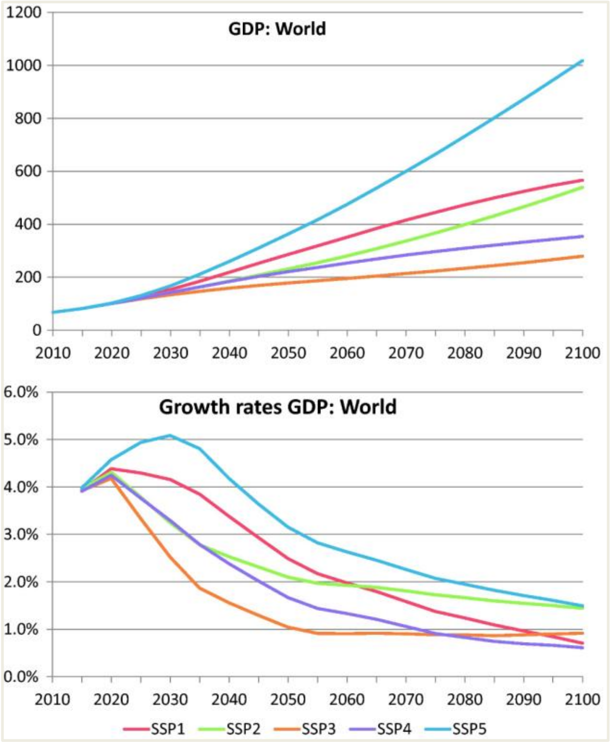
[15] The International Institute for Applied Systems Analysis (IIASA). https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

Figure 9. Global GDP (trillion 2005 dollars) and income levels (thousand 2005 dollars) for the five SSPs and associated average annual growth rates over 5 years (%/year) (from Dellink et al., 2017).



All SSP trajectories consider positive economic growth (O'Neill et al., 2017) for all countries in the long run, which leaves no room for exploring trajectories with low, zero, and negative growth (Kim et al., 2018) that could emanate from conservation strategies or simply the consequences of geopolitical and environmental barriers. The only attempt to recast SSPs 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.

The SSP demographic trajectories are computed given future assumptions of fertility, mortality, migration, and education (KC & Lutz, 2017). According to IIASA (KC, 2020), in 2100, the population is expected to decrease slightly for SSP1 and SSP5, reaching about 7.2 billion instead of 9.5 billion for SSP2 and SSP4. The largest increase is expected for SSP3, with 13.6 billion people. For comparison, the latest world population projections for 2100 are estimated at 10.4 billion (UN, 2022).

The most common models used to detail SSP trajectories at the sectorial level are integrated assessment models (IAMs) such as AIM (National Institute of Environmental Studies; Fujimori et al., 2014 and 2016), GCAM (National Institute of Environmental Studies; Wise et al., 2014), IMAGE (PBL; Stehfest et al., 2014), MESSAGE-GLOBIOM (IIASA; Kindermann et al., 2006; Havlík et al., 2014; Riahi et al., 2012), REMIND/MAgPIE (National Institute of Environmental Studies; Popp et al., 2011 and 2014), and WITCH (European Institute on Economics and the Environment, Riahi et al., 2021). IAMs and climate models can translate combinations of SSPs and RCPs into land-use change and climate change projections. Subsequently, biodiversity and ecosystem service models can be used to translate these changes into impacts on nature, see section 3.4.1 for more details.

3.3.2 Additional quantitative trajectories related to biodiversity

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. Some authors, however, 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 the development of biodiversity scenarios as it is one of the main pressure factors driving land-use change, with more than a third of the world's land area and nearly three quarters of the world's water resources devoted to livestock and crop production (Brondizio et al, 2019).

The trajectories attributed to this sector are mainly supply-side, and trajectories related to the agricultural sector productivity are the most widely modeled.

In the baseline scenario of Leclère et al. (2020), agricultural productivity is supposed to increase by 60% by 2100 (under the SSP2 pathway), and global demand for land-based production by more than 70% over the century. In their supply-side policies pathway, crop yields follow the SSP1 scenario, and land productivity in developing countries rapidly converges to the level of developed countries. For example, in their most ambitious scenario (in terms of efforts to reverse biodiversity trends), productivity increases by 34% to 63%, depending on the IAM for the 2010-2050 period. Adversely, Johnson et al. (2021) simulated the effect of a 90% reduction in wild pollination sufficiency [16] on agricultural yields (i.e., partial collapse of pollinator ESs) only for crops that are dependent on wild pollination.

In the baseline scenario of Kok et al. (2020), an extension of the current land-use pattern is simulated. When the baseline is coupled with additional climate change mitigation, hunger elimination, and agricultural and energy system changes, productivity and nutrient use efficiency increase in line with the FAO agricultural outlook and future GDP projections (Doelman et al., 2018). In the "Half-Earth" scenario, agriculture is separated from natural areas. When additional measures are added to this scenario, crop yields increase by 20% compared to the baseline (in line with SSP1) (Doelman et al., 2018). Irrigation efficiency increases by 0.1% per year for all irrigated areas, and fertilizer use efficiency is 20% higher than in the baseline scenario; nevertheless, efficiency decreases in countries with nutrient mining. Alternatively, the "Sharing the Planet" scenario proposes a combination of agriculture and natural habitat patches via agroforestry in tropical biomes and mixed cropland-nature patterns (70/30) in temperate biomes. When additional measures are added, productivity

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[16] Wild pollinator sufficiency corresponds to the amount of pollinator-friendly habitat around farmlands.

increases moderately (10% higher than in the baseline scenario). Irrigation and fertilizer use efficiency follow similar trajectories to the "Half-Earth" scenario. Neither Leclère et al. (2020) nor Kok et al. (2020) mention which crops will be affected by these productivity increases and in what proportion. Moreover, the SSP1 trajectories imply, among other things, that Sub-Saharan Africa will double its crop yields between 2010 and 2050, which will require a lot of investment and innovation and be constrained by climate change's impact on crop productivity (Rosenzweig et al., 2013).

In addition, Obersteiner et al. (2016) calculated productivity trajectories for different crops and livestock products as a function of countries and SSP trajectories, based on an econometric analysis of the historical correlation between GDP per capita and growth rates of crop and livestock productivities. Indeed, they assumed a "yield increase" of 30% or 50% without additional inputs (i.e., fertilizer or waste). The productivity increase is the largest of all the studies; for example, in the SSP1 scenario, crop productivity in Latin America, Africa, and the Middle East will increase by 153% or 173% between 2010 and 2050, depending on the policy adopted. As a result, these countries would then need to invest heavily in research and development to achieve these trajectories.

In addition to these trajectories, authors quantify policies related to agricultural subsidies. Indeed, it is estimated that governments spend at least $500 billion per year on fiscal support to agricultural, forestry, and fisheries producers (including fossil fuels support), which is potentially harmful to biodiversity (OECD, 2020b). For example, in 2017, OECD countries paid $228 billion to support farmers, of which $116 billion is considered harmful to biodiversity (OECD, 2020a). 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. In addition, one of their scenarios simulates the implementation of an R&D policy for the agricultural sector by removing all subsidies from agriculture and allocating these "savings": 20% are invested in R&D, and 80% become lump-sum transfers for landowners. Nevertheless, to quantify this path, the authors only adjusted ex-post GDP by an amount equivalent to the annualized estimate of R&D expenditures in 2030 instead of quantifying the impact of an R&D policy on the economy. The main reason is that their general equilibrium model does not consider R&D as a sector or a costly expenditure.

Kok et al. (2020) quantified the introduction of a 10% import tax on all agricultural products by 2050. Once again, this policy requires the cooperation of all countries and raises questions about implementing this measure in developing countries.

- **Some demand-side policies are nevertheless modeled. They are related to changes in food systems production, such as reducing food losses (from harvesting, processing, distribution, and final household consumption) and changes in the consumption of animal products.** In Kok et al. (2020) and Leclère et al. (2020), the baseline scenario projects current levels of food loss (equivalent to the implementation of the SSP2 trajectory). The more ambitious trajectories propose a 50% reduction in current food loss by 2050 relative to the baseline scenario. These authors have also simulated diet shifts in animal products and, as for food losses, their baseline scenario projects the current trends. In their most ambitious scenarios, animal calorie consumption is reduced by 50%

compared to the baseline trajectory. Nevertheless, this trajectory is applied to all regions except those with low incomes and levels of animal calorie intake (North Africa, West Africa, East Africa, rest of South Africa, India, rest of South Asia, and Indonesia). Similarly, Obersteiner et al. (2016) projected two different diet trajectories: meat demand increases in developed and developing countries or increases in developing economies but decreases in developed regions.

- *Land-use trajectories*

Expansion of PAs is the most widely modeled biodiversity conservation policy. A flagship measure of the CBD is the protection and conservation of species habitats through the expansion of PAs and Other Effective area-based Conservation Measures (OECMs)[17] to protect at least 30% of the terrestrial and marine surface by 2030. In the "Post-2020 Biodiversity Framework", the CBD includes the need to select these areas based on their importance to biodiversity and their contribution to people so that conservation is effective and equitable. 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%[18]. It is worth noting here that the surface area parameter does not seem to be sufficient to act on land use pressures, since the effectiveness of current protected areas is often questioned in terms of biodiversity outcomes (Geldmann et al., 2019).

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. For example, Waldron et al. (2020) established 20 different scenarios, in terms of PAs allocation, for conserving 30% of the planet: some focus on production, others on biodiversity conservation, and the rest represent a trade-off between the two (Table 2). Furthermore, within these three objectives, it is possible to allocate land differently depending on the biodiversity indicators and databases used.

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[17] 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).

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

Tableau 2. Waldron et al. (2020) scenarios for achieving the 30% land and/or sea area conservation target (adapted from Waldron et al., 2020). T = terrestrial realm, M = marine realm.

REALM	CATEGORY	NAME	DESCRIPTION
T	Non-PA-expansion baseline	Reference Scenario (REF)	The counterfactual for comparison of not expanding protected areas post-2020. Maintain the protected area estate at its current coverage (as of July 2019).
M	Non-PA-expansion baseline	Reference Scenario (REF)	The counterfactual for comparison of not expanding protected areas post-2020. Maintain the marine protected area estate at its current coverage (as of July 2019).
T	Production-focused	Three Conditions (THC)	Protect all global habitat that retains a state of minimal human intervention ('wilderness'), plus existing PAs.
T	Production-focused	Harsh Political Reality (HPR)	First disqualify from protection any area needed for agricultural production up to 2050, then choose the areas of non-disqualified land that optimally minimizes global species extinctions (plus existing PAs).
M	Production-focused	Harsh Political Reality Marine (HPR)	Marine reserves are not allowed on any areas of ocean that are currently high-value fishing grounds. The existing MPA system is then expanded to the next-best set of ocean sites to preserve marine biodiversity.
T	Biodiversity-focused (hybrid)	Biodiversity/ Wilderness consensus (BIWI)	"Protect all wilderness, KBAs[19] and existing PAs, plus the optimal set of all other sites needed to maintain global species viabilities (based on minimum range coverage). NB 43% terrestrial coverage, compensated by lower coverage in the paired marine scenario.
M	Biodiversity-focused (hybrid)	Biodiversity/ Wilderness consensus (BIWI)	All existing MPAs and marine wildernesses are protected, then the optimal set of areas needed to prevent marine biodiversity decline (NB cover 26% of marine global area).
T	Biodiversity/ Production Compromise (BPC)	Biodiversity/ Production Compromise	Add ~5% more of the land surface to the existing PA network (up to 20% planetary land), choosing sites to optimally reduce global species extinctions. The remaining 10% of new PAs are not allowed to go on potential agricultural land, but are placed in the next-best set of sites instead (using the same criteria).
M	Biodiversity/ Production Compromise	50:50 EEZ (5050EEZ)	Expand the existing MPA system to the 30% of ocean that optimally reduce global species extinctions, but 50% of the protected area inside Exclusive Economic Zones permits sustainable fishing, while the other 50% bans all economic activity.
M	Biodiversity/ Production Compromise	50:50 Coastal (5050COAST)	Expand the existing MPA system to the 30% of ocean that optimally reduce global species extinctions, but 50% of the protected area immediately adjacent to coasts (where small scale fisheries tend to operate) permits sustainable fishing, while the other 50% bans all economic activity.
T	Biodiversity-focused	Save Species from Extinction (SSE)	Expand the existing PA system to the 30% of land that optimally reduce global species extinctions.

T	Biodiversity-focused	Global Deal for Nature (GDN)	Conserve a wide range of sites that have biodiversity importance under different criteria, including current PAs, sites with rare or endemic species, areas needed for wide-ranging mammals, etc.
M	Biodiversity-focused	Top 30 (TOP30)	Expand the existing MPA system to the 30% of ocean that optimally reduce global species extinctions.

In addition, establishing a PA network and implementing an effective management system is costly, as it can include monitoring habitat health, enforcing regulations, and investing in research fees. Such costs are however rarely taken into account in the scenarios. Management is fundamental for preventing illegal activities in PAs, such as logging, poaching of protected animals, mining, and encroachment by human settlements and agriculture. Waldron et al. (2020) estimated that achieving the protection of 30% of the world's lands and oceans would require an average annual investment of about $140 billion by 2030. Johnson et al. (2021) estimated this cost at $115 billion, but if the benefit of avoided carbon emissions is considered, it is reduced to $13 billion. The world currently invests just over $24 billion per year in PAs (the bulk of this amount comes from upper-middle and high-income countries' national PA budgets). The necessary investment increase will likely be largely financed by the poorest and middle-income countries, as they have the richest biodiversity territories, requiring money transfers and cooperation between countries. However, shifting financial flows away from biodiversity-negative outcomes and toward biodiversity-positive outcomes can lower the pressures on biodiversity and the costs of these land-use trajectories.

Nevertheless, PAs offer economic and social benefits and mitigate climate change's economic risks. However, only some countries will have the capacity to capture these economic benefits, particularly in terms of tourism development (Waldron et al., 2020).

At a local scale, equity and justice issues need to be considered. More than half of high conservation value lands are traditionally owned, used, or occupied by indigenous peoples and local communities, who are the *de facto* managers (Brondizio et al., 2019). Putting these areas under protection can also affect the actors who use the resources as a livelihood or value them culturally. At the global scale, it is not easy to consider all these aspects, but what is essential to keep in mind is that depending on the scenarios and the choice of land allocation, future socio-economic and human well-being trajectories will be different.

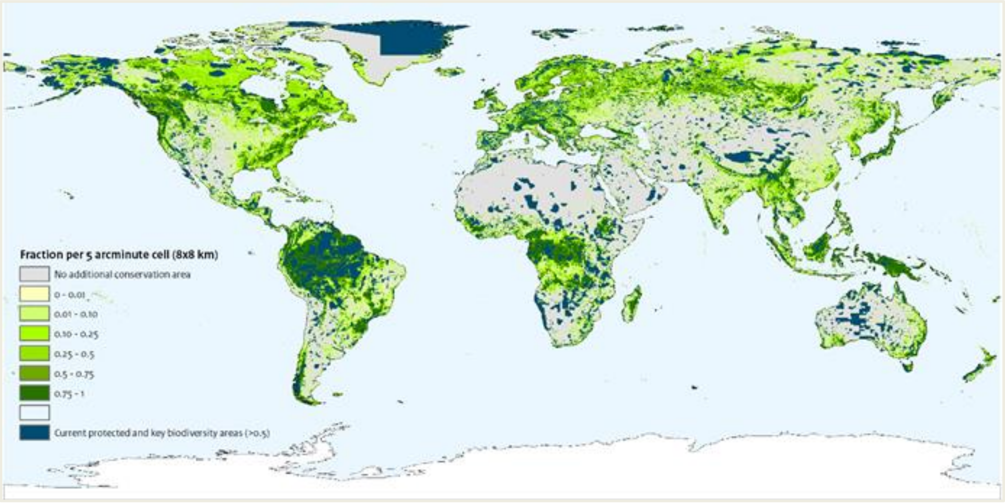
Moreover, in the articles, the type of protection envisaged in PAs and whether or not human activities can be developed within them is sometimes unclear. Indeed, the type of activity authorized within the PAs will not have the same impact on the degradation of biodiversity; it is thus necessary to dissociate the recreational activities of walking or gathering non-timber forest products, for example, from silvicultural activities.

In their baseline scenario, Kok et al. (2020) limited PAs to the Aichi target of protecting 17% of the land area. They also added the possibility of urban expansion as population and urbanization increase (based on Klein Goldewijk et al., 2011).

Alternatively, their "Sharing the Planet" and "Half-Earth" scenarios describe worlds where respectively, 30% (see Figure 10) and 50% (see Figure 11) of the Earth will become regulated by PAs by 2050.

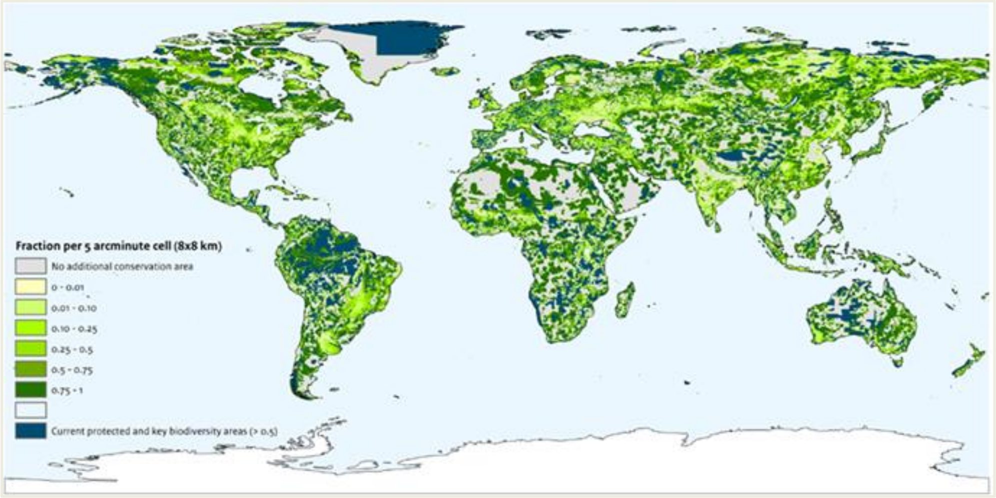
Specifically, in the "Sharing the Planet" scenario, high-carbon forests, riparian areas, water retention areas, peatlands, urban green spaces, and key biodiversity areas are added to current PAs to cover 30% of the Earth's planet by 2050. Expansion of urban development and agriculture is not allowed in conservation areas. In addition, around large (300 m buffer) and medium (150 m buffer) rivers, buffer zones of natural vegetation are created to reduce nutrient loading to the water. Only Kok et al. (2020) considered the impact of human activity around PAs in the allocation of land to be protected. Finally, urban expansion trajectories follow the baseline scenario, but no expansion is allowed in areas identified for conservation, including existing urban green space.

Figure 10. Conservation areas for the "Sharing the Planet" scenario aim to conserve 30% of the world's land and freshwater area by 2050 (from Kok et al., 2020).



In the "Half-Earth" scenario, PAs are expanded to cover at least 50% of all terrestrial and freshwater ecoregions by 2050. Encroaching activities are reduced over time. Urban development and agricultural expansion are not allowed in conservation areas, and urban expansion follows baseline trajectories in the rest of the world.

Figure 11. **Conservation areas for the “Half-Earth” scenario aim to conserve 50% of the world’s land and freshwater area by 2050 (from Kok et al., 2020).**



To prioritize conservation areas for their two scenarios, Kok et al. (2020) combined mainly KBA[19] databases, current PAs[20], important bird areas[21], and a database of the most endangered species[22]. Then at the ecoregion scale, a land allocation model was used to determine which areas to protect to maximize policy effectiveness. For the “Sharing the Planet” scenario, land allocation required a more complex process to incorporate areas rich in ESs into the final decision.

Johnson et al. (2021) simulated the implementation of the "Great Deal for Nature" scenario illustrated in Waldron et al. (2020). This scenario involves retaining current PAs and expanding them so that each country unit retains 15.3% of its land area to meet the 30% target by 2030 (see Figure 12). Areas are selected based on indicators of biodiversity and carbon storage.

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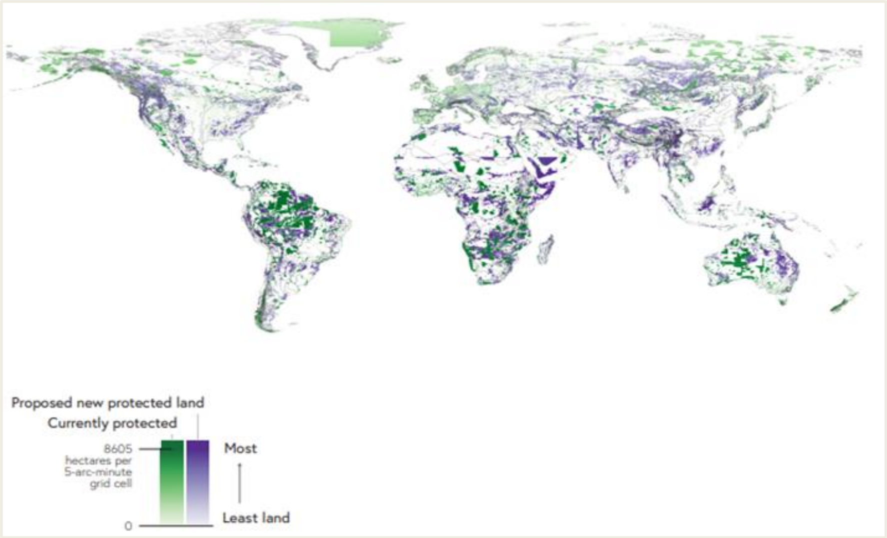
[19] Key Biodiversity Area Partnership World Database of Key Biodiversity Areas. (BirdLife International, accessed 5 October 2017).
https://www.keybiodiversityareas.org/

[20] The World Database on Protected Areas. https://www.protectedplanet.net/en (UNEP-WCMC, accessed October 2017).

[21] Important Bird and Biodiversity Areas. http://datazone.birdlife.org/site/ibacriteria.

[22] Alliance for Zero-Extinction Sites. https://zeroextinction.org/.

Figure 12. PAs to achieve the 30% land area conservation target by 2030 (from Johnson et al., 2021).



Leclère et al. (2020) also analyzed the expansion of PAs to cover 40% of the land area by 2020 (see Fig 1.a from Leclère et al., 2020). This policy thus lacks credibility, given that only about 17% of the world's land area is currently protected or under OECMs. To simulate this intervention, they overlaid maps of current PAs, KBAs, and wilderness areas (Allan et al., 2017). In addition, PA management efforts are added to the policy, meaning that land-use changes resulting in further habitat degradation are not allowed in expanded PAs from 2020. Another policy analyzed by Leclère et al. (2020) is the increasing restoration of degraded lands and the integration of landscape-level conservation planning into land-use decisions, intending to increase biodiversity outside of extended PAs while considering spatial gradients of biodiversity and seeking synergies with agricultural and forest production.

Overall, all the PA allocation maps show strongly divergent assumptions. For example, we compare the 30% PA expansion policy of Kok et al. (2020), see Figure 10, with the 40% expansion policy designed by Leclère et al. (2020), see Fig 1.a from Leclère et al. (2020). 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, while not protecting, for example, the tropical forests of the Congo Basin, which represents a key zone in terms of biodiversity.

- *The high-sea fishing sector & sea-use trajectories*

The policies and trajectories implemented to improve marine biodiversity are diverse and creative. They may focus on sectoral subsidies, ex-vessel pricing, MPAs, or fisheries management techniques. At the global scale, however, they do not distinguish between different fishing sectors (i.e., recreational, subsistence, and commercial) and types of commercial fishing methods: whether industries are 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 erosion of biodiversity and capacity to satisfy the growing seafood demand.

Costello et al. (2016) constructed three scenarios that involve different fisheries management objectives. The first scenario forces all fisheries to equalize their catch rates at MSY indefinitely. This is a trade-off between conservation and exploitation. The second scenario describes a world where fishing trajectories maximize the long-term fishing profit's Net Present Value (NPV). This policy implies that fish regeneration is optimal from an investment point of view. The ex-vessel price of fish increases by 31% and the variable cost of fishing decreases by 23%, in line with the literature. The last scenario corresponds to business-as-usual trajectories, although it is adapted to the types of current fisheries management: catch shares fisheries[23] will follow the trajectory of the second scenario; fisheries under restricted access management (RAM)[24] will follow the current trajectories of fish mortality; and all others, i.e., neither RAMs nor known catch shares fisheries, are assumed to follow open access dynamics. These policies were evaluated for all fisheries, then only for "overexploited" fisheries, and finally for "fully exploited" ones according to the FAO (2011) classification.

Cheung et al. (2019) quantified and adjusted three SSP narratives to reflect the societal considerations of high seas narratives. In the SSP1 trajectory, the ex-vessel price of high-seas harvested marine species is unchanged. The operating and capital cost of fishing will increase by 50% by 2050, and the rate of increase in catch remains unchanged. Fisheries subsidies are eliminated for poor and medium-rich countries; in rich countries, they are reduced by 75%. Currently, more than half of global fisheries subsidies (mainly fuel subsidies), which are estimated at $35 billion per year, go to overfishing (Sumaila et al., 2016). The SSP2 implies that the ex-vessel price of marine species exploited in the high seas is low (25% decrease by 2050) due to the increase in supply. The operating and investment cost of fishing will decrease by 25% by 2050, and the rate of increase in catch is unchanged. Subsidies to the fishing sector increase by 25% for poor countries and 50% for medium-rich and rich countries. The SSP3 trajectory describes a world where the ex-vessel price of marine species exploited on the high seas is high (i.e., increasing by 25% by 2050). The operating and investment cost of fishing will decrease by 50% by 2050, and the rate of increase in catch will increase by 25% for the medium-rich and rich countries. This world experiences a 25% increase in fishing subsidies for all countries. Cheung et al. (2019) also added a baseline trajectory that matches current trends. For all of these scenarios, MPA constraints are simulated for 2050, from 0 to 50% expansion with a median target of 30% of the total high sea area, and radiative forcing trajectories are defined (RCP 2.6 or RCP 8.5).

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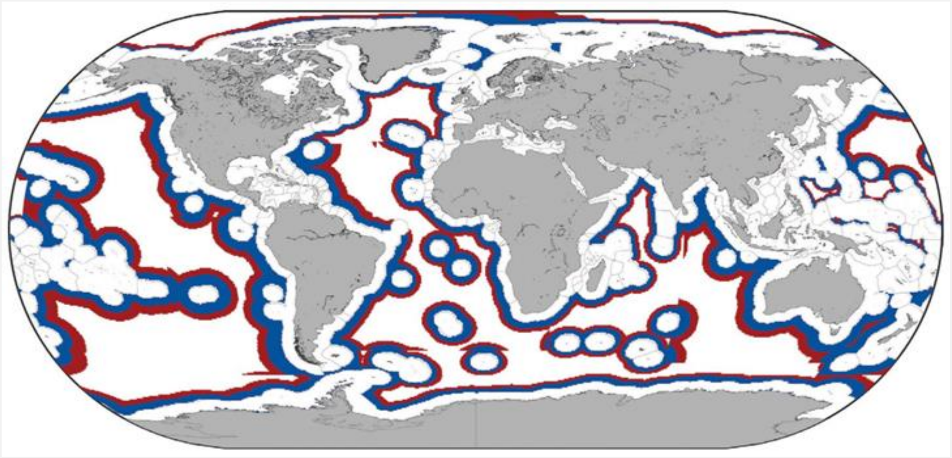
[23] **Catch shares** are fisheries management systems that allocate a catch privilege over a specific area or a percentage of the total catch to individual fishermen, communities, or associations. Catch shares provide long-term secure privileges to participants and, in theory, an incentive for the efficient and sustainable use of fish stocks. Catch share programs fall into two categories: quota-based programs that establish a catch limit for the entire fishery; and area-based programs that allocate a secure and exclusive area to participants.

[24] **Restricted Access Management (RAM)** limits the number of people, vessels, or fishing gear that can be engaged in catching a specific species of fish or shellfish. Restricted access can also restrict the catch allocated to each participant in the fishery through harvesting rights such as individual or community quotas.

For the 30% or 50% MPA expansion policy, Cheung et al. (2019) chose the cells closest to the EEZ boundaries (see Figure 13). To ensure that MPAs were evenly distributed across ocean basins, they used the statistics provided by the FAO major fishing areas as geographic units and pro-rated the hypothetical PAs based on the size of each FAO area. However, areas were not selected based on their importance in biodiversity or profitability, so this MPA policy is incomplete. Indeed, according to the global fishing watch maps[25] fishing efforts are more concentrated in EEZs than in the high seas; the study thus did not necessarily target the priority areas to be protected to reduce biodiversity decline. In addition, current MPAs only cover about 8.15%[26] 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.

Figure 13. Scenarios for expanding MPAs in the high seas to 30% (blue) or 50% (blue and red) in 2050 (from Cheung et al., 2019).



Finally, Johnson et al. (2021) designed a sudden 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.

- *The forestry sector*

Measures to mitigate global warming by maintaining carbon storage through avoiding deforestation were explored in the scenarios. These policies assume that all countries implement payments in a coordinated manner, although the SSP narratives propose different degrees of coordination between countries. Indeed, Kok et al. (2020) developed two Reducing Emissions from Deforestation and forest Degradation (REDD)[27] policies. The first

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[25] Global Fishing Watch. https://globalfishingwatch.org/map/?latitude=19&longitude=26&zoom=1.5&start=2022-06-09T00%3A00%3A00.000Z&end=2022-09-09T00%3A00%3A00.000Z

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

[27] **Reducing Emissions from Deforestation and forest Degradation (REDD)** is a mechanism that puts a financial value on the carbon stored in forests to encourage developing countries to reduce deforestation and invest in lower carbon alternatives.

aims to implement a REDD program protecting all intact forest landscapes, while the second only targets forests with a carbon density greater than 100 t C/ha. The article, however, does not provide any information on which countries are likely to pay or receive financial support from the program and in what proportion. In their policy-screening scenarios, Johnson et al. (2021) identified two different trajectories depending on the type of 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 made by rich countries based on their historical GHG emissions, and payment is received by poorer countries based on avoided deforestation.

In addition, in the exploratory scenario designed by Johnson et al. (2021), a sudden collapse in timber production is quantified. They assumed an 88% decrease in forest cover for all tropical regions and suggested a reduction in the ability to expand forestry in the Amazon basin. The economy is impacted by a 90% reduction in wood supply from native forests in humid tropical areas with a longer growth period.

- *The energy sector*

Only some studies have implemented trajectories that target the energy sector. Contrary to the climate scenarios for which this sector is determinant, biodiversity dynamics is less impacted by a single sector. The main argument in favor of scenarios focusing on biodiversity change is that they provide a clearer understanding of which policy intervention will be the most effective in conserving biodiversity.

As a result, studies hardly implement climate change mitigation and adaptation policies (e.g., through the forestry or the energy sector), despite the growing interest of countries in these issues. As an example of climate mitigation trajectory, Kok et al. (2020) explored the reduction of energy crops (wheat, sugarcane, corn, and oilseeds), i.e., plant species grown to produce biomass for the creation of first-generation biofuels (ethanol and biodiesel). Moreover, Obersteiner et al. (2016) simulated two different policies to reach the 2°C target of global warming by imposing either a moderate share of bioenergy and nuclear energy or a high percentage of bioenergy and no nuclear energy by 2030.

Some measures to mitigate global warming do not produce "co-benefits" for biodiversity or even degrade it further and vice versa. The expansion of hydropower plants, for example, is strongly simulated in the climate scenarios because it provides clean electricity with significantly lower GHG emissions than most other energy sources while degrading biodiversity (e.g., by fragmenting watercourses and disrupting certain biological cycles). Kok et al. (2020) added this pathway to preserve biodiversity, although it does not seem to mitigate climate change. In the "Half-Earth scenario", hydropower does not increase in conservation areas, and 25% of hydropower sites are removed to restore natural water flow. In the "Sharing the Planet" scenario, hydroelectric infrastructures are prohibited until they meet ecological flow requirements. Although In the baseline scenario, hydropower will increase by 80% through 2050.

Cross-sectionally, Obersteiner et al. (2016) simulated two tax policies on GHG emissions for all major sources. Sinks of emissions apply to the energy sector, agriculture, and livestock, but also industries impacting peatlands and converting soils. The first represents a tax of \$10/tCO2eq, and the second a tax of \$50/tCO2eq.

As there is currently little overlap between the climate and biodiversity scenarios, we therefore recommend bridging between them, especially to identify the potential for compounding and cascading impacts on the economy.

3.4 Modeling trajectories

3.4.1 Models of change of direct and indirect drivers of biodiversity loss

The first category of models commonly used to assess scenario trajectories are models of change of direct and indirect drivers of biodiversity loss. Given the quantified parameters and assumptions of a chosen scenario, they determine for multiple time horizons how socio-economic and environmental pressures may evolve (see Figure 4). This category is composed of many different models providing either spatial results (e.g., crop distribution) or aggregate indicators (e.g., food prices). Table 3 shows the models[28] for change in direct and indirect drivers of biodiversity loss used by the authors.

Tableau 3. Models of change of direct and indirect drivers of biodiversity loss

ARTICLE	MODEL OF DIRECT AND INDIRECT DRIVERS	TYPE OF MODEL
Kok et al. (2020)	IMAGE	Integrated Assessment Model (IAM)
Johnson et al. (2021)	GTAP	General equilibrium model
Leclère et al. (2020)	AIM, GLOBIOM, IMAGE, MagPIE	Land-use modules
Cheung et al. (2019)	Bioeconomic model	Economic and biophysical dynamics
Obersteiner et al. (2016)	GLOBIOM	Land-use module
Costello et al. (2016)	Bioeconomic model	Economic and biophysical dynamics
Schipper et al. (2020)	IMAGE	Integrated Assessment Model (IAM)
Pereira et al. (2010)	LPJ-GUESS, LPJ, CABLE-POP	Dynamic Global Vegetation Models (DGVMs)

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[28] See the website of IAM consortium for decriptions of these models. https://www.iamconsortium.org/

Two of the studies selected for this literature review used IAM[29] to quantitatively describe key processes in human and earth systems and their interactions. Kok et al. (2020) and Schipper et al. (2020) used IMAGE[30], which is a computable general equilibrium model. The modeling is "integrated," meaning it uses information from many scientific disciplines. The term "assessment" emphasizes generating valuable information for decision-making, even under large uncertainties. IAMs were developed to anticipate the evolution of climate trajectories and related issues, which implies, among other things, that when they are not designed to respond to research questions on biodiversity. As a result, they do not provide sufficiently precise information, particularly in sectors and sub-sectors impacting biodiversity.

In general, IAMs use GDP and demographic trajectories as inputs (often from the quantification of SSP), policies and trajectories (e.g., RCP targets and specific policies for biodiversity improvement), and other options such as agents' preferences or technological changes. Then, these inputs are implemented into different modules to explore energy, land, climate systems, and the economy, among others (see Figure 14). These modules are linked to assess certain cascading effects, "co-benefits" and unintended consequences, tracing how choices in one domain affect the rest of the modeled world. For example, if the demand for food increases because the total population is growing, the need for agricultural land will rise. Therefore, deforestation, GHGs in the atmosphere, and food prices will increase. The main advantage of IAMs, thus, is their ability to explore the trade-offs and interactions between different parts of society. The models provide information on new allocations of pressures in the form of economic outcomes, emissions, energy trajectories, or land-use.

IAMs, however, are only tailored to explore terrestrial systems. It is thus not yet possible to use them to assess the dynamics of the fisheries sector (notably in the high sea).

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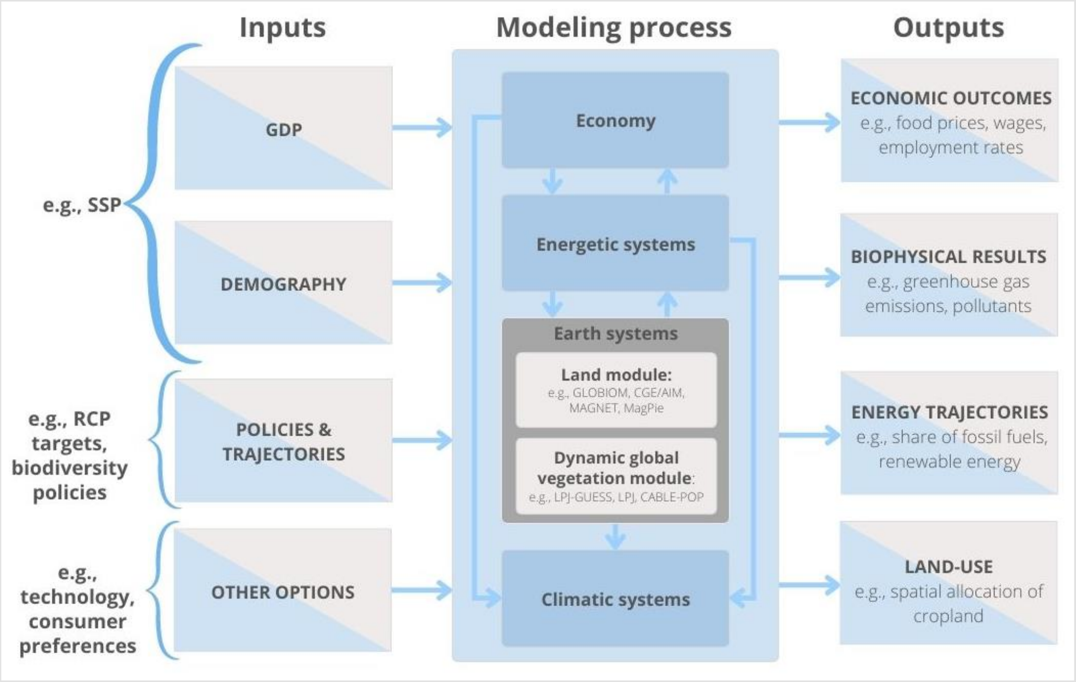
[29] When we speak of **IAMs**, we are referring to the category of "complex" IAMs, i.e., those that describe future development paths in terms of technology change, energy mode choice, land-use change, or societal trends towards protecting or not protecting the biosphere, and that provide sectoral information 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.

[30] The **IMAGE** model, created by the PBL, allows the simulation of future global dynamics between societies, biosphere, and atmosphere and their interactions until 2100. For each 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.

Figure 14. Simplified representation of an IAM (note that interactions and modules may vary between IAMs). The gray color represents the modeling process of the earth system module, and the blue refers to the entire IAM. The figure is adapted from Carbon Brief, by Evans S & Hausfather Z, 2018. https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change/



Leclère et al. (2020) used only the land system modules of some IAMs:

- The CGE/AIM module (from the AIM IAM);
- MagPie (from the REMIND IAM);
- GLOBIOM (from the MESSAGE IAM); and
- MAGNET (from the IMAGE IAM).

On the other hand, Obersteiner et al. (2016) used only the GLOBIOM model to assess changes in direct and indirect land-related pressures. Land modules' process is similar to IAMs as they consider the same inputs (e.g., policies and GDP trajectories) and provide the same outputs (e.g., land-use allocation and energy trajectories) (see Figure 14). The main difference is their inability to be as comprehensive as IAMs: they do not explore the dynamics of energy systems or the economy as a whole. Thus, they calculate only partial equilibria and are not "integrated". For example, 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.

Surprisingly, IAMs and associated land system modules seek to know what economic structure (e.g., demand and exports) will give them the desired socio-economic trajectories (e.g., GDP, demographics, and policies). They take, for example, future GDP trajectories, and no matter what policies are modeled or how emissions are projected to change, these economic growth trajectories will remain unchanged. The main tool that allows them to make these trade-offs is the variation of relative prices. This modeling process considerably impacts the analysis of an ecological transition, as the SSP projects positive GDPs for all countries until 2100, even if a long-term structural change is modeled, e.g., through ecological transition policies and hypotheses.

Moreover, whether using a IAM or only an earth system module, the quantification of SSP trajectories will depend on each model and the choices 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 related assumptions such as agricultural productivity, the environmental impact of food consumption, international trade, globalization, and land-based climate change mitigation policies are different between IAMs (Popp et al., 2017). Because crop yields and livestock intensification strongly influence land-use dynamics, a lack of harmonization between models will lead to different results across IAMs for the same SSP. Nevertheless, proposing different alternatives limits quantitative harmonization and explores the uncertainties of the scenarios and models. The only two trajectories that are almost common to all IAMs are those for economic growth (Dellink et al., 2017; Dietrich et al., 2014) and demographic growth (KC & Lutz, 2017).

Because the models are designed on a global scale, they severely lack accuracy at many levels. For example, GLOBIOM 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, and high-input irrigated). Thus, these classifications remain very general and do not allow for the targeting of activities and practices likely to be the most impacted and/or those having the highest impact in the event of an ecological transition.

Pereira et al. (2020) used only three Dynamic Global Vegetation Models (DGVMs): LPJ-GUESS, LPJ, and CABLE-POP. DGVMs modeled the impact of climate change on vegetation and associated biogeochemical and hydrological cycles. They use climate time series datasets and, given the constraints of latitude, topography, and soil characteristics (input data). These models are often integrated into the land modules of IAMs (such as GLOBIOM, which uses LPJmL), but they can be used alone to calculate partial equilibria (see Figure 15). Nevertheless, they are not able to take into account a large number of dynamics, notably socio-economic.

Alternatively, Johnson et al. (2021) used the Global Trade Analysis Project (GTAP) model, a multi-regional, multi-sector (which includes the fisheries sector), and a computable general equilibrium model. They combined it with Agro-Ecological-Zones (GTAP-AEZ) to cover 137 regions. The main advantage of this model over the IAMs is that it offers a broader sectorial disaggregation of results, which, in the context of a transition risk assessment, improves the possibility of linking the impacts of biodiversity on sectors/industries.

In the absence of integrated models adapted to the high-sea fishing sector, Cheung et al. (2019) and Costello et al. (2016) have used bioeconomic models, i.e., models that capture both economic and biophysical dynamics. Cheung et al. (2019) chose a biological model (i.e., a Dynamic Bioclimate Envelope Model), which takes as inputs pressures related to ocean conditions (sea surface, temperature, salinity, oxygen content, sea ice extent, and ocean relief) and species life history data. These data will allow them to explore, for each country, changes in distribution, species abundance, and potential fish catch rate and thus calculate the Maximum Catch Potential (MCP), which is a proxy for MSY.

Then they used an economic model (i.e., an Effort Dynamic Model) that simulates changes in fishing effort (i.e., the number of fishing vessels) for fisheries to maximize their profit. This model considers both the results of the biological model (i.e., biomass and potential catch rate) and the policies developed by the authors (subsidies, ex-vessel price of fish, cost of fishing, and rate of increase of catches).

Cheung et al. (2019) did not model the socio-economic trajectories of SSP but used them to design policies related to the high-seas fishing sector. For example, the model does not assess country demographics or economic growth differences. Still, these factors will impact a country's high or low ex-vessel fish prices. In addition, the quantification of policies and their incorporation into the models is only very briefly detailed in the study, which does not offer any additional material at this time and is in the process of being published. It is, for example, not clear how the model accounts for the link between the 30% MPA expansion and the impact on fish catch rates.

Similarly, Costello et al. (2016) used a bioeconomic model to analyze changes in fisheries management type on fish biomass and profits. They took several databases of fish farms worldwide, fish catch rates, fish resources, and fish life cycle parameters. They coupled this information with a biological model (i.e., the Pella-Tomlinson Surplus Production Model) and an economic model to calculate MSYs, fish biomass trajectories, profits for each fishery, and fish mortality rates. These results are measured for each fishery management policies.

In terms of pressure, Cheung et al. (2019) were able to quantify the impact of resource extraction and climate change on fisheries, and Costello et al. (2016) only consider resource extraction as a direct driver for biodiversity decline. Climate change is not mentioned once in the study. These two representations of the possible futures of high-seas fisheries, nevertheless, incorporate fairly accurate population dynamics data, and they consider that biodiversity loss (in terms of biomass) can impact economic outcomes (fisheries profit).

Finally, the introduction and development of invasive species is a significant pressure on biodiversity loss that is never taken into account by any direct or indirect factor change models.

3.4.2 Biodiversity models

Biodiversity models allow direct and indirect drivers of biodiversity loss to be translated into biodiversity impacts. These impacts are measured through the biodiversity indicators they provide (see Figure 4).

The authors used various biodiversity models and indicators (Table 3). Some, such as Pereira et al. (2020), combined several models and indicators to assess the impact of a single scenario on biodiversity, while others chose a single pair. This choice 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.

Tableau 4. Biodiversity models and indicators from articles identified in the literature review. The "biodiversity indicator" column does not correspond to the model indicator but rather the indicator used in the articles (i.e., some articles have adapted the biodiversity model indicator).

ARTICLE	BIODIVERSITY MODEL	BIODIVERSITY INDICATOR	SPECIES
Kok et al. (2020)	GLOBIO	MSA	Birds, mammals, plants
	GLOBIO-Aquatic		?
	GLOBIO-Species	RLI, LPI, AOH	Mammals
Johnson et al. (2021)	?	Biodiversity index	?
Leclère et al. (2020)	AIM-biodiversity	ESH	Amphibians, birds, plants, reptiles, mammals
	INSIGHTS		Mammals
	LPI-M	LPI	Birds, mammals, fish, reptiles, amphibians
	GLOBIO	MSA	Birds, mammals, plants
	PREDICTS	BII	Birds, mammals, plants, fungi, insects
	cSAR_CB17	FRRS	Mammals, birds, amphibians
	cSAR_US16	FGRS	Mammals, birds, amphibians, reptiles, plants
	cSAR_CB17		Mammals, birds, amphibians
	BILBI	FGRS	Plants
Cheung et al. (2019)	Bioeconomic model	MSA	Fish, invertebrates
Schipper et al. (2020)	GLOBIO	MSA	Birds, mammals, plants
Costello et al. (2016)	Bioeconomic model	Biomass	Fish
Obersteiner et al. (2016)	?	Environmental index	?

Pereira et al. (2020)	AIM-biodiversity	Species richness, mean species habitat score	Amphibians, birds, plants, reptiles, mammals
	InSIGHTS	Species richness, mean species habitat score	Mammals
	MOL	Species richness, mean species habitat score	Amphibians, birds, mammals
	BILBI	Species richness	Plants
	cSAR-IIASA-ETH	Species richness	Amphibians, birds, plants, reptiles, mammals
	cSAR-iDiv	Species richness	Birds
	PREDICTS	Species richness, species-abundance based biodiversity intactness	Birds, mammals, plants, fungi, insects
	GLOBIO	MSA	Birds, mammals, plants

Biodiversity is multidimensional and cannot be summarized in a single indicator, unlike climate change with the proxy of CO2-equivalent. Indeed, biodiversity is a large concept that includes diversity within species (i.e., genetic diversity), between species (i.e., species diversity), and ecosystem diversity (i.e., ecological diversity).

The articles we identified measure biodiversity between species, and some also measure ecosystem diversity. None, however, explores genetic diversity, which is essential for analyzing the ability of species to adapt to future environmental changes. Climate change, for example, can alter genetic traits, which, in some cases, impact species resilience, such as decreased body size (Gardner et al., 2011) or dispersal ability (Hill et al., 2011). However, it must be recognized that genetic data are scarce on a global scale.

There exist many biodiversity indicators; however, biodiversity models often influence the indicators that can be used. For example, the GLOBIO model calculates the Mean Species Abundance (MSA), PREDICTS measures the Biodiversity Intactness Index (BII), and INSIGHTS the Extent of Suitable Habitat (ESH).

The indicators identified in the studies measuring ecosystem integrity are the MSA and the BII. The predominant measure is the MSA, which was used by half of the authors. It represents the change in biodiversity caused by human pressures compared to a non-degraded ecosystem. It is defined as the average abundance of original species compared to their abundance in intact ecosystems, i.e., undisturbed by human activity (reference situation). 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 (Esch, 2016).

This indicator, however, 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? Moreover, the pressure-impact relationships of the GLOBIO model are the result of a meta-analysis whose information is not accessible from published articles, requiring reference to the voluminous technical documentation that could not be analyzed in the time allotted for this work. Furthermore, the so-called cause-effect relationships in GLOBIO are often correlational, and the context of the studies from the meta-analysis likely influences the results.

The second indicator of ecosystem integrity is the BII, which measures the average abundance of species in a given geographic area relative to their reference populations.

The main difference between both indicators is that each hectare has the same weight in the calculation of the MSA, whereas the BII gives more weight to the areas with the highest species richness. In addition, the MSA normalizes abundance to the undisturbed situation for each species, while the BII does so at the species group level. Unlike the BII approach, 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. An indicator similar to the MSA and BII, which GLOBIO-Species and LPI-M can also calculate, is the Living Planet Index (LPI). It measures changes in terrestrial populations relative to a specific year (i.e., 1970).

Kok et al. (2020) and Leclère et al. (2020) used the GLOBIO-Species, AIM-B, or INSIGHTS models to calculate the Area of Habitat (AOH) (also known as ESH). This indicator maps the available habitat for each species to the base year 1970 or 2010, depending on the model, and it thus provides information on the risk of species extinction. To measure habitat availability, it considers the interaction between the species' geographic range and environmental preferences (e.g., vegetation cover, elevation, and proximity to the water). The indicator is set to zero when no more space is available for the species, one when the area is unchanged from the base year and greater than one when new space is available.

The same two authors also used another measure related to species extinction risk, the Red-List Index (RLI), which measures changes in overall extinction risk among species groups. It is based on historical changes in the number of species in the International Union for Conservation of Nature (IUCN) red list of threatened species. It gives a level of extinction risk for each species.

There are other indicators to measure the extinction risk of a species, Leclère et al. (2020) used the Fraction of Regionally Remaining Species (FRRS) and the Fraction of Globally Remaining Species (FGRS), which cSAR_CB17 and BILBI, cSAR_CB17, cSAR_US16 can model respectively (see table 3). These indicators calculate the proportion of species that are not yet extinct or facing extinction in a region (or across all land areas) relative to 2010. If the indicator is 0, all species are extinct or threatened with extinction; if it is 1, there are as many threatened or extinct species as in 2010, and if it is more, there are fewer threatened or extinct species compared to 2010.

Obersteiner (2016) and Johnson et al. (2021) combined several biodiversity indicators into one measure. Indeed, Johnson et al. (2021) mapped four biodiversity indicators:

- The total species richness, which corresponds to the number of species present in an area as a function of land type, human intensity, and habitat age;
- The endemic biodiversity, representing the amount of habitat available for endemic species[31];
- The red-listed species biodiversity, mapping the amount of space available for threatened or endangered species; and
- Key Biodiversity Areas, showing sites of importance for the global persistence of biodiversity, it includes different indicators such as the presence of threatened species or ecosystems, geographically restricted species and ecological integrity.

This method allows for the possibility of weighting biodiversity indicators differently. Johnson et al. (2021) gave the same weight to each indicator, but some areas are likely favored over others just because they are counted twice. For example, the KBA already considers the IUCN red list criterion of extinction risk so that this criterion would have more weight in the biodiversity index.

Obersteiner et al. (2016) calculate an environmental index that averages several indicators, such as a biodiversity measure, but also a measure of GHG emissions, food prices, or fertilizers. The biodiversity measure corresponds to the change in land-use in key biodiversity areas, but it is difficult to identify how the key biodiversity areas were determined. Another problem with this approach of combining indicators is the interpretation of the measure.

One aspect of interspecies diversity indicators that interested us is the type of species the models can assess. Indeed, we looked for the types of species analyzed in the methodology of biodiversity models when the information was not present in the article. **It can be seen that around 35% of the indicators treated by the authors take into account mammals (see Figure 15). In comparison, wild mammals represent only 0.001% of the total biomass; the next most described 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.

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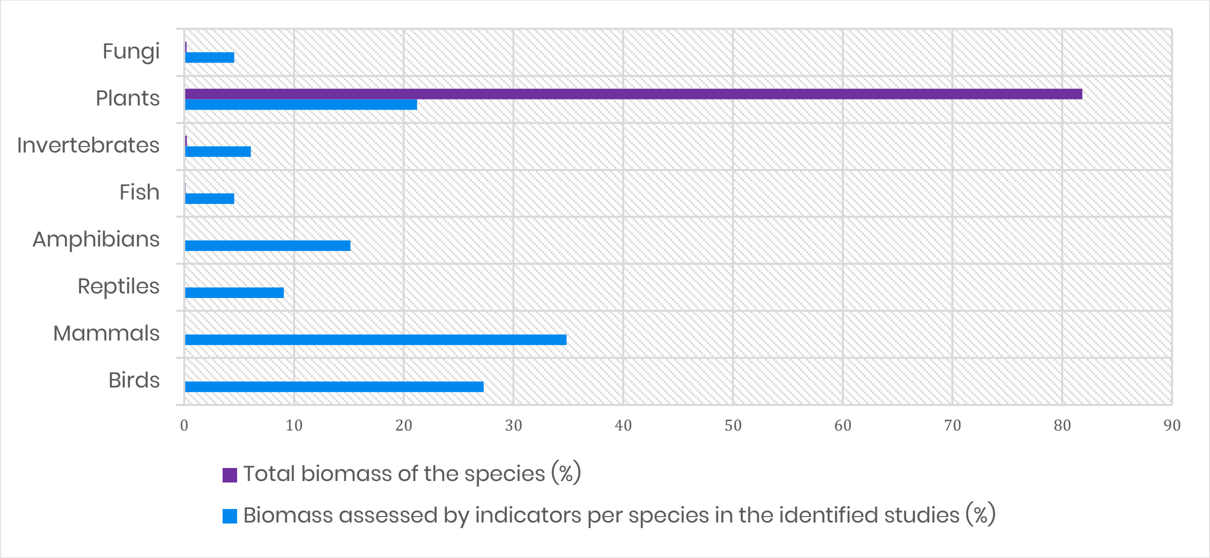
[31] A species is **endemic** when it is present exclusively in a delimited geographical region. The endemism of species is one of the proxies used to determine the risk of extinction.

Figure 15. **Share of biomass covered by biodiversity indicators in selected studies per species. The total biomass accounted for in the studies ranges from 82% for plants, followed by invertebrates and fungi at around 0.2% each, then fish at around 0.1% and other life forms are less than 0.01%.**



3.4.3 Ecosystem Service (ES) models

Only three studies analyzed changes in specific ESs following the implementation of their transition scenario. In general, these models used the results of models of change of direct and indirect drivers of biodiversity loss or biodiversity models to assess the evolution of ESs given the transition or exploratory scenario (see Figure 4).

Kok et al. (2020) primarily used the GLOBIO-ES model, Johnson et al. (2021) used InVEST, and Pereira et al. (2020) predominantly used these two models. These are the most represented ES models at the global scale. On the other hand, authors sometimes only use the output of models of direct and indirect drivers of change that can be used as proxies for ES assessments (Table 4). For example, IMAGE gives total crop production in calories per year, which is a proxy for the food-providing ESs.

InVEST is a suite of models that map ESs and assign a monetary value to them through a production function. It uses maps as a source of information and as a result. The model is quite complex and requires precise data, which implies that it is difficult to use all its components at the global scale. Indeed, Johnson et al. (2021) simplified some of the sub-models of InVEST to use it globally, notably the pollination service. The model can assess twenty-one different ESs, but Johnson et al. (2021) and Pereira et al. (2020) only evaluated four and two, respectively (Table 4).

GLOBIO-ES is a complementary model to GLOBIO that calculates the current status, trends, and possible future scenarios of ESs at the global level. It allows for the analysis of eight cultural, material, or regulatory ESs, although Pereira et al. (2020) and Kok et al. (2020) only analyzed two and three regulatory services, respectively (Table 4). The methodology is closely related to the IMAGE model. GLOBIO-ES takes as spatially explicit input data: direct pressures (i.e., land-use and management system and climate change), indirect pressures (e.g., revenues and food demand), and ecosystem properties (e.g., relief, soil properties, and climate variables).

The main problem with existing ES models is that they do not incorporate possible tipping points and regime shifts in their analysis. Moreover, the interconnections between the different ESs are not or only marginally taken into account, models mainly analyze each service separately (Aguedo 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 are much better documented than others, such as pollination.

Finally, in the studies identified, regulating ESs predominate over provisioning services, and cultural services (e.g. sources of aesthetic inspiration and spirituality, recreation and ecotourism) **and supporting services** (e.g. geochemical cycling of water or decomposition of organic matter that contributes to soil fertility) **are completely absent.** This means that the scenarios are not currently able to take into account the evolution of the major geochemical cycles that are important for the maintenance of life on the planet, nor the ecosystem services that underpin activities to the tertiary sector (e.g. leisure and tourism) but also cultural and spiritual activities of human societies.

Table 5. ESs and associated models that were used in the selected studies

		JOHNSON ET AL. (2021)	**KOK ET AL. (2020)**	**PEREIRA ET AL. (2020)**
MATERIAL ESs	Food and feed production		IMAGE	LPJ-GUESS
	Timber production	InVEST		CABLE-POP
	Marine fish production	InVEST		
	Bioenergy production			LPJ-GUESS
REGULATING ESs	Crop pest control		GLOBIO-ES	GLOBIO-ES
	Nitrogen retention			InVEST, GLOBIO-ES, LPJ-GUESS
	Pollination	InVEST	GLOBIO-ES	InVEST
	Coastal resilience			InVEST
	Climate regulation	InVEST	IMAGE	CABLE-POP, LPJ-GUESS, LPJ
	Soil protection		GLOBIO-ES	?
	Healthy lakes		GLOBIO-Aquatic	
	Natural water purification		GLOBIO-Aquatic	

3.5 The evaluation of quantitative results

3.5.1 The comparison of biodiversity outcomes

Unsurprisingly, all scenarios found a biodiversity indicator that only declined over time.

In the business-as-usual scenario of Leclère et al. (2020), the terrestrial biodiversity intactness indicator (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%, and their aquatic MSA declined by 3% from 2015 to 2050. Furthermore, Kok et al. (2020) estimate a much broader decline than Leclère et al. (2020) for similar indicators: they found respectively a decline in the extent of suitable habitat within the range of species (AOH) of 12.5% and 2.6%, and a drop in population of vertebrate species (LPI) of 20% and 9.7% by 2050. At the marine scale, Cheung et al. (2019) found a 7-20% loss of MSA by 2050 and 15-55% by 2100, depending on the RCP trajectories. Moreover, Costello et al. (2016) found a biomass decline equivalent to 37.6% from 2012 to 2050.

Only two studies have constructed scenarios aiming at reversing the terrestrial biodiversity curve. In Kok et al. (2020), two scenarios reach this target by 2050 for the LPI indicator and by 2030 for the MSA. These scenarios require ambitious biodiversity conservation, climate change mitigation, and food security policies, including expanding PAs to 30% or 50% of the planet. The most ambitious scenario of Leclère et al. (2020), which includes various demand side, supply side, and 40% PA expansion policies, achieves biodiversity growth as early as 2050 for the LPI and AOH indicators (for all models). With this scenario, however, MSA trends become positive only by 2075 on average. The only model that does not predict the recovery of MSAs is IMAGE, even out to 2100.

Inversely, the most ambitious scenarios of Schipper et al. (2020) and Pereira et al. (2020), i.e., the SSP1, do not achieve positive MSA or species richness trajectories by 2050.

At the high-sea fishing sector level, only the SSP1 scenario of Cheung et al. (2019), coupled with an RCP2.6 trajectory and a 50% expansion of MPAs, envisions a positive MSA change for 2100. In Costello et al. (2016), applying contrasting management regimes to global fisheries could drastically increase biomass. Indeed, the current biomass is estimated at 840 million metric tons. In contrast, in the best-performing scenario, the biomass is projected to be over 1,143 million metric tons (about 520 million metric tons more than their baseline scenario).

Finally, the most ambitious scenario of Johnson et al. (2021) is the "Global Deal for Nature" scenario, which consists of expanding PAs to 30% of the land. It is the only one that significantly improves biodiversity (the biodiversity indicator increases by 29%).

3.5.2 The comparison of food security outcomes

In the Kok et al. (2020) business-as-usual scenario, the number of people at risk of hunger decreases until 2070 (reduction from 10.1 to 2.8 % between 2015 and 2070), although animal and plant food prices increase. On the contrary, the baseline scenario of Leclère et al. (2020)

projects, on average (depending on the land system models), a slight decrease in the relative prices of crops that are not dedicated to energy between 2010 and 2050. Nevertheless, there are considerable differences between the models; for example, prices increase by about 10% with the IMAGE model, and with GLOBIOM and MAgPIE, they decrease by about 10%.

When Kok et al. (2020) project their scenario that only incorporates biodiversity conservation measures, the risks of food insecurity are reduced, but not to the same extent as in the baseline scenario: about 1.5 to 2 times more people are likely to be at risk of hunger compared to the business-as-usual scenario by 2070. As land available for agriculture becomes scarcer, as a transition to agro-ecology takes place (for the "Sharing the Planet" scenario), and as agricultural intensification is implemented (for the "Half-Earth" scenario), prices will increase and access to food will be restricted. However, if additional measures are added, such as reducing meat consumption or food waste, food security loss can be compensated for. Indeed, these measures will reduce the demand for food and food prices compared to the baseline scenario and thus improve food security. Moreover, 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. Overall, the scenarios have little impact on the distribution of inequalities.

In Leclère et al. (2020), almost all policies, on average, project price decreases. Like Kok et al. (2020), the only exception is the conservation scenario (which consists of expanding PAs and restoring environments). Moreover, on average, the scenarios that impact demand (reduction of animal calories and waste) project the most significant price decreases. Nevertheless, for all scenarios, GLOBIOM and MAgPIE project a price decrease, and, in general, AIM and IMAGE project a price increase, so it would seem that the parameterization of the models would have strong influences on the results whatever the policy evaluated.

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. This correlation was calculated with GLOBIOM, whereas in the Leclère et al. (2020) study GLOBIOM tended to find price decreases for all scenarios. Moreover, with an SSP2 trajectory, the policy that decreases the most (i.e., 14% reduction) prices between 2010 and 2030 is the policy of reducing meat consumption, as in Leclère et al. (2020), followed by policies of increasing agricultural productivity without new inputs. Conversely, policies that limit agricultural expansion and land-use intensify the trade-off between food security and prices; as a result, prices are projected to increase by about 5% between 2010 and 2030.

3.5.3 The comparison of ecosystem service (ES) outcomes

In the reference scenario of Kok et al. (2020), material ESs improve from 2015 to 2070 with the expansion of agricultural land. On the contrary, in the study by Johnson et al. (2021), material ESs will decrease by 2030, particularly timber production, which loses 0.3%, and fisheries production, which loses 2.8%. For regulating ESs, the authors find that the carbon sequestration service will vastly decrease. According to Johnson et al. (2021), new carbon emissions will have an economic impact of $135 billion by 2030. Nevertheless, in their baseline scenario, the ES of pollination increases (i.e., the productivity of pollinator-dependent crops increases by 2.8% between 2021 and 2030). In contrast, in the Kok et al. (2020) scenario, it decreases by 2070.

In the studies of Pereira et al. (2020) and Kok et al. (2020), for any SSP or conservation policy scenario, respectively, material services will improve 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).

3.5.4 The comparison of economic outcomes

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

In the Johnson et al. (2021) study, the decline in ESs (i.e., timber production, marine production, and pollination) under the business-as-usual pathway translates into a loss of global GDP in 2030 of between $90 billion and $225 billion, depending on whether or not climate-related costs are considered: from -0,4% to 0.2% of GDP depending on countries. According to their projections, the poorest countries will suffer the smallest drop in GDP, and the upper middle-income countries the most impressive drop in GDP. Nearly all of the global population in 2030 will live in countries that lose in terms of GDP if climate change damages are included. The most considerable impacts on GDP per capita are found in the poorest countries. Furthermore, all policy-screening scenarios allow for an increase in GDP while conserving natural ecosystems. All the single policies (i.e., decoupled agricultural support, local and global forest carbon mechanisms) will increase global GDP by $50 billion to $56 billion in 2030. In addition, the most ambitious policy (i.e., decoupled support to farmers and R&D investment and global forest carbon payment) will increase global GDP by $150 billion in 2030.

In Johnson et al. (2021) exploratory scenario, the partial collapse of the ESs of pollination, timber production, and marine production will lead to a global GDP decrease of only 2.3% (-$2.7 trillion) between 2021 and 2030 compared to the baseline. The poorest countries will largely suffer this drop in GDP (-10% of GDP on average), notably because of the reduction in timber production. The wealthiest countries will experience a decline of 0.7% of GDP, explained in large part by the decrease in pollination. Regionally, Sub-Saharan Africa will experience the most significant reductions in GDP, 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 primarily caused by the decline in pollination.

Without any MPAs expansion, Cheung et al. (2019) found that in SSP1, the high seas contribute the least, on average, to income generation and livelihoods compared to the other two scenarios. Although catches will rise widely and incomes increase slightly for all country groups (i.e., high, low, and mid-income countries). However, fishing costs will increase by 50% for all countries by 2050 and continue to grow because of rising fossil fuel prices coupled with declining subsidies, which will increase the cost of fishing and reduce fishing efforts. Overall, the fishing sector will be unprofitable. In SSP3, catches will increase, and fisheries revenues will be more or less stable as the increasing supply of seafood products decreases prices. In addition, the unit cost of fishing decreases with unethical means (e.g., forced and underpaid labor), but as fishing effort increases beyond the economically optimal levels, the total cost of fishing increases. Although subsidies will climb as demand for seafood increases, profits will decrease, especially for the poorest countries. In SSP5, revenues will be maintained as prices and fish catches increase. However, the increase in fishing efforts will raise the total cost of fishing. In the end, a decline in profit is expected in all income group countries. In conclusion, fishing has a chance of being or remaining marginally profitable by 2100 only in rich countries and for the SSP1 and SSP5 scenarios, but in the SSP5 scenario, fishing is only profitable because there are subsidies to offset the high cost of fishing. For middle-income countries and poor countries, the study found that the declines in fishing profits were most remarkable in the SSP1 and SSP3 scenarios, respectively.

According to Costello et al. (2016), 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. Policies that aim to equalize fish catches at MSY offer fewer advantages in terms of profit and fish biomass than policies where fishing trajectories maximize the NPV. For example, with MSY policies, profits reach $58 billion compared to $80 billion with NPV policies.

4. Discussion

4.1. The long-term prospects

Given the absence of physical risk scenarios, we encourage research to address this knowledge gap and to continue efforts to understand better the timing and geographical criteria of regime shifts and ecosystem tipping points. Scenarios such as the exploratory of Johnson et al. (2021) are interesting from a methodological point of view, but given their arbitrary construction, they will not be sufficient to assess BRFRs. As shown in Figure 17, once research has taken hold of this type of scenario, it will be easier to jointly evaluate physical and transition shocks. **In the shorter term, it is, however, likely possible to make some improvements, such as integrating the planetary boundaries threshold to mark out the planetary safe operating space for human activities and directly including tipping points and regime shifts in qualitative narratives (Häyhä et al., 2016).**

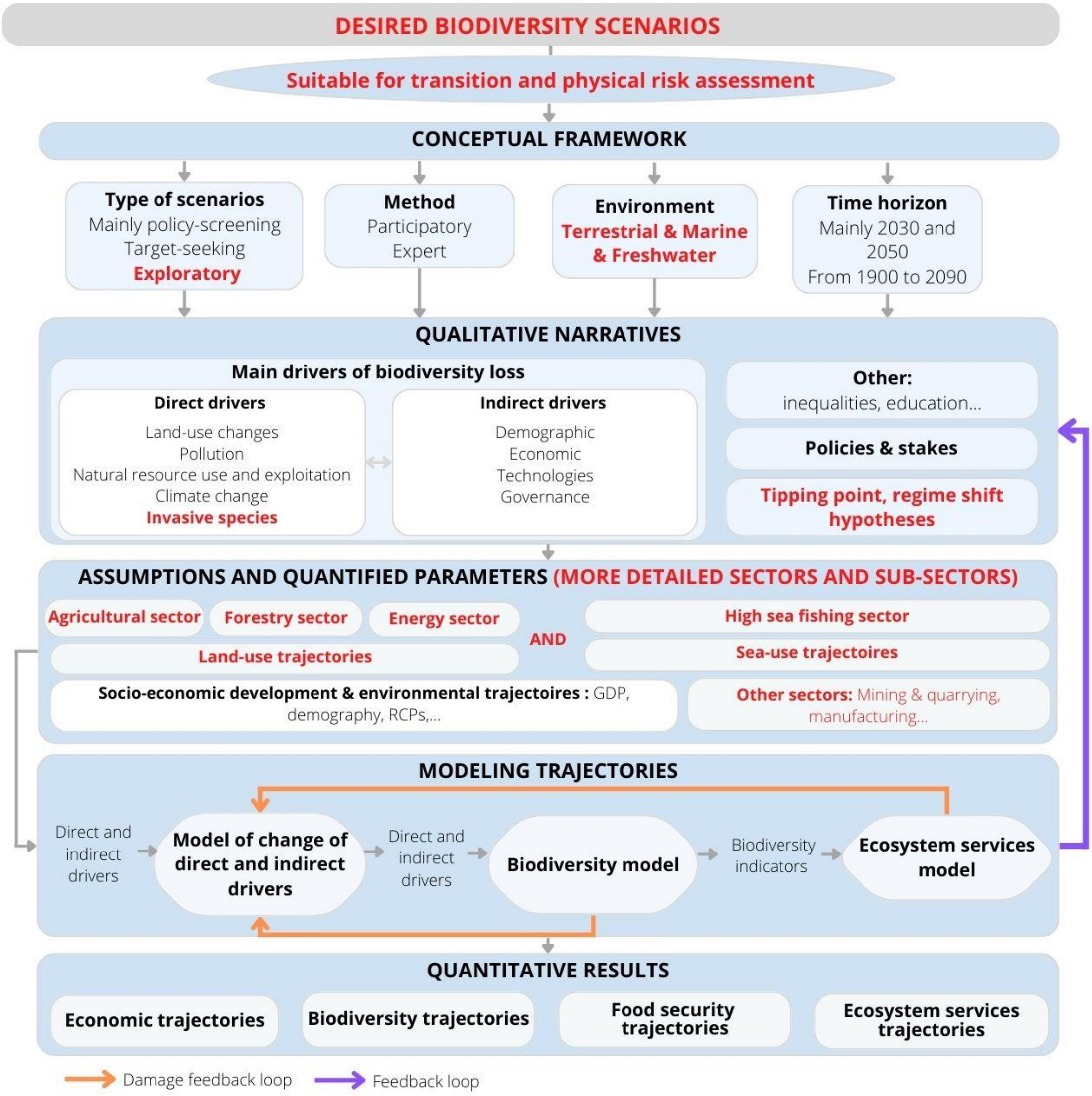
Moreover, among the major pressures that lead to biodiversity loss, the introduction of invasive species is still missing in the narratives. Invasive species, however, pose significant threats to ecosystems and economies, notably for human and animal health (e.g. some species are disease vectors), for the agricultural (e.g., lower yields, affect soil quality, and increase pest control costs), the forestry (e.g., they can threaten trees and in some cases lead to their death) and fish sector (e.g., displacement and extinction of native fish species) (Andersen et al., 2004; Olson, 2006; Stohlgren & Schnase, 2006).

The quantification of narratives and modeling of biodiversity scenarios remain shaped like climate scenarios. In the medium- to long-term, many improvements need to be made. Indeed, quantitative trajectories and models of change of direct and indirect pressures, including IAMs, offer only a superficial representation of sectors. The main sectors represented are the energy, agricultural (for the IAMs or GTAP model), and fish (for bioeconomic models) sectors. Some activities are thus absent from the analysis, such as mining or high-sea fishing (for the IAMs), although these sectors considerably impact biodiversity. Moreover, many modeling issues remain even within the sectors accounted for. Indeed, if an industry is specialized in organic farming or agro-ecology, its impacts on biodiversity will be different from those that practice intensive agriculture. The same is true for the fishing and energy sectors. This differentiation of practices within industries will allow for a better understanding of transition policies in terms of both positive and negative incentives. Furthermore, this will enable the financial system to manage better risks, assets, liquidity, and operations related to biodiversity loss.

To improve the modeling process of biodiversity scenarios, we want to alert the reader to two damage feedback loops missing from existing models (i.e., the orange arrows in Figure 16). The first one corresponds to the consequences of biodiversity loss on economic activity and hence on countries' economic growth. This link is missing as the dynamics emerging out of the biodiversity model do not influence the model determining the changes in direct and indirect factors (i.e. the SSP scenarios used as input are not impacted by biodiversity outcomes). As a result, the analysis is highly biased because 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 (i.e., the violet feedback loop in Figure 16). The exogeneity of model variables (e.g., GDP and RCP) must thus be questioned and put into perspective in the narratives to better understand the interactions between the economy and biodiversity.

Figure 16. Proposal to improve biodiversity scenarios development for BRFR analysis. The blue objects represent the current biodiversity scenario process, and the red refers to the knowledge gap.



4.2. Short run and medium run research recommendations

We have found only a few comprehensive and quantitative physical risk scenarios that allow us to assess the risks of regime shifts in ESs. Well aware that building such comprehensive scenarios (and the model to simulate them) is a long-term process, we propose a solution to overcome this in the short term. These short-term recommendations 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.

First, an alternative way of constructing physical risk scenarios would be to build methodologically on the Environmental Sustainability Gap (ESGAP) framework developed for European countries (Usubiaga-Liaño & Ekins, 2021a and 2021b) and being tested in other regions (ISPONRE & UCL, 2022; 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. For each of these sub-indicators, it measures whether, under 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.

Based on the trends of the 19 environmental functions included in the European SESPI and without predicting any tipping point, this methodology allows to construct an "all else being equal" biophysical risk scenario indicating which critical environmental functions are being degraded and whether an economy is moving towards or away from the probability where some ES regime shifts are more likely to occur. However, to construct this, it would be necessary to specify the correspondence tables between ESGAP critical environmental functions and ENCORE ESs [32], which are unavailable yet and require further research. Research is also underway to conduct an economic assessment of the gap identified and translate it into ecological debt.

In addition, one approach for assessing exposition to transition risks would be to work on the compatibility between IAM outputs and EE-MRIO tables such as EXIOBASE[33] or GLORIA (see Figure 17). As previously mentioned, the challenge is to offer a finer sectorial disaggregation of the results to identify and locate the industries/sectors most impacted by an ecological transition. It is already possible to obtain more precise results on the different

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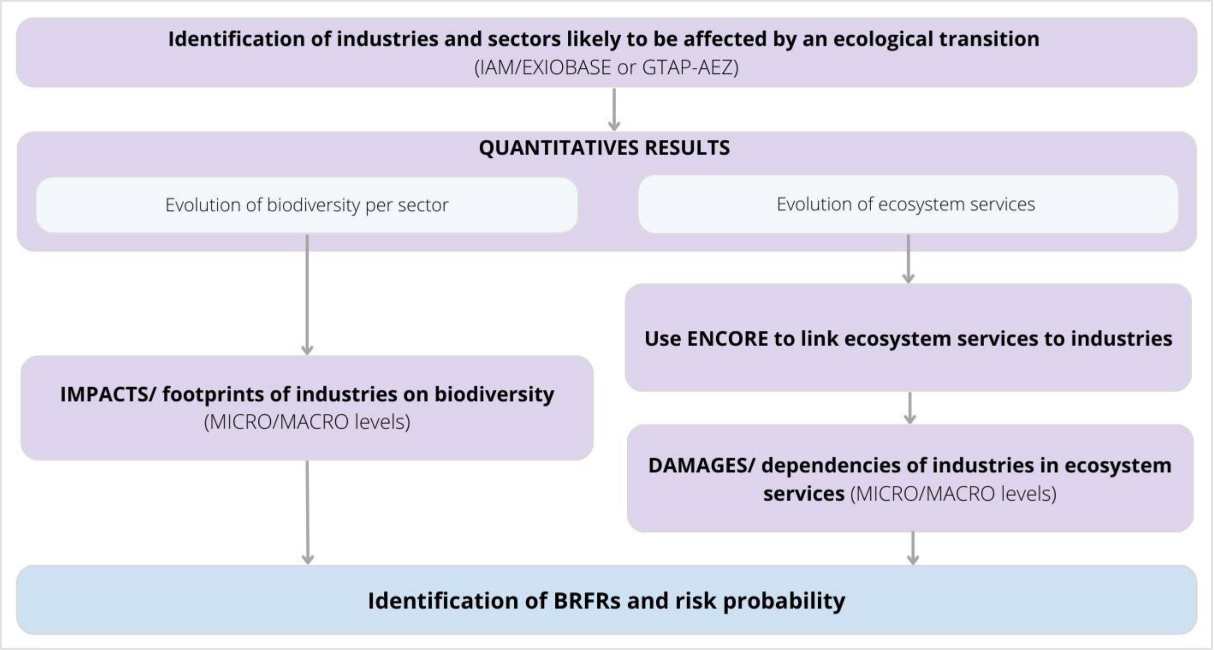
[32] **Exploring Natural Capital Opportunities, Risks, and Exposure (ENCORE)** breaks down the industry's direct and indirect dependence on ESs by business process. It also provides the level of dependence of an industry's activities on ESs, five scores from very low to very high are available.

[33] 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).

economic activities using the GTAP-AEZ model. Moreover, if scenario outputs are disaggregated at a fine sectorial level, it becomes possible to assess damages in terms of dependencies of industries on ESs with ENCORE.

Figure 17. Short-term possibilities for the assessment of transition BRFR



If the link between IAM and EE-MRIO tables suggested above proves to be difficult, **another alternative would be to adapt recent work on transition risk analysis for the climate to the case of biodiversity (Espagne et al., 2021).** This alternative would consist of comparing the sectors dependent on and impacting biodiversity in a given country with its equivalents on the scale of equivalent biomes to identify possible innovation opportunities to reduce dependence or impact on biodiversity under roughly equal ecological conditions.

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Appendices

1. Detailed Shared Socio-economic Pathways (SSPs)

SSP1 Sustainability - Taking the Green Road (few mitigation and adaptation challenges): Gradually, the world is moving toward a more sustainable path within environmental limits. Management of the commons is slowly improving through cooperation and collaboration among nations and within countries, including the private sector and civil society. Governments are increasing their education and health investments, accentuating the demographic transition to a relatively low total population. Currently, wealthy countries focus on human well-being rather than economic growth, which is lower in the long-run. The commitment of societies to meet development goals is accelerating, and this is beginning to reduce inequalities between and within countries. Material consumption is growing slowly, and resource and energy intensities are declining while improving the environment.

This world strongly regulates land-use; for example, deforestation in tropical forests is drastically reduced. Crop yields are increasing rapidly in poor and middle-income countries, allowing them to catch up with richer countries. Diets are becoming healthier, with fewer animal calories and food waste. As the world is globalized, food is traded freely. All GHG emissions from land-use are facing a carbon price equivalent to the energy sector.

SSP2 Middle of the Road (medium-high mitigation and adaptation challenges): This world corresponds to the projection of historical socio-economic and technological trends into the future. Inequalities persist between countries in terms of development and income growth. Although international and national institutions are working on development goals, progress is very slow. The biosphere is degrading; however, on average, there is a decrease in natural resources and energy use. Countries' dependence on fossil fuels is decreasing despite no barrier to using non-conventional fossil fuels. Population growth is moderate and stabilizes in the second half of the 21st century. However, the less wealthy countries do not complete their demographic transition due to a lack of investment in education.

Land-use change is not fully regulated, and deforestation of tropical forests continues, although it slightly decreases over time. The increase in crop yields is slowly decreasing over time, although the poorest countries are almost catching up with the richest. Calorie consumption and the share of animal food are gradually converging to high levels. International trade remains regionalized to a large extent. Moreover, international cooperation on climate mitigation is delayed due to the transition phase to a uniform carbon price by 2040. During this transition phase, the price of emissions from agricultural production is aligned with emissions from the energy sector and avoided deforestation and afforestation are only considered in 2030.

SP3 Regional Rivalry - A Rocky Road (high mitigation and adaptation challenges): Rising nationalism, increasing competitiveness and security issues, and regional conflicts cause countries to focus on national or regional issues (including security policy). At the regional level, governments are focusing on food security objectives at the expense of development issues, and several regions are adopting authoritarian governance. Investment in education and technology is declining. Economic growth is low, consumption is material-intensive, and inequality persists over time, especially in developing countries. Population growth is high in developing countries and low in industrialized countries. The international community gives a low priority to environmental issues, and the lack of cooperation between societies is increasing the erosion of the biosphere.

Land-use changes are hardly regulated. The increase in crop yields is drastically reduced over time due to the limited transfer of new agricultural technologies to developing countries. Unhealthy diets rich in animal calories dominate, and food waste is high. The regionalized world does not favor trade flows of agricultural products. Forestry mitigation and GHG emission reduction face implementation barriers such as weak institutional capacity in developing countries. In 2020, the wealthiest countries implemented a uniform carbon price, and the poorest countries started in 2030.

SSP4 Inequality - A Road divided (weak challenges for mitigation and strong for adaptation): Investment in human capital is uneven, and disparities in economic opportunity and political power increase inequality between and within countries. Society is separated into two groups; internationally connected societies that contribute to knowledge- and capital-intensive economic sectors and a fragmented set of low-income societies composed of poorly educated populations that rely heavily on labor rather than technology. Conflicts are emerging more and more often, and social tensions are increasing. Technological development is high in the high-tech sectors. The energy sector is globally connected, diversifying its investments in carbon-intensive fuels such as coal and unconventional oil and low-emission energy sources. Environmental policies are localized in middle and high-income areas.

Land-use changes are highly regulated in rich countries, but deforestation continues to progress in poor countries. Rich countries increase their agricultural yields strongly, while the poorest countries remain unproductive in agriculture. Calorie consumption and the share of animal calories are converging towards average levels. Food trade is globalized, but market access is limited for poor countries, which become more vulnerable. International cooperation on climate change is starting rapidly (after 2020), but emissions from agriculture and land-use are not fully priced. In addition, avoiding deforestation and afforestation issues are only included in 2030.

SSP5 Fossil-fueled Development - Taking the Highway (strong mitigation challenges and weak adaptation challenges): This world relies on competitive markets, innovation, and participatory societies to produce technological advances, develop human capital, and move toward a sustainable development pathway. Investments in health, education, and institutions to improve human and social capital are increasing. The global economy is growing rapidly, coupled with the exploitation of abundant fossil fuel resources and resource- and energy-intensive lifestyles. The world population peaks and then declines during the 21st century. Local environmental problems are successfully addressed, and the world is optimistic about its ability to manage ecological and social systems, including through geoengineering if necessary.

Land-use is not fully regulated, and deforestation in tropical biomes continues, although it is declining slowly over time. Crop yields are increasing rapidly. Unhealthy diets composed of a large share of animal calories are the norm, and food waste is high. Barriers to international trade are greatly reduced. All GHG emissions from land-use are priced and aligned with the energy sector carbon prices. However, international cooperation to mitigate global warming is delayed, and uniform carbon prices will emerge in 2040.

2. Detailed scenario narratives of Cheung et al. (2019)

In the SSP1 scenario, consumers demand more transparency on the source of the seafood they consume, the production conditions, and the catch rates, which leads to the implementation of certification and traceability programs (which are reflected in prices). Consumers are limiting their fish purchases from deep-sea fisheries and supporting sustainable fisheries. Less developed countries see their socio-economic situation (e.g., education, profits, investments, and welfare) improve thanks to economic incentives to process fishery products on their territory. With the help of coordination between the different private, public and civil society actors, PAs will be set up to conserve marine biodiversity. The implementation of a carbon price and the elimination of subsidies linked to fishing activities will reduce fishing efforts on the high seas. Marine biodiversity will thus recover, and less developed countries will capture the associated socio-ecological benefits.

The SSP3 describes a world where industrial fishing expands to meet the increasing demand for seafood. Depending on the Exclusive Economic Zone (EEZ), catch rates are either maintained at current levels or increased. Industrialized countries continue to heavily subsidize fishing, which increases fishing efforts without improving fishing efficiency, as countries invest little in technology development. The costs of fishing are reduced due to the exploitation of underpaid workers. The most developed countries capture the benefits of fishing. The fishing effort will increase due to high subsidies from industrialized countries, leading to biodiversity degradation. These declines will particularly affect the less developed countries that are highly dependent on fish for food and are major exporters. The fishing activity aims at maximizing profit, which favors environmentally destructive fisheries. As fishing effort is not limited and controlled, catches decrease, and overfishing dominates.

In the SSP5 trajectories, the fishing sector consolidates, and a few large companies own its activities. Developed countries promote technology transfer, which allows less developed countries to expand their fleets on the high seas. Developed countries are investing in technology, such as the creation of automatic fishing robots. Activities on the high seas are increasing, including the exploration of genetic resources and the mining search. The massive use of fossil fuels is increasing CO2 emissions and ocean temperatures with disastrous effects on acidification. Geoengineering is being used to mitigate human impacts on fish abundance and distribution; however, the effectiveness of these techniques is uncertain. As fuel costs are low and technology is advanced, deep-sea fishing becomes more accessible and profitable. There are fewer fisheries monitoring and science-based management systems, which leads to a decline in target species, which decreases the stock in countries' EEZs and the associated catches.

3. Detailed scenario narratives of Kok et al. (2020)

The "Half-Earth" scenario aims to protect the intrinsic values of nature. It is based on the assumption that to halt biodiversity loss; it is necessary to promote wilderness areas separate from areas under human influence. It is a scenario based on the principles of "land sparing" agriculture and ESs are considered as "co-benefits" and are not prioritized. It focuses on PA expansion, conservation of natural areas, and restoration. The space available for agricultural production and forestry will thus be limited; as a result, a drastic improvement in agricultural productivity and sustainable intensification of agriculture will become necessary (Garnett et al., 2013; Phalan et al., 2016). This intensification will rely on technological developments and innovation (e.g., making irrigation and nutrient use systems more efficient, improving pest control, and crop genetics) while seeking to reduce negative externalities.

The "Sharing the Planet" scenario aims to "live in harmony with nature" by building on the instrumental and relational values of nature (Hinchliffe & Whatmore, 2006; Turnhout et al., 2013). It reflects the "convivial conservation" approach, which aims at bridging social justice issues with conservation (Büscher et al., 2017; Büscher & Fletcher, 2020) and describes the principle of "land sharing". This scenario is based on the assumption that to halt biodiversity loss; it is necessary to create value at the local level; not to seek to separate humans from nature, and to ensure that social inequalities and injustices are reduced. It prioritizes measures that support and increase the provision of ESs and nature's contributions to people, promoting landscapes that are a mosaic of natural habitat patches and agriculture ("agroecological matrix"). Biodiversity conservation is one of the benefits provided by this landscape. This scenario uses local ecological knowledge, labor-intensive and smart mechanization systems while optimizing other ecosystem benefits, as applied in agroecology, organic farming, agroforestry, and diversified farming systems (Kremen 2020; Tittonel 2014) to implement an "ecological intensification".

List of acronyms and abbreviations

AOH	Area of Habitat
BRFR	Biodiversity-Related Financial Risk
BII	Biodiversity Intactness Index
CBD	Convention on Biological Diversity
CRFR	Climate-Related Financial Risk
DGVM	Dynamic Global Vegetation Model
DNB	De Nederlandsche Bank NV
EEZ	Exclusive Economic Zone
ES	Ecosystem Service
ESH	Extent of Suitable Habitat
ESGAP	Environmental Sustainability Gap
FGRS	Fraction of Globally Remaining Species
FRRS	Fraction of Regionally Remaining Species
GDP	Gross Domestic Product
GTAP	Global Trade Analysis Project
GTAP-AEZ	Global Trade Analysis Project Agro-Ecological-Zones
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
INSPIRE	International Network for Sustainable Financial Policy Insights, Research, and Exchange
LPI	Living Planet Index
MCP	Maximum Catch Potential
MPA	Marine Protected Area

MSA	Mean Species Abundance
MSY	Maximum Sustainable Yield
NGFS	Network for Greening the Financial System
NRFR	Nature-Related Financial Risk
OCDE	Organisation for Economic Co-operation and Development
PA	Protected Area
PBL	Planbureau voor de Leefomgeving
PIK	Potsdam Institute for Climate Impact Research
RCP	Representative Concentration Pathway
REDD	Reducing Emissions from Deforestation and Forest Degradation
RLI	Red List Index
SESPI	Strong Environmental Sustainability Progress Index
SSP	Shared Socio-economic Pathway
TNFD	Taskforce on Nature-related Financial Disclosures

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Publication Director Rémy Rioux
Editor-in-Chief Thomas Melonio

Legal deposit 3rd quarter 2022
ISSN 2492 - 2846

Graphic design MeMo, Juliegilles, D. Cazeils
Layout Denise Perrin, AFD
Printed by the AFD reprography service

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