Network for Greening the Financial System
Technical document

Recommendations toward the development of scenarios for assessing nature-related economic and financial risks

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Acknowledgements

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Foreword

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Exactly a year ago, the Kunming-Montréal Global Biodiversity Framework (GBF) was adopted at the 15th Conference of Parties (COP15) to the United Nations Convention on Biological Diversity. It set concrete targets to reverse nature loss and put our ecosystems on a path to recovery. Accelerating action to realise the goals of the GBF is urgent as the deadline to meet these targets comes closer with each passing day.

The need to act is equally urgent for central banks and supervisors. Nature loss is a material source of risks for our economies and financial systems. As such, in March 2022 the NGFS recognised in a Statement on nature-related financial risks that the degradation of nature, and actions aimed at preserving and restoring it, can have macroeconomic, macroprudential, and microprudential consequences. This year, we took an important first step towards the shared understanding of these risks with the publication of the NGFS Conceptual framework for Nature-related Financial Risks. A logical next step is the development of tools that will help central banks and supervisors assess how our economies and financial systems might be affected by various assumptions of nature-related physical risks and transition policies.

We are proud to present this Technical document providing recommendations towards the development of scenarios to assess nature-related financial risks. The recommendations take into account the specificities of nature-related issues by building on our existing knowledge on climate-related scenarios. It will allow central banks and supervisors to eventually conduct full-fledged forward-looking nature risk assessments.

This work by the NGFS on nature-scenario endeavours represents an important first step towards an integrated assessment of climate and broader nature-related risks. Finding ways to accurately capture nature-related hazards remains key and while complex, is not a task we should shy away from. As this Technical document makes clear, we cannot let perfect be the enemy of the good.

We are sincerely grateful for the commitment and dedication of all Task Force members, who have contributed to this document, as well as the extensive work of the external experts who provided technical inputs during the past year. Our special thanks go out to the team leads and the NGFS Secretariat.

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1. Introduction

The following introduction provides context on this Technical Document on nature scenarios and develops a rationale for the necessity of such scenarios. It then sets out a step-wise approach to the design of such scenarios, as well as some preliminary considerations on the challenges linked to the design of nature scenarios and the potential benefits that overcoming those challenges could present for scenario design at large. This chapter borrows heavily from the NGFS Conceptual Framework (NGFS, 2023a) and goes one step further by explaining how this framework should lead to practical considerations (explored throughout the whole report).

1.1 Background

Nature can be broadly defined to encompass the whole of the natural world, with an emphasis on the diversity of living organisms and their interactions among themselves and with their environment (IPBES Conceptual framework, 2015)[1]. Beyond the fundamental fact that nature has value(s) on its own (Pascual et al., 2023), it is widely acknowledged as the purveyor of key ecosystem services that help maintain human life and wellbeing, thereby forming the bedrock of all human economic activities and values. These ecosystem services – or nature's contributions to people – include provisioning services (e.g., food, raw materials and fresh water); maintenance and regulating services (e.g., climate, water and air quality regulation, pollination, and pest and disease control); and cultural services (e.g., recreation, mental and physical health, and spiritual and religious values). They are enabled by supporting services, such as nutrient cycling and soil formation (NGFS-INSPIRE, 2022). The world economy could not function without nature (Dasgupta, 2021).

There is, however, a clear scientific consensus that these ecosystem services have been declining due to increased human-led pressures on natural systems (IPBES, 2019; IPCC, 2022). For instance: around 1 million plant and animal species face extinction, and the global rate of species extinction is tens to hundreds of times higher than it has averaged over the past 10 million years (IPBES, 2019). It is also clear for other forms of environmental degradation, for example related to soil erosion or freshwater availability (Ripple et al., 2017). The consequences of these forms of nature loss appear all the more dire when looked at through the prism of "planetary boundaries" (Rockström et al., 2009). Planetary boundaries denote the safe operating space for humanity across multiple natural processes that regulate the Earth system. It is widely recognised that these natural processes are interconnected with each other and with climate change, such that the continued degradation of any one of them could generate self-reinforcing feedback loops that destabilise the entire Earth system. Recent scientific evidence suggests that six out of the nine planetary boundaries have been exceeded (Richardson et al., 2023; see **Figure 1.1**), including boundaries related to biodiversity, freshwater and land-use.

The crossing of planetary boundaries implies an increased risk of large-scale abrupt or irreversible environmental changes putting planetary processes at risk (Persson et al., 2022; Steffen et al., 2015). In addition, cascading effects could trigger several "tipping points" that make ecosystems shift towards a new stage where damage to global biodiversity and ecosystem functions becomes irreversible (Lenton et al., 2019). For example, there is a rising likelihood of reaching an Amazon dieback tipping point that could, in turn, trigger tipping points in other biomes (Willcock et al., 2023).

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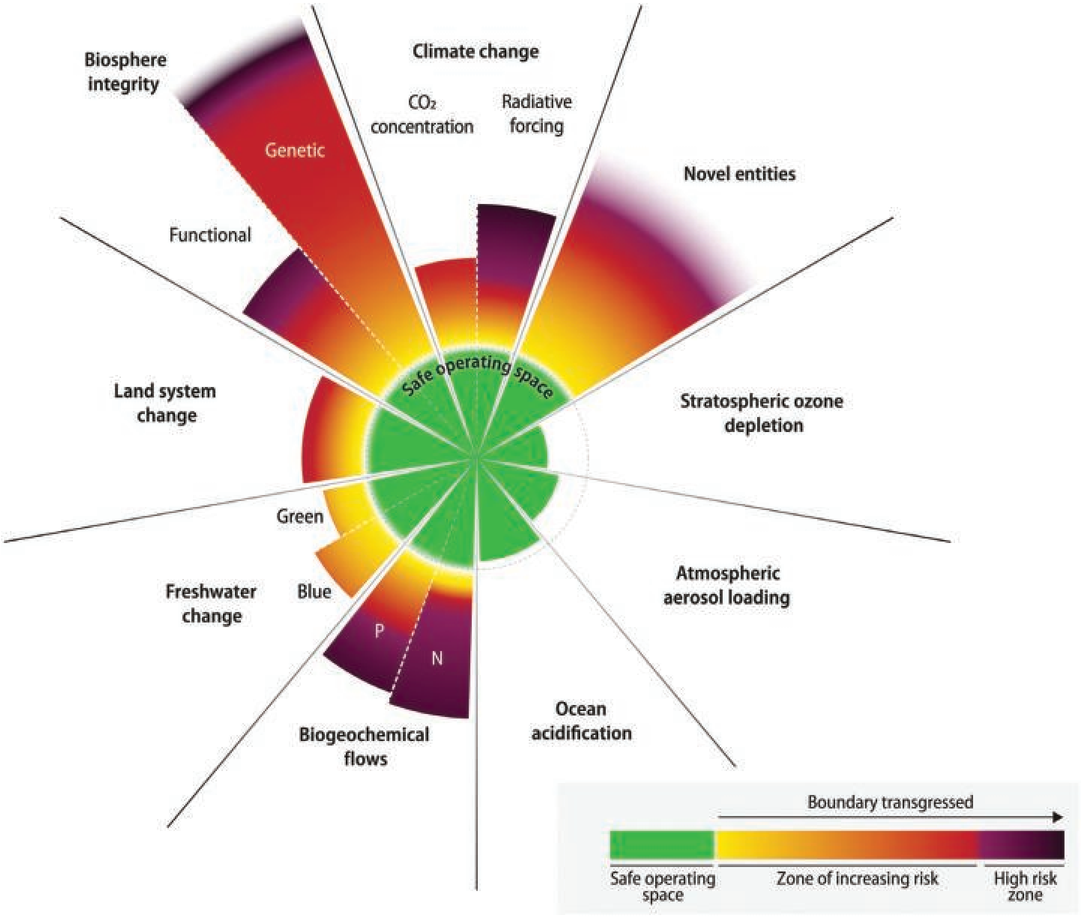
[1] This document aligns on the NGFS Conceptual Framework on Nature-related Financial Risks (2023) in considering that nature includes biodiversity – i.e., the variability among living organisms from all sources (…) and the ecological complexes of which they are part (CBD, 1992) – but goes beyond by capturing both the biotic (living) and abiotic (non-living) elements on our planet.

The consequences of this increasing nature loss – and its related environmental risks – are increasingly acknowledged in the policy arena and is at the root of many policies and actions taken at the local or regional level (e.g., article 29 of French Energy Climate Law introducing mandatory reporting for biodiversity, EU 2021 law banning the import and consumption of products considered as "main drivers of deforestation" – see Section 4.3.2). Recognition of the increased dangers posed by intensifying environmental degradation also led to the adoption of the Kunming-Montreal Global Biodiversity Framework (GBF) in December 2022 by nearly 200 countries. The GBF established a set of four broad goals and 23 targets to achieve in the short- to medium-term. These include the 30x30 target of preserving 30% of the Earth's land and sea by 2030 (GBF Target 3), reducing the risks of harm from pesticides, pollution and hazardous chemicals (GBF Target 7), aligning all financial flows by 2030 with the GBF targets and goals (GBF Target 14) removing or reforming subsidies harmful to biodiversity (GBF Target 18), and increasing financial flows aimed to protecting nature (GBF Target 19).

Figure 1.1 **Planetary Boundaries, or the need for a comprehensive approach to nature loss**

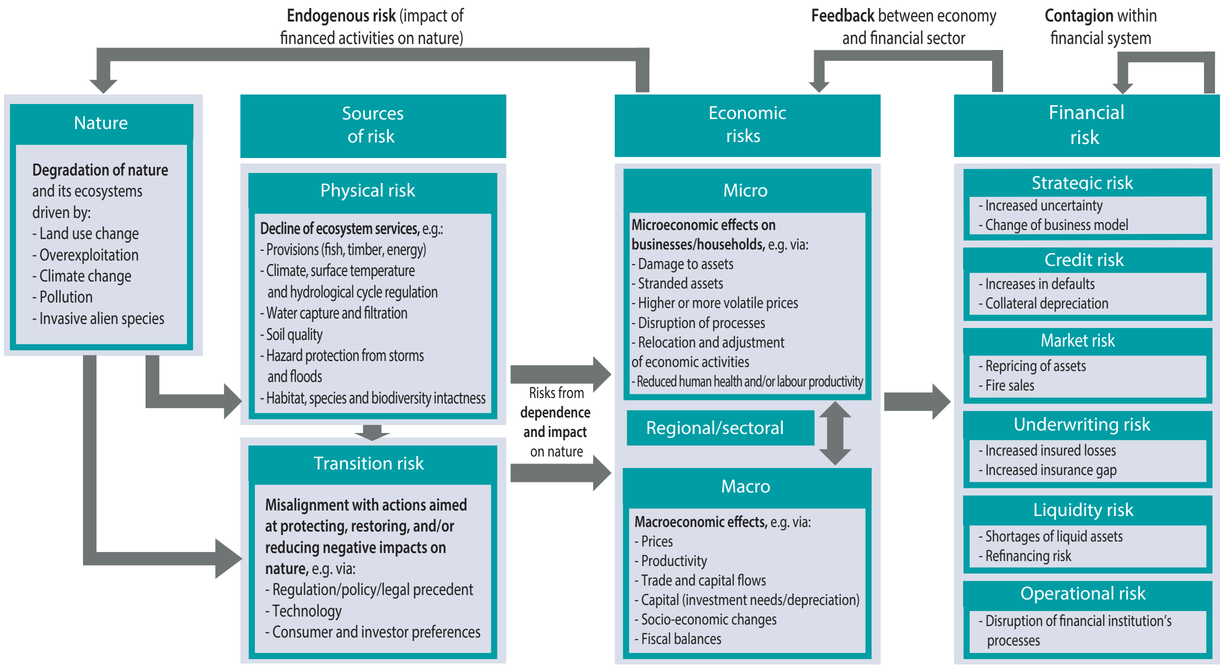


Source: Richardson et al., 2023.

In this context, there is a growing consensus among financial actors that the current trend of nature degradation is a source of economic and financial risks. As shown in **Figure 1.2**, just like climate-related risks, nature-related risks can be divided into physical risks (risks resulting from the consequences of nature loss) and transition risks (risks resulting from a misalignment of economic actors with actions aimed at protecting, restoring, and/or reducing negative impacts on nature). Physical risks can arise as a result of chronic hazards (e.g., the gradual decline in pollinators resulting in reduced crop yields) or acute hazards (e.g., the sudden disruption of an ecosystem service such as water provision). Transition risks may arise as a result of gradual changes (e.g., a gradual, law-induced decrease in net land take towards zero, or progressive changes in consumers' preferences for more environmental-friendly products) or sudden shocks (e.g., an immediate or unexpected policy shift, or a change in investor sentiment). Each of these risks can have both microeconomic impacts – damage to assets, disruption and relocation of activities, etc. – and macroeconomic impacts – impacts on trade and capital flows, disruptions along value chains, socioeconomic changes, etc. These impacts can then transmit to the financial system and adversely affect individual financial institutions in the form of traditional financial risk categories, or even financial systems as a whole if they amplify via feedback loops within the financial sector (NGFS, 2023a).

This potential aggregation into systemic financial exposures can all the more warrant the attention of central banks and financial supervisors (NGFS-INSPIRE, 2022) and puts nature-related risks squarely within their mandate. Indeed, the combination of widespread and worsening environmental degradation alongside growing pressure for "transformative" policy changes (IPBES 2021) point to growing possibilities for system-wide "fat-tail" macro-financial risks (Conte & Kelly 2021). In terms of physical risks, these may include the full collapse of biophysical systems that are key to the stability of even basic Earth system functions (Willcock et al. 2023), or an increased likelihood and severity of global pandemics (Lawler et al. 2021). In terms of transition risks, this may imply increasingly abrupt policy changes, or conservation and preservation policies which strand key assets held by systemically significant financial institutions (e.g., an increase in protected land area).[2]

Figure 1.2 **The sources and transmission channels of nature-related risks**



Source: NGFS (2023), adapted from Svartzman et al. (2021).

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[2] Those assets that may be most at risk of stranding, particularly those related to fossil fuel and mineral extraction and land-use (e.g., agriculture, forestry, etc.), can cause sharp revaluations across the financial sector (Cahen-Fourot et al. 2021).

The Network of Central Banks and Supervisors for Greening the Financial System (NGFS) has started to study the impact of nature degradation on the financial system for several years, through a variety of endeavors that are incrementally laying the groundwork towards assessing and addressing nature-related financial risks within the NGFS[3]. First, and relying on some preliminary studies conducted at individual central banks (Svartzman et al., 2021; van Toor et al., 2020), the NGFS partnered with the research network LSE-INSPIRE to launch a joint study group on 'Biodiversity and Financial Stability'. The three Occasional Papers produced by this working group (NGFS-INSPIRE, 2021a, 2021b, 2022) set out clear links between biodiversity loss and the economic and financial system.

Second, in light of the findings of these reports, the NGFS issued a Statement acknowledging that "nature-related risks (…) could have significant macroeconomic implications, and (…) that failure to account for, mitigate, and adapt to these implications is a source of risks for individual financial institutions as well as for financial stability" (NGFS, 2022), and set up an NGFS Task Force on biodiversity loss and nature-related risks. The mandate of this Task Force is to help mainstream the consideration of nature-related risks across all NGFS activities, along with climate-related risks. It also explicitly states that the" Task force should take stock of « the main transmission channels and variables that may be relevant to NGFS members and possibly differ across jurisdictions », i.e., lay the ground work towards efficient and comprehensive nature-risk assessment by central banks and supervisors. In September 2023 the Task Force set a milestone in the NGFS approach to nature-related risks, through the publication of a Conceptual Framework providing a common basis to understand, assess and address nature-related risks through a principle-based approach. Building strongly on the NGFS-INSPIRE (2022) final report – which benefitted from external expertise – the NGFS Conceptual Framework on nature-related financial risks lays out a common set of definitions and a principle-based approach to the assessment of nature-related risks, while stating that this static, conceptual approach needs to be complemented by further steps. In that light, the present Technical Document constitutes another, complementary key deliverable of the Task force that draws from the Conceptual Framework to start developing a forward-looking and dynamic perspective on nature-related risks from a more quantitative, in-depth perspective.

1.2 The need for scenarios

The most important next step explicitly underlined by these different reports as well as by other stakeholders (TNFD, 2023a, 2023b, 2023c) is the need for developing scenarios through which nature-related economic and financial risks can be better understood. Indeed, scenario design is critical to envision different possible pathways that the world could take, before assessing the economic and financial implications of these pathways.

Both environmental science (e.g., IPCC, 2014) and the financial literature consider a risk as the combination of three elements: hazard, exposure and vulnerability[4] (see Figure 1.3). As such, narratives of scenarios are essential to identify which hazards could occur in the future (e.g., which tipping point could be crossed and what could it generate? Or which policy could be implemented and which actors could be impacted?).

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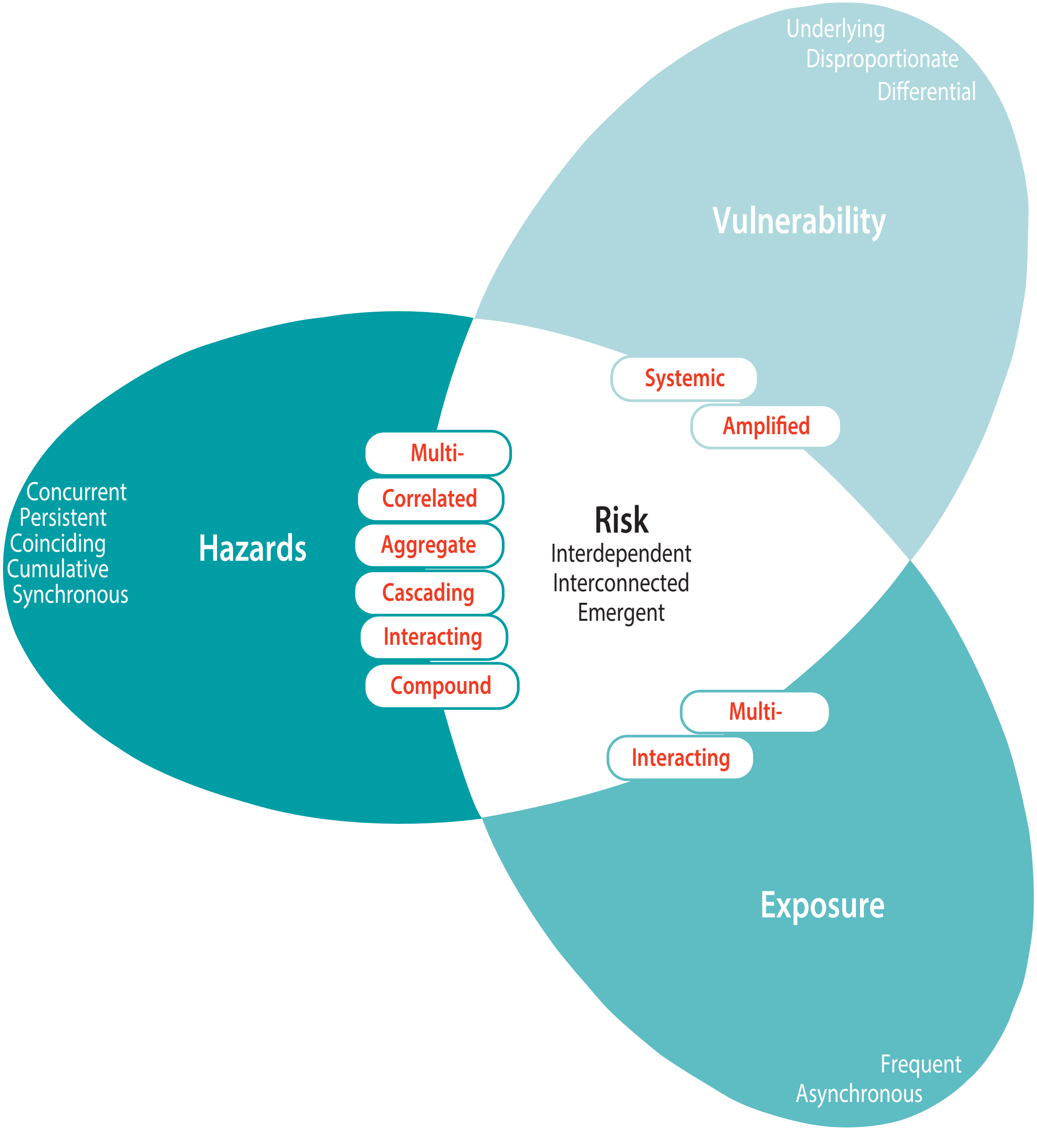
[3] While recognizing that differences in mandate, capacity, experience and context should be taken into account when member jurisdictions consider to develop such scenarios.

[4] Following the definitions of IPCC (2014), **hazard** refers to the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. Extrapolating from this, hazards can also consist in transition hazards, e.g., specific policies or socioeconomic trends that suddenly render specific activities and assets stranded. **Exposure** implies the presence of people, livelihoods, species, or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by the hazard. **Vulnerability** is the propensity or predisposition to be adversely affected by the hazard. It encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Figure 1.3 **Risk results from the combination of three elements: hazard, exposure and vulnerability**



Source: Ranger et al., NGFS 2023 (forthcoming) Adapted from IPCC 2014.

Another way to represent the same idea – with a stronger focus on economic and financial risks[5] – is to consider that a three-step approach is essential to conducting a full-fledged economic and financial risk analysis (see Figure 1.4):

- The first step would be to identify the type of hazard (or 'shock') that could occur, be it physical or transition, and develop narratives stemming from those hazards.
- The second step would be, for every likely hazard identified, to assess the exposure of agents (whether it be individuals, businesses, financial institutions or sovereigns) to this transition or physical shock. For example, in the case of a policy shock, as mentioned above, the exposure of a given business to this shock depends on whether it has production facilities or suppliers located in the future protected area.
- The third and last step would be, for every given hazard and its correlated exposure of agents, to understand the level of vulnerability of the agents, both in terms of propensity to be impacted by the hazard (i.e., sensitivity) and in terms of being able to cope with that hazard or its consequences (i.e., adaptive capacity and resilience).

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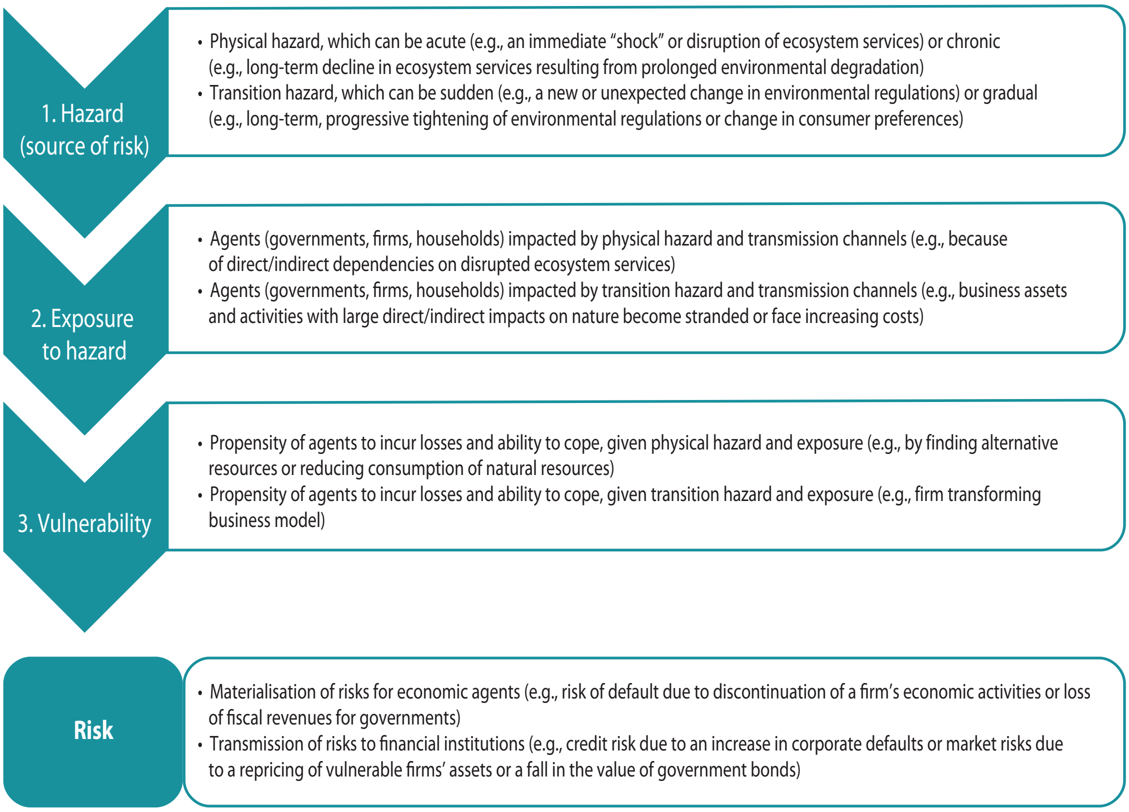
[5] Also see TNFD (2023c) for some additional details and definitions.

Figure 1.4 **The materialisation of risks as the consequence of hazard, exposure, and vulnerability**



1. Hazard (source of risk)

- Physical hazard, which can be acute (e.g., an immediate "shock" or disruption of ecosystem services) or chronic (e.g., long-term decline in ecosystem services resulting from prolonged environmental degradation)
- Transition hazard, which can be sudden (e.g., a new or unexpected change in environmental regulations) or gradual (e.g., long-term, progressive tightening of environmental regulations or change in consumer preferences)

2. Exposure to hazard

- Agents (governments, firms, households) impacted by physical hazard and transmission channels (e.g., because of direct/indirect dependencies on disrupted ecosystem services)
- Agents (governments, firms, households) impacted by transition hazard and transmission channels (e.g., business assets and activities with large direct/indirect impacts on nature become stranded or face increasing costs)

3. Vulnerability

- Propensity of agents to incur losses and ability to cope, given physical hazard and exposure (e.g., by finding alternative resources or reducing consumption of natural resources)
- Propensity of agents to incur losses and ability to cope, given transition hazard and exposure (e.g., firm transforming business model)

Risk

- Materialisation of risks for economic agents (e.g., risk of default due to discontinuation of a firm's economic activities or loss of fiscal revenues for governments)
- Transmission of risks to financial institutions (e.g., credit risk due to an increase in corporate defaults or market risks due to a repricing of vulnerable firms' assets or a fall in the value of government bonds)

Source: Authors, adapted from Svartzman et al. (2021).

As has already been shown with climate change – and is even more the case for nature – the complexity of environmental phenomena forces financial institutions and their supervisors to go beyond static sensitivity analysis (or locally-grounded case studies) to gain insight on the evolution of a given sector or actor. The movement towards a dynamic assessment of nature-related risks requires the development of scenarios. Given the uncertainty at stake when it comes to envisioning the future – especially as this future does not look like the past and as potentially catastrophic consequences could occur (Bolton et al., 2020; Kemp et al., 2022) –, scenarios are needed because they rely precisely on a number of detailed hypotheses and mutually exclusive choices that allow for various plausible futures to be laid out rather than for a "simple" prevision or prediction. Scenarios help to identify the potential "trigger points" that could come to affect the course of action that financial actors had set upon (Boissinot & Heller, 2020). In the context of deep uncertainty, models and scenarios allow for users to "explore rather than predict" in order to help to better understand the drivers of individual and system-level responses to shocks in comparison with forecasting models (Schinko et al., 2017). This approach is consistent with the standard requirements for stress testing and vulnerability assessment by many Central Banks (e.g., IMF, 2019).

Reversely, in the absence of scenarios, one can rely only on static analysis or locally-grounded case studies, but those are not sufficient to understand financial risks, let alone macrofinancial risks that can result from the interactions of several patterns (e.g., different physical hazards interacting among themselves or different policies with diverse economic impacts). As acknowledged by central banks and supervisors who moved first on nature (see **Box 1.1**), static analyses approximating risks based on methodologies and measurement approaches like ENCORE and case studies are a good starting point to get familiarised with nature-related risks, but they cannot replace a full-fledged risk analysis relying on a transparent set of plausible hypotheses regarding the future.

Scenarios can be more or less complex and address different needs (also see TNFD, 2023c), but one cannot act without them if one is to understand nature-related risks, as presented in Figure 1.4 above. Scenarios can, for instance, focus on one single event that already took place or is taking place and extrapolate it to other events. However, the latter may fall short of understanding the fact that nature loss and the measures needed to reverse it cannot be grounded in the past (as extensively discussed throughout this Technical Document, and as already acknowledged by the NGFS when it comes to climate-related risks).

Scenarios can also be more local or global, with pros and cons in each case: the more global and aggregated the narrative of the scenario, the less it may capture local specificities that are essential to appreciate nature-related patterns (even more than for climate change); the more local and disaggregated the narrative of the scenario (e.g., a collection of case studies focused on a few regions and sectors, or envisioning specific policies aimed at relieving different pressures on nature), the less it may be able to create a common language and to inform how nature loss and related policies can generate macro-financial impacts.

At the current juncture we do not, however, have access to all the necessary tools to implement this three-step approach to risk analysis for central banks and supervisors. Each of the three steps of the process currently presents challenges in the way of conducting a full-fledged nature-related risk analysis, one for every step of the process. As regards step 1 (of **Figure 1.4** above) – the completion of which is needed in order to go on performing the following two steps – the identification would have to be as accurate as possible and implies developing narratives stemming from the most likely and/or important physical and transition hazards, based on adequate data and metrics (see **Annex 7.1.1**) that can take into account as much as possible the extent and propagation of these hazards. For instance, for physical risks the question could be (to name just a few examples): should we focus on the possibility of an Amazon dieback and/or on invasive species in high-income countries? And for transition risks, if we choose to refer to globally significant objectives such as the Kunming-Montreal GBF targets: should we focus on the removal of harmful subsidies and/or on the need to protect 30% of land and sea areas? Each potential pathway of investigation can reveal important factors of economic and financial instability resulting from nature-related risks, while possibly ignoring others.

The purpose of this Technical Document is therefore precisely to provide recommendations regarding how we can move from static analysis (or isolated case studies) toward consistent scenarios through which nature-related risks can be better understood and assessed.

Box 1.1

Static analysis and case studies as a result of a lack of available scenarios for nature

Until now, a large part of the existing literature on nature-related risks conducted by central banks and supervisors has focused on the "exposure" approach consisting in step 2 without providing details on the other steps. In addition to studies such as the assessment of financial sector exposure to nature degradation of Brazil (Calice et al., 2021) or Malaysia (World Bank & Bank Negara Malaysia, 2022) two of the most frequently quoted examples are the impact and dependency studies conducted by De Nederlandsche Bank (van Toor et al., 2020) and the Banque de France (Svartzman et al., 2021) to estimate the impact and dependencies on nature of their respective financial systems.

In order to approximate physical risks, both use the ENCORE methodology (Natural Capital Finance Alliance, 2021) to provide a proxy of the direct exposure to physical shocks, by assessing the dependencies of the economic activities financed by Dutch/French financial institutions on a range of ecosystem services, assuming that a business that is highly dependent on ecosystem services is more likely to be directly affected by a physical shock.

In order to approximate transition risks, both studies provide a measure of the total impacts of the economic activities financed by Dutch/French financial institutions on biodiversity (i.e., the "biodiversity footprint" of their portfolio). Svartzman et al. (2021) do so by using the Biodiversity Impact Analytics – Global Biodiversity Score (BIA-GBS) methodology, which builds on the GLOBIO model used by the DNB (van Toor et al., 2020). The rationale is that in the absence of standard scenarios of transition shocks, we can assume that a business with a significant negative impact on biodiversity has a higher chance of being affected by a biodiversity transition shock than a business with a low impact.

A common challenge of each of these approaches is therefore that they do not fully quantify risk in a way compatible with standard approaches recommended, for example, by financial regulators and supervisors or the climate or catastrophe risk communities (e.g., IPCC 2014). More specifically, static approaches do not capture the likelihood or potential magnitude of a hazard or to what extent a specific level of loss (if it occurred) would translate into a physical loss of output – as well as the indirect impact it would have, including through interdependencies that are also not taken into account. As such, their results could be considered an upper bound estimate of the potential scale of the risk, not the premises of a plausible future.

1.3 The need to develop nature-related scenarios that are consistent with NGFS climate scenarios while acknowledging the specificities of nature-related issues beyond climate change

If some of the lessons learnt in developing climate scenarios can be used in the case of nature scenarios (NGFS-INSPIRE, 2022), this use needs to be done in the full knowledge of both the deep connections and the trade-offs between climate and nature. Climate change and broader nature risks have been positioned as distinct but interrelated issues (NGFS, 2023a) that cannot be treated in silos but rather form what is usually called a "climate-nature nexus". This interconnection has been illustrated in the representation of planetary boundaries (see **Figure 1.1**). It can be further evidenced by the fact that climate change can be a driver of nature loss (e.g., climate change-induced ocean acidification accelerating biodiversity loss) just as much as nature loss can be a driver of climate change (e.g., deforestation hampering carbon sequestration). Conversely, although nature-based solutions can alleviate climate risk (e.g., forest preservation for carbon-capture purposes), actions undertaken to reduce climate-change can be detrimental to nature (e.g., attempt at enhancing carbon capture through the planting of tree varieties that are ill-adapted or not diverse enough and damage the ecosystem into which they are introduced).

As such, nature-related scenarios should ideally be as integrated as possible with climate scenarios (NGFS, 2023b), while acknowledging the specific features of nature beyond climate change. While it would be counterproductive to ignore that the potential users of nature-related scenarios will likely have experienced climate scenarios or be familiar with them – and could therefore pragmatically use them as a starting point – the NGFS has recognised that an integrated, i.e., indiscriminate approach of climate and nature will not always be possible or desirable (NGFS, 2023a). In that respect the NGFS Task force Nature team in charge of this Technical Document was tasked with the elaboration of recommendations toward the development of nature-related scenarios that would make them as compatible as possible with NGFS climate scenarios (NGFS, 2023b) while recognizing and taking into account the specific features of nature.

The NGFS (2023b) currently designs climate scenarios by relying on different types of integrated assessment models (IAMs). Process-based IAMs, which are the main models supporting the climate scenarios of the NGFS, are models that describe the potential evolution of the global energy system, as well as other systems with important GHG emissions, including agriculture and land use changes. Such models allow for the study of both land use changes and the transition of the energy system, including the investment needed for such transformation of the energy matrix. They generate optimal trajectories according to the transition costs subject to a set of constraints imposed by the scenario narrative. They also allow for an estimate of both the global and regional marginal abatement costs and enable the study of the emissions trajectories under each NGFS scenario subject to the carbon budget restriction.

However, nature-related risk assessment scenarios must factor in broader considerations by taking into account a number of particular features of nature that render their design challenging. While some of these features are shared with climate, others are unique and did not have to be taken into account in the development of climate scenarios heretofore. This additional complexity could present both modelers and financial institutions –first among whom NGFS members – with an opportunity to better understand and overcome some limitations of the current climate-related NGFS scenarios.

Three main challenges must be taken into account in order to perform all the steps necessary to a full-fledged nature-related risk assessment: the complexities and interconnectedness of nature's ecosystems, the absence of a single metric to measure nature-related changes and risks, and the limited substitutability of nature. These are discussed in more detail in the next section but briefly summarised here:

- **A characteristic that was already present with climate scenarios and is exacerbated in the case of nature is the inherent complexity and non-linearity of natural processes, which plays an important part in the difficulty to capture nature changes and their consequences adequately (IPBES, 2019; Kedward et al., 2020).** Part of that complexity lies in the fact that nature loss materialises through local phenomena that have an impact on or come from global processes or policies. Moreover, ecosystems and the services they provide are often interconnected, meaning among others that degradation and loss in one ecosystem (or ecosystem service) has implications for others (Dasgupta, 2021). Such phenomena have so far remained out of the modelling scope of the NGFS (2023b), and it would be particularly problematic to do so for nature-related issues.
- **A second challenge in direct relation to the complexity of natural processes is the need to account for nature-related risks through the use of multiple metrics, as opposed to more direct approaches leading them to be assessed through a single metric (TNFD, 2023a, 2023b, 2023c).** One aspect of this complexity is that, unlike in the case of climate change, where a common measurement unit (ton of CO_2 equivalent) can be used to summarize effects, natural processes cannot be described through the prism of a single indicator (Chevassus-au-Louis et al., 2009). Some metrics are used for specific purposes like the impact analysis of a portfolio, as was done in the exposure analyses previously mentioned (van Toor et al., 2020; Svartzman, 2021), but there is currently no agreed-upon general metric that can be used to aggregate nature data and assess nature loss. Hence, for nature, there is no single global nature goal akin to the 1.5°C global temperature change target for climate. Other methods that could be used for the purpose of scenarios, like the translation of the contribution of different ecosystem services into monetary units ("natural capital") to be fed into models, would also have little relevance for the purpose of scenario design and of the correlated economic and policy-making (Costanza et al., 1997).

- **Another distinct feature of nature-related scenarios is the fact that nature and the ecosystem services it provides are not easily substitutable with more manufactured capital and/or labor.** Most of the models assume that nature and the ecosystem services it provides can be replaced by labor and/or man-made capital (what is sometimes referred to as a "weak sustainability" approach) whereas a growing literature (e.g., Daly & Farley, 2011; Dasgupta, 2021; Dietz & Neumayer, 2007) call for assuming the quasi absence of substitution possibilities between nature and other factors, at least in the short run.[6] What's more, regardless of the approach, the understanding of substitution possibilities is currently limited. Scenario narratives (and models) must therefore consider a much more complex biophysical and socio-economic reality than is often assumed.

All the challenges thus identified account for one of the major hurdles towards the development of nature scenarios: the existence of a "local-global tradeoff" for nature-related issues. Indeed, they all hint at the existence of varying but very specific elements and at the need of getting a global picture. This "local-global tradeoff" translates in the fact that nature-related scenarios require a greater consideration of locally specific biomes, sectors and firms to understand how distinct policies and processes may drive changes at the smallest level; and on the other hand, an aggregation of local socio-economic and environmental changes in order to account for the global drivers and impacts of those local changes, as well as maintain their tractability. The tradeoff lies in the importance of managing to both capture local granularity and specificities to accurately model nature-related risks, and maintain the global macrofinancial criticality of nature loss and the related sustainability transition. A new approach to scenarios may therefore be needed to connect global macro and sectoral dynamics to local environmental changes.

The challenges above, and in particular the one related to the limited substitutability of ecosystem services, means that nature-related hazards are likely to propagate through value chains in ways that are not accounted for today in most climate scenarios and models. By merging the need for sectoral granularity discussed above with the need for a global and as exhaustive as possible picture of risk, it appears clearly that the scenarios to be developed for the purpose of nature-related risk assessments should also include indirect impacts of nature-related hazards and ideally capture the contagion channels that can exist across sectors (see **Figure 1.5**)[7]. This aspect will be discussed extensively throughout the report.

Importantly, this exploration could also benefit the NGFS climate scenarios, as they start evolving to address some of the current limitations underlined by scenario users and NGFS members (NGFS, 2023b). In 2022, building on the first climate exercises conducted by NGFS and FSB Members, the NGFS highlighted a number of limitations of its current climate scenarios, and of the approaches implementing them, in order to raise awareness among the financial community that climate scenario analysis is complex and still nascent. In particular, it was highlighted that the limitations of current climate scenarios might lead central banks and financial supervisors to underestimate climate-related risks[8]. The NGFS then conducted a survey to collect users' feedback, following the publication of the third vintage of its climate scenarios.[9] This survey helped to identify a number of issues to guide the NGFS work plan going forward, aiming in particular to improve users' accessibility and understanding of its climate scenarios. In those documents the main limitations and areas for improvement regarded, among other things:

- The need to tailor the scenario analysis to the specific context and objectives of users to better analyse vulnerabilities (NGFS & FSB, 2022);

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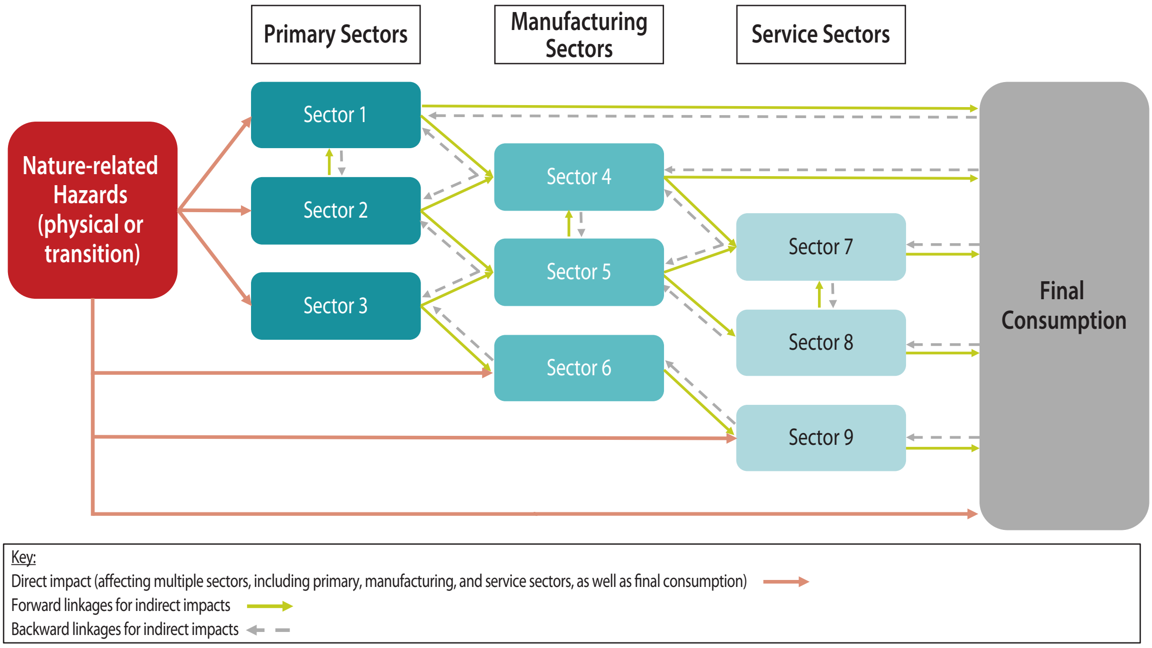
[6] The extent to which substitutability can be assumed for the purpose of nature-related scenarios will be discussed in greater length in Chapter 2 on narratives.

[7] Note that here we do not discuss the fact that interconnections among ecosystems can increase the indirect impacts we discuss (that is, here we focus strictly on *economic* indirect impacts, where indirect impacts due to ecosystem processes should be addressed as part of the narrative of the scenario).

[8] Current climate scenario analysis exercises may understate climate exposures and vulnerabilities, warn FSB and NGFS – Financial Stability Board.

[9] Note on NGFS Survey on Climate Scenario: Key Findings.

Figure 1.5 **Propagation of nature-related hazards throughout value chains until final consumption**



Sources: Authors' illustration.

- The need – sometimes put in practice on an ad hoc basis by users themselves (NGFS Survey, 2023) – for adapting or adding new variables to increase the geographical coverage and/ or sectoral granularity of the macro-financial results obtained through scenarios;
- The need to take into account non-linearities and indirect impacts. One overarching message of the initial exercises described in NGFS & FSB (2022) is that, at least for now, the impacts from climate-related risks have been limited to the perspective of only domestic financial systems (to the exclusion of studying the contagion of global risks), that the tail risks associated with climate change are currently not captured, and that the current measures of exposure and vulnerability permitted by NGFS climate scenarios were likely understated. Among the reasons listed for this understatement was the fact that metrics capturing neither second-round effects nor potential climate non-linearities (NGFS & FSB, 2022).

In the wake of these findings the NGFS continues to enhance its climate scenarios (NGFS, 2023b), in particular through work priorities that match the needs of nature-scenario development and will be subject to recommendations in this Technical Document, such as the improvement of modelling of non-linear and indirect impacts, the addition of more sectoral and geographical granularity, and the development of short-term scenarios.

Other challenges are beyond the scope of this Technical Document (although briefly discussed). Importantly, the challenge of integrating the endogeneity of nature-related financial risks is not fully explored here. Indeed, much like for climate-related risks, the financial sector does not only receive nature-related risks but can also contribute to their emergence. While this challenge is an essential one, the focus on NGFS climate-related scenarios so far has remained on the interactions between climate and the economy. This Technical Document therefore focuses on how to make similar progress with regards to nature. We nevertheless call for further research into the exploration of the endogeneity of nature-related financial risks (in line with the NGFS Conceptual Framework on nature-related risks (NGFS, 2023a)) and briefly discuss this topic in Chapter 2.

1.4 Outline of the report

In light of all this, the present Technical Document provides recommendations on the development of nature-related risk assessment scenarios, highlights the specificities of nature-related risks as opposed to climate-related risks, and discusses and outlines potential ways forward.

The Technical Document is structured around the two steps typically needed to conduct forward-looking risk assessments: (i) envisioning consistent narratives through which different hazards can be identified; (ii) exploring methods and tools (e.g. models and data needs) through which the economic (and ultimately financial) impacts of these hazards and the ability to mitigate them can be assessed.

- **Chapter 2** provides a comprehensive overview of the challenges related to the development of nature-related narratives of scenarios, in view of the specific and complex features of nature that end up creating the aforementioned "local-global tradeoff". It then proposes approaches to developing narratives that could overcome this tradeoff and consequently serve as starting points for the assessment of nature-related financial risks, distinguishing between approaches for physical risks and approaches for transition risks.
- **Chapter 3** reviews a range of modelling approaches for scenarios of two main types, namely nature-economy models and biophysical models. It assesses the extent to which those approaches are able to integrate the outputs of nature-specific narratives as inputs to a modelling exercise; and the extent to which they account for the transmission channels through which specific nature-related hazards can propagate in the economy.
- **Chapter 4** examines alternative approaches to the examined models to assess nature-related financial risks, with a focus on those that are able to both represent multiple hazards in multiple sectors and capture the indirect (cascading) impacts of these hazards throughout value chains. It therefore mostly analyses the insights and limitations of Multi-Regional Input-Output (MRIO) tables and models, without excluding the possibility of exploring other approaches. It develops two case studies connecting nature-related narratives to MRIOs in order to give an example of how these tables and models can be used.
- **Chapter 5** concludes with a list of options for central bankers and supervisors, to help them moving forward with the development of quantified nature-related scenarios both in the short-term and within a longer-term program.

2. Developing narratives to assess nature-related financial risks: rationale, challenges and ways forward

The essential first step to any scenario-based risk assessment is to generate narratives. Narratives are storylines that describe how the world could evolve in the future, considering likely socio-political, macro-financial and environmental trends. Narratives can include different pathways of global development (e.g., shared socio-economic pathways – SSPs), assumptions of technological changes, changes in consumer preferences, regulatory shifts, and changes in environmental conditions. In essence, narratives can help to characterise the transformations of the direct and indirect drivers of nature loss or the economy that could take place.

For the purposes of assessing nature-related risks, an essential component in narrative creation is to identify specific physical and/or transition hazards that can become sources of risks (depending on the exposure and vulnerability to such hazards, see Figure 1.4). For instance, a narrative of a physical hazard might describe the potential collapse of a critical biome (such as the Amazon rainforest) due to deforestation. Such a narrative could even envision how this deforestation-driven collapse might trigger multiple other physical hazards (e.g., the loss in rainfall in several other regions of the world, destabilisation of the global climate system and ocean currents), resulting in additional material risks for the economy (e.g., potentially severe impacts on domestic and global agricultural activities). Likewise, a transition hazard narrative could describe the implementation of policies aimed at preventing the deforestation of a critical biome (e.g., an increase in protected forest area in the Amazon, a ban on non-deforestation-free imports in the EU), which could be the source of new transition risks (e.g., loss in revenues for countries that export deforestation-linked agricultural products due to deforestation, and potential increase in the price of agricultural inputs for importing countries).

Once the specific hazards are identified, it is then possible to study their direct macroeconomic impacts, and transmission of indirect impacts. Hazard narratives are typically translated into quantified sectoral 'shocks' (impacts) by ad hoc methodologies, which are then used as inputs in a macroeconomic or sectoral model (as discussed in the next two chapters of this Technical Document).

However, before jumping into proposing narratives of scenarios to assess nature-related risks, it is first important to understand the unique challenge this represents. In the first part of this chapter, we therefore identify some of the key challenges for scenario development related to the complexity, nonlinear patterns and interconnectedness (e.g., between climate and biodiversity) of Earth's systems, as well as the facts that ecosystem services cannot be captured by a unique indicator and are also largely non-substitutable and complementary. As a result of these challenges, developing relevant narratives of nature-related scenarios must be able to overcome the inherent tradeoff between capturing locally specific environmental changes, while maintaining global relevance. That is: the more global and aggregated the narrative of the scenario, the less it may capture local specificities that are essential to appreciate nature-related patterns (even more than for climate change); the more local and disaggregated the narrative of the scenario (e.g., a collection of isolated case studies focused on a few regions and sectors), the less it may be able to inform how nature loss and related policies can generate global and macrofinancially significant impacts.

The second part of this chapter therefore suggests some ways forward to developing narratives of scenarios that could overcome this local-global tradeoff, for both physical and transition risks. We propose two complementary methodologies for physical risks, ESGAP-SESi and INCAF-Oxford, and one methodology for transition risks based on a comprehensive assessment of different frameworks that help understand the variety of policies and socioeconomic evolutions that could be implemented to reverse nature loss. The outcomes of such narratives could then be used as inputs to economic models and tools aimed at assessing nature-related financial and economic risks (as discussed in the rest of the report).

2.1 Challenges related to the development of scenarios to assess nature-related risks

2.1.1 Accounting for ecosystems' complexities and interconnectedness

Nature is composed of an interdependent network of complex adaptive systems whose diversity, specificity and expansiveness make them difficult objects of study. As such, measuring nature's diversity and composition in even just a small area can be highly problematic. Many components of the living world remain either fully invisible or poorly understood. For example, a single gram of soil may contain as many as 10 billion bacterial cells (Dasgupta, 2021, p. 53). Moreover, scientists are still discovering the ways that both the biotic and abiotic elements of natural systems overlap and interact across scales (Lade et al., 2019; Willcock et al., 2023). Local biomes are therefore both highly geographically specific and yet invariably connected within a complex global tapestry of interdependent relations.[10] Attempts to understand the evolution of natural systems are thus characterised by a high degree of uncertainty, and usually rely upon multiple indicators to capture both the existing state and progress across various spatial and ecological dimensions (species richness, species population, ecosystem integrity, etc.).

Natural systems and processes are also subject to non-linear dynamics and potentially irreversible changes when critical ecological thresholds ('tipping points') are crossed (Rockström et al., 2009; Steffen et al., 2015). For instance, Lovejoy & Nobre (2018) find that a tipping point for the Amazon system could be reached at 20-25% deforestation. Past this point, large parts of the Amazon could shift to a savanna vegetation, with potentially catastrophic consequences for biodiversity and climate change, given the critical role the Amazon plays in storing CO_2 emissions. However, identifying when tipping points may be reached and how a natural system may change once this happens is ultimately uncertain, especially as ecosystems continue to be stressed in new ways, by multiple local and global forces, and with an intensity that is previously unseen in human history (Willcock et al., 2023).

Ecosystems are not only diverse and subject to nonlinear patterns, they are also deeply interconnected among themselves. The concept of "planetary boundaries"[11] (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015) is particularly useful to show these interconnections, and is gaining traction among the scientific and policymaking spheres. For instance (as highlighted in **Figure 2.1**), land-system change – typically associated with deforestation and agricultural intensification – is contributing to climate change, but it also contributes to biodiversity loss and increasing flows of harmful biogeochemicals (typically via the use of fertilisers). In turn, these reduce the resilience of local ecosystems and therefore contribute to even more land-use change, further accelerating climate change and loss of biosphere integrity. These are just some of the interdependencies that exist between planetary boundaries (Lade et al., 2019), and it is clear that such interactions can heighten social and ecological risks. For example, climate change and biodiversity loss can also combine to increase the risks of pathogens, potentially leading to new pandemics (Pörtner et al., 2021). This "climate-biodiversity nexus" is increasingly emphasised in recent scientific literature (see **Box 2.1**).

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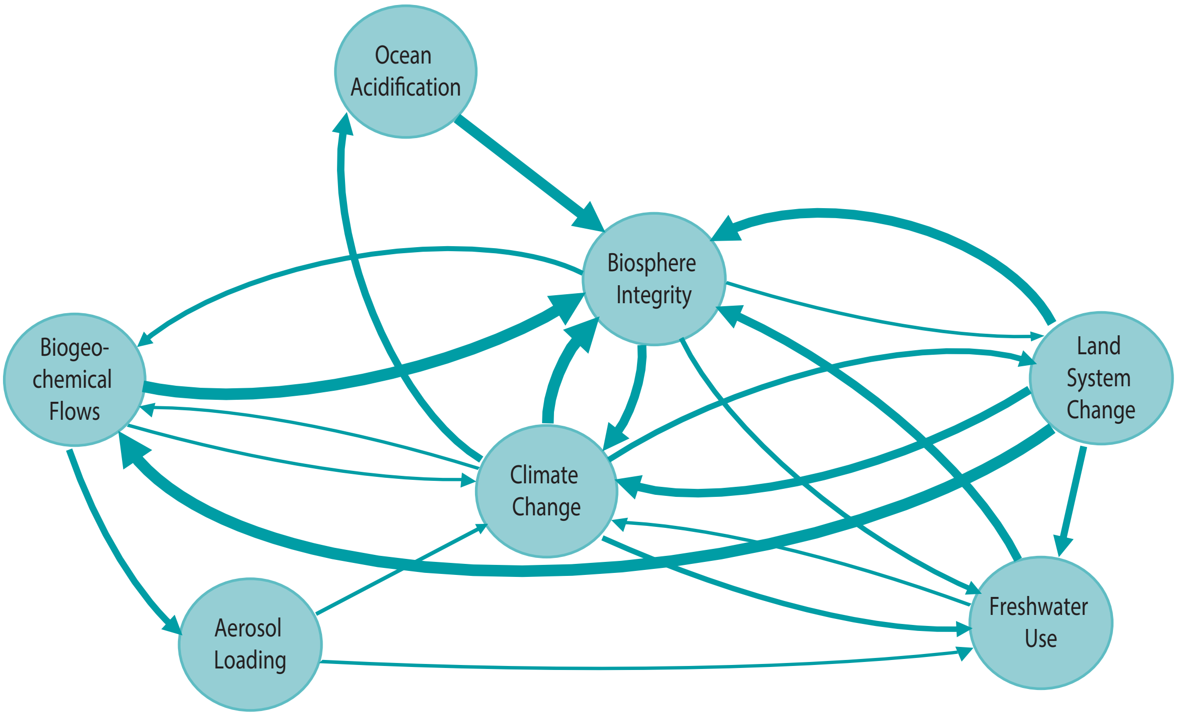
[10] Importantly, policies that regulate human-nature relations (e.g., global trade, socio-economic regulations, etc.) are inseparable from global ecosystem processes (e.g., hydrological and geochemical cycles, climate regulation) and may amplify, dilute, repair and/or degrade their functions in different ways across time and space. Similarly,

[11] Planetary boundaries refer to nine Earth processes that define the "safe operating space for humanity". When this safe operating space is not respected (e.g., when biodiversity loss passes certain thresholds, or when CO_2 atmospheric concentration reaches certain levels), Earth subsystems are more likely than not to irreversibly shift toward a new state, with potentially devastating consequences for human populations and other forms of life.

Figure 2.1 **Planetary boundaries and their interdependencies**



Note: Only 7 of 9 planetary boundaries are shown here for readability. Thickness of arrows depicts the relative degree to which one Earth system process impacts another. Further information and methodology for quantifying interdependencies can be found in Lade et al. (2019).

Source: Authors, adapted from Lade et al. 2019.

The existence of multiple, interdependent planetary boundaries means that a focus on any one Earth-system process alone (e.g., climate change) is not sufficient to comprehend the full severity and complexity of nature-related risks. Indeed, it is increasingly understood that crossing tipping points in one ecosystem are likely to exacerbate stresses in other ecosystems, resulting in additional abrupt ecosystem transition thresholds being passed. The interaction of multiple human and non-human environmental stressors suggest the possibilities for "an ever-deepening vortex of degradation" over time and space, accelerating processes leading to ecosystem collapse (Willcock et al., 2023, p. 9).

Box 2.1

The climate-biodiversity nexus

Climate change and biodiversity loss are linked through self-reinforcing feedback loops. Climate change is causing biodiversity loss globally largely because species can survive in only limited thermal and geographic ranges. Warming therefore pressures species to move to higher latitudes, higher altitudes, or deeper waters, shifting species interactions, "with cascading effects on species abundances, species composition, and ecological functions" (Pörtner et al., 2023, p. 1). Biodiversity loss also contributes to climate change through the loss of wild species and biomass. In particular, biodiversity losses reduce carbon stocks and sink capacity in natural and managed ecosystems, increasing emissions. Biodiversity losses driven by human activities (e.g., deforestation, the expansion of livestock production or pollution) are now also increasingly exacerbated by climate change, resulting in positive feedback loops of environmental harm (Brodie et al., 2023). While healthy ecosystems can reduce the risk and negative macrofinancial impact of natural disasters, the continued degradation of critical ecosystem functions is also a major factor in intensifying the severity of storms, floods, droughts, wildfires, etc. (Depietri, 2020). There is also evidence of a temperature threshold above which photosynthesis in tropical trees begins to fail, which is especially relevant for tropical forests that serve as critical carbon stores and sinks and biodiversity hotspots (Doughty et al., 2023).

Given these interdependencies, it is difficult to resolve any one issue without worsening the other. This recognition has spawned a growing literature on the ways that mitigation and adaptation responses can actually be maladaptive, increasing the potential for future socio-economic and environmental risks (Reckien et al., 2023). Current attempts to attain net zero emissions via projects like afforestation/reforestation, for example, are now regularly shown to have negative impacts for biodiversity and food security (Pörtner et al., 2023, p. 7). Additionally, the shift to alternative energy systems (wind, solar, etc.) and the adoption of sustainable technologies (e.g., electric vehicles, new batteries) to combat climate change can also come with new challenges for the biodiversity. While risks associated with the low-carbon transition remain undoubtedly low compared to a scenario of continued exploitation of fossil fuels, they nonetheless present a major potential "stumbling block in the 'race for our lives' towards a sustainable economy" (Miller et al., 2023). For instance, mining for critical minerals necessary for the transition is also linked to potential disruptions in ocean ecosystems, acute water scarcity and deforestation in extraction areas – sometimes in biodiversity hotspots (Kramaraz et al., 2021; Sovacool et al., 2020). In this sense, even the most optimistic shared socioeconomic pathways (SSP) identified in the IPCC climate scenarios could come with unforeseen consequences that worsen environmental and macrofinancial risks.

2.1.2 The need for multiple metrics and for narratives that capture synergies and trade-offs among biophysical patterns and goals

As a result of these features, three pathways that might initially appear valid for the purpose of developing nature-related scenarios are ultimately not suitable: relying on a unique, all-encompassing metric such as the CO_2-equivalent for climate; translating ecosystem services into monetary units that can feed into existing models; and dealing with one environmental issue at a time, in a silo. The implications of such challenges and some ways forward are then proposed in the following sub-sections.

First, there is no agreed-upon means or easily identifiable metric for aggregating environmental data to assess ecosystem health or ecosystem degradation, meaning that nature-related scenarios will need to build on a large number of metrics and indicators (TNFD, 2023a, 2023b, 2023c). While NGFS climate scenarios can rely on a relevant indicator like CO_2-equivalent (CO_2-eq), "it is illusory to hope to describe biodiversity by a single indicator" (Chevassus-au-Louis et al., 2009, p. 15).[12] Some studies rely on metrics like "Mean Species Abundance

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[12] This does not mean that putting a price on CO_2 equivalent is sufficient, as many debates in climate economics discuss. One can nevertheless consider that the metric itself provides a relevant measure for aggregating pollution emissions data from firms across the world.

per Square Kilometer" (MSA.km^2) for specific tasks such as evaluating the biodiversity impact of a whole portfolio (e.g., Svartzman et al., 2021; van Toor et al., 2020), yet they readily acknowledge that a global indicator for biodiversity can conceal more than reveal the actual drivers of nature loss when it comes to designing full-fledged and potentially realistic scenarios. For this reason, the concept of Essential Biodiversity Variables (EBVs) was developed to identify, collect and share data necessary to understand biodiversity developments (Pereira et al., 2013).[13] In fact, indicators like MSA.km^2 are regularly coupled with multiple other proxies for biodiversity and ecosystem health to create a more meaningful proxy (Leclère et al., 2020).

Second, translating the contributions of different ecosystem services into monetary units, which could then feed into economic models, is a task fraught with difficulties and shortcomings for the purpose of assessing nature-related risks. Indeed, while it can be useful to include natural capital in national accounts (not the least because it can increase awareness among policymakers), it is not sufficient to generate scenarios aimed at assessing physical and/or transition risks: different physical disruptions or policies will result in indeterminate changes in the "stock" of natural capital across space and time. Moreover, the IPBES recognises that a key factor to generating scenarios is to recognise that nature carries different values to different social groups. In other words, nature does not have a 'fundamental' value that can be "discovered" with additional data or improved technology. Rather, nature's values are continually reinterpreted and internalised through social deliberation, cooperation and conflict (Pascual et al., 2017). In fact, many scholars (e.g., Costanza et al., 1997) engaged in the monetary valuation of ecosystem services acknowledge that this task is useful to raise awareness, but ultimately has little meaning for economic and policy-making.

Third, it is impossible to develop relevant nature-related narratives that consider multiple hazards in isolation of each other, as they are deeply interconnected. The loss of multiple critical ecosystem services (e.g., climate regulation, water purification, and maintenance function of species diversity) may stem from the degradation of a single ecosystem (e.g., forest). Moreover, the health and functioning of any one ecosystem is interdependent with the health and functioning of others (e.g., forests and watersheds). If scenario narratives approach interdependent environmental issues – like climate change and nature loss – separately, forecasts risk to greatly underestimate the likelihood and severity impacts. This can result in incomplete or weak policy responses that fail to protect human well-being while heightening risks of increased poverty, food insecurity, involuntary displacement, political conflict, and macrofinancial instability (Pörtner et al., 2023). In order to achieve maximum scientific and policy relevance, nature-related scenario narratives should therefore treat climate change and nature loss – and policies meant to overcome them – as inseparable phenomena with both positive and negative synergies. At a minimum, these narratives will need to be able to embrace some of the most well-known interdependencies between diverse forms of environmental degradation, as well as both the opportunities and trade-offs inherent in different responses to them.

2.1.3 Considering the non-substitutability of nature, and the resulting need to account for indirect impacts of nature-related hazards

While the implications of this topic are discussed in more depth in Chapter 3 it is important to emphasise that another challenge for developing scenarios to assess nature-related risks has to do with the treatment of substitutability of nature and the services it provides within economic models. Most existing models considering nature loss take the perspective of what is sometimes called a "weak sustainability" approach: the more or less implicit assumption that the negative effects of nature loss can be compensated for – i.e., substituted – with increases in labor and/or human-made capital.

As such, these models can lead to suggest that even in that case of a major disruption in ecosystem provisioning services, economies could always remain on relatively stable growth paths.[14] Indeed, as long as substitutability is deemed feasible, prices will automatically adjust to enable a

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[13] https://geobon.org/ebvs/what-are-ebvs/.

[14] As will be seen in Chapter 3, stable growth paths are an "exogenous" assumption in integrated assessment models, guaranteed by the presumed productivity increases. The additional assumption that factors of production are substitutable means that producers and consumers will easily adapt and adjust their behavior to mitigate potential losses. Any shock is therefore likely to result in only small and temporary deviations from a projected growth path.

smooth transition that allows for both continued economic growth and reduced environmental impacts (Godin et al., 2022; Rezai et al., 2013). For example, by assuming that arable land can be easily substituted by additional capital, labor or new technology, positive biodiversity outcomes in these models are virtually guaranteed by investments in agricultural productivity. Productivity-enhancing investments are assumed to automatically "spare" available land by relieving the pressure to expand cultivated area, thereby reducing deforestation. However, the assumption that agricultural intensification actually reduces land-use or environmental impacts remains highly debatable (Goulart et al., 2023; Lim et al., 2023).[15]

Hence, for the purpose of understanding whether and how nature loss could generate macrofinancial risks, it is essential to adopt what is sometimes called a "strong sustainability" approach (Daly & Farley, 2011; Dietz & Neumayer, 2007). This approach recognises that there is "little-to-no substitution possibilities between key forms of natural capital and produced capital, or for that matter any other form of capital" (Dasgupta, 2021, p. 330). The assumption of strong sustainability may increase the complexity of scenario development and even require a shift in the way we consider the interactions between nature, society and the economy. Nonetheless, it allows for more realistic assessment which integrates the potential for non-linear shocks to output, large disequilibria, and negative growth paths, from which economies do not easily recover.

Note that the assumption of "strong sustainability" does not imply that all forms of adaptation or substitution of some goods in a basket are impossible. Rather, it means that physical or transition hazards and shocks can undermine access to goods for which there is weak or non-existent substitutability, particularly in the short-run. Depending on the extent and intensity of shocks, adaptation in the medium- and long-run may be feasible. For example, the loss of the capacity to grow certain products in an agricultural zone (because it loses its ecological capacities or because it becomes protected) may be "overcome" by switching to alternative crops, importing the same crop or shifting towards an alternative diet. Even the possibilities for substitution in the long-run are ultimately constrained, however, particularly in the case that an irreversible tipping point is crossed, leaving an ecosystem in a permanently altered and degraded state.

Of particular importance for the purpose of assessing nature-related risks, the "strong sustainability" approach implies that when a hazard impacts a specific sector the initial impact is likely to be amplified as it ripples through multiple other sectors (Cahen-Fourot et al., 2020, 2021). This is particularly the case when an initial hazard is concentrated at the very beginning of value chains (e.g., agriculture and forestry or the fossil fuel and mining sectors), as is often the case with nature-related issues. Indeed, the assumption of no or low substitutability means that agents are not fully able to replace one missing input by another one, at least in the short to medium term. For instance, a physical hazard or shock on the agricultural sector (e.g., a drought or a stringent transition policy that limits agricultural production) could generate second-round impacts on the food processing and industrial sectors that use the agricultural input (e.g., a "stranding" of key inputs to production, an increase in input prices, and/or fall in value added), followed by additional shocks further along the value chain, ultimately impacting final consumption.

Accounting for such patterns is even more important in the case of simultaneous and interacting physical hazards or shocks, as can happen with nature-related patterns. Such simultaneity could, among other impacts, amplify shocks to value chains, especially if it limits their resilience by generating compounding and/or geographically broader knock-on effects and/or more persistent shocks. Similarly, interactions and simultaneity between nature- and climate-related hazards and shocks (see the discussion on nature-climate synergies in the previous sub-section) could generate powerful amplification mechanisms.

Not accounting for such indirect impacts could result in analyses that almost entirely overlook why nature matters, e.g., by focusing on marginal valuation methods. As ironically asked by Dasgupta, discussing

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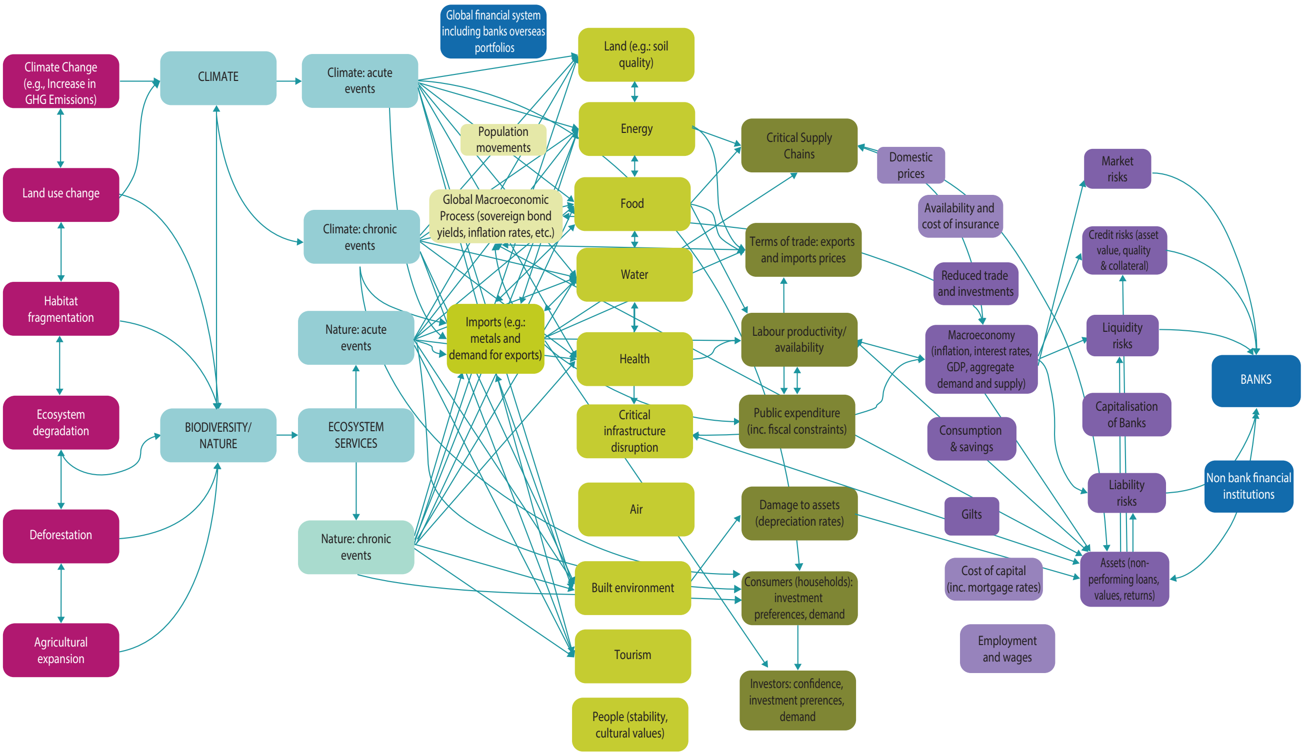
[15] Indeed, higher agricultural productivity may actually drive deforestation: First, farmers could be incentivised to expand by the potential for earning greater returns per hectare (Busch & Feretti-Gallon, 2023). Second, consumption demand from households or other sectors could increase as productivity gains drive down market prices for agricultural outputs. Third, the increase in agricultural productivity could drive employment and macroeconomic growth, resulting in additional demand for agricultural outputs and further increasing land pressures (Rezai et al., 2013). The existence of such environmental "rebound effects" imply that there may be inherent limits to sustainability strategies based on increasing resource productivity, alone (Lange et al. 2021).

the finding that pollination contributes to agricultural outputs corresponding to 0.03% of the UK's GDP in 2019: "why care whether any pollinators are left?" Dasgupta (2021, p. 324). Focusing only on the direct contribution to GDP of a given ecosystem service fails to account both for its biophysical relevance and systematically underrepresents its economic relevance.

When accounting for indirect impacts, it is possible to highlight how a natural hazard can have an overall economic effect that is amplified by losses in multiple sectors – upstream sectors (primary and extractive sectors, at the beginning of value chains) and/or downstream sectors (advanced manufacturing and services, at the end of value chains) – and across borders. For example, a reduction in the use of pesticides that negatively affects agricultural output may have only minimal apparent 'direct' impacts in a high-income country where the primary sector represents a small share of GDP and food costs are a small part of household budgets. Yet if the same sector is important for supplying global food markets (as the invasion of Ukraine has shown), the indirect macrofinancial implications could be large, and particularly acute for low-income food-importing countries.

This means that the narratives of scenarios should be designed in such a way that makes it clear that the assessment of their impacts (through models and tools discussed later in this Technical Document) should include different indirect impacts that they could generate. Figure 2.2 represents some risk transmission channels through which nature loss can pose risks to banks. The red boxes on the left-hand side represent different drivers of change (climate change, land use change, habitat fragmentation, ecosystem degradation, deforestation and agricultural expansion) which affect climate and nature and can result in acute and/ or chronic nature/ climate events. These in turn impact on different natural, human and economic capital that effect the preliminary economic receptors. Impacts on these primary economic receptors can directly generate financial risks, for example through increases in non-performing loans to specific sectors, as well as second-round domestic and global macroeconomic impacts that can also create financial risks.

Figure 2.2 **Schematic of Nature-Related Risk Transmission Channels**



Source: Ranger et al., 2023, developed as part of the INCAF project.

Accounting for all these variables and transmission channels could theoretically be approached through the use of system dynamics models, which are particularly adept at considering the relationships between multiple interacting variables (Uehara et al., 2021). To our knowledge, however, there is no single model that captures all of these interactions, and doing so would likely require years of work, if even possible (indeed, the uncertainty at stake would remain a limitation, no matter how complex and comprehensive the model is) (Maurin et al., 2022). As such, the rest of this Technical Document seeks to provide recommendations regarding how one can generate relevant narratives and use relevant models and tools that, even if they do not account for all possible variables and transmission channels, are at least more capable of representing some of the key dynamics that could ultimately generate macrofinancial impacts and risks. In what follows, we turn to the need to generate narratives with these elements in mind.

2.1.4 The need to overcome the "local-global tradeoff" generated by the challenges identified

Accounting for the challenges discussed above poses a major challenge to development of narratives of scenarios, which we refer to as the "local-global tradeoff". The local-global tradeoff refers to the inherent difficulty of coordinating between the (local) micro-level scale of analysis and the (global) macro-level. On the one hand (given the features discussed above), nature scenarios require consideration of how locally specific ecosystems, sectors and firms interact to understand how distinct policies and processes may drive changes at the smallest level and through very precise transmission channels. One could be tempted to assess such patterns through case studies or microeconomic analysis. On the other hand, however, local socio-economic and environmental changes must be aggregated to maintain tractability for scenario development, especially if the purpose is to assess macrofinancially-relevant impacts while generating a common language for central banks and supervisors across the globe. Indeed, local issues are likely to have multiple indirect, complex and compounding features which can then have cascading effects along global value chains – to other sectors and economies – through which they can become macrofinancially and globally relevant.

Overcoming the local-global tradeoff is not an easy task when attempting to assess both physical and transition risks. When assessing physical risks, scenario development should therefore be able to connect nature loss at the local scale (e.g., Amazon dieback) to its global drivers (e.g., global price and demand developments for livestock and cereal grains and implications along the global supply chain) and global impacts (e.g., a new pandemic, runaway climate change, food insecurity, etc.). When assessing transition risks, scenario development should be able to capture how decisive regulatory changes at multiple scales (e.g., local, national and global regulations) can have transformational impacts globally. IPBES refers to the concept of "transformative change" to capture this potential for multi-layered and broad-based social changes associated with the sustainability transition. Transformative change is defined as "a fundamental, system-wide reorganisation across technological, economic and social factors, including paradigms, goals and values, needed for the conservation and sustainable use of biodiversity, long-term human wellbeing and sustainable development" (IPBES, 2019, p. 889)[16].

In short, the local-global tradeoff for nature-related scenarios creates an imperative to use a framework that can help to aggregate locally specific environmental and economic dynamics across geographic scales and sectors. A new approach may therefore be needed to connect global macro and sectoral dynamics to local environmental changes. Importantly, this exploration could also benefit the NGFS climate scenarios, as they start delving into sectoral analysis (NGFS, 2023b). Note that while case studies are an important tool for illustrating specific nature-related risks, at best they only offer very limited guidance to overcome this tradeoff.

In what follows we suggest a general approach and specific methodologies through which we could overcome this tradeoff (and, more broadly, account for the challenges discussed above), for both physical and transition risks. This approach seeks to enable different countries to better identify what kind of hazard they could

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[16] Rodrik and Sabel (2020) note that uncertainty about behavior, technology and effectiveness of policies – which is especially large for policies aimed at reversing biodiversity loss – implies "optimal" policies that range over multiple margins of intervention and several different types of policy instruments.

prioritise and what type of data they could use to do so. We nevertheless acknowledge that more granular calibration may be needed for each country aiming to develop a more specific scenario, and we provide some guidance and examples in this respect. The focus nevertheless remains on describing a general approach that could create a common language across central banks and supervisors. As a reminder, Chapter 3 will then assess the extent to which existing models are capable of responding to some of the key challenges of scenario development mentioned above, and consider their ability to integrate the narrative outputs from the rest of this chapter.

2.2 Suggestions for developing physical and transition scenario narratives in light of the challenges identified

In this sub-section we suggest some ways forward to developing narratives of scenarios that could overcome the local-global tradeoff discussed above, while accounting for the challenges identified. We propose two complementary methodologies for physical risks: ESGAP-SESi – which enables for comparability across countries and can be understood as a way of downscaling the concept of planetary boundaries to the national level – and INCAF-Oxford – which focuses on specific potential physical hazards (or shocks) and their connections (backwards) to the specific natural assets and ecosystem services affected, and (forwards) to specific 'primary economic receptors' (e.g., sectors) of the hazards identified. For transition risks we carry out a comprehensive assessment of different frameworks that help understand the variety of policies and socioeconomic evolutions that could be implemented to reverse nature loss, showing that it is possible to focus on some of them and translate them into potential 'shocks' for specific countries and sectors (while calling for more work to better calibrate them). The outcomes of such narratives could then be used as inputs to economic models and tools aimed at assessing nature-related risks (as discussed in the rest of the report).

2.2.1 Two avenues toward developing narratives for physical risk assessments

2.2.1.1 Identifying physical hazards using ESGAP Strong Environmental Sustainability index (SESi)

For assessing physical risks, we suggest as a first option the use of a framework based on the Environmental Sustainability Gap – Strong Environmental Sustainability index (ESGAP-SESi, hereafter "ESGAP").

ESGAP provides an aggregate measure for identifying the distance between the current state and a "healthy" operating state for different ecosystems. As such, it is a tool that can help identify which ecosystems and their functions are more degraded than others, and thus more likely to collapse. In this way, it can help to translate the broad concept of planetary boundaries into observable trends at the national scale.

ESGAP combines multiple metrics on environmental health to determine the state of the environment (Figure 2.3). These indicate the degree to which a country's ecosystems are able to provide critical ecosystem functions – including acting as a source of natural resources, serving as a sink to recycle pollution, supporting life processes and biodiversity, and contributing to human health and wellbeing. The ESGAP-SESi methodology is built by normalizing, weighing and aggregating 21 sub-indicators of environmental sustainability.[17] For this reason, it can potentially serve as a more meaningful aggregate measure for nature loss (or improvement) than singular metrics of the same type.

Although ESGAP does not directly quantify the probability of collapse due to crossing tipping points (such knowledge is not scientifically discernable, given the complexity of natural systems), it provides a next-best method for approximating them. Indeed, the rationale is that the closer a country is to crossing thresholds for the 21 indicators identified, the less resilient the

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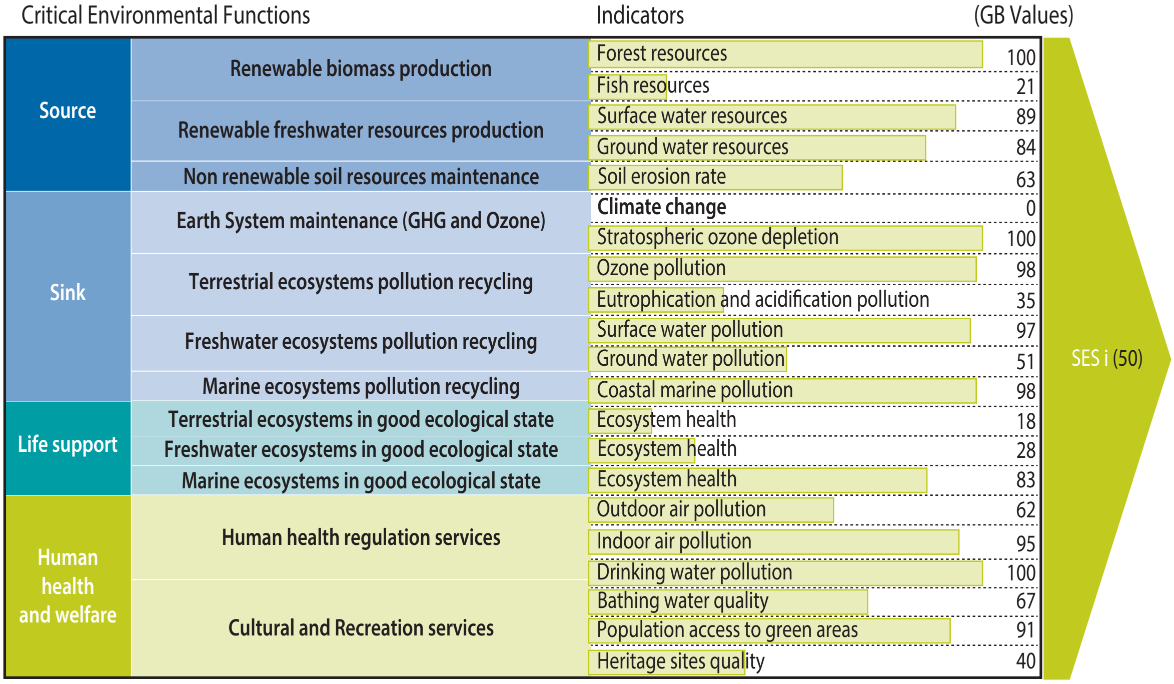
[17] More precisely, ESGAP combines the SESi (which makes it possible to identify the most problematic environmental functions in a given country) with the SESPi – Strong Environmental Sustainability progress Index –, which makes it possible to identify the environmental functions that are moving the fastest away from a standard of good condition. This makes it possible to construct a physical risk narrative by looking for which of the 21 sub-indicators that are both the most 'critical' in terms of the SESi and the SESPi (Usubiaga-Liaño and Ekins, 2022). In this way, for a given country, one can identify which functions are both in a more deteriorated state and have continued to deteriorate in recent years, thereby justifying their prioritisation. Similarly, it is also possible to identify those ecosystem functions that are already in a healthy condition, and those that are in poor condition but improving, according to the SESPi.

Figure 2.3 **The ESGAP-SESi (Strong Environmental Sustainability Index), with data for Great Britain**



Critical Environmental Functions		Indicators	(GB Values)
Source	Renewable biomass production	Forest resources	100
		Fish resources	21
	Renewable freshwater resources production	Surface water resources	89
		Ground water resources	84
	Non renewable soil resources maintenance	Soil erosion rate	63
Sink	Earth System maintenance (GHG and Ozone)	Climate change	0
		Stratospheric ozone depletion	100
	Terrestrial ecosystems pollution recycling	Ozone pollution	98
		Eutrophication and acidification pollution	35
	Freshwater ecosystems pollution recycling	Surface water pollution	97
		Ground water pollution	51
	Marine ecosystems pollution recycling	Coastal marine pollution	98
Life support	Terrestrial ecosystems in good ecological state	Ecosystem health	18
	Freshwater ecosystems in good ecological state	Ecosystem health	28
	Marine ecosystems in good ecological state	Ecosystem health	83
Human health and welfare	Human health regulation services	Outdoor air pollution	62
		Indoor air pollution	95
		Drinking water pollution	100
	Cultural and Recreation services	Bathing water quality	67
		Population access to green areas	91
		Heritage sites quality	40

Note: ESGAP-SESi construction and its value for Great Britain, adapted by authors from Usubiaga-Liano & Ekins (2021a). The larger the light green area, the closer the ecosystem function is to a healthy state (i.e., there is a smaller "gap" between the current state of the environment and the "good" environmental standard). The smaller the yellow area, the further the ecosystem function is from a healthy state, (i.e., there is a large "gap" between the current state of the environment and the "good" environmental standard). The overall ESGAP-SESi value for Great Britain (based on 2018-2019 data) of 50 indicates that it meets 50% of the standards for a healthy and sustainable environment. This 50% value is calculated by the geometric mean of the 21 sub-indicators, which makes it possible to identify which environmental functions are in a better condition than the most problematic ones. It is then possible to construct a scenario narrative based on the most degraded environmental functions specific to the country.

Source: Adapted from Usubiaga-Liano & Ekins (2021a).

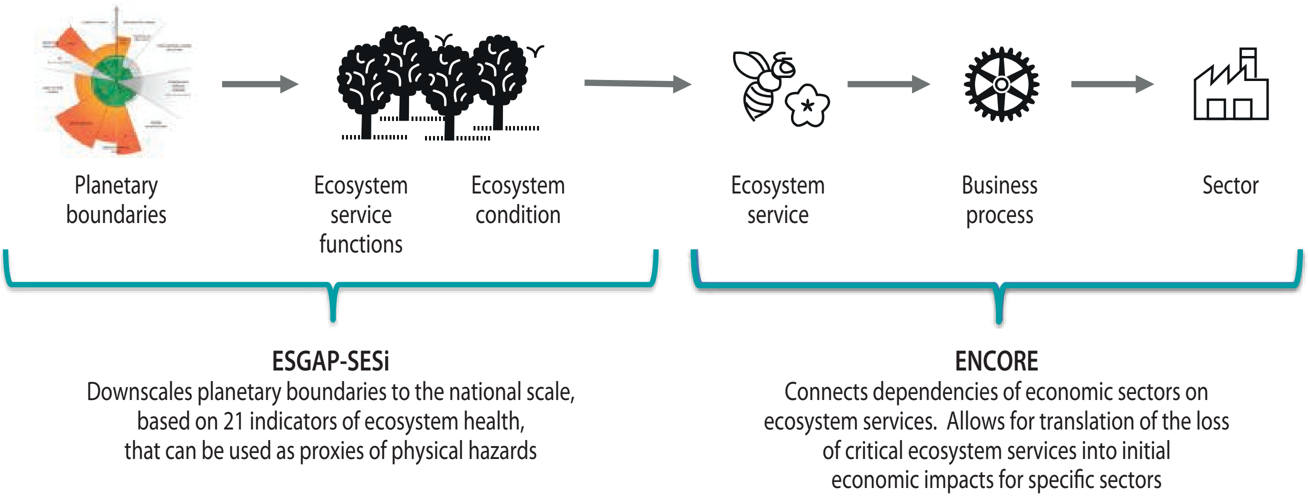
ecosystem and the more likely a physical hazard becomes. ESGAP can therefore serve as a proxy for determining the potential appearance of potential physical hazards, without having to rely on an aggregated indicator.

Importantly, the ESGAP framework also incorporates the concepts of strong sustainability in its measurements, since natural capital is counted only in terms of its biophysical dimensions, and cannot be reduced to monetary values. Moreover, aggregation of individual indicators is weighted to penalise low values (by taking the geometric mean), implying both interdependence and poor interchangeability between ecosystem functions (Usubiaga-Liano & Ekins, 2021b). In this way, the ESGAP framework is able to overcome many of the difficulties described in the previous section related to data aggregation and the non-substitutability of nature.

By combining ESGAP with different datasets (matrices combining ecosystems to ecosystem services and matrices combining ecosystem services to sectorial activity), it is possible to identify which economic sectors are more likely to be *directly* impacted by physical hazards. For example, the ESGAP methodology can be combined with ENCORE (**Figure 2.4**). The ENCORE (Exploring Natural Capital Opportunities, Risks, and Exposure) database assesses the interdependence of 86 types of production processes with 21 ecosystem services (see **Annex 7.2.1** for more details). By linking ESGAP and ENCORE, research can provide a snapshot in time of both ecosystem integrity and ecosystem dependency. In this way, it is possible to understand which sectors in which countries are most exposed to particular forms of environmental degradation, based on their dependence on particular ecosystem services. This was precisely done to assess the potential economic impacts from biophysical pressures in New Caledonia (Comte et al., 2023) and Vietnam (Nguyen et al., 2022).

Although the ESGAP framework offers a promising

Figure 2.4 **Proposal for Connecting ESGAP to tools such as ENCORE, so as to translate ecological patterns into specific hazards for specific sectors/countries**



Source: Authors.

avenue for scenario assessment, the tool is not yet usable by all countries – particularly given the need for additional data to fill the 21 indicators for every country across the globe. However, ongoing research and the use of proxy data has enabled researchers to add to a database of countries for analysis (Fairbass et al., 2020), which is increasingly complete.[18] Future research could also rely on more disaggregated versions of ESGAP (e.g., to assess risks at the regional or municipal levels) or sector-specific ESGAP indices in order to better approximate the potential for physical hazards.

2.2.1.2 Identifying physical hazards using INCAF-Oxford analysis

A second option for identifying physical hazards has been developed by a team of researchers at Oxford University as part of the INCAF[19] project (herein INCAF-Oxford). The INCAF-Oxford team has developed an indicator-based approach that aims to provide a comprehensive tool to identify and understand the most important material financial risks to a country, sector, or portfolio. Indicator-based approaches have been promoted in recent years as useful tools for assessing, comparing, and monitoring the complexity of environmental risk from local to global scales. By connecting data across multiple relevant metrics, indicator-based approaches can allow users to identify potential physical hazards and their likely impacts. Indicator approaches are able to simplify complex and interacting parameters by quantifying key environmental changes, exposure and vulnerability to assess risks. **Annex 7.2.2** includes a list of prominent indicator-based risk assessments that are commonly used within a range of environmental, economic and financial policy contexts.[20]

This methodology for creating narrative scenarios focuses on evaluating risk through the lens of hazard, exposure, and vulnerability. For instance, this could involve utilizing metrics that gauge the likelihood of events such as storms and the degradation of mangrove ecosystems,

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[18] Several case studies have already published calculations of SESi in different contexts, including New Caledonia, Kenya, Vietnam and Senegal, and others are in progress, such as Japan, South Africa and Colombia. Other research is underway to establish preliminary SESi for 237 countries using global databases. The data available provides information on 14 of the 20 environmental function sub-indicators established on this global scale. The difficulties encountered at this stage for 6 environmental functions mainly concern the functions of absorbing pollutants from terrestrial and marine ecosystems, maintaining freshwater biodiversity and renewing forest biomass.

[19] https://www.eci.ox.ac.uk/research/greening-finance-nature-nature-related-risk-and-impact.

[20] Interestingly, such indicator-based risk assessments can be broadly complementarity with the ESGAP approach. The indicators listed in **Annex 7.2.2** are generally "state indicators", without reference to the ideal value that these indicators should keep for a particular region or country. ESGAP could specifically contribute in this case, since it provides an index of the present environmental state relative to a "healthy" standard. In other words, rather than presenting the state value of the environment, ESGAP computes the distance between the state and the ideal (sustainable) value.

deteriorating water quality coupled with water stress, or the emergence of antimicrobial resistance in areas with inadequate sanitation. Hazard, exposure, and vulnerability coefficients are applied to each distinct ecosystem service to quantify the potential scope of impact.

Focusing on the hazards (i.e., shocks) to natural capital, and their relationships to specific ecosystem services in a particular country or region, reduces the complexity of the analysis. Moreover, it allows for greater flexibility, by introducing the main degradation drivers, exposures and vulnerabilities into the framework. For example, a physical hazard has the potential to affect multiple natural assets and ecosystem services, as well as exert a cascading effect on the economy through various channels. Each hazard can be studied alone, constituting its own scenario, or shown to intersect with other risks (resulting from this initial hazard) to create multifaceted narratives, including those that involve compounded risks.

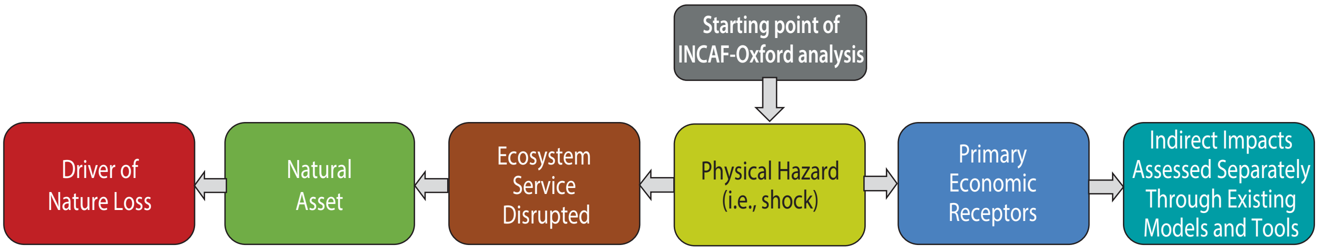
A long-list of potential material hazards (and associated risks) generated by nature loss and degradation of ecosystem system services was compiled for the purpose of this Technical Document through drawing upon the academic and grey literature, including from synthesis reports such as IPBES (2019); UNEP WCMC (2018); the Millennium Ecosystem Assessment (2005) and IPCC (2022) as primary sources, as well as the Stockholm Resilience Centre's Regime Shifts Database (Rocha et al., 2015) and references therein. From this basis, the INCAF-Oxford team compiled a synthesis of historical analogues from which to analyse hazards and risk transmission channels and combined this with evidence on individual dependencies, impacts and risks both from the empirical literature and simulation models (Ranger et al. 2023). This long list was then tested for comprehensiveness through desk-based data collection and literature review on risks to specific countries and specific risk transmission channels conducted as part of the INCAF project, as well as comparing with the existing literature on nature-related financial risk assessment.

Hazards were then mapped *forwards* to economic impacts and *backward* to ecosystem services, natural assets and drivers of degradation along the impact chain, as illustrated in Figure 2.5. The backward linkages are based on evidence collected from the literature (notably findings as reviewed by the IPBES) and consultations with experts through the INCAF project. The forward linkages are calibrated using ENCORE (**Annex 7.2.1**) dependency scores per sector, which can generate estimates of scope 1 and scope 3 nature-related exposures through coupling ENCORE with the EXIOBASE input-output modelling approach (building upon Svartzman et al., 2021).

Moving *forward* along the impact chain from the hazard, the focus of the analysis is on the *'primary economic receptors'* in the economy. Primary economic receptors, as defined here, includes the economic sectors that are directly impacted by the specific hazard, but also non-sector specific receptors, such as labor productivity, public expenditure or fixed capital assets, that are also directly impacted by nature-related hazards.

Importantly, at this stage we do not seek to understand how sectors other than the 'primary economic receptors' could be impacted by such hazard. Indeed, this analysis will be conducted in the next chapters of this Technical Document, which precisely aim to assess whether economic models and tools are capable of representing both the nature of the hazard on the 'primary economic receptors' and the indirect impacts on other sectors and final demand.

Figure 2.5 **Building blocks of INCAF-Oxford process to generate scenario narratives to assess physical hazards**



Source: Authors, adapted from Ranger et al. 2023.

Table 2.1 summarises the initial set of narrative scenario building blocks. This contains around fifty unique hazards and more than eighty risk-receptor pairs. The table does capture climate shocks and change but only where there is a known nature-related aspect to the impact chain. The table contains information on key characteristics of hazards and impacts that can be useful in building scenarios. For example, it identifies where an acute climate hazard (or shock), such as a drought, could compound with the nature-related hazard to trigger or heighten further impacts. It characterises the hazard in terms of chronic, acute or regime shift, where a regime shift entails an event that could occur rapidly and lead to large, non-linear and irreversible change. Hazards are also characterised in terms of their scale.

To generate the final risk indices, a further layer is added that represents the differential vulnerability and exposure to this hazard across countries, as well as any compounding hazard. For example, to represent the risk related to the 'flood and storm protection' ecosystem service, it is necessary to include information on the vulnerability of a country to floods and storms as well as the likelihood of floods and storms. Similarly, for 'disease control' a risk index is constructed that combines both the likelihood that the disease control ecosystem service will be impacted and the vulnerability of the country in terms of pre-existing health vulnerabilities.

Extensive literature research, detailed in Ranger et al. (2023), was conducted to build such risk indices, with sources including UN SD, AQUASTAT, FAOSTAT, UN SDG, World Bank, UNICEF, WHO, WAHO, ECMWF, INFORM index. All information on the individual variables that contribute to the risk indices and their rationale are also described in Ranger et al. (2023). All of the selected variables are open source and continuous, provide consistent global coverage, and have the potential to be scalable from the national to the local level, as well as from the yearly to the seasonal (monthly) scale. Only the most recent information was used for all indicators.[21] Moreover, all selected indicators are aggregated with equal weight method, which remains the most frequently chosen in rapid data-driven risk assessments.[22]

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[21] Missing values were first replaced by the latest record available within a five-year period of the selected year. If there were no records available, the median values of the corresponding regional income groups were used to replace the missing information.

[22] There are numerous examples of this method producing effective results, such as the Human Development Index and the Environmentally Sensitive Areas (ESA) index (Kosmas et al., 2014; Becker et al., 2017). Other methods are distinguished by their various benefits and drawbacks. However, when complex weighting schemes are chosen, the unavoidable customisation of the process increases its inherent subjectivity, while the uncertainty surrounding decision formulation may reach critical levels. Thus, if various weighting methods produce comparable results, the simplest method should be selected (OECD, 2008).

Table 2.1 **Selected examples from INCAF-Oxford Nature-Related Risk Scenario-Building Tool**

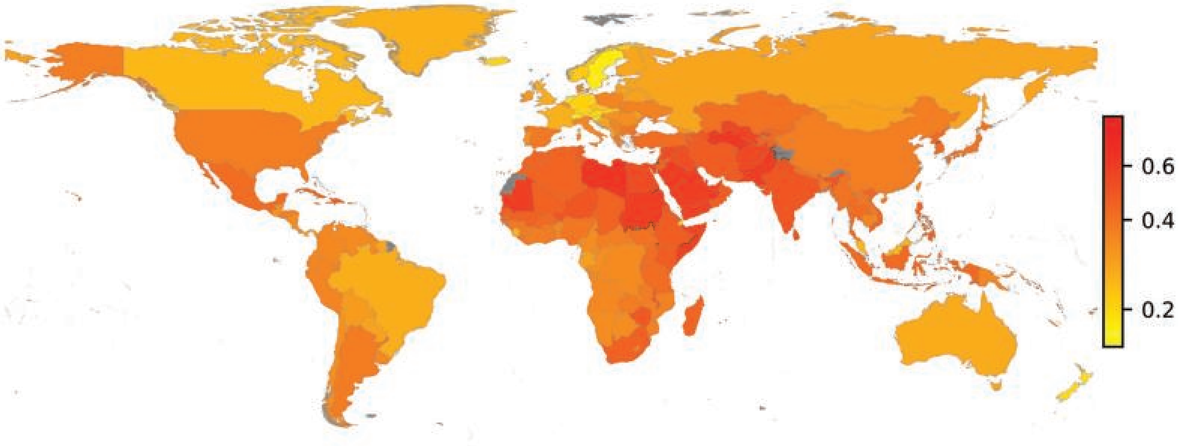
Driver of nature loss	Amplifier	Natural capital [impacted by driver]	Indirect natural capital [impacted by driver]	Ecosystem service disrupted [ENCORE, italics indicates missing]	IPBES NCP [primary]	Physical hazard (i.e., shock)	Chronic / Acute / Regime shift	GEO scale	IPBES NCP / ENCORE dependency impacted	Primary receptor	Primary economic receptor
Land conversion	Climate change	Water		Water flow maintenance/ Mass stabilisation and erosion control	Regulation of freshwater [6 and 7]	Hydropower water shock	Acute/ Cchronic	National	Energy (11)	Energy Prices (Hydro)	TFP; prices
Land conversion	Climate change	Water		Water flow maintenance/ Mass stabilisation and erosion control	Regulation of freshwater [6 and 7]	Energy – nuclear/ Gas/coal	Acute/ Chronic	National	Energy (11)	Energy prices	TFP; prices
Land conversion, pollution	Climate change	Diseases / Pests		Disease Control/ Pest Control	Regulation of organisms detrimental to humans (10) , Food and feed (12)	Grain crop pest/ Pathogen outbreak	Acute	National	Food and Feed (10)	Agricultural production	Prices; TFP
Land conversion, pollution	Climate change	Diseases / pests	Biodiversity	Disease Control/ Pest Control	Regulation of organisms detrimental to humans (10)	Forestry outbreak (e.g. Silka spruce pest; red maple in US)	Acute	Local	Materials and assistance (13); Energy (11)	Forestry	TFP
Land conversion, pollution	Climate change	Diseases / pests	Biodiversity	Disease Control/ Pest Control	Regulation of organisms detrimental to humans (10)	Amazonian parasites on hevea brasiliensis (i.e. conducive rubber trees)	Acute	National	Materials and assistance (13)	Industry (aviation, rubber dependant sectors)	Prices; TFP
Land conversion, pollution	Climate change	Land	Climate	Climate Regulation / Flood and Storm Protection	Regulation of climate (4)	Changing intensity of extremes – floods	Acute	National		Real-estate	Capital depreciation rates
Land conversion, pollution	Climate change	Land	Climate	Climate Regulation / Flood and Storm Protection	Regulation of climate (4)	Changing intensity of extremes – floods	Acute	National		Industry (BI & damage)	TFP

Land conversion, pollution	Climate change	Land	Climate	Climate Regulation– / Water flow maintenance	Regulation of climate (4)	Changing AG productivity (inc drought)	Chronic/ Acute / Regime shift	National	Food and feed (10)	Agriculture	Prices; TFP
Land conversion, pollution	Climate change	Land	Climate	Climate Regulation / Water flow maintenance	Regulation of climate (4)	Forestry collapse	Chronic/ Regime	National	Materials and assistance (13)	Forestry	Prices; TFP
Land conversion, pollution	Climate change	Land	Climate	Climate Regulation / Water flow maintenance	Regulation of climate (4)	Water supply shock	Acute	National		Industry	TFP
Land conversion, pollution	Climate change	Land	Climate	Climate Regulation / Water flow maintenance	Regulation of climate (4)	Impacts on energy production (wind/ hydro/solar/ nuclear/gas/coal)	Acute/ Chronic	National	Energy (11)	Energy	Prices; TFP
Land-conversion/ deforestation/ overexploitation (aggravated drought – multiple breadbasket)	Climate change	Land		Climate Regulation	Regulation of climate (4)	Major global food system shock	Acute / chronic	Global	Food and feed (10)	Food prices	Prices; TFP
Land-conversion/ deforestation/ overexploitation (aggravated drought – multiple breadbasket)	Climate change	Land		Climate Regulation	Regulation of climate (4)	Major global food system shock	Acute/ Chronic	Global	Food and feed (10)	Migration	Labour productivity; public exp

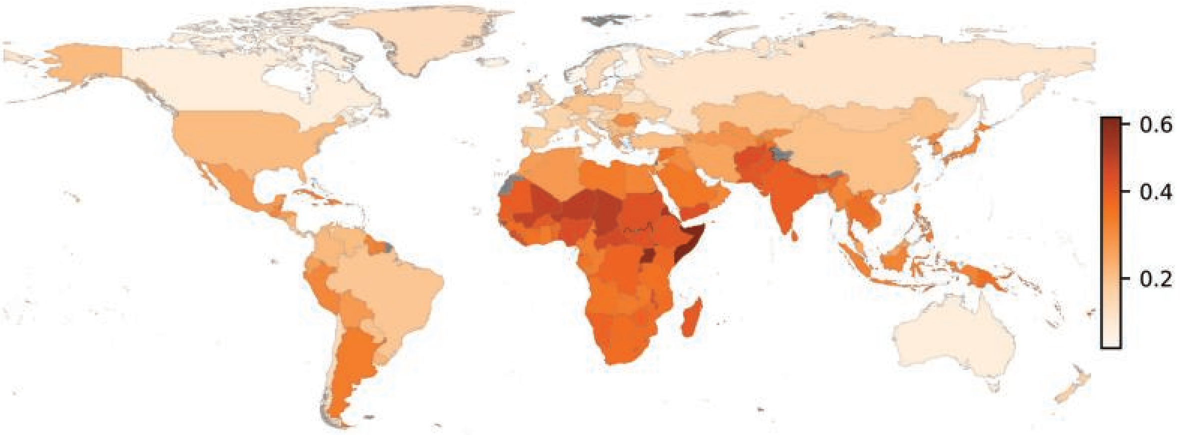
Note: INCAF-Oxford nature-related risk scenario building tool connects multiple types of hazards (orange column) to their sources (backwards, leftward) and impacts (forwards, rightwards). Hazard sources can be uncovered while moving backwards in the scenario tool (leftward from hazards column). Each hazard is connected to disruptions in specific ecosystem services. These ecosystem services are functions of natural assets, which are degraded by multiple different drivers of nature loss. Hazard impacts can be seen while moving forwards in the scenario tool (rightwards from hazards column). The severity of each hazard's impact will depend on whether it is a chronic problem, an acute shock, or resulting in a major regime shift in a given biome. Moreover, each hazard will result in direct impacts on multiple different sectors ("primary receptors"), with consequences on key macroeconomic variables ("primary economic receptors"). From there, it is possible to connect impacts on primary economic receptors to indirect effects and cascading impacts on other sectors both domestically and internationally (not shown in table), as will be explored in the next chapters.
Source: Ranger et al. 2023.

Through this indicator-based approach, one can rapidly understand how different countries are potentially vulnerable to different hazards, as shown in Figure 2.6, below.

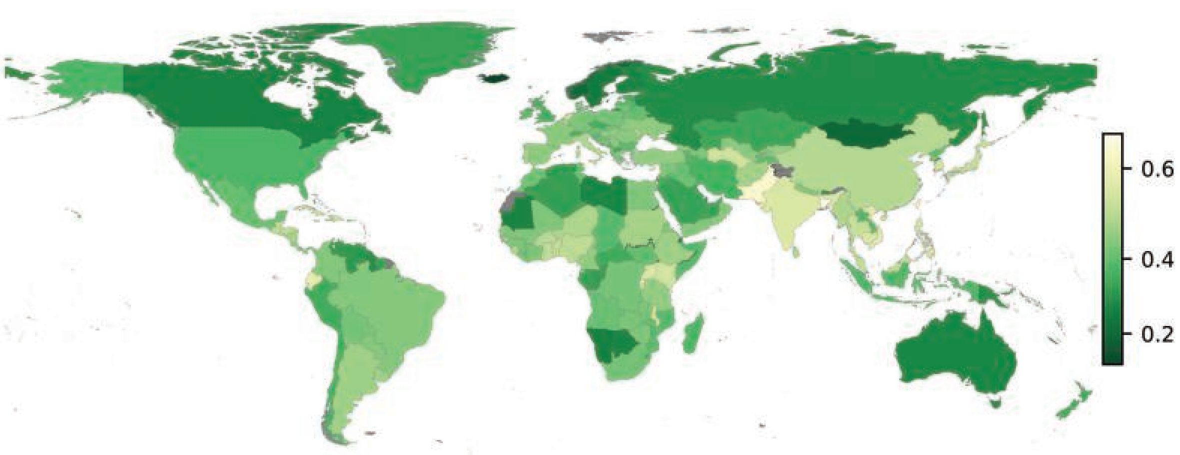
Figure 2.6 **Global maps of hazard-vulnerability indices: (a) Surface water; (b) Water quality; (c) Pollination; (d) Ventilation (air quality risks); (e) Ground water**



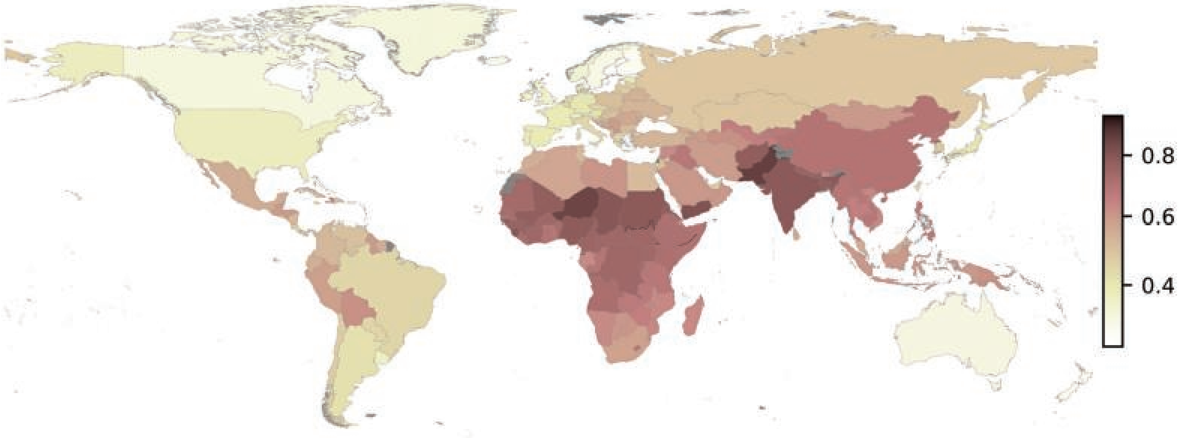
(a)



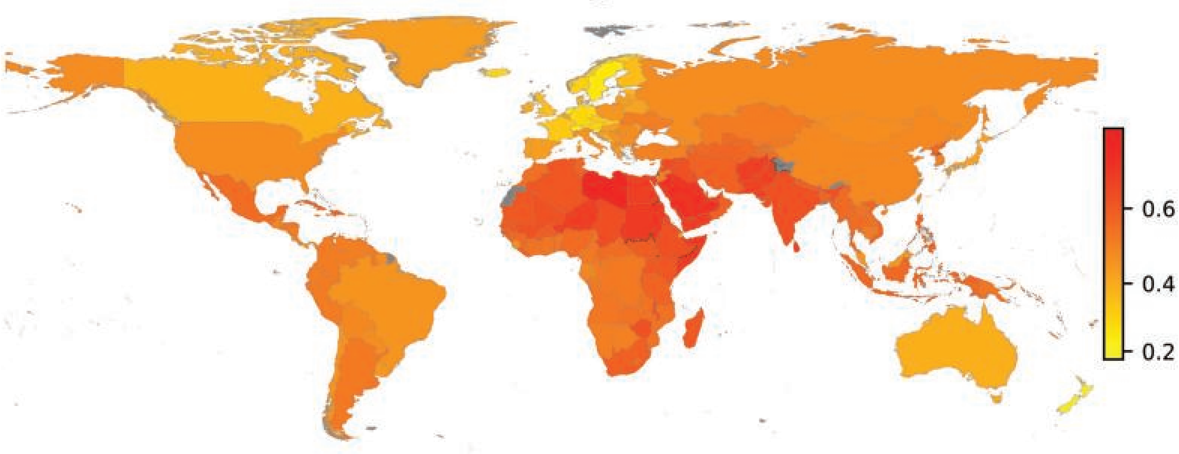
(b)



(c)



(d)



(e)

Note: Hazard-vulnerability indices depicted here are scaled from 0 to 1. These indices represent a combination of the hazard (scale and likelihood of hazard) and vulnerability to the hazard. See Ranger et al. 2023 for more details.
Source: Ranger et al. 2023

However, it is also possible to work at a more granular level by combining the different databases and hazards in ways deemed relevant for a specific analysis. For instance, if one were to focus on potential droughts in a country like France, it would be possible to select specific hazards, such as the ones listed in **Table 2.1**, so as to translate them into specific shocks for different 'primary economic receptors'. Such an exercise is conducted in Chapter 4 of the report, wherein a severe drought in France is used as a case study. In this case, according to the INCAF-Oxford methodology a major drought event in France would hinder the ecosystem services of surface water and dilution by atmosphere and ecosystems, resulting in increased water and heat stress, air pollution, and fire risk. These then have a number of impacts on multiple sectors including agriculture and manufacturing, in particular.

In summary, the INCAF-Oxford methodology for identifying and assessing physical hazards provides a clear pathway forwards for developing physical risk narratives for scenario assessment. This framework offers a scientifically rooted assessment of the most important or likely hazards that can be experienced, and connects them both forwards (to their direct impact on "primary economic receptors"), and backwards (to the drivers of environmental degradation which cause them). **Interestingly, because the INCAF-Oxford methodology is also based on the use of both (i) indicators of environmental risk and (ii) the ENCORE tool, it may also be possible to combine the use of ESGAP and INCAF-Oxford methodologies to build physical risk scenario narratives, in the future.** For example, it would be possible for ESGAP to serve as an additional criterion for selecting physical hazards by determining which ecosystem services are furthest from the safe operating space. This complementary approach would allow each central banks and financial supervisors to then country to select the hazard that is most likely to occur within their particular jurisdiction.

2.2.2 Avenues toward developing narratives for transition risk assessments

2.2.2.1 Translating multiple transition pathways into initial hazards for specific countries and sectors

As discussed above, the transition to a nature-positive economy is unlikely to be triggered by a singular event (the passing of one law or the implementation of a single price) and it cannot be "proxied" by a single metric like CO_2-equivalent for climate change. Instead, it will combine a multiplicity of regulations and policies at multiple levels of governance, in many countries at once. These may range – to name just a few – from local regulations on water use (Albert et al., 2021), to national policies to remove environmentally harmful subsidies (Matthews & Karousakis, 2022), to internationally-binding agreements on issues such as deforestation or payments for ecosystem services from high-income to low-income countries.[23]

Narratives for transition risk assessments must therefore account for a wide and concomitant range of socio-economic and political changes aimed at relieving a broad range of environmental pressures. In the case of biodiversity, at least five drivers of nature change should be taken into account (IPBES, 2019): land- and sea-use change; direct natural resources exploitation; climate change; pollution; and invasive alien species (see **Figure 2.7**). Other planetary boundaries may require accounting for alternative pressures. Ideally, a comprehensive narrative would be able to translate the different pressures that economic activities are putting on nature into specific policies (or other vectors, such as changes in technologies, new agricultural practices, consumer preferences, and so on), which can then impact specific sectors in specific countries, thereby generating different macroeconomic impacts (on final consumption, government revenues, and so on).

However, no standardised scenarios are available today that can be used as such by stakeholders, such as the NGFS. It is therefore critical to develop a tailored approach to how the narratives of such scenarios could be built for the purpose of assessing nature-related risks. As a result, the "local-global tradeoff" discussed earlier is also at play here: the more disaggregated a narrative, the less it can be tailored to global scenarios; the more global the narrative, the less realistic and adapted to specific policies that each country may implement.

In order to start overcoming this challenge – and while calling for more work in this area – we conducted a review of eleven different frameworks covering different transition policies (or trends beyond policies) that could take place. The full review of each framework is in **Annex 7.2.3**, and we simply include a brief description of these frameworks in **Table 2.2** as well as a detailed review of one of these frameworks: the Global Biodiversity Framework below (**Table 2.3**).

The purpose of this review is to identify the key policies or trends that emerge as common factors, and that could therefore be used as relevant transition hazards whose impacts should be assessed by economic models and tools. For instance, a review of the Global Biodiversity Framework Targets would seek to assess how the following transition trends, among many others, could impact different countries and sectors: policies and regulations that seek to align with (i) GBF Target 3 to protect up to 30% of terrestrial and marine surfaces by 2030; (ii) GBF Target 7 to reduce the risk of harm from pollution, pesticides and hazardous

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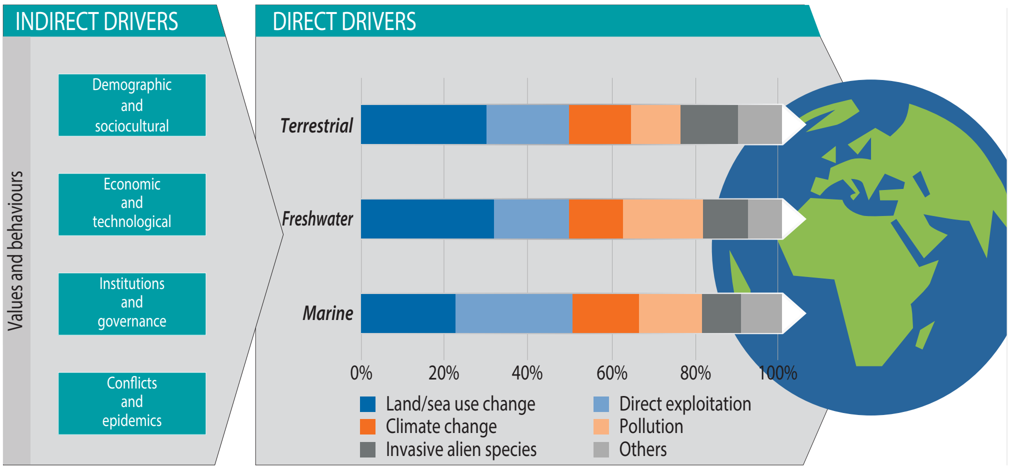
[23] See for example the recent summit called by Brazil for all countries that share parts of the Amazon rainforest: https://wwf.panda.org/wwf_news/?9463416/Amazon-Summit-Belem.

Figure 2.7 **The drivers of biodiversity loss, and the challenge of translating them into specific hazards (or vectors of potential transition risks)**



Source: Authors, based on IPBES (2019).

chemicals by 2030; and (iii) GBF Target 18 to remove or reform US $500 billion environmentally harmful subsidies by 2025. While none of these may be sufficient on their own to bring about the "transformative change" necessary to achieve a nature-positive future (IPBES, 2021), these narratives can be seen as a useful basis for scenario development.

It nevertheless goes beyond the scope of this Technical Document to assess how each of these potential policies could impact specific sectors in specific countries. The latter should be done jointly with experts and with relevant stakeholders.[24] The next chapter (Chapter 3) precisely assesses the extent to which existing economic models are able to integrate such types of policies. Moreover, given that present models are shown to be capable of assessing policies in only a very limited manner, Chapter 4 presents a case study conducted to indicate how a specific policy could be translated into impacts for some sectors in some countries, before propagating to other sectors and countries.

In order to better assess how each transition-related hazard could impact different sectors and countries (thereby feeding into models and tools assessed in the next chapters of this Technical Document), future work can focus on the following two steps.

First, relatively simple metrics could be developed to assess how different countries and sectors could be impacted by each policy covered. This type of exposure analysis could enable central banks and supervisors in different regions of the world to distinguish the types of hazards upon which they should focus. For instance, in order to identify the impact of the implementation of GBF Target 3 aimed at protecting 30% of terrestrial surfaces worldwide, analyses could begin by assessing countries based on the degree to which key macroeconomic variables depend on agricultural production (including exports and imports), the share of territory designated as a "high-priority" conservation zone for biodiversity, and/or the share of agricultural land area likely to be displaced by protection measures. Likewise, one could envision a transition scenario narrative based on alignment with GBF Target 19, which seeks the reversal and reform of environmentally harmful subsidies. In this case, analyses could begin by building on (and completing) existing databases assessing how much each sector (in each country) receives in environmentally harmful subsidies (Koplow & Steenblik, 2022; Matthews & Karousakis, 2022). It would then be possible to model relatively simple shocks by removing such subsidies from the value added generated by the sectors.

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[24] For example, the TNFD (2023b, 2023c) has expressed the intention to work on more advanced scenarios for financial institutions or larger non-financial corporates with more complex analytic or reporting needs and in-house capabilities.

Table 2.2 **A brief overview of transition-risk frameworks**

Tool / framework	Description
Global Biodiversity Framework (GBF)	Kunming-Montreal Global Biodiversity Framework (GBF), agreed at the COP15 UN Convention on Biological Diversity, establishes global targets for biodiversity conservation. It includes four goals and 23 targets for achievement by 2030-2050 and establishes an ambitious policy framework for government and whole-of society action on nature. This hinges on a collective mission of halting and reversing biodiversity loss by 2030, by promoting conservation, restoration, sustainable use of nature, and equitable sharing of benefits, and a vision of "living in harmony with nature" by 2050. While CBD resolutions are non-binding, all 196 signature parties agreed at COP15 in Montreal to update their national biodiversity strategies and action plans (NBSAPs) to proceed with the implementation of the GBF at their jurisdiction level. By mainstreaming nature across policies and decision-making processes, signatories encourage the implementation of the GBF through regulatory and other measures by all actors of society.
Environmental Sustainability Gap (ESGAP)	The Environmental Sustainability Gap (ESGAP) framework is a tool that can be used to measure the environmental sustainability performance of nations. It provides a metric of analysis that links concepts of strong sustainability and critical natural capital to determine whether the essential functions of natural capital can be sustained in the long term. Generally applied via static index (SESi) and dynamic index (SESPi),. **Strong Environmental Sustainability index (SESi):** an index built from 21 indicators of critical ecosystem functions' distance to standards of environmental sustainability. A 'snapshot' view as to whether countries currently meet science-based environmental standards for a wide range of environmental and resource topics. **Strong Environmental Sustainability Progress index (SESPi):** an index developed to measure sustainability progress. Comprises the same 21 indicators of critical ecosystem functions as for SESi, but to measure whether, under current trends, standards of environmental sustainability will be reached by any chosen time horizon (e.g., in 2030 in a recent article on Europe[1]). Provides a sense of whether 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.
Inevitable Policy Response (IPR)	IPR forecasts the possibility that governments will be driven to act decisively on climate change and nature loss – far more than they have thus far – thereby leaving private financial portfolios and public balance sheets exposed to potentially major transition risks. Forecasts suggest a generalised acceleration in policy responses, driven in part by increasing environmental disruptions, social costs, and growing public pressure for change. Policy responses may become "increasingly be forceful, abrupt, and disorderly leaving financial portfolios exposed to significant transition risk". Forecast Policy Scenarios for Climate and Nature (FPS + Nature) model the impact of the forecasted policies on the real economy and the environment up to 2050. Scenarios are based on assessments with leading experts on likely policy outcomes and projected technological changes. Attempts to consider the effects of policy responses and climate change on all major economic sectors, tracking changes to energy demand (oil, gas, coal), transport, food prices, crop yields, and rates of deforestation.
Science-Based Targets Network (SBTN), Science-Based Targets (SBT) for nature	Science-Based Targets Network (SBTN) is a network of 45+ organisations which develops methods and resources for establishing and implementing science-based targets (SBTs) for nature for both companies and cities. Its goal is for the world's major companies and cities to have adopted science-based targets to take action on water, land, ocean, and biodiversity by 2025. SBTs are defined as measurable, actionable, and time-bound objectives, based on the best available science, that allow actors to align with Earth's limits and societal sustainability goals. SBTs are designed to help organisations and cities to assess impacts and dependencies on nature and the environment and prioritise areas of action.
Taskforce On Nature-Related Financial Disclosures (TNFD)	TNFD offers a risk management and disclosure framework for organisations to assess, manage and disclose on evolving nature-related issues. The TNFD provides guidance on scenario analysis (TNFD, 2023a, 2023b, 2023c) developed to help organisations understand risks and test the resilience of their strategy, given complex uncertainties. It allows individual organisations to explore the possible consequences of ecosystem degradation and the ways in which governments, markets and society might respond, and the implications of these uncertainties for business strategy and financial planning. It describes an approach to scenario analysis built around two critical uncertainties, ecosystem service degradation and the alignment of market and non-market forces. A 'toolbox' of tools and templates is provided to facilitate workshop-based scenario exercises by corporates, along with insights from four pilot tests. Scenario analysis can support an integrated assessment of nature-related issues, based on the TNFD "LEAP" approach. This includes four phases, following an initial scoping of organisational priorities: **Locate** the organisation's interface with nature; **Evaluate** dependencies and impacts on nature; **Assess** the organisation's risks and opportunities; and **Prepare** to respond to, and report on, nature-related risks and opportunities.

[1] See Usubiaga-Liaño & Ekins (2022).

Millennium Ecosystem Assessment (MA)	The 2005 Millennium Ecosystem Assessment (MA) developed a set of four scenarios to explore alternative development paths for world ecosystems and their services over the next 50 years and the consequences of these paths for human well-being. It proposes a methodology for developing qualitative narratives and modeling quantitative scenarios that integrate social, economic and environmental dimensions. It includes an analysis of global changes, alongside regional disaggregation of global patterns, and aims to reflect the deep uncertainties of long-range projections for key social and environmental variables, particularly acknowledging the possibility of multiple feedback effects and ecological regime shifts. Four scenario narratives of global trajectories: **Global Orchestration:** Depicts a worldwide connected society in which global markets are well developed. Supra-national institutions are well placed to deal with global environmental problems, such as climate change and fisheries. However, their reactive approach to ecosystem management makes them vulnerable to surprises arising from delayed action or unexpected regional changes. **Order from Strength:** Represents a regionalised and fragmented world concerned with security and protection, emphasizing primarily regional markets, and paying little attention to the common goods, and with an individualistic attitude toward ecosystem management. **Adapting Mosaic:** Depicts a fragmented world resulting from discredited global institutions. It sees the rise of local ecosystem management strategies and the strengthening of local institutions. Investments in human and social capital are geared toward improving knowledge about ecosystem functioning and management, resulting in a better understanding of the importance of resilience, fragility, and local flexibility of ecosystems. **TechnoGarden:** Depicts a globally connected world relying strongly on technology and on highly managed and often-engineered ecosystems to deliver needed goods and services. Overall, eco-efficiency improves, but it is shadowed by the risks inherent in large-scale human-made solutions.
Shared Socioeconomic Pathways (SSP)	Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are typically used to derive scenarios of different climate policies to project future concentrations of greenhouse gas emissions. SSPs describe five different scenarios of trends in socio-economic development (economic growth, technology, demography, inequality, etc.) and global integration (cooperative development, increasing division, etc.). Five scenario narratives of SSP trajectories: **SSP1: Sustainability (Taking the Green Road):** Represents a world that shifts gradually toward a more sustainable path, emphasizing more inclusive development that respects environmental boundaries. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries, alongside improvements in education and health. Consumption is oriented toward low material growth and lower resource and energy intensity. **SSP2: Middle of the Road:** Depicts a world where social, economic, and technological changes do not shift markedly from historical patterns. Development, income growth, and environmental protections proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. **SSP3: Regional Rivalry (A Rocky Road):** Depicts a world in which resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. With little investment in technology and social policy, economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. **SSP4: Inequality (A Road divided):** Considers a world in which highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Social cohesion degrades and conflict and unrest become increasingly common. The globally connected energy sector continues to diversity with investment in both high-and low-carbon energies. Environmental policies focus on local issues around middle and high income areas. **SSP5: Fossil-fueled Development (Taking the Highway):** This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated... The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world.
WWF Biodiversity Risk Filter (BRF)	The Biodiversity Risk Filter is a spatially-explicit, corporate- and portfolio-level screening tool for determining biodiversity related risks. The tool is designed to allow companies to understand and assess the biodiversity-related risks of their operational locations and their suppliers, and to allow financial institutions to assess biodiversity-related risks for all companies in a given portfolio. The tool builds heavily on WWF's Water Risk Filter tool, which provides similar company-level and portfolio-level data for risk screening. The tools provide location-specific and industry-specific assessments of biodiversity and water-related risks. The tools aim to help companies and financial institutions to better prioritize where and on what to focus contextual responses as well as inform their biodiversity- and water-related stewardship strategies and target setting. BRF currently focuses on physical risks and reputational risks by analysing biodiversity-related dependencies and direct biodiversity impacts. Dependency and impact scores are measured for 33 different indicators with ranges from "very high" to "very low". Regulatory risk assessments will be incorporated in future versions of the BRF.

WWF Always Environmentally Harmful Companies database	The WWFs classification of "Always Environmentally Harmful Companies" delineates economic activities, companies and sectors that have the highest negative environmental impacts and are considered to be universally and undeniably environmentally harmful in all cases. While the definition of "green" is open for debate, certain industries can be classified as always harmful for the climate and biodiversity and, therefore, as always contributing to financial risk.
WWF Always Environmentally Harmful Companies database	These include companies involved in coal, oil and gas and other forms of fossil fuel extraction, as well as cement manufacturers, mining and other deforestation-intensive companies (many of which are active in biodiversity hotspots). Such companies and sectors are invariably linked to climate and biodiversity crises. As such, their assets are likely to face threats due to (i) physical scarcity and increasing environmental damages brought on by harmful environmental changes, or (ii) new regulations which may "strand" these assets as the world transitions. These have the highest concentration of physical, transition and litigation risks, and therefore result in substantial threats for price and financial stability. Moreover, transition risks may arise through regulation of the financial sector, as financial institutions that are lending to companies involved in environmentally harmful activities may face far higher capital requirements to account for the long-term risks involved.
Nature Futures Framework (NFF)	The Nature Futures Framework (NFF) is a heuristic tool for identifying possible futures for nature and people. It seeks to open up a diversity of futures by exploring different value perspectives on nature. NFF aims to help integrate nature in policy-making and better link the efforts of scientists and regulators to diverse values for nature and people. Human-Nature value perspectives in the NFF are described through the lenses of Nature for Nature (NN), Nature for Society (NS), and Nature as Culture (NC) - The Nature for Nature (NN) perspective appreciates and preserves nature for what it is and does and maps to intrinsic and existence values of biodiversity (e.g., maintaining natural processes and function such as evolution and migration). The Nature for Society (NS) perspective focuses on instrumental values as in benefits that nature provides to people (e.g., supporting crop production and climate regulation). The Nature as Culture (NC) perspective values the relationships that nature and people co-create, not as separate entities but as an indivisible whole (e.g., preserving emblematic species, sacred landscapes, traditional knowledge). Following Kim et al. (2023), the NFF integrates (i) multiple value perspectives on nature as a state space where pathways improving nature toward a frontier can be represented, (ii) mutually reinforcing key feedbacks of social-ecological systems that are important for nature conservation and human wellbeing, (iii) indicators of multiple knowledge systems describing the evolution of complex social-ecological dynamics.

Source: Authors. Additional information available in **Annex 7.2.3**.

Table 2.3 **Excerpt from Annex 7.2.3 of some key transition-related policies (and related hazards) that emerge from the assessment of the Global Biodiversity Framework**

Tool / framework	Description	Methodology	Key policy proposals / insights	Timeframe
GLOBAL BIODIVERSITY FRAMEWORK (GBF)	Kunming-Montreal Global Biodiversity Framework (GBF), agreed at the COP15 UN Convention on Biological Diversity, establishes global targets for biodiversity conservation. It includes four goals and 23 targets for achievement by 2030-2050 and establishes an ambitious policy framework for government and whole-of society action on nature. This hinges on a collective mission of halting and reversing biodiversity loss by 2030, by promoting conservation, restoration, sustainable use of nature, and equitable sharing of benefits, and a vision of "living in harmony with nature" by 2050. While CBD resolutions are non-binding, all 196 signature parties agreed at COP15 in Montreal to update their national biodiversity strategies and action plans (NBSAPs) to proceed with the implementation of the GBF at their jurisdiction level. By mainstreaming nature across policies and decision-making processes, signatories encourage the implementation of the GBF through regulatory and other measures by all actors of society.	Expert analysis and political considerations. The GBF evolved from earlier agreements to protect biodiversity, including the 1992 Earth Summit in Rio de Janeiro and the targets established by the 2011 UN Convention on Biological Diversity in Aichi. As with previous international agreements, the GBF was developed through political negotiations between signatory countries, based in part on a mix of expert analysis and scientific evidence, alongside stakeholder interest groups (firms, NGOS, etc.).	4 goals and 23 targets, among which include the following examples: [Target 1] Ensure [sufficiently participatory and/or effective management processes] to bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030, while respecting the rights of indigenous peoples and local communities. [Target 2] Ensure that by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity. [Target 3] Effective conservation and management of at least 30% of the world's lands, inland waters, coastal areas and oceans. [Target 4] Ensure urgent management actions, to halt human induced extinction of known threatened species and for the recovery and conservation of species, in particular threatened species, to significantly reduce extinction risk, as well as to maintain and restore the genetic diversity within and between populations. [Target 7] By 2030, reduce by half both excess nutrients and the overall risk posed by pesticides and highly hazardous chemicals. [Target 14]: Ensure the full integration of biodiversity and its multiple values into policies, regulations, planning and development processes, […] progressively aligning all relevant public and private activities, and fiscal and financial flows with the goals and targets of the GBF. [Target 15]: Take legal and policy measures to encourage and enable business to regularly monitor, assess, and transparently disclose their risks, dependencies and impacts on biodiversity, including with requirements for all large and transnational companies and financial institutions along their operations, supply chains and portfolios in order to reduce biodiversity-related risks to business and financial institutions, and promote actions to ensure sustainable patterns of production. [Target 16] Cut global food waste in half and significantly reduce overconsumption and waste generation. [Target 18] Progressively phase out or reform by 2030 incentives, including subsidies that harm biodiversity by at least $500 billion per year, in a just and equitable way, and scale up positive incentives for the conservation and sustainable use of biodiversity. [Target 19] Mobilise by 2030 at least $200 billion per year in domestic and international biodiversity-related funding from all sources – public and private.	2030 - 2050

Source: Authors. Additional information available in Annex 7.2.3

However, this first step is not sufficiently specific to calibrate the shock to any country's features for full scenario assessment. For instance, it would enable two countries with similar production structures (e.g., share of agriculture in GDP, share of employment in agriculture) and similar exposure to a transition hazard (e.g., share of territory designated as "high priority" conservation zone) to develop scenarios related to measures aiming to increase protected areas to align with GBF Target 3. Yet it would not enable these countries to decide how the shock should be calibrated, based on more granular considerations. Differences will naturally arise based on whether the country has already made strong commitments to land protection in the past, whether the commodities produced in newly protected areas can still be produced (but in more environmental-friendly manner), or whether the losses incurred from restricted production can be offset by the production of similar commodities elsewhere.

As a result, the second step of the approach proposed would consist in developing a methodology tailored to each country so that they can better calibrate the transition narratives while building on a common framework (thereby generating comparable narratives). This step could consist in providing guidance to central banks and supervisors about how to better quantify the initial hazard or shock that will then be modelled (e.g., via a questionnaire). Importantly, this calibration should ideally be conducted in coordination with local environmental authorities (e.g., Ministry of the Environment, Department of the Interior) and other interested parties (e.g., NGOs, scientists, indigenous groups) in order to more accurately assess relevant variables - the likely social and environmental impacts of new regulations, local environmental qualities – and calibrate their risk assessment to the particularities of the country.

Both of these steps should enable the NGFS to develop and assess transition risk scenarios that overcome many of the challenges highlighted in the beginning of this chapter. By connecting specific transition hazards to identifiable characteristics of each country, it is possible to quantify the potential direct and indirect impacts (benefits and losses) from new measures designed to protect ecosystem health. With the additional granularity provided through a questionnaire that allows central banks and financial supervisors to quantify the on-the-ground reality of each country more precisely, multifaceted transition risks and their diverse impacts can be further accounted for.

In order to provide an example of how the above can be used, we develop a case study in Chapter 4, focusing on a theoretical 'disorderly' transition risk that explores the impacts of a potential sudden European Union (EU) policy to ban non-deforestation-free products from Brazil.

2.2.3 Additional avenues to explore for comprehensive nature-related risk assessment

While the above framework provides a method for moving forward in identifying specific physical and transition hazards and quantifying their impacts for different countries and sectors, it remains only a first step in developing a comprehensive methodology for assessing nature-related risks. In this section, we point to two avenues of further exploration if central banks and financial supervisors wish to conduct more thorough scenario analyses. First, we consider the possibility integrating "transformative changes" (IPBES, 2021) – including deeper systemic and institutional reforms and new value paradigms – within transition risk narratives. Second, we consider what it might take to study the endogenous production of nature-related risks stemming from the financial sector, itself.

2.2.3.1 Considering "transformative changes" in transition risk narratives

Given the scale and intensity of environmental degradation at present, IPBES (2021) has recognised that piece-meal policy reforms are likely to be insufficient to bring about the kinds of "transformative changes" necessary to both reverse negative biodiversity trends and anchor more sustainable ways of living and relating across the globe. The call for "transformative changes" includes sweeping reforms that would bring about a full "system-wide reorganisation" marked by new social "paradigms, goals and values needed for the conservation and sustainable use of biodiversity, good quality of life and sustainable development" (IPBES,2019, p. 889). Despite the increasing international scientific and political consensus in calling for transformative change, it is not immediately clear how NGFS nature scenario assessments could integrate such sweeping reforms. In short, scenarios based on "transformative transition narratives" would be used to assess major institutional changes that go far beyond the sectoral impacts from new policy adoption studied in this Technical Document.

In order to develop scenarios that embrace the call for transformative changes, it will be necessary to integrate multiple different ways of relating to and valuing nature. The multiple values of nature are well-recognised by institutions like IPBES (2022), and have also been enshrined in global sustainability goals. The post-2020 Kunming-Montreal Global Biodiversity Framework, for example, calls for "the full integration of biodiversity and its multiple values" into all regulations, planning, development processes and governance frameworks (GBF Target 14). Additionally, it sets the goal for embracing alternative ways of being in and relating to nature that institutionalise non-monetary values for nature (e.g., sacred and religious values) and alternative forms of resource sharing and governance. This includes altering resource governance by "*enhancing the role of collective actions…by indigenous peoples and local communities, Mother Earth centric actions and non-market-based approaches including community based natural resource management and civil society cooperation and solidarity aimed at the conservation of biodiversity*" (GBF Target 19)[25].

Scenarios that integrate such transformative changes would necessarily require additional qualitative insights that include in-depth analysis of possible (geo-) political tensions between conflicting value paradigms, alongside an exploration of the kinds of institutions, beliefs and values that may be creating a structural obstacle to "living in harmony with nature" (CBD, 2019) (e.g., over-reliance on metrics like GDP, consumerism, structural inequalities), and how to reform them.

One useful heuristic tool that has been developed in this regard is IPBES's Nature Futures Framework (NFF) (Pereira et al., 2020; Kim et al., 2023; Pascual et al., 2023). The signature feature of the NFF is that it brings together multiple value perspectives to understand how people relate to nature in different ways.[26] In doing so, it is possible to develop scenarios that integrate the views of policy-makers, firms, scientists, and other knowledge-holders (e.g., indigenous peoples) under one method for predicting nature futures.

One advantage of the NFF is that it can highlight which transition policies may be more likely, given synergies between different value perspectives, and which may be more prone to stalemate or conflict, as a result of competing claims for value. Value conflicts can produce transition risks via regulatory uncertainty, increased legal costs, reputational risks, rising socio-economic or geopolitical tensions, and reduced international cooperation. Such conflicts can have major economic, social, and environmental consequences with potentially large direct and indirect macro-financial implications.

However, it is unclear how the NGFS could develop scenarios that practically integrate the kinds of socioeconomic and policy measures required to bring about transformative changes and respect the multiple values of nature. Indeed, neither the transition policies themselves nor their ultimate macro-financial impacts can be easily identified in this case. Such a shift would likely imply a qualitative departure from present forms of social organisation, and require alternative indicators of well-being and social and environmental stability, alongside the use of new (as yet unidentified) modelling frameworks. At a minimum, comprehensive scenario development by the NGFS will therefore require an interdisciplinary approach in order to ensure that they remain consistent with international goals and targets and scientific consensus.

More broadly, the presence of "transformative transition risks" demonstrates the limits of modelling approaches and points to the need for other types of scenario analysis based on qualitative risk assessment – e.g., using expert elicitation (Pindyck, 2017). This topic is beyond the scope of this Technical Document, but is

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[25] The GBF also recognises that indigenous peoples and local communities should be granted "equitable participation in decision-making related to biodiversity" while ensuring and respect for their rights over land, resources, and traditional knowledge and cultural practices (GBF Targets 1, 3, 5, 9, 21, 22).

[26] Human-Nature value perspectives in the NFF are described through the lenses of Nature for Nature (NN), Nature for Society (NS), and Nature as Culture (NC). The Nature for Nature (NN) perspective appreciates and preserves nature for what it is and does and maps to intrinsic and existence values of biodiversity (e.g., maintaining natural processes and function such as evolution and migration). The Nature for Society (NS) perspective focuses on instrumental values as in benefits that nature provides to people (e.g., supporting crop production and climate regulation). The Nature as Culture (NC) perspective values the relationships that nature and people co-create, not as separate entities but as an indivisible whole (e.g., preserving emblematic species, sacred landscapes, traditional knowledge).

something central banks and supervisors should bear in mind when designing transition scenarios and could be explored in the future.

2.2.3.2 Integrating the endogeneity of nature-related financial risks in nature-related risk assessments

Aside from the need to consider interdisciplinary approaches to study scenarios of transformative change, future NGFS scenarios should consider the way that both physical and transition risks are endogenously produced. As the NGFS (2023, p. 16) has recognised "economic actors are not only exposed to nature-related physical and transition risks. Via the negative impacts they have on nature, these actors also contribute to the risk they need to manage." In particular, the financial system itself can be subjected to nature-related risks, while simultaneously actively contributing to the emergence of such risks (Boissinot et al., 2022; Oman & Svartzman, 2021). While the financial sector is not solely responsible for economic activities that exert negative impacts on nature, it plays a major role as an enabler of economic activities (Battiston et al., 2021). For example, despite widespread and increasing commitments to global climate and biodiversity goals, major financial institutions have invested trillions of dollars into the continued exploitation of fossil fuels (Noor, 2023; RAN et al., 2023). Given the financial sector's unique role in the endogenous production of risks, future scenarios should therefore scrutinise its role more closely.

Despite the recognition of the fact that the financial sector both suffers from and generates risks, it remains unclear how to develop narratives that integrate both the potentially socially costly and beneficial impacts of finance within scenarios. A first approach would be to include the expectations of the financial system. Gourdel et al. (2022), for example, develop a model to assess climate physical and transition risks in the euro area by including firms' climate sentiments and the financial sectors' climate risk assessments as an endogenous variable. They find that orderly transitions are far more likely when early and credible transition policies are announced, thereby allowing for endogenous adaptations. Meanwhile, disorderly transitions can result when firms face challenges to access to credit and to invest in low-carbon energy technologies, thereby leading to the growth of carbon assets, whose stranding can bring negative implications for economic and financial stability.

A second approach would be to study the possibility for transformational changes in the behavior of financial players or regulators (Boissinot et al., 2022). In order to address present environmental challenges, central banks and financial supervisors may see it as being within their mandates to proactively support the ecological transition. Indeed, financial regulators may decide to proactively support financial practices that are considered more compatible with the ecological transition, including by going as far as disincentivizing (or banning) loans for dirty activities (WWF, 2022). On the flipside, private financial institutions are increasingly involved in the financing of nature conservation and restoration and economic activities that avoid and/or reduce harmful impacts on nature, including through new nature-related financial instruments that could also generate new financial risks on their own (Kedward et al., 2023). The monetary and financial policy implications of such an approach are potentially far-reaching, presenting new challenges and opportunities for scenario development.

Finally, future scenarios could study how broader financial reforms might encourage a greater alignment of fiscal and financial flows with international targets for nature. Indeed, GBF Target 15, for example, points specifically to the need for regular monitoring, assessment, transparency and disclosure to reduce biodiversity related risks for firms and financial institutions and to promote more sustainable forms of production. Meanwhile, GBF Target 19 argues for a number of important measures that could be useful in mobilizing the desired minimum of $200 billion per year by 2030. These measures include, but are not limited: to (i) increasing total biodiversity related international financial resources from developed countries; (ii) promoting blended finance to encourage the private sector to invest in biodiversity; and (iii) developing innovative schemes such as payment for ecosystem services, green bonds, and debt-for-nature swaps.

Considering the role of the financial sector and the endogenous production of risks is a matter that should ultimately be done jointly with NGFS climate scenarios. While adding the financial sector adds a new level of complexity, the NGFS should begin assessing models based on their capacity to include the role of the financial system.

2.3 Conclusion

This chapter discussed avenues towards identifying specific physical and/or transition hazards that can become sources of risks. The identification of such physical and transition hazards (i.e., potential sources of risks) is the essential first step to develop any nature-related scenario.

However, developing such narratives of nature-related scenarios poses at least three significant challenges. First, given the local specificities, complexities, and non-linearities of natural systems, aggregate measures (the equivalent of CO_2-equivalent for climate change) for determining ecosystem integrity and damages are inevitably incomplete. Second, narratives of scenario assessments must treat different planetary boundaries – such as those related to climate, land use and biodiversity integrity – as interdependent processes with both positive and negative synergies. For instance, climate change and biodiversity loss can aggravate each other through different channels but also lead to tradeoffs in terms of policy decisions. Third, nature-related scenarios aimed at understanding potential nature-related risks need to embrace the possibilities that nature cannot be (or not easily) substituted, particularly in the short- to medium-runs.

As a result of these challenges, developing relevant narratives of scenarios aimed at assessing nature-related financial risks must be able to overcome the inherent tradeoff between capturing locally specific environmental changes, while maintaining global relevance (herein referred to as the "local-global tradeoff"). We therefore propose approaches to developing narratives of scenarios that could overcome this local-global tradeoff, and consequently serve as starting points for the assessment of nature-related financial risks.

For physical risks, we suggest two complementary avenues for identifying the most relevant physical hazards: ESGAP-SESi and INCAF-Oxford. The Environmentally Sustainability Gap – Strong Environmental Sustainability index (ESGAP-SESi) provides an aggregate measure for identifying the distance between the current state and a "healthy" operating state for ecosystems, and can translate the broad concept of planetary boundaries into observable trends at the national level. Importantly, the ESGAP tool integrates the assumption that the contributions of nature to people cannot be substituted by more manmade capital or labor. The INCAF-Oxford approach to generating scenario narratives centres on potential hazards themselves (e.g., increased occurrence of storms due to the degradation of mangroves) rather than on ecosystem services, as most approaches do. Hazards can then be mapped *backwards* (to ecosystem services, natural assets and drivers of degradation along the impact chain) and *forwards* (to economic impacts), thereby translating nature-related processes and hazards into specific initial 'shocks' to be assessed by economic models and tools (assessed in the following chapters).

For transition risks, we build on an in-house review of eleven nature-related frameworks covering multiple potential policies, to suggest a two-step approach through which relevant narratives can be generated. The first step consists in *roughly* identifying, through relatively simple yet not aggregated metrics, how different sectors in different countries could be impacted by some of the key policies that could emerge from frameworks, such as the Global Biodiversity Framework (GBF) Targets (e.g., protecting 30% of land and sea area, reducing the risks related to pesticides, or reforming environmentally harmful subsidies). The second step consists in providing central banks and supervisors with some guidance through which they could better calibrate such hazards to their national economy. Note that we only provide initial suggestions for this two-step approach, which should be further developed through dedicated research.

While all these approaches (ESGAP-SESi and INCAF-Oxford frameworks for physical risks, and our desk review for transition risks) would require more work to be fully implementable, they already show that it is possible to overcome the local-global tradeoffs discussed above, and to identify specific physical and transition hazards and translate them into initial economic impacts ('shocks') for different sectors and countries. That is, the complexity of nature-related trends cannot serve as an excuse for only using aggregated metrics, for conducting decontextualised or isolated case studies, or for simply ignoring the issue.

3. Review of modelling approaches for nature scenarios

The quantification of the macroeconomic and financial consequences of the nature-related hazards presented in the previous chapters may require the use of economic and biophysical modelling. To this end, this chapter reviews a range of global macroeconomic and biophysical models[27] and assesses their ability to: (i) integrate the outputs of the narratives presented in the previous chapter as inputs to the modelling exercise; (ii) account for the transmission channels through which specific hazards (e.g., in the agricultural sector) can propagate in the economy (e.g., in the form of higher input costs for industry and/or decrease in final consumption). A comprehensive assessment of each model ("ID card") is available as part of the Supplementary Material to this Technical Document.

This chapter first evaluates six of the most commonly used modelling frameworks[28] that combine nature and macroeconomic aspects at the global level (so-called "nature-economy" models). The material for this assessment was composed of an "ID card" for each modelling framework, listing the most important characteristics of the models. Such "ID cards" were developed based on: an extensive assessment of the models' documentation; an interview with each modelling team (with questions sent ahead of each interview); a revision (when needed) of the "ID cards" based on the modelling teams' feedback on the first draft.

Our evaluation of the models assesses two dimensions. First, we investigate the transmission channels between nature and the economy that these models represent, which provides insights into the type of narratives that they are able to implement. If some transmission channels appear to be missing, for example if the lack of water provision by ecosystems only affects agricultural output but not the production of the energy nor the industry sector, then the economic effect of the shock obtained by the model will likely be an underestimate. This assessment of the transmission channels also explores the transition policies that these models can capture (e.g., land or sea protection, reduction of negative subsidies in one sector, reduction of pesticides, and so on), and how the models represent the impacts of such policies on the economy.

Second, we assess the mechanisms by which each model estimates sectoral and macroeconomic consequences resulting from physical or transition scenarios. This part of the analysis focuses in particular on underlying economic modelling assumptions, and how they might minimise, or conversely amplify, the economic impacts of physical or transition hazards.

We complement this model evaluation by focusing in depth on 14 "biophysical" models – taken from the ISIMIP models suite29 – to assess the extent to which their use could help overcome some of the limitations identified above (in particular the inability to account for several nature-related physical and transition patterns.

3.1 Nature-Economy Models Review[30]

3.1.1 Review method

We selected a set of modelling frameworks based on specific criteria. Firstly, we chose models that have global coverage to ensure that the scenarios we build are useful for all members of the NGFS across the world. Secondly, we looked for models that represent ecosystem services and the dependency of economies on those services, as well as drivers of nature loss and policies to mitigate them. It is important to note that we did not limit our search to models focused solely on climate change as driver of nature

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[27] The review of models conducted for this report does not aim to be exhaustive, and it could be completed by assessments of additional modeling frameworks. For instance, as detailed in Liu et al. (2020), the ARIES model incorporates Bayesian probability models, process models, and agent-based models with the aim of depicting the flow of ecosystem services. It can characterise the supply, demand, and value of ecosystem services and holds broad prospects for decision-making applications. The SAORES model, independently developed by Chinese scholars, is also based on ecological processes and environmental indicators. Relying on the trade-off relationships of ecosystem services, it optimises spatial land use, and is considered to have unique advantages in the field of ecological spatial planning.

[28] We sometimes refer to modelling frameworks to emphasise that two or more models can be 'plugged' and assessed jointly.

[29] See: ISIMIP – The Inter-Sectoral Impact Model Intercomparison Project.

[30] This section is adapted from Kedward, Salin and Dunz (forthcoming working paper).

loss. Lastly, we chose models that produce macroeconomic variables such as GDP or employment, and can also provide more detailed economic variables at a sectoral level.

In combination with those criteria, we based our selection of models on a few publications that assessed the effect of nature-related hazards on the economy. The first type of publication is the climate scenarios that were produced by the NGFS. Those were obtained by using integrated assessment models that initially focus on climate and energy-related issues and their macroeconomic consequences (REMIND, MESSAGE, GCAM[31]). However, they can all be linked to a land-use module (REMIND-MAgPIE, MESSAGE-GLOBIOM and GCAM, which includes a land module as well as a water module). We also based our selection of models on the seminal article published by Leclère et al. (2020), which specifically explores scenarios aimed at reversing biodiversity loss. The authors use models with important land-use components (MAgPIE, GLOBIOM, AIM-Hub and IMAGE) and assess the effect on policies on biodiversity by linking the land-use maps obtained by those models to biodiversity models. Finally, we also cover the "Global Earth-Economy model" (Johnson et al., 2021), which we call "GTAP-InVEST" in the rest of this review, as it was specifically developed to assess the economic consequences of both physical risk scenarios (e.g., a definitive loss in key ecosystem services), as well as a transition risk scenario (e.g., global measures to increase the amount of protected land in alignment with GBF Target 3).

In summary, we have reviewed six "modelling frameworks"that connect multiple models and share two common characteristics: they are global in scope, and they link nature and macroeconomic issues. These are the following (modelling teams in parenthesis):

(1) **GTAP-InVEST** (World Bank, University of Minnesota, Purdue University and Natural Capital Project)
(2) **REMIND-MAgPIE** (Potsdam Institute for Climate Impact Research (PIK))
(3) **AIM Hub** (National Institute for Environmental Studies (NIES), Kyoto University, Mizuho Information & Research Institute and others)
(4) **IMAGE-MAGNET-GLOBIO**[32] (The Netherlands Environmental Assessment Agency (PBL) and Wageningen University)
(5) **MESSAGE-GLOBIOM** (International Institute for Applied Systems Analysis (IIASA))
(6) **GCAM** (Pacific Northwest National Laboratory)

We conducted an assessment of these modelling frameworks by extensively reviewing the documentation of each model. Additionally, we conducted oral interviews and written exchanges with the modellers to gather further information. This allowed us to create "ID cards" for each model. All the "ID cards" were reviewed by the modelling teams, although the final assessment is the responsibility of the authors. The "ID cards" we created for each model focused primarily on understanding the type of macroeconomic models and their underlying assumptions, as well as the methods used to connect economic and biophysical aspects. During our interviews with the modellers, we aimed to gain a better understanding of how the models function and the types of hazards they can account for, whether physical or transition-related. These interviews also allowed us to learn more about recent or ongoing developments of the modelling framework regarding biodiversity and nature issues, which may not yet be included in the models' documentation. The "ID cards" for each model and our final assessment of each model, which was written after our exchanges with the modellers, can be found in the Supplementary Material accompanying this Technical Document.

3.1.2 Main characteristics of the reviewed modelling frameworks

This section describes the main characteristics of the models. Figure 3.1 illustrates the modular structure and linkages of the models reviewed. The reviewed modelling frameworks often consist of multiple models that form different modules, which are either directly linked ('hard-linked') or indirectly linked ('soft-linked').

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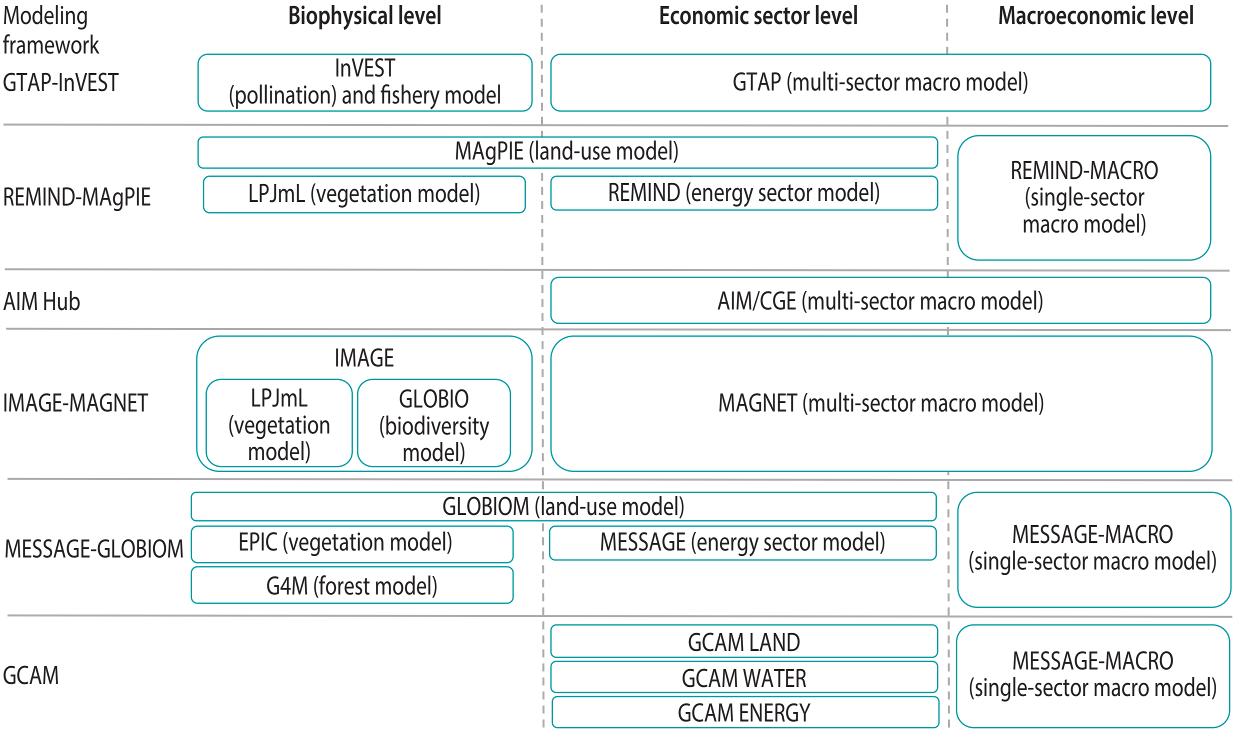
[31] In the NGFS scenarios, the version of GCAM that is used is a partial equilibrium model, which therefore prevents one from obtaining macroeconomic outputs. However, the version 7 of GCAM, which we assess here, includes a macroeconomic module.

[32] The GLOBIO model allows to obtain the effect of economic pathways on biodiversity, but the biodiversity outputs from GLOBIO do not feedback in the MAGNET macroeconomic model. Therefore, we focus our analysis on IMAGE-MAGNET in this Technical Document, but an ID card describing the GLOBIO model can be found in Annex.

Figure 3.1 **Structure of the global nature-economy models reviewed**



Source: Authors, adapted from Kedward, Salin and Dunz (forthcoming working paper).

Three broad categories are identified, with "Biophysical Level" referring to the modelling of ecological variables, while "Economic Sector Level" refers to the generation of outputs such as value added at the sector level. "Macroeconomic Level" refers to the modelling component that generates macroeconomic results, such as GDP.

The modelling approach and scope of economic sectors represented can be grouped according to two dimensions. One group uses multi-sector general equilibrium models (GTAP, AIM-Hub, MAGNET[33]), some of which are linked to suites of biophysical models (INVEST in the case of GTAP, and IMAGE and GLOBIO in the case of MAGNET). The second group uses aggregated single-sector general equilibrium models[34] (REMIND-MACRO, MESSAGE-Macro, GCAM-Macro) which are then linked to partial equilibrium models focusing on land-use and agriculture (MAGPIE, GLOBIOM, GCAM-land) in addition to energy (GCAM-energy, REMIND, MESSAGE). These partial equilibrium models can themselves be linked to biophysical vegetation models (e.g., LPJmL, EPIC, G4M).

The models we reviewed operate on the principles of market equilibrium, meaning they solve for the set of market prices that balance supply and demand for all represented markets. Allocation of resources and production factors within those models is usually guided by market principles. The models typically represent endogenous land use change within a market equilibrium framework, where land is allocated to the most profitable economic activity, subject to constraints such as land suitability and protected areas. The allocation of land use is spatially explicit and varies in resolution from 10 x 10 arc-seconds (equivalent to 300 x 300 m at the equator) to 30 x 30 minute arc-minutes (equivalent

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[33] These three macroeconomic models are "computable general equilibrium models" with multiple production sectors, producing multiple types of goods.

[34] The macroeconomic models in GCAM and MESSAGE (which we call in this report GCAM-Macro and REMIND-Macro) are "computable general equilibrium" models but use only one (energy) sector for production and produce a single homogeneous good. The macroeconomic model in REMIND (REMIND-MACRO) is an "optimal growth models", also producing a single homogeneous good.

Table 3.1 **Geographic and spatial scope of reviewed global nature-economy models**

	GTAP- InVEST	REMIND- MAgPIE	AIM-Hub	IMAGE-MAGNET	MESSAGE-GLOBIOM	GCAM
Nº. of aggregated world economic regions	37	12	17	26 world regions	11	32
Spatial resolution of land use maps	10 arc seconds	30 arc minutes[1]	30 arc minutes	5 arc minutes	30 arc minutes	5 arc minutes
(Equivalent distance at the equator)	(~300 x 300 m)	(~50 x 50 km)	(~50 x 50 km)	(~10 x 10 km)	(~50 x50 km)	(~10 x 10 km)

1 MAGPIE also has a link to the SEALS model, which disaggregates physical results to the 300 m x 300 m level.

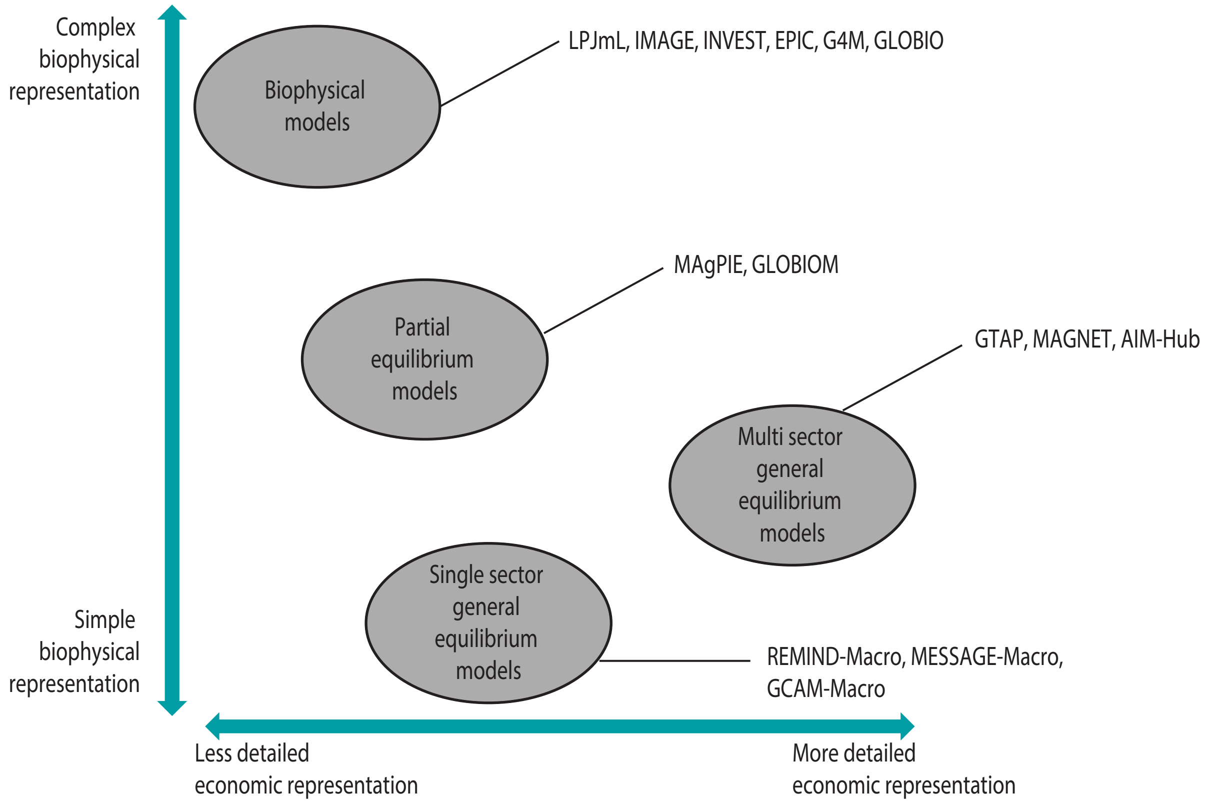
Source: Authors, adapted from Kedward, Salin and Dunz (forthcoming working paper).

to around 50 x 50 km at the equator). This level of spatial detail allows for biophysical attributes of each land grid cell, such as water availability and soil fertility, to be factored into the allocation decision through linkages to vegetation and hydrological models. **Table 3.1** below summarises the global geographical coverage and spatial resolution of the models reviewed.

Partial and general equilibrium model both have their selective advantages and disadvantages with partial equilibrium models allowing more detailed sectoral representations and general equilibrium models better capturing economic feedback effects (Figure 3.2). Partial equilibrium models offer the advantage of providing more detailed information within specific sectors (e.g., energy, agriculture). However, unlike general equilibrium models such as CGEs or optimal growth models, they do not capture the economic effects of a shock across the entire economy, including macroeconomic aggregates. For instance, a partial equilibrium model would not be able to demonstrate how a hazard affecting a particular sector could potentially have negative impacts on households' income and consumption, and the subsequent effects on investment. In contrast, general equilibrium models represent the interactions between household consumption and production, and for multi-sector CGEs, they can also represent upstream and downstream linkages between sectors across the entire economy (although at a coarser level of detail), as well as global trade patterns. **Figure 3.2** illustrates where each type of model is positioned in terms of modelling economic or biophysical detail.

It is important to note that, whilst the models share many commonalities, they do not all have the same scope, structure, and objectives. Comparing them in a consistent way thus necessarily requires making categories and simplifications.

Figure 3.2 **Illustrative comparison of models according to level of biophysical versus economic detail**



Source: Authors, adapted from Kedward, Salin and Dunz (forthcoming working paper).

3.1.3 Results

3.1.3.1 Modelling nature's impact on the economy: an emerging field of research

Overall, nature-economy modelling appears less mature than climate-economy modelling[35], given the complexities of the interactions between nature and the economy. Figure 3.3 conceptualises physical and transition risk considerations within a framework of nature-economy interactions. To study nature-related transition risks, it is necessary to examine both the impact of social, political, and economic changes aimed at protecting nature on the economy (green arrow), as well as the impacts of economic developments on nature (yellow arrow). This approach ensures that policies to mitigate one driver of nature loss are ambitious enough to reach their goal and will not negatively affect other aspects of nature. For nature-related physical risks, it is important to consider both the dependency of economic activities on nature (red arrow) to understand possible economic disruptions resulting from a physical hazard, and the way ecosystems and ecosystem services are interconnected (blue arrow). For example, vegetation models demonstrate how the provision of food is dependent on services such as soil quality, the water cycle, and protections against pests.

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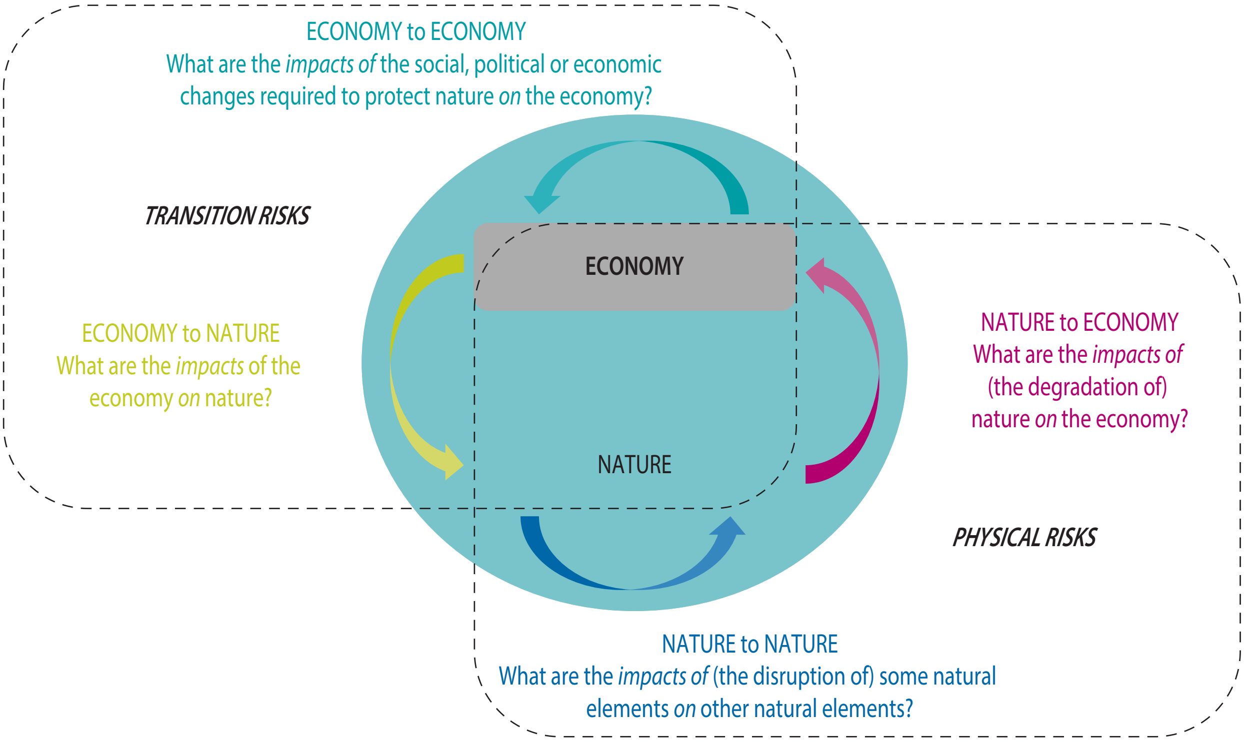
[35] Notwithstanding the many limitations of such models (Pindyck 2013) which are beyond the scope of this report.

Figure 3.3 **Positioning transition and physical risk in a framework of nature-economy interactions**



Source: Authors, adapted from Kedward, Salin and Dunz (forthcoming working paper).

To our knowledge, most of the studies that were made using the modelling frameworks we review focus on assessing the effects of the economy on nature (yellow arrow). This is for example the case of Leclère et al. (2020), who use five of the models we review to assess the effect of several transition scenarios (sustainable intensification, protected areas, increases in plant-based diets, etc.) to produce associated land-use maps. They then link those to biodiversity models (such as the GLOBIO model, detailed in **Annex Table 5**.) to obtain the effect of the scenarios on terrestrial biodiversity. Another example is the "Biodiversity and Ecosystem Services Scenarios-based Model Intercomparison (BES-SIM)" exercise (Kim et al., 2018), which assessed the consequences of a very optimistic scenario intersecting shared socioeconomic pathway SSP1 ("green growth") and RCP2.6 on biodiversity, also using the land-use maps produced by some of the models we review in this section. These models have also been used to assess the interaction between land use change mitigation policies, climate change, and the Sustainable Development Goals (e.g., Janssens et al., 2022).

The reviewed models produce land use-related outputs, such as spatial maps of land use change, which are often linked to additional biophysical models to estimate the impacts of development pathways on nature. For instance, Leclère et al. (2020) used land use change outputs from AIM, IMAGE, MAgPIE, and GLOBIOM to generate six different biodiversity metrics, including mean species abundance (MSA) using the GLOBIO model and biodiversity intactness index (BII) using the PREDICTS database. However, this linkage only provides a one-way assessment of impacts on biodiversity, as the economic implications of estimated biodiversity loss are not accounted for in the macroeconomic modelling.

However, the green (impact of nature protection policies on the economy) and red (impact of loss in ecosystem services on the economy) arrows of this diagram have been less frequently explored. Some partial equilibrium models have been used to assess the effect of certain policies aimed at avoiding land-use change on food prices (e.g., Leclère et al., 2020; Prudhomme et al., 2021), but without investigating their macroeconomic consequences and general equilibrium effects. On the physical risks side, to our knowledge, only one model (GTAP-InVEST) has been used to explore the macroeconomic impacts of the partial collapse of a few ecosystem services, including pollination, timber, and fish provision (Johnson et al., 2023). We note that the REMIND-MAgPIE model can now also estimate an economic cost associated with impacts on the BII, which is derived heuristically based on the BII associated with different types of land uses. However, this economic cost currently only affects output in an indirect way.

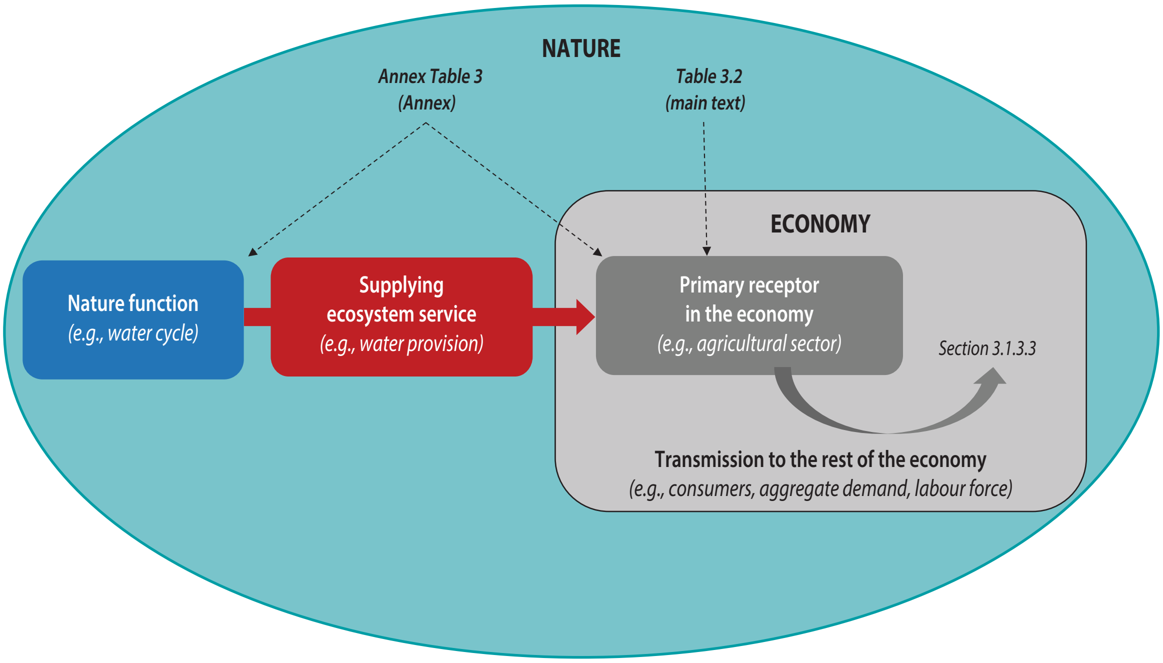
3.1.3.2 Representation by the reviewed modelling frameworks of the economic impacts of physical and transition hazards

A. Representation of the economic impacts of physical hazards

For models to effectively assess physical risk scenarios, particularly the economic consequences of a disruption in ecosystem services, it is crucial that they can accurately depict the dependencies of the economy on nature.

This section evaluates how models represent the economy's dependency on ecosystem services. Using a list of ecosystem services from the ENCORE database (which was used to generate the narratives in the previous chapter), we assess how each modelling framework reviewed represents the link between ecosystems and the economy. We evaluate: (i) which ecosystem services are accounted for by each model; and (ii) how these models represent the economy's dependence on those services to function. Tables providing a more detailed assessment of these two aspects can be found in **Annex 7.3.** By separating these two aspects, we can evaluate the level of detail in the models. For instance, some models represent the economy's dependency on ecosystem services such as crop provision (i.e., step 2 above), but do not explicitly model the way crops are grown or the influence of biophysical variables on those crops (step 1).

Figure 3.4 **Focus of the assessment tables on the "physical risks" side**



Source: Authors.

Our main finding (detailed in Table 3.2) is that while the dependency of the economy on provisioning services is frequently included in nature-economy models, this is not the case for regulating and cultural services.

Provisioning ecosystem services, particularly the provision of food crops and livestock, are more frequently integrated into models, as these sectors are typically represented in input-output tables, used as input data to CGE models, and often enter models' production functions. Provision of food crops and livestock are also a significant focus of land-use models, which explain how land is divided between cropland, pastureland, and natural land. The dependency of the economy on water provision is also represented in a few models, likely because it is a direct input to some production processes. However, we note that models only depict the dependency on water for agriculture, not for the rest of the economy (e.g., industry). Even models that depict the energy sector in great detail (e.g., MESSAGE, REMIND) tend to only quantify the water consumption and withdrawal associated with the energy mix (i.e., the «water footprint» or «water impact») but do not explicitly represent the water dependency of energy production (e.g., they do not allow exploration of what would happen for energy production if water were to become scarce). Finally, some provisioning services, such as fibres and fish provision, tend to be overlooked, possibly because they are a lower part of GDP in many countries. Likewise, modelling those aspects is not a trivial task, given the multiple persisting knowledge gaps with respect to ocean-related aspects.

Table 3.2 **Representation of the direct dependency on ecosystem services of economic processes in reviewed modelling frameworks**

		How is the impact of the ecosystem service (and of its disruption) on the economy represented in:					
Ecosystem services		**GTAP-InVEST**	**REMIND-MAgPIE**	**AIM/CGE and AIM/PLUM**	**IMAGE-MAGNET**	**MESSAGE-GLOBIOM**	**GCAM**
Provisioning services	Surface- and Ground- Water provision	□	▨	□	▨	▨	■
	(Food) crop provision	■	■	■	■	■	■
	(Food) livestock provision	■	■	■	■	■	■
	Fish provision	■	□	■	■	□	□
	Timber provision	■	■	■	■	■	■
	Fibres provision	■	■	□	■	■	■
	Bioenergy	□	■	■	■	■	■
	Genetic material	□	□	□	□	□	□
Maintenance and regulation services	Pollination	■	▨	□	▨	□	□
	Climate regulation	▨	■	□	▨	▨	▨
	Mass stabilisation and erosion control	□	▨	□	▨	▨	□
	Soil quality	□	▨	□	▨	▨	□
	Flood and storm protection	□	□	□	□	□	□
	Water flow maintenance	□	▨	□	▨	▨	■
	Water quality	□	□	□	□	□	□
	Pest control	□	□	□	□	□	□
	Disease control	□	□	□	□	□	□
	Dilution by atmosphere & ecosystems	□	□	□	□	□	□
	Filtration	□	□	□	□	□	□
	Ventilation	□	□	□	□	□	□
	Buffering and attenuation of mass flows	□	□	□	□	□	□
	Bioremediation	□	□	□	□	□	□
	Maintain nursery habitats	□	□	□	□	□	□
	Mediation of sensory impacts	□	□	□	□	□	□
Cultural services	Tourism	□	□	□	□	□	□

■ Dark green= multiple and/or direct transmission mechanisms included (NB: assessment is relative to the other models).

▨ Light green = incomplete compared to other models, or indirect mechanism.

□ Gray = not included.

Source: Authors, adapted from Kedward, Salin and Dunz (forthcoming working paper).

Models linking nature and the economy tend to overlook maintenance and regulating services, except for the regulating service from pollination (cf. red parts at the bottom of Table 3.2). This could be because representing their supply is more complex and usually requires an additional layer of biophysical modelling, which has additional complexities relating to the need for spatially explicit data. Furthermore, the multiple simultaneous and dynamic interactions that would need to be modelled often cause computational issues in a general equilibrium framework and are hence addressed (if) in partial equilibrium frameworks. Additionally, estimating the economic effects of losses in maintenance and regulating ecosystem services is subject to significant uncertainty. For example, air filtration is one important ecosystem service that is challenging to connect to any element of a macroeconomic model. It is worth noting that the IMAGE model captures a wide array of ecosystem services provided by nature (see **Annex Table 3**), although the connection with economic sectors in the MAGNET model is not necessarily made.

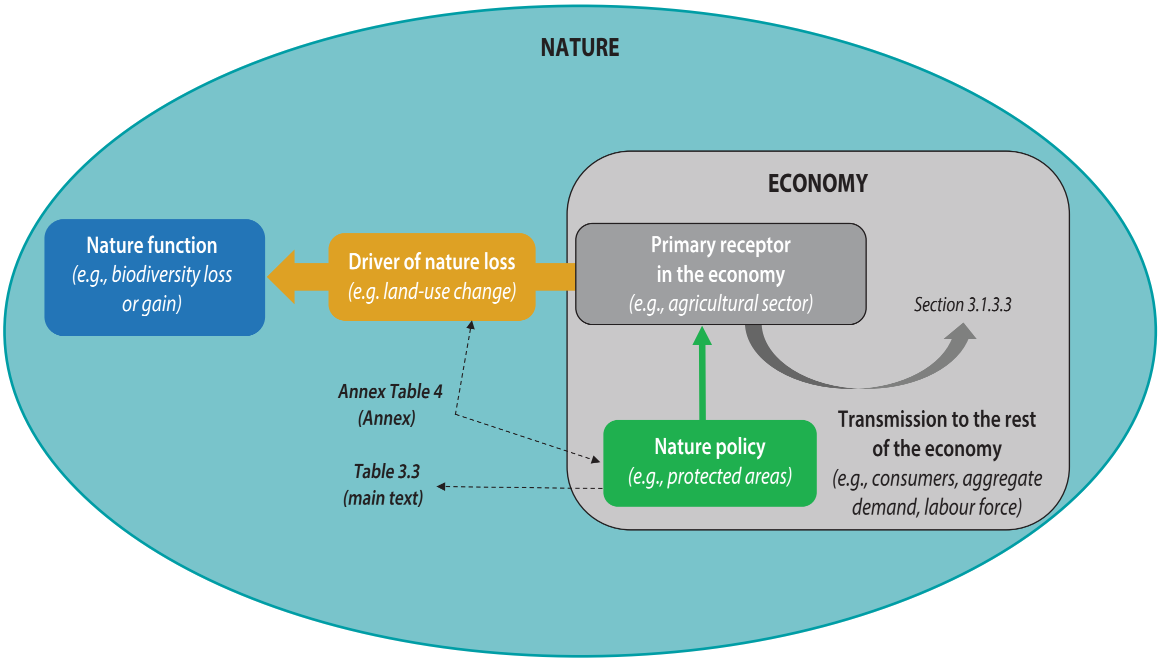
B. Representation of the economic impacts of transition hazards

For models to effectively assessing transition risk scenarios, such as the economic consequences of actions to mitigate the loss of nature and biodiversity (e.g., as defined under the Global Biodiversity Framework in Kunming-Montreal in 2022), it is essential that they can represent the impact of economic activities upon nature and allow for different policy options. Understanding the impact of an activity on nature (e.g., how much a sector or firm emits CO_2 or contributes to deforestation) is critical to comprehending how it may be exposed or vulnerable to policies aimed at mitigating or preventing this impact (e.g., the implementation of a carbon price or a ban on deforestation, in the examples above).

This section evaluates the ways in which the reviewed models capture the direct drivers of nature loss and represent the associated policy actions aimed at mitigating those drivers. The drivers listed in Table 1.3 below are based on those identified by the IPBES (2019, Chapter 2.1). There are also two dimensions to understanding transition hazards and related risks. First, we assess (i) which drivers are represented in the models reviewed, and then (ii) which policies are included in the models to evaluate the economic consequences of mitigating the direct drivers. A detailed table, with full descriptions of the precise drivers and policies included and an explanation of our categorisation, can be found in **Annex Table 4.**

Regarding the drivers of nature loss (and biodiversity in particular), we find that coverage of land-use change, resource extraction and climate change, is relatively well covered, while sea-use change, pollution and invasive alien species tend to be overlooked. Additionally, some models capture some drivers but do not represent related policy interventions. As we are primarily concerned with the economic consequences of transition hazards, the colour-coding of the **Table 3.3** below corresponds to the evaluation of policies included.

Figure 3.5 **Focus of the Assessment Tables on the "transition risks" side**



Source: Authors.

Table 3.3 **Representation of policies to mitigate direct drivers of biodiversity loss in reviewed modelling frameworks**

		How are policies to mitigate direct drivers of biodiversity loss represented in:					
Direct drivers of biodiversity loss covered		**GTAP-SEALS-InVEST**	**REMIND-MAgPIE-LPJmL**	**AIM/CGE and AIM PLUM**	**IMAGE-MAGNET-GLOBIO**	**MESSAGE-GLOBIOM**	**GCAM**
Land and sea use change	Expansion of cropland and pastureland	■	■	■	■	■	■
	Expansion of managed forests	■	■	■	■	■	■
	Expansion of cities	□	□	□	□	□	□
	Fragmentation	□	□	□	□	□	□
	Land use intensification	□	■	□	■	■	■
	Sea use intensification	□	□	□	▨	□	□
	Land degradation	□	▨	□	■	□	□
Resource extraction	Rates of extraction of living materials from nature (e.g. biomass)	■	▨	▨	■	▨	▨
	Rates of extraction of non-living materials (e.g., fossil fuels, metals, minerals)	□	▨	▨	▨	▨	▨
	Freshwater withdrawals	□	▨	□	■	▨	■
Climate change	GHG emissions	▨	■	■	■	■	■
Pollution	NOx	□	□	□	▨	▨	▨
	SO_2	□	□	□	▨	▨	▨
	PM2.5	□	□	□	▨	▨	▨
	Mercury	□	□	□	□	□	□
	Nitrogen/nutrient runoffs	□	□	□	■	▨	▨
	Noise	□	□	□	□	□	□
	Untreated wastewater	□	□	□	■	□	□
	Pesticides	□	□	□	□	□	□
	Pharmaceutical residues	□	□	□	□	□	□
	Plastics	□	□	□	▨	□	□
	Dissolved metals	□	□	□	□	□	□
	Oil spills	□	□	□	□	□	□
	Salinisation	□	□	□	□	□	□
Invasive alien species		□	□	□	□	□	□

■ Dark Green = multiple and/or direct transmission mechanisms included (NB: assessment is relative to the other models).

▨ Light Green = incomplete compared to other models, or indirect mechanism.

□ Gray = not included.

Source: Authors, adapted from Kedward, Salin and Dunz (forthcoming working paper).

Aside from climate change, land use change as a direct driver and policies aimed at mitigating this driver are captured by the models with the most detail. This emphasis likely stems from many of the models' historical use as climate-economy models with coupled land-use modules – mostly to assess land-use GHG emissions and bioenergy capacity. A variety of nature policy interventions can however be modelled, including protected areas, different agricultural management systems, REDD+, payments for ecosystem services, land use planning regulations, and land restoration. Even so, the focus is very much on agricultural land uses. Urban expansion and impacts resulting from habitat fragmentation are both included as drivers within IMAGE-MAGNET, but without relevant policy interventions in its current version. In the same model, sea use and its intensification is similarly only partially included as a driver. Production quotas, e.g., for fishing or mining, can be modelled as a transition policy, however the economic modelling of fish markets in MAGNET is not yet connected to biophysical modelling of fish stocks within IMAGE.

All of the models represent land use intensification as a strategy to avoid land use expansion but there are differences in their representation. Some models rely on an exogenous increase in agricultural yields to proxy for intensification (GTAP-InVEST, AIM-Hub) while other models represent intensive management systems endogenously as part of how agents choose to allocate land uses (REMIND-MAgPIE, IMAGE-MAGNET, MESSAGEix-GLOBIOM, GCAM). Only the latter four modelling frameworks include policies to mitigate the damaging ecological effects of land use intensification, such as restrictions on fertiliser use and improved efficiency of nutrient use and irrigation.

However, it is often observed in the real world that intensive land use can exacerbate land degradation. This interconnected relationship between the two drivers is not explicitly accounted for in any of the reviewed models. Human-induced changes in soil fertility are incorporated in MAgPIE and IMAGE-MAGNET, derived from connected biophysical models (such as the LPJmL crop/vegetation model), and focus on water- and climate-induced effects. Few models represent policies to mitigate the effects of land degradation through changes in crop and livestock management systems, such as organic farming. Of particular interest, the MAgPIE model is currently developing an agro-forestry management option as part of its link to the LPJmL biophysical model. The GLOBIOM model also includes organic farming as a possible management practice, but only for Europe.

Resource extraction is mainly captured in the models by inputs to the energy and agricultural sectors. Living material extraction includes forestry products and crops for food, feed, fibre, and biomass energy. Non-living material extraction focuses on primary fossil fuel and nuclear energy resources. Most models have a limited set of policies to mitigate both drivers, most including just protected areas and various GHG emissions reduction measures that will have an indirect influence upon fossil fuel extraction.

Freshwater use for the agriculture, energy, and household consumption sectors is modelled in some detail in AIM-Hub, GCAM, REMIND-MAgPIE and IMAGE-MAGNET. However, only the latter includes water-specific policies, such as improved rainwater management, improved irrigation efficiency, and increasing water storage capacity. IMAGE-MAGNET is also able to model the impacts of land use, water availability and quality upon freshwater biodiversity, calculated through the linkage to the GLOBIO-Aquatic model.

All of the models have good coverage of greenhouse gas emissions (GHG) and relevant emissions reduction measures, with the exception of the GTAP-InVEST model, which models the carbon sequestration effects of CO_2 only, instead of the full range of GHG emissions.

The remaining pollution-related drivers of biodiversity loss are not captured in any comprehensive detail by any of the models reviewed; the same also being true for invasive species. Pollution flows are difficult to include within global models due to their spatial heterogeneity. Transition policies are also tricky to represent, given that the governance of polluting activities is determined as much by regionally diverse institutional arrangements as by markets. The invasive species driver shares these challenges and is not captured by any of the reviewed modelling frameworks.

It is important to note that some of the transition policies discussed in this section are represented by manually adjusting model parameters to proxy for the policy intervention as part of an 'ad hoc' scenario modelling

process. This approach does not account for the costs of implementing the policies. For example, it is possible to exogenously improve efficiency of nutrient use in IMAGE, but the economic costs of introducing this transition policy (e.g., costs to farmers of new equipment, etc.) are not captured.

3.1.3.3 How models represent nature-to-economy transmission channels

This section describes how the physical and transition hazards represented in the models, outlined above, are transmitted to the rest of the economy. We refer to these mechanisms, which correspond to the red arrows in **Figures 3.4** and **3.5** above, as "nature-to-economy transmission channels".

As shown in Table 3.4 below, multiple nature-to-economy transmission channels are captured by macroeconomic models in diverse ways. All the models reviewed have a particular focus on land-based sectors (agriculture, forestry) and energy sectors, but these are linked to macroeconomic output in different ways depending on the type of model.

For the multi-sector (computable) general equilibrium models, each sector contributes to macroeconomic production and land is explicitly included as a production factor for agricultural sectors. The production function, which represents how different inputs are combined to produce output, adopts a 'nested' structure. Hazards affecting, for example agriculture, therefore feed through directly to affect macroeconomic output through changes in sector productivity and output, and changes in the cost of land. Constraints on the availability of land for production result in higher relative land prices, increasing factor costs for land-based sectors and feeding through to the macroeconomy through higher relative prices for agriculture goods, and its subsequent effects on production and consumption choices.

In the modelling frameworks relying on single-sector computable general equilibrium and optimal growth models, however, land is usually not included in the production function: changes in agricultural output only affect macroeconomic production indirectly through changes in the prices of bioenergy and the price of carbon, which are likely to have relatively small effects at the macro level.[36, 37] The agricultural sector is detailed in a connected partial equilibrium model that can represent the impact of hazards upon agricultural commodity yields and output. Nature-related hazards (physical or transition) can affect bioenergy capacity and price, which will impact the price of energy and macroeconomic output – because energy is a production factor in those optimal growth models. Additionally, land use policies will affect carbon sequestration in soils and therefore the amount of GHG emissions that need to be abated. This then influences the price of carbon and then the price of energy, which is a production factor.

Overall, however, these energy-related transmission channels are likely to have small effects due to substitution possibilities between competing sectors and technologies. This topic and its implications are detailed in the next section.

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[36] To make the linkage more direct, REMIND-MAgPIE also calculates agricultural costs and subtracts them from macroeconomic output.

[37] The version assessed for this report is GCAM version 7. A future version of GCAM is planning to include agriculture as an intermediate input to the macroeconomic production function (in addition to energy, capital and labour). Hence, shocks on the agriculture sector would directly impact GDP.

Table 3.4 **Coverage of nature-to-economy risk transmission channels within reviewed models**

	GTAP- INVEST	REMIND-MAgPIE	AIM-Hub	IMAGE-MAGNET	MESSAGEix - GLOBIOM	GCAM v7
Type of core economic model	**Multi-sector Computable General Equilibrium models**	**Single sector Optimal growth model + partial equilibrium model**	**Multi-sector Computable General Equilibrium models**	**Multi-sector Computable General Equilibrium models**	**Single sector CGE model + partial equilibrium model**	**Single sector CGE model + partial equilibrium model**
Production / Supply side						
Sectors (number of sectors/technologies)						
– Agriculture (crops)	√ (6)	√ (20)	√ (6)	√ (9)	√ (30)	√ (5)
– Agri (livestock)	√ (2)	√ (5)	√ (3)	√ (10)	√ (4)	√ (3)
– Fishery	√ (1)	-	√ (1)	√ (6)	-	-
– Forestry	√ (1)	√ (1)	√ (1)	√ (4)	√ (1)	√
– Energy	√ (2)	√ (>50) Including bioenergy	√ (19) Including bioenergy	√ (7) Including bioenergy	√ (?) Including bioenergy	√ (?) Including bioenergy
How do shocks in these sectors impact aggregate macro output?	All sectors contribute to the production of aggregate output	Energy sector contributes to the production of aggregate output. Agricultural costs are subtracted from aggregate output	All sectors contribute to the production of aggregate output	All sectors contribute to the production of aggregate output	Energy sector contributes to the production of aggregate output	Energy sector contributes to the production of aggregate output[1]
Factors of production in macroeconomic production function						
– Labour	√	√	√	√	√	√
– Capital	√	√	√	√	√	√
– Energy	√	√	√	√	√	√
– Land	√ for agricultural and forestry sectors	-	√ for agricultural and forestry sectors	√ for agricultural and forestry sectors	-	-
Consumption / Demand side						
Are the impacts of food prices on final consumption currently accounted for?	-	Agricultural costs are accounted for in the budget equation of the macroeconomic module	√	-	-	-
Are the impacts of nature loss on human health accounted for?	-	-	-	-	-	-
Indirect effects						
– Trade	√	√	√	√	√	√
– Sector inter-linkages	√ (CGE model)	Not included (only link is between agriculture and energy)	√ (CGE model)	√ (CGE model)	Not included (only link is between agriculture and energy)	Not included (only link is between agriculture and energy)

[1] Agriculture will contribute to the production of aggregate output in a forthcoming version of GCAM.

Source: Authors, adapted from Salin, Kedward and Dunz (forthcoming working paper).

Aside from land and energy, the other factors of production – labour and capital – are generally treated as perfect markets whose productivity growth is not affected by nature hazards, hence potential feedback channels from nature-related shocks are not captured. One exception is the treatment of labour in MAGNET, which assumes workers face difficulties moving between agricultural and non-agricultural work. This rigidity in labour mobility results in farmers potentially accepting lower wages in the event of a shock, influencing purchasing power and potentially aggregate demand. In addition, physical hazards could result in lower labour or capital productivity, but this factor productivity is another important transmission channel that is not endogenously captured by the models reviewed. However, these effects could be simulated in an 'ad hoc' fashion by adjusting labour productivity parameters to fit certain scenario narratives.

Nature-related hazards can also impact aggregate demand through changes in consumption resulting from relative price changes in consumption goods. However, most models do not capture broader effects from rising food prices at this stage. When food prices increase, we would expect demand for other non-essential goods to fall as consumers reallocate their budgets to prioritise food as an essential good. This is particularly important for emerging and developing economies, for which food expenditure is already a large share of household consumption. Only the AIM-Hub model explicitly captures such dynamics (Hasegawa et al., 2019) through their specific choice of utility function (Stone-Geary), which treats food as an essential good. None of the models reviewed capture other potential demand-side nature-to-economy transmission channels, such as the economic consequences of human health impacts.

3.1.3.4 Factors mitigating (or reducing) nature-to-economy transmission channels

Regardless of how well the transmission channels between nature-related hazards and the economy are captured by models, there are several features of the economic part of the models that are likely to reduce economic impacts by assumption. The rest of this section identifies and explains them.

The magnitude of estimated economic impacts resulting from transmission channels is related to how the model represents the relative importance of the affected sector(s) in the economy. This relative importance can be determined by both the relative size of the sector(s) and the assumed ability of the economy to adapt to the shock.

First, the models reviewed all assume that economies have a high degree of adaptability to hazards. This can be partly explained by the fact that the reviewed models are typically designed and deployed for medium- to long-term policy analysis, rather than short-term stress testing. However, structural aspects of these models may underestimate results even in the longer term (e.g., Johnson et al., 2021, pp. 44-45). Most importantly, it is generally assumed in CGE models that producers and consumers are able to instantaneously adapt to the effects of shocks through substitution and trade. If the price of one production input (e.g., land) or consumption good (e.g., food) increases relative to another, that option can be substituted for an alternative, with the ease of switching governed by 'elasticity' parameters. For instance, the bioenergy transmission channel, identified in the previous section, forms a small portion of the final energy mix in most countries, and can be easily substituted by alternative technologies in the event of price increases resulting from constraints on land use. Similarly, most of the models reviewed do not capture many broader indirect socioeconomic impacts of threats to food security, as higher food prices can be mitigated by households swapping out expensive food for cheaper items (e.g., clothing, manufactured goods, etc.) in their consumption choices.[38]

These types of substitution possibilities can result in 'smoothing' effects on the magnitude of economic impacts resulting from nature-related hazards. A broad academic literature has argued that substitution possibilities may be limited or even impossible for environmental goods and services that are critical to human wellbeing (e.g., Dasgupta, 2021; Neumayer, 2013). Recognising this, Johnson et al. (2021) ran a sensitivity analysis to limit price-induced substitution possibilities, finding that the drop in agricultural and forestry output was twelve

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[38] The AIM-Hub model is the exception here, as detailed in the previous section.

[39] The authors reduced by 50% relative to baseline values the (1) constant elasticity of substitution between land, labour, capital (primary production factors); (2) the ease of transformation between land uses; and (3) ease of transforming land uses between different types of crops.

times larger under the business-as-usual scenario.[39] Such sensitivity of scenario modelling results indicates the importance of clearly communicating parameter choices and justifications. Not least because substitution elasticities are typically calibrated according to historical data (which implicitly assumes high substitutability, due to the lack of consideration of the importance of nature on economic activities), and, especially because they are assumed constant, they will not reflect how substitution possibilities may be limited in the event of extreme hazards or in the immediate aftermath of certain shocks (Geerolf, 2022). Whilst CGEs can adjust substitution elasticities up to a certain point, 'limited' or 'no substitutability' assumptions can prevent the model from solving under more extreme scenarios (future scenarios in which tipping points are crossed are of extreme interest and belong to this class).[40] Therefore, other types of methods, e.g., input-output models (at least for short-term scenarios), may be more appropriate for exploring non-substitutability coupled with more extreme hazards (as discussed in the next chapter of this Technical Document).

Due to the high adaptation capacities for producers and consumers in the models, the final economic impact obtained may not be higher than the sector's share in value added. The magnitude of the final impact of a shock on agriculture, for example, would be quite small in high- and middle-income countries, where agriculture represents a small proportion of GDP (4.3% of global GDP, 1.3% in high-income countries, and 8.8% in middle-income countries, according to 2022 World Bank data). This potentially suggests that only low-income countries could be significantly impacted, given that agriculture represents 25% of GDP on average for these countries. However, this does not reflect well the importance of food provision for human well-being and the possible spillover effects to other sectors of the economy along the supply chain. Additionally, as the importance of land as a factor in value added is small compared to labour, even for agricultural sectors, a shock on the price of land would likely lead to low final economic impacts. Similarly, in western economies today, consumers do not allocate a large portion of their incomes to purchasing water or food. Hence, given their current features, the models will fail to account for the economic importance of health and sanitation services.

Second, the exogenous scenario assumptions which are used to calibrate the models can also mitigate modelled economic impacts. Current models typically calibrate total factor productivity so that, when the model is run without being shocked, the GDP path obtained reproduces an exogenous GDP taken from Shared Socioeconomic Pathways (SSPs – usually SSP2). Some models also take exogenous labour and land productivity and sectoral technological change as inputs. This means that a portion of GDP growth is assumed to always increase regardless of the magnitude of any shock. This type of analysis aims to assess marginal changes, i.e., impacts holding all other things equal. Whilst such an approach can be useful for comparing different incremental policy approaches, its suitability is called into question when exploring scenario narratives of radical and structural changes. For instance, high-impact nature-related hazards or transformative policy changes implied by the Global Biodiversity Framework (GBF) targets will both influence long-term growth trajectories and cause structural changes, not marginal ones (as discussed earlier in this Technical Document, e.g., through the concept of transformative change).

Thirdly, all models represent changes in land use as a process conducted by agents, such as landowners, who behave in an economically rational way by maximizing the rent they draw from the land. While this assumption may accurately represent land-use change mechanisms in areas where agriculture is well integrated into markets, it may not adequately reflect local patterns in places where land is used for subsistence agriculture. Additionally, in some cases, competition between farmers may drive deforestation even though it may not be profitable in the long-term (Meyfroidt et al., 2018).

Fourthly, the models reviewed do not explicitly represent the financial system and its feedback effects on the economy. While some model outputs, such as changes to sectoral value added, can be input into financial risk assessment models, estimated economic impacts will not account for macrofinancial dynamics that could amplify the

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[40] As indicated by Johnson et al. (2023) in a later study using GTAP-InVEST: "We found, however, when running the GTAP-InVEST model with both the partial ecosystem collapse and limited substitutability that the model would not solve." (p. 4). Indeed, 'solving' the model refers to achieving an equilibrium where supply equals demand.

economic impacts of shocks, such as credit crunches, asset bubbles or financial contagion. Additionally, the financial sector could play an enabling role in required investments for a nature-aligned transition, as seen in the role of finance for climate investments (Battiston et al., 2021). Therefore, the lack of explicit representation of the financial system in the models reviewed may limit their ability to fully capture the complexities of the nature-to-economy transmission channels.

Finally, it is important to emphasise that modelling uncertainty in nature-economy assessments is exacerbated by the uncertainty surrounding data inputs, model specification, parameter values chosen, and biophysical and economic dynamics (Almeida et al., 2023). The nonlinearity of nature and the feedback effects of biophysical processes add complexity. Likewise, uncertainty arises as scenarios need to make assumptions about policy targets, and societal trends, including population, economic growth, technology, and societal preferences, often represented by the Shared Socioeconomic Pathways (SSPs), which were originally developed for climate change considerations only. To better capture the costs of future nature loss impacts and associated risks, it is important to understand and address uncertainties that underlie such assessments.[41]

Given the historically unprecedented nature of many of the physical and transition hazards identified, there may not be much or any empirical evidence to justify relevant behavioural parameters within modelling frameworks. For instance, Stehfest et al. (2014, p.51) details key areas of modelling uncertainty identified for the IMAGE-MAGNET framework. Likewise, reviewed models typically use the mean of the probability distribution of projected impacts, which neglects the low-probability, high-impact tails of the distribution, leading to an underestimation of the overall risk posed by nature degradation. It is important for exercises using these models to manage uncertainty through, e.g., sensitivity analyses of key parameters, and ensure modelling uncertainty is well-communicated to end users.

Overall, a key takeaway from our analysis is that the modeling approaches reviewed here are likely to deliver very conservative estimates (i.e., underestimates) of the economic consequences of nature-related hazards.[42] While macroeconomic models necessarily must make simplifications to capture complex nature-economy linkages at a global scale, our review has found that the representation of key transmission channels often does not reflect nature's importance to human well-being, as well as social and financial stability. Additionally, the reviewed models assume a high degree of adaptability to shocks and focus on marginal rather than structural effects of hazards on the global economy. As a result, the available global nature-economy models are currently not well-suited to capturing the systemic risks associated with the loss of ecosystem services and transformative policy changes. Therefore, caution is particularly warranted when using these models for exercises aiming to focus on «severe but plausible» scenarios and there is a need for further work and research on the development of models which are able to fully account for nature-related risks.

3.2 Biophysical models review

Biophysical models are simulations of one or several (potentially interconnected) biological systems, which can be used to predict the influence of biological and physical factors on complex systems.[43] Unlike the models discussed above, they do not account for economic dimensions (or only indirectly, when they are used to assess the impact of a specific policy on biophysical elements).

This section assesses the extent to which biophysical models can provide useful outputs for the development of nature-related scenarios. Indeed, with regards to physical risks, biophysical models allow for the representation of a wide diversity of ecosystem services and their disruption, as well as feedback loops in the natural system. As such, they could help link regulating ecosystem services

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[41] From the climate literature four types of uncertainty are well known that affect the forecast of climate impacts on macroeconomic variables (Auffhammer,2018; Pindyck, 2021). These include climate uncertainty, shock uncertainty, parameter uncertainty, and model uncertainty. Climate uncertainty refers to the unknown trajectory of global warming and is typically addressed with scenario analysis. Shock uncertainty pertains to the underlying probability distribution of shocks, which can be taken from climate science. Parameter uncertainty arises from the lack of knowledge of unobserved model parameters and can be represented by probability distributions over parameter values. Model uncertainty arises from the fact that models need to simplify reality and is the most difficult type of uncertainty to incorporate in the assessment of future climate damages.

[42] Many of the models covered here to determine their ability to assess nature-related risks are also used for assessing climate risks. As such, these models are also likely to systematically underestimate the severity of macrofinancial impacts stemming from climate change.

[43] See: https://www.nature.com/subjects/biophysical-models.

(e.g., water regulation) to the provisioning services that directly impact the economy (e.g., agricultural yields) (cf. blue arrow of Figure 4), thereby better calibrating a shock in productivity of the agricultural sector in a macro-economic model. With regards to transition risks, biophysical models could help design scenario narratives (e.g., by helping design maps of areas that should be protected to achieve a specific land protection target – cf. yellow arrow of Figure 4).

3.2.1 Review method

There exists a multiplicity of biophysical models: those we review in this Technical Document were chosen along two main criteria. First, we focused on global models – even though some can be applied in a relevant way to more regional or local spatial scales – given the global nature of the NGFS. Second, we picked a diversity of models so that they cover multiple aspects of nature: biomes (investigating plant processes), agriculture, water, biodiversity, fisheries, fire – energy and health are also covered but as they are particularly focused on climate change, we do not review them in detail in this Technical Document.

Technically speaking, we selected the models for review based on the number of output datasets found in the repository of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP[44]). We kept only the models with the largest numbers of output datasets, as a higher number of datasets in a model indicates a greater number of output variables and application possibilities. We have also opted for those models that are relatively well established and have already been applied with other sector model coupling (indeed, our purpose is to assess how they can be coupled to economic models).

To summarise, we reviewed 14 models that represent the functioning of diverse aspects of nature but have in common to (i) be global and (ii) provide a great number of outputs according to the ISIMIP repository. The following is the list of the reviewed models and their represented sectors:

- **CARAIB** (Biomes, Forests)
- **LPJ-GUESS** (Biomes, Forests)
- **ORCHIDEE** (Biomes, Water)
- **CLM45** (Biomes, Agriculture, Water)
- **LPJmL** (Biomes, Agriculture, Water)
- **GEPIC** (Agriculture)
- **WATERGAP2** (Water)
- **CWatM** (Water)
- **BioScen1.5-SDM-GAM** (Biodiversity)
- **BioScen1.5-MEM-GAM** (Biodiversity)
- **EcoOcean** (Fisheries)
- **BOATS** (Fisheries)
- **CLASSIC** (Fire)
- **TRM-Tsukuba** (Health)

The assessment of those models was conducted through an analysis of their documentation material, which allowed us to fill out "ID cards". The selected assessment criteria in the "ID cards" were mostly focusing on the type of biophysical outputs the models were able to provide. The idea was to then see how they could help framing physical and transition nature scenarios.

3.2.2 Main characteristics of the selected models

Biophysical models primarily focus on understanding and simulating the intricate relationships within ecosystems, emphasizing the flow of materials, energy, and species in the natural world. These models excel in capturing the dynamics of nature-nature interactions (for example, what are the impacts of the disruption of some natural elements on the other natural elements? see blue arrow in **Figure 3.3**), such as how species interact, nutrient cycling, and the functioning of ecosystems (see **Box 3.1** for details). They provide valuable insights into the ecological aspects of our planet and play a crucial role in assessing the state of biodiversity, ecosystem services, and the impacts of environmental changes. Therefore, biophysical models are essential tools for understanding the complex relationships within ecosystems and the functioning of the natural world.

Biophysical models often prioritise ecological complexity and accuracy in representing natural systems, and very few are linked to economic aspects. While this provides detailed insights into ecological processes, it can make the models computationally intensive and

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[44] See: ISIMIP – The Inter-Sectoral Impact Model Intercomparison Project.

Box 3.1

Main characteristics of biophysical models reviewed

This box outlines the main characteristics of the biophysical models we reviewed, by type of natural processes they focus on. We make a distinction between "process-based" and "statistical" models: the former describe the mechanisms driving the natural process at stake, while the latter only rely on statistical patterns drawn from observed data.

Process-Based Models

Models for Biomes

The models for biomes represent the growth and dynamics of plant species under various environmental conditions, incorporating processes like photosynthesis, respiration, and carbon allocation. CARAIB, LPJmL, LPJ-GUESS, ORCHIDEE, and CLM45 are all dynamic and process-based vegetation-terrestrial ecosystem models used to study various aspects of the Earth's climate, vegetation, and carbon cycle.

One of these biomes models, LPJmL, seems well suited for studying scenarios of agricultural expansion and land management. Indeed, LPJmL is specifically designed to simulate human-driven land use change and its impacts on the terrestrial carbon cycle, and considers economic and social factors influencing land use decisions. This is the reason why it is used by some "nature-economy models", such as REMIND-MAgPIE (see **Table 3.4** above). Other models like CARAIB, LPJ-GUESS, ORCHIDEE, and CLM45 might have representations of land use, but without capturing the detailed interactions of human decision-making processes or agricultural management practices as comprehensively as LPJmL.

Some of these biomes models can also be used to investigate fire disturbance. CARAIB and LPJ-GUESS include specific modules to simulate the effects of wildfires on vegetation dynamics and carbon cycling. They can account for changes in vegetation composition and biomass due to fire events. ORCHIDEE and CLM45 might also have some representation of fire disturbances, but the level of detail and accuracy in capturing the impacts of fires on ecosystem dynamics might not be as sophisticated as in CARAIB and LPJ-GUESS.

Biomes models also represent carbon and water cycle interaction: in particular, ORCHIDEE is specifically designed for this purpose. While other models might also consider the carbon and water cycles, the level of integration and process representation in ORCHIDEE might provide more accurate and detailed insights into these complex interactions.

Finally, one biomes model, CLM45, is part of the Community Earth System Model (CESM), which allows it to be coupled with atmospheric and oceanic models. This integration enables comprehensive studies of climate change and its impacts on terrestrial ecosystems, taking into account feedbacks between different components of the Earth system. Other models are rather standalone models without such strong coupling capabilities, limiting their ability to capture certain feedback mechanisms between the land surface and the atmosphere.

Agriculture models

The agriculture models simulate the impact of physical drivers of environmental change, like temperature, precipitation, CO_2 concentration, pollution or land use change (e.g., changes in agricultural management or forestry practices) on vegetation dynamics with a specific focus on food provisioning, carbon cycling, water availability, and ecosystem productivity. LPJmL, GEPIC, and CLM45 are process-based agriculture models. GEPIC is a modelling framework that combines the EPIC model with a Geographic Information System (GIS), allowing for spatially explicit simulations enabling to investigate the impacts of land use changes at various spatial scales. CLM45 explicitly considers interactions between land surface processes and the atmosphere, including the impact of land surface properties (e.g., vegetation cover) on local climate conditions, such as temperature and precipitation patterns. While it is primarily a land surface model, its capabilities extend to studying the effects of land use changes and environmental drivers on vegetation dynamics, carbon cycling, water availability, and ecosystem productivity.

…/…

Water models

The water models use hydrological processes to simulate the movement and availability of water resources, including precipitation, evapotranspiration, runoff, and groundwater flow. Both water models reviewed, WaterGap and CWatM, are process-based models and highly suitable for climate and water management analysis. CWatM is suitable for simulating all interrelations and interactions of the nexus system at global and regional scales, while WaterGap focuses on understanding the impact of land use changes on water availability, making it useful for local to regional-scale studies with a strong emphasis on the interactions between land cover patterns and water resources.

Fisheries models

Fisheries models use population dynamics and environmental data to understand how climate change and human activities, such as fishing, impact marine ecosystems and fish populations. Both EcoOcean and BOATS are process-based models. The BOATS model incorporates economic aspects of fisheries, such as fishing effort, ex-vessel fish prices, costs, and profitability, and it directly integrates technological progress into the model. EcoOcean provides a detailed and comprehensive representation of the interactions among various organisms in the marine ecosystem, including both commercial and non-commercial species. This level of detail in food web modelling may not be as explicitly emphasized in the BOATS model. EcoOcean examines the impacts of different stressors on marine biodiversity, including fishing pressure, habitat degradation, pollution, and climate change. BOATS primarily considers ocean temperature and net primary production as environmental factors.

Fire and Health models (related to climate change)

The last models of the list are rather focused on issues related to climate change. In particular, the reviewed model for fire, called CLASSIC, is simulating the impacts of climate (but also vegetation and human activities) on fire behavior, spread, and the subsequent impacts on vegetation and carbon stocks. A model for health was also reviewed, TRM-Tsukuba, which provides insights into the magnitude of health risks associated with heatwaves (but not to other sources of health issues, e.g., diseases) and identifies vulnerable populations.

Statistical models

Biodiversity models

The biodiversity models study how climate and land-use changes affect the distribution of animal species (specifically amphibians, mammals, and reptiles). Both BioScen1.5-SDM-GAM (SDMs) and BioScen1.5-MEM-GAM (MEMs) are statistical models. MEMs are a less computationally intensive alternative to SDMs and have been shown to predict patterns of current and future species richness similarly to SDMs'. MEMs only require total richness values and no species-specific information, making them particularly useful in cases where inaccurate data precludes the application of species-specific distribution models. However, they only allow rough estimates of the spatial variation in species richness.

less accessible for policymakers who require simplified, actionable information. These models may lack a strong economic context, making it challenging to directly assess the economic implications of environmental changes (**Table 3.5**). In addition, biophysical models may not fully account for the influence of human activities and economic drivers on ecosystems, potentially leading to an underestimation of the impact of human actions on the environment. However, the extent of these limitations can vary depending on the specific model and its design.

Some biophysical phenomena are well-captured by models, including hydrological processes, vegetation dynamics and climate change processes, whereas many Biodiversity, Health, Fire, and Fisheries models are relatively new and still in the process of being refined

Table 3.5 **Representation of transition and physical risk relevant interactions in different biophysical models**

Sectors	Models	ECONOMY ↓ NATURE (What are the impacts of economy on Nature?)	ECONOMY ↓ ECONOMY (What are the impacts of economic changes required to protect nature on the economy?)	NATURE ↓ ECONOMY (What are the impacts of degradation of nature on economy?)	NATURE ↓ NATURE (What are the impact of the disruption of some elements of nature on the other elements of nature?)
Water (Global)	WATERGAP2	▒	░	░	■
	CWatM	▒	░	░	■
Agriculture	LPjmL	▒	░	░	■
	GEPIC	▒	░	░	■
Terrestrial Biodiversity (amphibians, birds, and mammals)	BioScen1.5-SDM-GAM	▒	░	░	■
	BioScen1.5-MEM-GAM	▒	░	░	■
Health	TRM-Tsukuba	░	░	░	■
Biomes	CARAIB	▒	░	░	■
	LPJ-GUESS	▒	░	░	■
	ORCHIDEE	▒	░	░	■
	CLM5	▒	░	░	■
Fire	CLASSIC	▒	░	░	■
Fisheries (Global)	EcoOcean	▒	░	░	■
	BOATS	■	▒	■	■

■ Dark green = multiple and/or direct transmission mechanisms included (NB: assessment is relative to the other models).

▒ Light green = incomplete compared to other models, or indirect mechanism.

░ Gray = not included.

Source: Authors.

and validated. Overall, the Water (global), Agriculture, and Biomes models have a long track-record, having undergone extensive development and va,lidation. For instance, the CLM45, has been developed and used for several decades, making it one of the more mature models for studying land surface processes and biogeochemistry. The Water models (CWatM and WaterGap) have reached a mature stage as they are widely used in the water sectors. The WaterGap model is also well-calibrated with in-situ observation datasets. However, there is still uncertainty at the national or sub-national scale, while CWatM faces uncertainty in groundwater modelling. In contrast, the models focusing on Biodiversity, Health, Fire, and Fisheries are relatively new and still in the process of being refined and validated, leading to higher levels of uncertainty in their results.[45]

Finally, for some aspects of nature, global models are currently lacking, and hence those processes could not be included in this review. These include wetlands, forests (except for the CARAIB model), soil fertility and quality, freshwater recharge potential, water quality, pollution

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[45] In our review, this is the case of BioScen1.5-SDM and BioScen1.5-MEM, TRM-Tsukuba, EcoOcean and BOATS as it is focused on biophysical models. The review on health models only covers temperature-related mortality models, but there are other health-related models that should be considered for a more comprehensive assessment. For example, models that address vector-borne diseases (such as LMM 2005, a dynamic malaria model), water-borne diseases (such as WBD model), and the impact of pollution on human health should also be included. Similarly, the biodiversity models reviewed only focused on animal biodiversity, specifically amphibians, mammals, and reptiles, while neglecting plant biodiversity. However, plant biodiversity can be investigated using biome models.

impact on health, and the geosphere/lithosphere (the solid Earth, encompassing rocks, minerals, soils, landforms, and the Earth's interior structure).

3.3 Conclusion

This chapter has reviewed six global nature-economy models and 14 biophysical models to understand how existing approaches could be used and/or adapted to explore the macrofinancial impacts of different nature-related scenarios, including severe but plausible ones.

An important finding of this analysis is that the reviewed nature-economy models may underestimate or misrepresent the risks associated with nature loss and the transformative changes required to halt and reverse nature loss. Among the global nature-economy models reviewed, none account for all relevant biophysical or transition policy dynamics. We find that nature-economy models only partially represent both the drivers of nature loss and the dependency of the economy on nature. Additionally, they are generally not able to comprehensively capture important transmission channels from natural hazards (physical and transition ones) to different economic sectors that do not directly rely on ecosystems, such as manufacturing and tourism. Therefore, we recommend that future work considers potential linkages to relevant biophysical models to help quantify scenario narratives, as has been successfully demonstrated by some of the approaches detailed in this chapter. Regarding the representation of the macroeconomic impacts of hazards, we find that among the models reviewed, multi-sector CGE models have better coverage of sectors and their interlinkages, and overall representation of nature-to-economy risk transmission channels for both physical and transition hazards, compared to single-sector general equilibrium models.

The estimates of economic impacts resulting from scenario modelling exercises will remain subject to a high degree of uncertainty, hence calling for systematic sensitivity analyses and for relying on a variety of modelling approaches. This uncertainty is particularly important for exploratory scenarios over longer horizons or considering severe shocks. Sources of model uncertainty, such as sensitive parameters, should be clearly and transparently communicated in any scenario analysis exercise. Therefore, it is crucial to manage uncertainty through sensitivity analyses of key parameters and ensure that modelling uncertainty is well-communicated to end-users (in addition to systematically communicating on which types of hazards and transmission channels are included). We also recommend that nature-related scenario analysis be complemented with other modeling approaches, including some that are better able to account for the impacts of out-of-equilibrium dynamics. The next section focuses on one possible approach, building on input-tables and models.

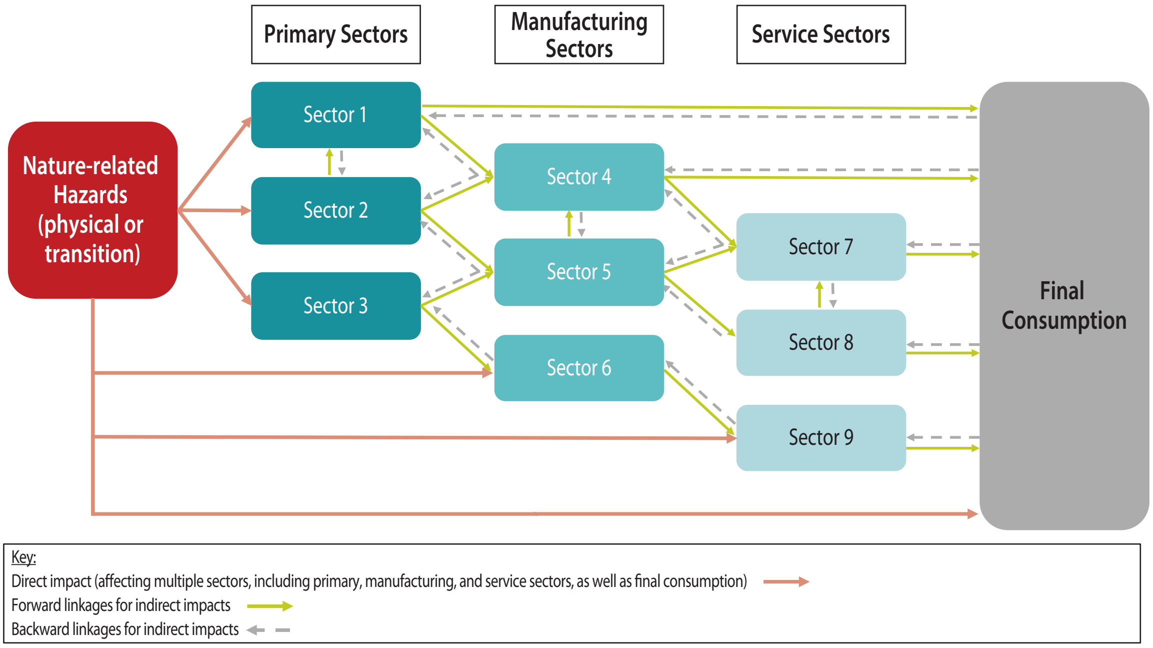
4. Using input-output tables and models to understand the propagation of nature-related hazards throughout value chains

An important finding in the previous chapter is the need to develop various complementary modelling approaches to account for the high degree of uncertainty resulting from scenario modelling exercises. The models reviewed in Chapter 3 demonstrate the value of integrating macroeconomic modules with various biophysical models. Nevertheless, these models also risk underestimating important nature-to-economy transmission channels, in particular due to underlying assumptions of a high degree of adaptability of economies to shocks.

To overcome some of these limitations, promising alternative modelling approaches can be explored to complement existing approaches, such as stock-flow consistent models, systems dynamics models, and multi-regional input-output models (see Box 4.1).

In this report, we focus in particular upon the promising avenues offered by Multi-Regional Input-Output (MRIO) tables and models, which have been gaining popularity as tools to explore indirect and cascading effects stemming from nature-related hazards that could occur in different sectors. More specifically, MRIO models have great potential to be useful in assessing the transmission of hazards under conditions of limited substitutability of forms of 'natural capital'. This assumption of the limited ability of economies to adapt to shocks is particularly relevant for short- to-medium term disruptions in critical ecosystem services (e.g., loss of wild pollinators impacting food production) or for very extreme physical scenarios (e.g., tipping points). **Figure 4.1** provides a visual representation of how nature-related hazards could propagate through the economy.

Figure 4.1 **Propagation of nature-related hazards throughout value chains until final consumption**



Source: Authors' illustration.

Box 4.1

Approaches than MRIO to explore indirect impacts of nature-related events

While this Technical Document focuses on the use of MRIO models, it is noteworthy that other approaches could also be explored. For instance, Production network models (PNM), which have been used to understand the transmission of shocks over input-output linkages and their aggregate impact, could also be useful. PNM build on the seminal paper by Long and Plosser (1983) and are used to study the propagation of microeconomic shocks over input-output linkages and to assess how the economy's production network can function as a mechanism for propagating shocks from one firm or sector to the rest of the economy. In this way, the PNM literature highlights the role of production networks in propagating shocks and in transforming microeconomic shocks into macroeconomic fluctuations.

Applied to environmental issues, Campiglio et al. (2022), Devulder & Lisack (2020), Frankovic (2022) and Krivorotov (2022) focus on carbon pricing and study the impact of the introduction of a tax on the global economy via international production networks and highlight the importance of forward and backward linkages from the entire IO structure of the economy in determining sectors most at risk. While the PNM literature has traditionally relied on the idea that shocks to the composition of demand may only have second-order effects (also known as the Hulten's theorem), recent contributions have moved beyond this to better account for the second order effects of a shock and non-linear impacts of a shock inherent in multi-sector models with production networks (see **Annex 7.4.1**).

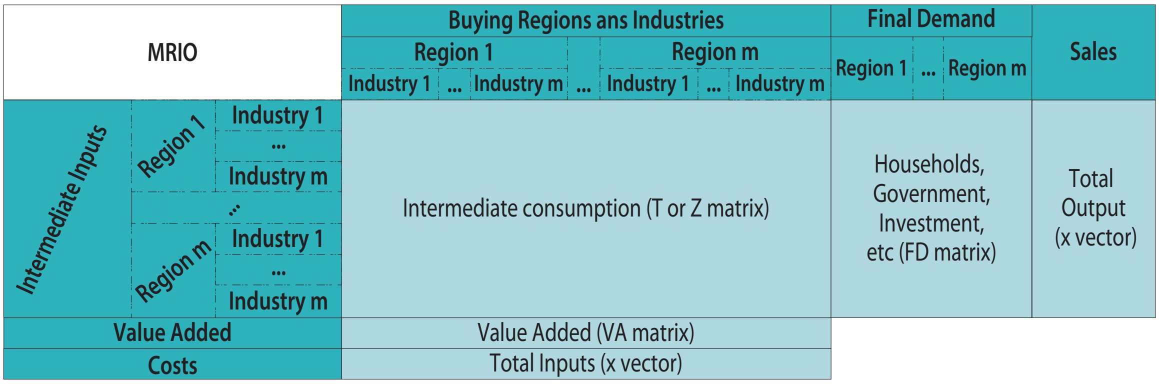
Structural Vector Autoregression Models (SVAR) could also be used to better assess the direct and indirect economic and financial impacts of nature-related hazards (see **Annex 7.4.2**) Vector autoregression (VAR) statistical models are multivariate time series models that relate current observations of a variable with past observations of itself and past observations of other variables in the system. Structural VAR (SVAR) models impose additional constraints on a VAR to examine the causal relationships between variables. These models are used to understand the macro effects of a shock hitting the economy and how these effects evolve over time through impulse response function analysis. This might be particularly important in the case of nature-related shocks as it allows to distinguish, for instance, between permanent and transitory shocks. The literature has increasingly investigated the impact of different shocks on the macroeconomy using VAR models, including weather (Kim et al., 2022) and supply chain (Finck & Tillmann, 2022) shocks.

However, it is noteworthy that many limitations to MRIO models (discussed in section 4.3) also apply to PNM models and SVAR, while specific limitations to these approaches also (e.g., Geerolf, 2022), as discussed in **Annexes 6.4.1** and **6.4.2**.

4.1 What are input-output models, and what insights can they provide into the assessment of nature-related risks?

First proposed by Leontief (1991 [1928]), Input-Output (I-O) tables are able to trace the origin of direct and indirect inputs needed for the production of goods and services in a national economy, and to display how this production generates profits, income and taxes. As shown in **Figure 4.2**, the basic structure of a MRIO model is composed of five main blocks of information concerning industries' intermediate consumption, value added by production, final demand, total output and additional information in the format of satellite accounts. Industries' intermediate consumption is represented by a squared matrix containing information at sectoral level of each country/region. Through combinations of the different blocks contained in MRIO tables, it is possible to find other matrices such as the (A) matrix of technical coefficients and the (L) Leontief-Inverse (see **Annex 7.4.5**). The use of these matrices for economic analysis, following Leontief's initial propositions, configures what we call MRIO models.

Figure 4.2 **MRIO table**



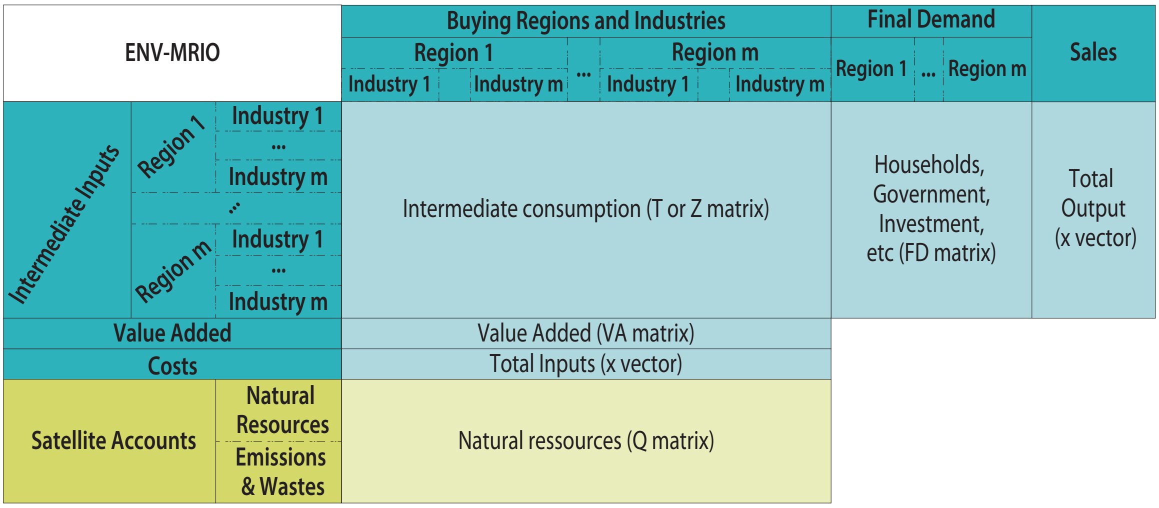
<table>
<tr><td colspan="3" rowspan="3">MRIO</td><td colspan="7">Buying Regions ans Industries</td><td colspan="3">Final Demand</td><td rowspan="3">Sales</td></tr>
<tr><td colspan="3">Region 1</td><td rowspan="2">...</td><td colspan="3">Region m</td><td rowspan="2">Region 1</td><td rowspan="2">...</td><td rowspan="2">Region m</td></tr>
<tr><td>Industry 1</td><td>...</td><td>Industry m</td><td>Industry 1</td><td>...</td><td>Industry m</td></tr>
<tr><td rowspan="7">Intermediate Inputs</td><td rowspan="3">Region 1</td><td>Industry 1</td><td colspan="7" rowspan="7">Intermediate consumption (T or Z matrix)</td><td colspan="3" rowspan="7">Households, Government, Investment, etc (FD matrix)</td><td rowspan="7">Total Output (x vector)</td></tr>
<tr><td>...</td></tr>
<tr><td>Industry m</td></tr>
<tr><td colspan="2">...</td></tr>
<tr><td rowspan="3">Region m</td><td>Industry 1</td></tr>
<tr><td>...</td></tr>
<tr><td>Industry m</td></tr>
<tr><td colspan="3">Value Added</td><td colspan="7">Value Added (VA matrix)</td></tr>
<tr><td colspan="3">Costs</td><td colspan="7">Total Inputs (x vector)</td></tr>
</table>

Note: If read vertically, each column displays which inputs a sector employs in its production process. Other factors that also contribute to the final value of the produced good, such as wages, taxes and consumption of fixed capital, are seen in the value added matrix, which is positioned under the intermediate consumption matrix. If read horizontally, each row shows which sectors purchase the output of a specific sector. What is not bought by other sectors is consumed directly by households, government or becomes fixed investment or inventories; these values are displayed in the final demand matrix that is positioned on the right of the intermediate consumption matrix. Both the final demand and value added information can also be aggregated into a column vector and a row vector, respectively.

Source: Authors' illustration.

Moreover, 'traditional' MRIO tables can be completed with environmental information, in what became called Environmentally Extended MRIO tables (EE-MRIO or Env-MRIO). When modeled, the snapshot of the economy provided by these tables will contain information about the natural resources used in production, the pollution generated by this process, the amount of natural resources and pollution embodied in the goods and services consumed, and the regional dynamics involving trade (Guilhoto, 2021). The additional information available in the satellite accounts is also organised in a matrix format which contains the same number of columns of the intermediate consumption matrix (see **Figure 4.3**). The content of this matrix varies from MRIO table to MRIO table, but in general it displays information about employment and environmental footprints at the industry level.

Figure 4.3 **Environmentally Extended MRIO (ENV-MRIO) Table**



<table>
<tr><td colspan="3" rowspan="3">ENV-MRIO</td><td colspan="7">Buying Regions and Industries</td><td colspan="3">Final Demand</td><td rowspan="3">Sales</td></tr>
<tr><td colspan="3">Region 1</td><td rowspan="2">...</td><td colspan="3">Region m</td><td rowspan="2">Region 1</td><td rowspan="2">...</td><td rowspan="2">Region m</td></tr>
<tr><td>Industry 1</td><td></td><td>Industry m</td><td>Industry 1</td><td></td><td>Industry m</td></tr>
<tr><td rowspan="7">Intermediate Inputs</td><td rowspan="3">Region 1</td><td>Industry 1</td><td colspan="7" rowspan="7">Intermediate consumption (T or Z matrix)</td><td colspan="3" rowspan="7">Households, Government, Investment, etc (FD matrix)</td><td rowspan="7">Total Output (x vector)</td></tr>
<tr><td>...</td></tr>
<tr><td>Industry m</td></tr>
<tr><td colspan="2">...</td></tr>
<tr><td rowspan="3">Region m</td><td>Industry 1</td></tr>
<tr><td>...</td></tr>
<tr><td>Industry m</td></tr>
<tr><td colspan="3">Value Added</td><td colspan="7">Value Added (VA matrix)</td></tr>
<tr><td colspan="3">Costs</td><td colspan="7">Total Inputs (x vector)</td></tr>
<tr><td colspan="2" rowspan="2">Satellite Accounts</td><td>Natural Resources</td><td colspan="7" rowspan="2">Natural ressources (Q matrix)</td></tr>
<tr><td>Emissions & Wastes</td></tr>
</table>

Source: Authors' illustration.

Each MRIO table can display different information at different levels of granularity. Consequently, there is no single "best MRIO table" available. The choice of which MRIO table should be employed depends on the goals of each analysis. Some of the MRIO tables available are described in **Table 4.1** below.

Table 4.1 List of main MRIO tables

Name	Sectoral Granularity	Country Granularity	Main Data Sources	General Comments	Main Reference
EORA 26	26 sectors	189 countries	• Input-output (I-O) tables and main aggregates data from national statistical offices. • The UN National Accounts Main Aggregates Database. • The UN National Accounts Official Data. • The UN Comtrade international trade database. • The UN Servicetrade international trade database. • I-O compendia from Eurostat.	• Very detailed satellite accounts. • Low sectoral granularity.	Lenzen *et al.* (2012); Lenzen *et al.* (2013)
Full EORA	Changes from country to country	189 countries	• Input-output (I-O) tables and main aggregates data from national statistical offices. • The UN National Accounts Main Aggregates Database. • The UN National Accounts Official Data. • The UN Comtrade international trade database. • The UN Servicetrade international trade database. • I-O compendia from Eurostat.	• Very detailed satellite accounts. • High sectoral granularity but with different sectoral aggregations.	Lenzen *et al.* (2012); Lenzen *et al.* (2013)
EXIOBASE 3	163 sectors	44 countries + 5 rest of the world regions	• The UN National Accounts Main Aggregates Database. • FAOSTAT. • IEA. • BACI – UN Comtrade. • The UN Servicetrade international trade database. • National Statistics. • EXIOBASE 2.	• High sectoral granularity. • Low country granularity. • Detailed information on energy sectors.	Stadler *et al.* (2018)
WIOD	56 sectors	43 countries + a model for the rest of the world	• Input-output (I-O) tables and main aggregates data from national statistical offices. • The UN Servicetrade international trade database. • Eurostat. • OECD data.	• More consistent data for time-series analysis.	Timmer *et al.* (2015); Timmer *et al.* (2016)
GLORIA	120 sectors	160 countries + 4 rest of the world regions	• The database combines multiple sources from Full EORA, EXIOBASE and WIOD.	• Good overall country and sectoral granularity. • Not so detailed satellite accounts.	Lenzen *et al.* (2017); Lenzen *et al.* (2022)

OECD ICIO	45 sectors	66 countries + rest of the world	• Input-output (I-O) tables and main aggregates data from national statistical offices. • The UN National Accounts Official Data. • The UN Comtrade international trade database. • OECD data and estimations.	• Low sector and country granularity. • Focused on manufacturing sectors.	OECD (2021)
FABIO	121 processes	191 countries	• FAOSTAT. • IEA. • EIA. • The UN Comtrade international trade database and BACI.	• Greatest country coverage. • Focused on agriculture, food and forestry products. • Industrial/manufacturing use is aggregated with final demand.	Bruckner *et al.* (2019)
FIGARO	21 sectors	45 countries + RoW	• National accounts data (as benchmark). • EU Member States National SUTs and IOTs. • International trade in goods statistics (ITGS) and Commodity Trade Statistics Database (UN Comtrade). • International services trade data and balance of payments data. • Business statistics.	• Uses official EU data with complementary information on the main non-EU trading partners. • Publications concerning employment and value added supported by EU exports and EU CO2 footprint.	Remond-Tiedrez and Rueda-Cantuche (2019)

Source: Authors.

In general, MRIO tables and models are able to produce a snapshot of the global economy, describing a static image of its organisation at sectoral level that comprises the global networks of production (forward and backward linkages) and consumption. As such, MRIO models can be particularly useful to assess the transmission of risks if non-substitutable inputs (or forms of 'natural capital') become stranded. Indeed, MRIO models can provide relevant information about indirect cascading effects caused by a materialised physical or transitional nature-related financial hazard in a specific sector or region, as well as the macroeconomic impacts of this materialised risk in terms of employment and GDP losses (see **Figure 4.1** above).

As covered in the previous chapter, many macroeconomic models currently in use for nature-related scenario assessments (e.g., CGE models) will tend to underestimate the impact of nature-related hazards due to their substitution mechanisms and optimising assumptions (Koks et al., 2016). MRIO models could present a possible method for overcoming such limitations. MRIOs, for example, are particularly useful to assess risks over a relatively short- to medium-term horizon, in which the existing relations across sectors and regions are not likely to drastically change. MRIOs are also adept for analyzing the impacts of extreme hazards, at least for short- and medium-term scenarios. That is, MRIO models can give us insights into the potential disequilibrium effects of hazards and shocks that other approaches reviewed in the previous chapter cannot.

One of the reasons for this is that MRIO models rely on the strong sustainability approach (Godin et al., 2022). In this approach, factors of production (nature, capital and labour) are not directly replaceable ex-ante by other factors of production. Each sector produces its output with a fixed proportion of inputs. In MRIO models, therefore, a reduction in the provision of a primary input of production does not prompt an automatic change towards a new optimal combination of factors of production.[46] Moreover, there is strong

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[46] In this sense, whilst CGEs tend to under-estimate them (due to substitutability assumptions, etc.), MRIOs can potentially over-estimate impacts from shocks (due to fixed technical coefficients).

evidence in the input-output modeling literature that technological coefficients of production are stable in 10-years horizon (Antille et al., 2000; Carter, 2014 [1970]; Miller & Blair, 2009). MRIO models may therefore provide a more accurate approximation of the effects of short-term and medium-term economic shocks than macroeconomic models that assume perfect factor substitutability and optimizing productive adjustments.

However, as will be discussed in greater detail later in this chapter, MRIO models alone do not yet represent a perfectly consolidated alternative to CGE models. As they are not equipped by default with behavioural mechanisms (e.g., investment, consumption, agents' reaction functions, etc.) relevant for dynamic analysis, as well as supply constraints, MRIO models alone do not yet offer a solid solution for the question of how to update the technical coefficients of production. This constrains their capacity to serve as a basis for longer-run scenario assessments. Nevertheless, new research is now moving towards the development of dynamic MRIO models. In fact, one of the main virtues of MRIO models is that they are "flexible" and can easily be further elaborated with the addition of new dynamic mechanisms without renouncing their major characteristic of drawing on extensive high granularity real data.

One possibility to develop short- and medium-run scenarios is to directly use MRIO tables and models (i.e., without prior reliance on other modeling approaches) to appreciate the potential impacts of a specific physical or transition hazard. For instance, Magacho et al. (2023) assess the direct and indirect exposure of countries to sunset industries. The authors use the hypothetical extraction technique to identify countries' direct and indirect dependence on carbon-intensive industries (see **Annex 7.4.3** for more details). This methodology was then applied in the context of the adoption of the Carbon Border Adjustment Mechanism by the European Union, and showed which economies are most exposed to this measure on social, fiscal and external dimensions (Magacho et al., 2023). The same methodology could enable central banks and supervisors to assess the propagation of different nature-related hazards (which could be further refined, as discussed in Chapter 2 on narratives).

4.2 Case studies and indicators for assessing cascading impacts

Building on the work of the Chapter 2 on Narratives, this section presents two exploratory scenario case studies with the objective of showing in practical terms how input-output models could be used to assess cascading effects stemming from both physical and transition hazards. The purpose is not to provide predictions of future nature hazards. Rather it is to explore how MRIO tables can be relevant to central banks and supervisors seeking to better assess nature-related risks, given a plausible set of nature hazards (or shocks) discussed in the chapter on narratives. The mathematical explanation of the MRIO model can be found in the **Annex 7.4.4**.

The first case study – a physical hazard – focuses on the direct and indirect economic exposures due to increased water stress stemming from a drought in France. The second case study – a transition hazard – studies how an EU policy seeking to ban the sale of products linked to deforestation might impact the Brazilian and European economies. Although more work would be needed to further calibrate these shocks, the main purpose here is to show how plausible natural or policy hazards/shocks can be used as inputs to MRIO models in order to assess direct and indirect (or cascading) effects.

4.2.1 Case study on physical risks: Assessing the direct and indirect exposures to a potential drought in France

4.2.1.1 Measuring the direct exposures by connecting the Narrative to an input-output table

The first exploratory case study is constructed from a hypothetical narrative of a physical hazard – a 1-in-20 year major heatwave and drought (equivalent to the drought in 2022) – that would affect the French and European economies. The narrative underlining the shock is built using the aforementioned INCAF-OXFORD methodology, which employs data from the ENCORE tool. One of the main physical hazards which presents great potential to disrupt the economic activity within a country is a drought.

The narrative details a major drought event in France would hinder the ecosystem services of surface water and dilution by atmosphere and ecosystems. It also provides estimations of the theoretical reduction in sectoral output for 111 directly impacted sectors. The narrative provides a percentage VaR (value-at-risk) for sectors affected by water supply and heat-related pollution impacts. These values are derived from a combination of dependency of French industries on water taken from EXIOBASE, surface and groundwater dependencies per industry from ENCORE, and water stress indices for France taken from AQUASTAT (Ranger et al., 2023, see **Figure 2.6**). Water quality impacts (as **Figure 2.7**) and air quality[47] due to pollutants are assumed to be further exacerbated by heat, in line with observations from previous heatwaves in the country and literature on heat-related pollution. **Table 4.2** displays the aggregated exposure of different sectors[48] of the French economy to the disruption related to each ecosystem service negatively impacted by the drought. The aggregated exposure to the direct shock in the French economy is of 424.2 billion EUR.

Table 4.2 **Direct exposure of aggregated sectors of the French economy to a drought, when examining heat-related pollution impacts and water supply ecosystem services (percentage of value-at-risk)**

	Agriculture	Construction	Electricity and Utilities	Manufacturing	Mining	Services	Transport
Heat-Related Pollution Impacts	4	0	0	5	0	0	1
Water Supply	14	2	12	17	21	4	11

Note: Percentages show potential value at risk for each sector as a result of a major heatwave and drought. For instance, 4% of agriculture output would be at risk from heat-related pollution impacts and 14% from shortages in water supply.

Source: Authors', based on preliminary data from INCAF-Oxford and ENCORE.

4.2.1.2 Indirect (or cascading) exposures – Identifying backward and forward linkages

While these values give an idea of the size of the direct economic exposure to a severe drought on French sectors, these initial shocks may cascade through the economic networks of production. MRIO modeling is a tool that can be used to assess these indirect exposures. For this exercise, the EXIOBASE 3 MRIO table from the year 2022 is coupled with the sectoral values at risk taken from the INCAF-OXFORD analysis. The EXIOBASE 3 MRIO dataset contains 44 countries and 5 rest of the world regions and has information about 163 different sectors (Stadler et al., 2018).

This case study offers an example of production and cascading effect by considering an aggregation of the 111 sectors that are directly impacted by the physical hazard. Once affected, these sectors could face a reduction in necessary ecosystem services leading to a smaller level of production. Consequently, with less output being produced, less inputs will be bought from other sectors and employed in the production. For sectors positioned upstream in the production network, this represents an indirect effect through a reduction in demand. This reduction spreads upstream to many sectors in a cascading fashion, as sectors are forced to reduce their output due to the lack of intersectoral demand in the short term.

The effects also spread downstream in the production network. The aggregated sectors also supply other sectors, as they produce inputs which are employed in production elsewhere. Downstream indirect effects could take the form of price increases and quantity restrictions for the sectors positioned ahead of aggregated impacted sectors. Akin to upstream effects, downstream effects also have the potential to spread to multiple sectors and impact the amount of output available for consumption in the economy.

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[47] Air quality risk indices calibrated based on World Bank data on mortality rates due to air pollution and particulate matter concentrations combined with ENCORE.

[48] The 111 affected sectors from the severe drought narrative are aggregated into 7 sectors displayed in **Table 4.2**.

From the aggregated sectors' perspective, the upstream and downstream production networks are understood as the backward and forward linkages. The "size" of the linkages indicates the cascading potential of indirect effects stemming from a direct shock in a sector (see **Figure 4.1** presented earlier, which displays a scheme for assessing upstream and downstream effects generated by nature-related hazards[49]). To assess backward linkages and upstream impacts, one can employ the total requirements matrix (so-called Leontief-Inverse Matrix) that can be obtained from MRIO tables. For forward linkages and downstream impacts, one can look at the output inverse matrix (so-called Ghosh-Inverse Matrix). The algebra transformations are described in **Annex 7.4.5**. In what follows, these matrices are employed to estimate impacts and exposure to the drought scenario previously described.

4.2.1.3 Estimation of the upstream indirect exposure from a drought in France

The upstream exposure to the drought originates with the affected sectors reducing their production and demanding less inputs from other sectors. For upstream supply sectors, there is no demand to absorb the pre-shock level of output, which forces them to also reduce their output. By combining estimations of the INCAF-OXFORD methodology with the total requirements matrix it is possible to assess the total direct and indirect exposure to a drought affecting France, in terms of potential reduction in total output (details in **Annex 7.4.5**).

The accumulated exposure for all upstream affected sectors amounts to a total output of 690.3 billion EUR for the French economy, a value that represents 15.06% of France's total output. Indirect effects constitute 26% (266 billion EUR) of the total output at risk.

Table 4.3 displays the values of the initial direct shock, the indirect shock, the sum of both direct and indirect shocks, and how much this value represents as a share of the total output of the sector.

Table 4.3 **Total output reduction in selected French sectors**

Sector	Initial Direct Shock (M. EUR)	Indirect Exposure (M. EUR)	Total (Direct + Indirect) Exposure (M. EUR)	Share of the Output at Risk in Total Output of the Sector (%)
FR – Raw milk	2,045.50	4,745.60	6,791.10	63.41
FR – Manufacture of fish products	1,880.30	1,091.30	2,971.60	60.37
FR – Cultivation of sugar cane, sugar beet	260	497.9	757.9	56.40
FR – Cultivation of paddy rice	8.97	16.1	25.1	54.09
FR – Processing of dairy products	8,797.00	3,550.60	12,347.70	53.62
FR – Processing vegetable oil and fats	618.05	233.35	851.4	52.62
FR – Pigs farming	628.9	1,030.00	1659	50.38
FR – Manufacture of other non-metallic mineral products	1,337.80	413.1	1,750.90	50
FR – Sugar refining	1,685.20	493.9	2,179.10	49.39
FR – Manufacture of bricks, tiles and construction products	926.9	265.4	1,192.40	49.14

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[49] For instance, when looking at **Figure 4.1**: imagine a sector 8 that purchases inputs from another sector 5 (dotted red arrow). Sector 5, in turn, purchases inputs from another sector 2. While sector 8 is not directly dependent on sector 2, it is indirectly dependent on it. In this sense, if a natural hazard negatively affects the production of sector 2, it should be expected that sector 5 would be affected and indirect effects would later affect sector 8 as well.

The results show that multiple agriculture-related sectors could be strongly affected by the drought. For some sectors the indirect effects are greater than the direct effects. For example, for the "Raw Milk" sector, 44.31% out of the total 63.41% of output at risk is from indirect effects; for the "Extraction of Crude Petroleum and Services related to Crude Oil Extraction, Excluding Surveying" sector, 38.34% out of the total 41.78% of output at risk is from indirect effects.

The upstream indirect effects could also impact foreign sectors which are direct and indirect suppliers of the drought affected ones. The aggregated value of foreign sectors' total output exposed is 181.2 billion EUR. Of this total, 86.8 billion EUR concern EU sectors. In total, by aggregating national and international, direct and indirect effects, the total output potentially impacted in the global economy (France included) amounts to 871.4 billion EUR, with 51.3% of this impact the result of indirect effects (447.2 billion EUR).

4.2.1.4 Estimating the downstream indirect exposure of a drought in France

Downstream sectors also face a reduction in supply and price increases of their inputs due to the fall in output of the directly impacted sectors. As all the production is eventually consumed, downstream effects may cascade up to final demand.

However, downstream impacts are harder to predict than upstream impacts. While upstream impacts represent losses in demand that leave sectors without the possibility to sell their production, downstream impacts take the form of missing inputs for other sectors. These missing inputs might be replaceable even in the short run. For instance, they could be imported from similar foreign sectors that had some idle productive capacity. In other words, the economy may absorb the downstream effects, and, for this reason, it is reasonable to address downstream impacts through an exposure perspective.

Here, we look at European Union's final demand exposure, but the same analysis could be replicated to other countries or regions. The French affected sectors supply EU's final demand both directly and indirectly through other sectors that employ their inputs in their production. Other sectors inevitably employ output of these French sectors as inputs to produce other goods and services that are ultimately consumed within the European Union.

In terms of exposure, the question which arises is: how much of the output from affected French sectors is produced to satisfy European Union's total level of final demand? This can be calculated by employing again the total requirements matrix (details in **Annex 7.4.5**) The results indicate the affected French sectors need to produce 2.2 trillion EUR of output to satisfy the EU's total final demand, both directly and indirectly. This value represents 81.01% of total output for these affected sectors.

With the use of a sectoral approach, MRIO modeling can be employed to assess the exposure of indirectly affected sectors. This focuses on sectors which incur indirect impacts through their connection to the directly impacted sectors. One can calculate vulnerability as the value in percentage which describes the importance of the shocked sector as a supplier for other sectors (details in **Annex 7.4.5**)

As there are 111 sectors being directly shocked, the results were aggregated in larger sectoral groups for a better presentation. Below in **Table 4.4** we display the results for the aggregation of all the affected French sectors of agriculture. The results demonstrate that the affected French agriculture sector is a key supplier to multiple downstream sectors.

Table 4.4 **Exposed French Agriculture Sectors Output Value as Share of Total Inputs Value in Selected Sectors**

Country – Sector	Share of Exposed Agriculture French Sectors Output as Direct Inputs of The Sector (%)
Re-processing of secondary construction material into aggregates	84.91
Sugar refining	71.31
Processing of meat cattle	50.36
Forestry, logging and related service activities	49.85
Processing of dairy products	34.72
Processing of meat pigs	31.22
Processing of food products nec	30.27

Reflecting the strong interconnectedness of French economic sectors, the drought affected agriculture sectors supply more than 30% of all inputs employed in production to at least 7 French sectors. Results in **Table 4.5** show that the affected agriculture sectors also play an important role as direct and indirect key-suppliers for other downstream EU sectors.

Table 4.5 **Share of exposed agriculture French sectors output that are direct inputs to other sectors**

Country – Sector	Share of Exposed Agriculture French Sectors Output as Direct Inputs of The Sector (%)
IT – Processing of meat cattle	11.89
PT – Cultivation of Wheat	10.49
RO – Processing vegetable oils and fats	9.61
BE – Manufacture of fish products	6.90
HU – Processing vegetable oils and fats	6.77
LU – Hotels and restaurants	6.00
DE – Processing of vegetable oils and fats	5.68

These results imply that a reduction in the output of the affected aggregated agriculture sector could generate a substantial impact in downstream sectors, hindering the supply of crucial inputs which might not be replaceable in the short run. Such impairment could be severe enough to create financial problems for these indirectly affected sectors that could eventually spread into the financial sphere of the economy.

4.2.2 Case study on transition risks: Assessing the potential economic exposures to an EU transition policy to ban Brazilian non-deforestation-free products

4.2.2.1 Connecting the Narrative to an input-output table

While a number of combined policies are likely to be put in place to support the transition to a "nature-positive" economy, perhaps the most widely studied include policies that are meant to expand the protection of lands (Johnson et al., 2021; Waldron et al., 2020). Such policies are specifically aligned with the GBF Target 3, which seeks to expand the amount of the Earth's surface that is effectively protected to 30% by 2030. Relatedly, some of the policies aimed at reducing the drivers of nature loss and protect land can take place via "demand-side" measures: whereas "supply-side" policies seek to restrict access to nature (e.g., via the explicit expansion of protected areas), demand-side protections restrict demand for particular goods (e.g., sales taxes, import/export taxes and quotas, price-floors, product bans, forced disclosures and labelling, etc.).

For the current case study, we use an MRIO table and model to assess a transition policy based on one such "demand-side" protection measure. We assess the economic exposure, in terms of potential reduction in output, to a recent policy by the European Commission 2021 meant to minimise the consumption of several products considered the main drivers of deforestation, including palm oil, cattle, soy, coffee, cocoa, timber and rubber (European Commission, 2021). The new law compels companies to ensure that products sold in the EU have not led to deforestation and forest degradation (including the conversion of primary forests or naturally regenerating forests into plantation forests or into other wooded land), whether in the EU or elsewhere in the world.

The interest of this case study is that it shows how many transition policies can simultaneously impact producers and consumers of commodities through global value chains, with both direct and indirect impacts. Indeed, a significant part of environmental degradation in low- and middle-income countries is linked to export demand for primary products stemming predominantly from high-income regions, like the EU (Dorninger et al., 2021; IRP, 2021).[50] Between 1990 and 2014, for example, the EU consumed crops that were linked to upwards of 11.3 Mha of deforestation – much of it occurring in rainforest biodiversity hotspots in Brazil and Indonesia (Fuchs et al., 2020). Rajão et al. (2021) found that at least 20% of soy exports and 17% of beef exports from the Amazon and Cerrado regions to the EU could be linked to illegal deforestation to satisfy foreign demand. It is therefore not surprising that the European Commission acknowledges that "the EU is a relevant consumer of commodities associated with deforestation and forest degradation and it lacks specific and effective rules to reduce its contribution to these phenomena" (European Commission 2021, p. 1).

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[50] For example, natural resource extraction and processing alone constitute approximately 50 per cent of the total greenhouse gas (GHG) emissions. Moreover, land-use changes associated with these sectors result in more than 90% of impacts on water stress and biodiversity loss (IRP 2021).

Demand-led policies aiming to increase transparency and due diligence along global supply chains are therefore likely to have impacts on both exporting countries – implying a decrease in agricultural exports and related fiscal revenues – and importing countries – implying that inputs necessary to industrial production and final consumption could no longer be available or only at a higher price. For example, Conte Grand et al. (2023) find that an EU ban on the import of "non-deforestation-free" products could impact as much as 17% of LAC exports.

In what follows, we therefore conduct an assessment using MRIO tables and models to determine the degree to which this EU policy to ban non-deforestation-free products could affect both the EU and Brazil (see Annex 7.4.6 for details). We assume a hypothetical 15% reduction in European Union imports for all Brazilian Forestry, Agriculture, Livestock, and Mining sectors.[51] We employ the same dataset as in the previous exploratory study.[52]

4.2.2.2 Estimating upstream impacts and vulnerabilities of the EU Policy in the Brazilian Economy

In this case study, the introduction of an EU policy to ban the consumption of non-deforestation-free products could directly impact sectors in Brazil that would be forced reduce their output (previously exported to the EU). Consequently, they would reduce their demand for inputs bought from other sectors of the economy. This is the beginning of an indirect and cascading effect which takes the form of sales reduction and demand contraction for multiple sectors that comprise the upstream production chains from the directly affected sectors. In the present case study, the effects of this demand reduction are expected to mostly affect the Brazilian economy.

Aggregating the direct and indirect upstream effects, the EU ban policy would expose all Brazilian sectors to a potential reduction in total output of 1.6 billion EUR, from which 40% (644 million EUR) are only indirect effects. With MRIO tables it is possible to analyse the total value exposed at a sectoral level. **Figure 4.4** displays a Sankey plot of first level upstream connections of the Brazilian targeted sectors. **Table 4.6** shows the top affected Brazilian sectors, separating direct and indirect impacts.

Table 4.6 **Top 8 Exposed Brazilian Sectors**

Sector	Direct Exposure (M. EUR)	Indirect Exposure (M. EUR)	Total Exposure (M. EUR)
Cultivation of crops nec	295.23	13.77	309.00
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	274.41	30.10	304.52
Mining of iron ores	91.79	6.35	98.14
Chemicals nec	0	84.71	84.71
Mining of copper ores and concentrates	81.04	0.16	81.20
Cultivation of cereal grains nec	71.74	4.63	76.37
Cultivation of vegetables, fruit, nuts	52.51	0.42	52.93
Petroleum refinery	0	42.20	42.20

The top 8 most potentially affected Brazilian sectors are (1) Cultivation of crops, (2) Extraction of crude petroleum and services related to crude oil extraction, excluding surveying, (3) Mining of iron ores, (4) Chemicals, (5) Mining of copper ores and concentrates, (6) Cultivation of cereal grains, (7) Cultivation of vegetables, fruit, nuts, and (8) Petroleum refinery. It should be highlighted that while the sectors of (4) Chemicals and (8) Petroleum refinery are not directly target by the EU policy, potential impacts on them aredue entirely to their exposure to indirect effects. Hence, the indirect effects under this scenario not only exacerbate the potential impact for directly exposed sectors but create impacts for additional sectors that were initially not concerned.

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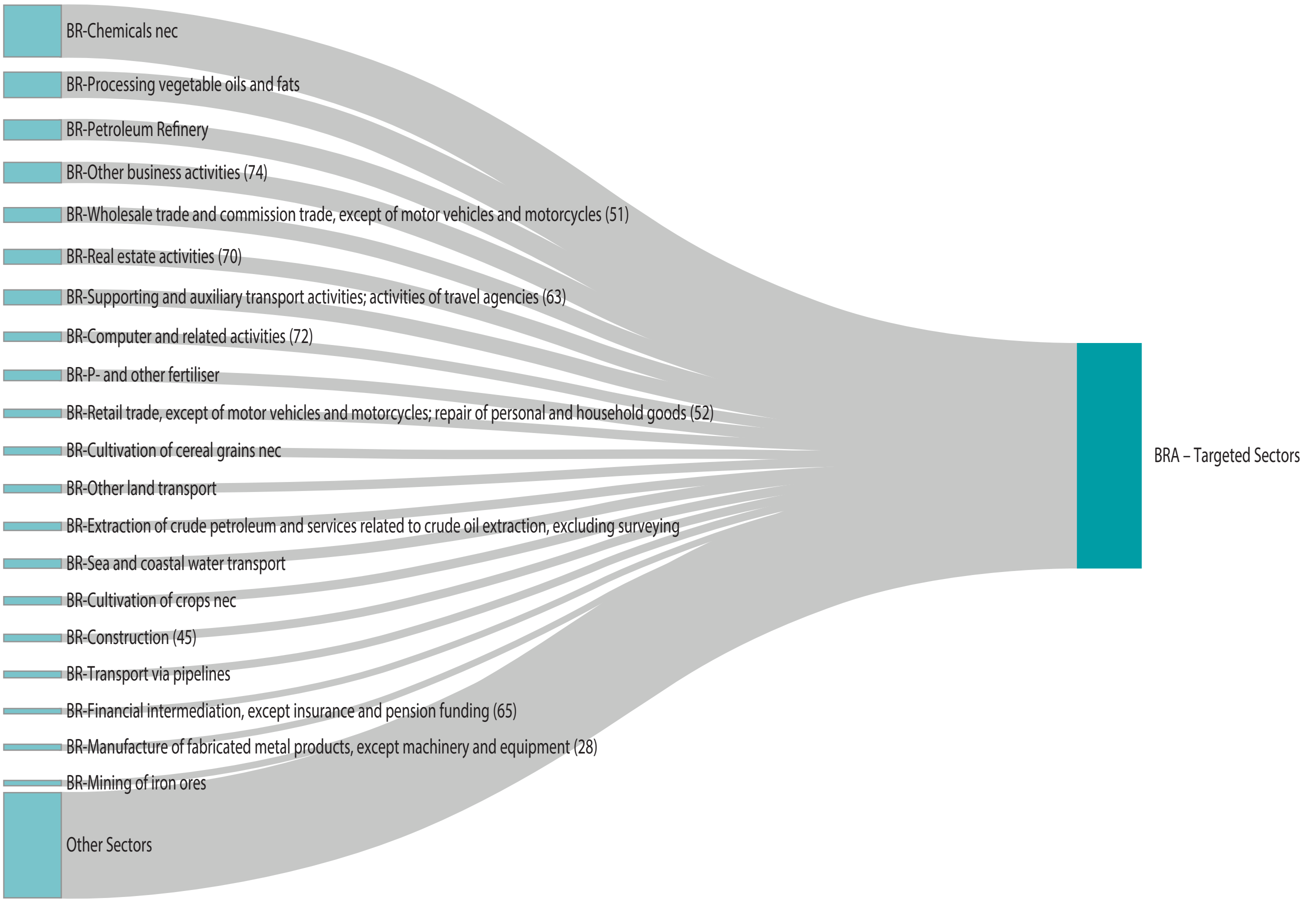
[51] This hypothesis of 15% should be further refined based on the work conducted in Chapter 2 (section on developing transition hazard narratives). Here, we seek to better understand how a specific transition shock can propagate to different sectors and countries. For this reason, we are less concerned about the calibration of the initial shock.

[52] **Annex 7.4.5** (although it focuses on the previous case study for assessing physical risks) provides all the methodological details of the approach discussed here in the transition risk case study.

Figure 4.4 **First Level Upstream Linkages of Affected Brazilian Sectors**



The upstream effects also generate exposures in other Latin American and EU sectors which provide inputs to the (directly and indirectly) exposed sectors in Brazil. For instance, the second most impacted Brazilian sector of "*Extraction of crude petroleum and services related to crude oil extraction, excluding surveying*" is the 7th main purchaser of the Irish Real estate activities sector. The effect of the assumed fall in demand for Brazilian production implies a potential aggregate reduction of 25.9 million EUR in total output for Latin American sectors and of 38.2 million EUR for EU sectors. **Table 4.7** displays the EU sectors most exposed to upstream impacts, in terms of potential reduction in output value.

Table 4.7 **EU Sectors Most Exposed to Upstream Impacts**

Country – Sector	Value Exposed (M. EUR)
NL – Other business activities	1.35
IE – Real estate activities	1.32
DE – Other business activities	0.74
DE – Manufacture of machinery and equipment nec	0.73
ES – Construction	0.68

4.2.2.3 Estimating downstream indirect exposure

The downstream impacts start from a reduction of inputs received by European sectors that import goods from the Brazilian policy targeted sectors. In total, the EU imports 6.4 billion EUR from the targeted sectors, being 4.7 billion EUR imported as inputs for European sectors and 1.6 billion imported for final consumption. Given our hypothesis of a 15% import reduction, a total of 960 million EUR of EU imports are directly exposed to the transition shock. **Table 4.8** displays the top European sectors that directly import from the targeted sectors.

Table 4.8 **Value of Imported Direct Inputs from Policy Targeted Brazilian Sectors for Selected EU Sectors**

Country – Sector	Value (M. EUR)
ES – Petroleum refinery	1,607.55
FR – Manufacture of basic iron and steel and of ferro-alloys and first products thereof	220.83
PT – Petroleum refinery	212.12
DE – Copper production	168.72
DE – Processing of food products nec	124.15

The current EU final demand level depends directly and indirectly on a total production of 10.8 billion EUR from the Brazilian targeted sectors, from which 1.6 billion is directly consumed by EU final demand and 9.2 billion indirectly. It should be noted that the direct effect of the policy exposes targeted sectors to as much as 960 million EUR in reduced output, a value that represents already 9% of the 10.8 billion needed for maintaining EU's current level of final demand.

If the focus is shifted to sectors which purchase inputs from the targeted sectors, it is possible to identify sectors that strongly rely on the targeted sectors for the supply of inputs. Table 4.9 displays the EU sectors with highest share of targeted sectors as suppliers. For instance, 5.3% of the inputs necessary to the Spanish petroleum refinery sector could go missing under this hypothesis (and assuming lack of substitution).

Table 4.9 **EU Sectors with Higher Shares of Inputs Purchased from The Policy Targeted Sectors (value added excluded)**

Country – Sector	Share of Direct Inputs Purchased from The Policy Targeted Sectors (%)
ES – Petroleum refinery	5.33
PT – Petroleum refinery	3.47
LU – Manufacture of tobacco products	3.08
ES – Copper production	3.04
IE – Aluminium production	2.56

4.3 Limitations of input-output models and potential ways forward

Input-output models are not exempt of limitations. We discuss two of them below: the fixed nature of technical coefficients of production, and the inability to provide intra-sectoral information that is particularly important to assess nature-related hazards and their impacts.

4.3.1 Fixed technical coefficients of production

First, MRIO models usually work with fixed technical coefficients of production, considering all outputs to always be produced with the same proportion of inputs. While technological coefficients of production tend to be stable in the short-term (Antille et al., 2000; Miller & Blair, 2009), the latter is not true in the medium to longer term, i.e., on the time horizon under which the ecological transition is supposed to take place. Technical coefficients may also be modified by physical shocks that would force different sectors to seek inputs from new regions, if substitution allows (if no substitution is possible, other impacts not captured by IO may also take place over the medium term, especially if macroeconomic variables such as employment become impacted and generate feedback loops in terms of demand for multiple sectors, for instance).

For instance, when looking at the case study of a drought in the French economy: while the values indicate a very high level of dependency and exposure of the EU economy to the risk of a drought affecting ecosystem services and hitting the French economy, it is difficult to predict exactly what would happen in the case in which a shock takes place, especially when looking downstream. This will ultimately depend on how the sectors that are impacted would redirect the shock and adapt. Some sectors may still be supplied while others may cease to be supplied necessary inputs. For instance, a shock that hinders the output of the affected French sectors by around 15% could be passed forwards along the network of production in such a way that the 81% of the output needed by European Union's final demand wouldn't be affected, as the shock impact could be channeled towards the 18% remaining of the output that is not needed to keep EU's final demand level.

Political decisions may also generate specific dynamics not captured by the case study. For example, there could be a strong political preference for safeguarding the national supply for some impacted sectors such as agriculture, particularly in the event of a major drought where domestic food security may be impacted. In this case, French exports may be restricted. Alternatively, some sectors might be labeled as high priority to be supplied to international markets, particularly if they are an important source of foreign exchange earnings for the country. Companies may also prefer to supply their biggest clients and cut provisioning to smaller companies and sectors, or even prefer to supply its direct final demand rather than the intermediate demand from other sectors. In another scenario, the shock could also be absorbed little by little, as the impact cascades throughout the production chain. While some companies may be able to resort to retained excess inventories that could be used to fill shortfalls, others may not have sufficient inventories available to meet demand, after a time.

A critical challenge is therefore to assess how MRIO can be made more dynamic (and potentially more useful for medium-term scenarios). More dynamic MRIO-based approaches would require a framework capable of endogenously updating the technical coefficients of production within the MRIO tables. The technical coefficients of production define the amount of direct inputs from other sectors that one sector needs to produce its final product. As such, they are one of the main parameters that characterise the productive structure[53] of an economy in a given time.

Specific methods using mathematical algorithms to update technical coefficients exist, such as the RAS method (Schneider & Zenios, 1990). The main problem with these algorithms is that they rely on information already contained in the matrix, as well as on presumed values of total row and column sums, to impute missing values. As such, the supplied matrix values will strongly determine the final values in the matrix (Distefano et al., 2020). For instance, Temurshoev et al. (2021) propose a multi-regional generalised RAS (MR-GRAS) to project climate scenarios within a multi-region IO until 2050, which can be used as a baseline in a computable general equilibrium model. Some studies also apply regressions for forecasting future technical coefficients of production (Nieto et al., 2023; Uehara, Cordier & Hamaide, 2018). Nevertheless, this approach suffers from essentially the same problems as when imputing past trends and information structure.

A related promising avenue for future research would be to integrate input-output models with other models currently employed for ecological and environmental economic analysis (e.g., partial equilibrium models of land-use and the agriculture sector), which can simulate different agents' reaction functions, and use them to change the technical coefficients. For instance, the NGFS is currently exploring how its climate scenarios could be complemented by downscaling IAM series to industrial sectors using final energy weights from the EXIOBASE IO model. The output of this exercise would be used as an input into the NiGEM model sectoral production function. In light of this, the assessment of NRFR could use models to explore the impacts specific impacts in the agricultural sector, and then MRIO to assess how such impacts could propagate to other sectors.

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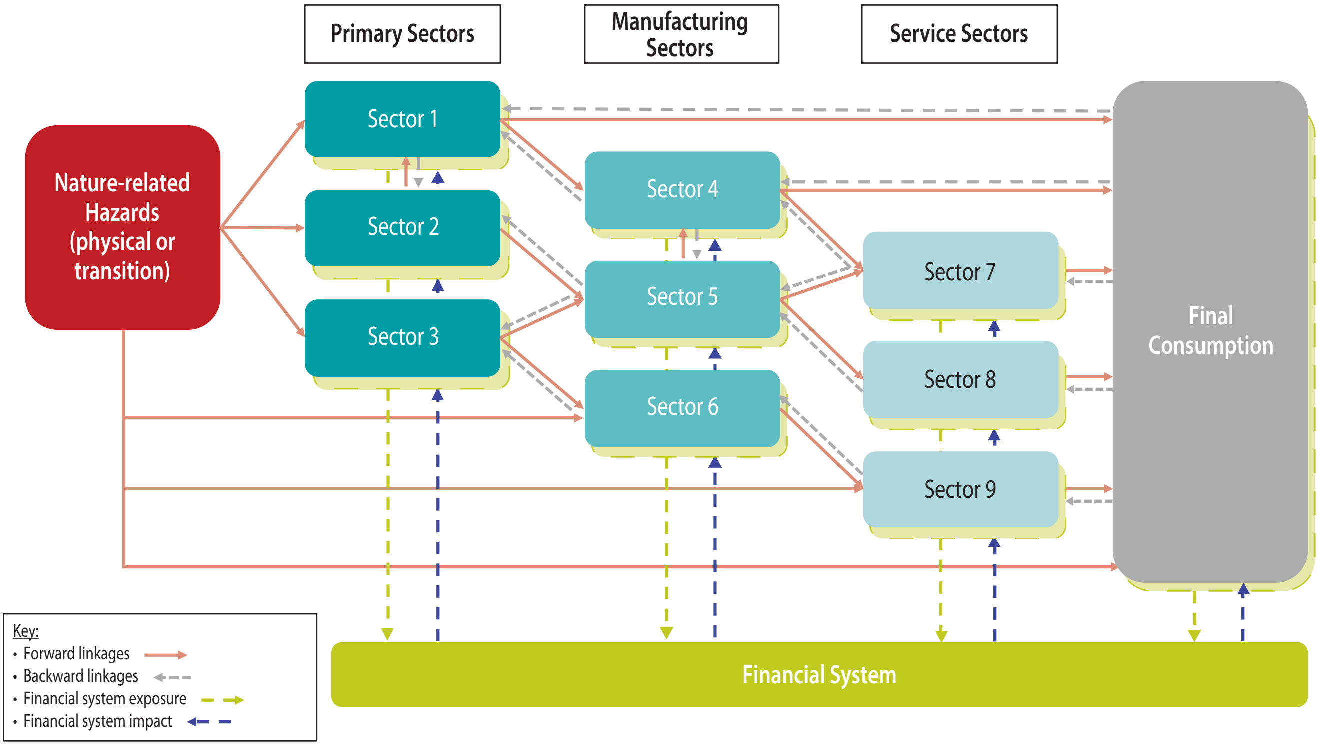
[53] RAS is an iterative procedure of bi-proportional adjustment that rescales the rows and the columns, by the minimum amount necessary, to respect the sum constraints until it converges toward a balanced matrix. There are many extensions of this method such as the GRAS, KRAS, TRAS and SPIN algorithms (Beaufils & Wenz, 2022; Wang *et al.*, 2015).

These approaches nevertheless raise a question regarding the dynamic approach of the first step (modeling) and the rather static approach of the second step (MRIO). For example, depending on the characteristics of the model in which MRIO tables are integrated, the strong sustainability hypothesis may no longer hold (e.g., input-output tables used in CGE models). Moreover, changing technical coefficients alone would not be sufficient to capture more structural transformations of the economy triggered by new socio-economic patterns – including the development of new technologies, the emergence of new sectors that do not yet exist, new consumption habits or new diets, – which will also be crucial when it comes to engaging in the ecological transition (as discussed in Sections 2.2.2 and 2.2.3). While CGE models can forecast technological change, for example, this is done through optimizing operations in a context of relative scarcity of factors of production. As such, CGEs fail to simulate the path dependency of technological transitions where increased adoption leads to increased diffusion through cost reduction in an S-shaped form. They also fail to incorporate heterogeneous behavior, non-instantaneous reaction, inertia, lock-ins, and intangible preferences (Mercure, 2012; Mercure et al., 2016).

Merging MRIO tables and models that specifically aim to capture structural change and the nonlinear development of new patterns or technologies could also be a way forward. For instance, MRIO models could be incorporated into Stock and Flow Consistent models (SFC) which not only admit dynamic functions that would allow the extension of the analysis to the medium – and long-run, but also account for the monetary and financial side of the economy with great level of detail, something that is missing in MRIO tables (see **Figure 4.5** below). Although this has been done at theoretical level (Berg *et al.,* 2015) and to some extent in a more applied manner (d'Alessandro et al., 2020), even simplified SFC-IO models can be highly complex, and require data that may not be available for all countries to link trade and financial flows at the global level. The Future Technology Transformations (FTT) model could be a promising avenue to explore in this respect, for forecasting medium- and long-run technological changes, as it is able to incorporate the characteristics of technological transitions mentioned above (Knobloch et al., 2021; Mercure, 2012; Mercure et al., 2016; Mercure et al., 2018) (**Annex 7.4.7**).

Figure 4.5 **Accounting for financial exposures and impacts when conducting input-output analysis – A critical gap to be addressed in future research**



*Note: This figure builds on **Figure 4.1** presented at the beginning of this chapter, and adds the fact that the financial sector is both exposed and contributes to each impact in the "real" side of the economy. However, methodologies reconciling input-output analysis and models factoring in the role of the financial system are still in their infancy.*

Source: Authors' illustration.

Apart from the avenues for future research mentioned above, a more qualitative approach could consist of bringing dynamics to the model based on transition scenarios designed with the help of experts. The flexibility of MRIO models provides them the ability to accept a vast array of adjustment types and modifications concerning investment, consumption, policy and agents' reactions that might be suggested in different qualitative scenarios. Manually changing technological coefficients according to external scenarios is also possible, but requires further attention. While it may work for particular sectors such as energy, where it is possible to orientate the changes based on the IEA's extensive studies (Wiebe et al., 2018; Wiebe et al., 2019), for example, it would be an enormous challenge to provide accurate forecasting of technological coefficients for every sector in every country for every year.

4.3.2 The need for intrasectoral granularity

As discussed above, input-output tables have the advantageous characteristic of taking a sector-based approach which accounts for the structure of different sectors as well as their interaction; however, for the purpose of firm-level risk analysis, there is a need for greater granularity. Input-output tables, regardless of how granular they are, do not differentiate firms within the same sector, although such firms may have very different practices and therefore display a very different exposure to specific events. For example, among two firms selling tomatoes, one may rely on production techniques requiring a lot of pesticides, while the other may use no pesticides at all. Whereas the former would likely be vulnerable to new regulations aiming to ban pesticides, the latter would not. It is important to note that the constraint posed by the limited granularity of data also applies to most existing climate scenarios, which usually do not distinguish intrasectoral winners and losers.

For instance, in the case study of a drought in the French economy presented above: downstream companies could also switch suppliers to other sectors around the world that would increase their production level towards full capacity. However, it should also be noted that a shock that affects the output of sectors in which France is a major market player would also directly impact the prices set by firms in the same sectors around the world, due to the increasing scarcity and/or power in the market. This effect is not captured by MRIO modeling, but could be estimated through other methods and plugged into MRIO modeling in order to also account for these indirect cascading effects. In addition, the cascading effects of environmental shocks are not accounted in this example as, for instance, droughts may prompt other environmental shocks such as wildfires that could directly affect other sectors. Feedbacks from the economy that could amplify the environmental shock are also missing.

Similar limitations apply to the second case study detailing the impact of the EU ban on non-deforestation-free products. For instance, the analytical exercise does not consider whether different firms which undertake 'Mining of iron ores' are located in areas of deforestation or elsewhere, which would determine whether they are subject to the EU ban. Some firms in the EU impacted sectors could also purchase the missing inputs produced by similar sectors from other countries that were not operating at full productive capacity or that had significant inventory levels and comply with the policy. But they could also not be able to find new suppliers in the short and medium run, and the inputs scarcity could lead to rising prices. Consequently, it is difficult to estimate how and the extent to which the downstream effects would spread through the network of production.

As such, the use of input-output should be complemented by an in-depth knowledge of the metrics to be tracked at the firm level. Private corporations and financial institutions (such as those contributing to and adopting the TNFD) may be particularly well-positioned to explore this issue by assessing in a more granular manner how different firms in the same sector could display different reaction functions to the same scenario. However, this approach can hardly be replicated by a central bank or a supervisor aiming to have an understanding of a whole economy (i.e., including every single firm in the economy).

In order to benefit from firm-level analysis while having an economy-wide approach, different methods exist. The literature on firm-level supply chain analysis has focused on the use of granular data across different countries to document the propagation of shocks at the firm level. Firm-level supply chain analyses consider both (i) customers and suppliers of the firms that are directly hit by the shock, as well as (ii) firms that are indirectly linked (for instance, the customer of a firm whose supplier was hit) (Acemoglu et al., 2016; Barrot & Sauvagnat, 2016;

Boehm et al., 2019; Carvalho, 2014; Carvalho et al., 2021; Di Giovanni et al., 2014; Foerster et al., 2011; Malysheva & Sarte, 2011; Pankratz & Schiller, 2021). For instance, Barrot & Sauvagnat (2016) look at the impact of natural disasters on the growth of firms' sales in the US. They show that the negative effect is particularly significant when the disrupted supplier produces inputs that are difficult to substitute. Pankratz & Schiller (2021) examine the impact of physical climate risks on firms' financial performance and supply chain management. They show that natural disasters not only reduce the operating performance (revenues and operating income scaled by assets) of suppliers and their customers, but they can also lead to the termination of supply chain relationships.

While the studies above provide evidence for the propagation of shocks from a firm to its direct suppliers and customers, the impact of the shock on the overall economy depends on the extent to which the shock eventually propagates to firms that are more distant and indirectly connected. Understanding the broader impact of these shocks on the overall economy requires detailed information on the interconnectedness of firms across the entire economy. To this end, Carvalho et al. (2021) introduce additional layers of relationships, and look at the negative impact caused by the Great East Japan Earthquake and tsunami of 2011 on the direct and indirect customers and suppliers. Their findings highlight the indirect propagation effects of localised disturbances, emphasizing that even if the individual, firm-level impact of the disruption may not be substantial, particularly for indirectly exposed firms, its cumulative effect (across production networks) can be significant. Inoue and Todo (2019) obtain similar results when modelling the potential impact of a future potential earthquake based on the impacts of the Great East Japan Earthquake 2011: The authors find that the indirect effects of the natural disaster on production due to propagation (10.6% of GDP for the future potential earthquake) are substantially larger than their direct effects (0.5%).

Lastly, specific tools such as remote-sensing data may also be relevant to overcome the barrier of sectoral analysis. Remote-sensing data is an overarching term that contains a host of different data types captured through different sensors abroad satellite missions, including high-resolution imagery, hyper-spectral imagery and LiDAR technology (see **Annex 7.4.8** for more details). This data can therefore provide valuable information on changes in land use, habitat loss, and ecosystem degradation, which are also partial indicators of biodiversity loss. By integrating this data with IO/MRIO data, it is possible to estimate the environmental footprints associated with different economic sectors at a more disaggregated level than what traditional IO/MRIO analyses allows. As such, remote-sensing data may provide a useful indication of changes in local ecosystem health and firm impacts, while overlooking some important changes taking place at different scales. An important step for future research will therefore be to assess which indicators can be extracted from remote sensing data (e.g., urban sprawl, land-use change or vegetation indices), and how they can be linked with both MRIO tables and in-depth knowledge of a firm's strategy.

While higher spatial resolution data can identify habitat loss, fragmentation, and specific changes in land cover with greater precision, it is important to remember that assessing the impacts of nature loss requires considering multiple scales, as ecological processes occur at various spatial extents, from local to regional and global levels.

4.4 Conclusion

This chapter discussed how, in light of the structural limitations of the examined models to assess nature-related financial risks, it is necessary to explore alternative approaches, with a particular focus on their ability to both represent multiple shocks in multiple sectors and capture the indirect (or cascading) impacts of nature-related hazards throughout value chains.

Against this background, and without excluding the possibility of exploring other approaches, Multi-Regional Input-Output (MRIO) tables and models can be particularly useful to both represent how a specific nature-related hazard can generate concomitant direct shocks in different sectors, and provide insights into how such initial shocks can propagate to other sectors through value chains.

MRIO tables and models can be used *without* prior reliance on other types of models (e.g., CGE models), to appreciate in a more transparent and simple manner the potential direct and indirect impacts of a specific physical or transition hazard. They can also be extended – still from a static or short-term perspective – to study macroeconomic impacts and connected to other models, in order to bring a dynamic perspective.

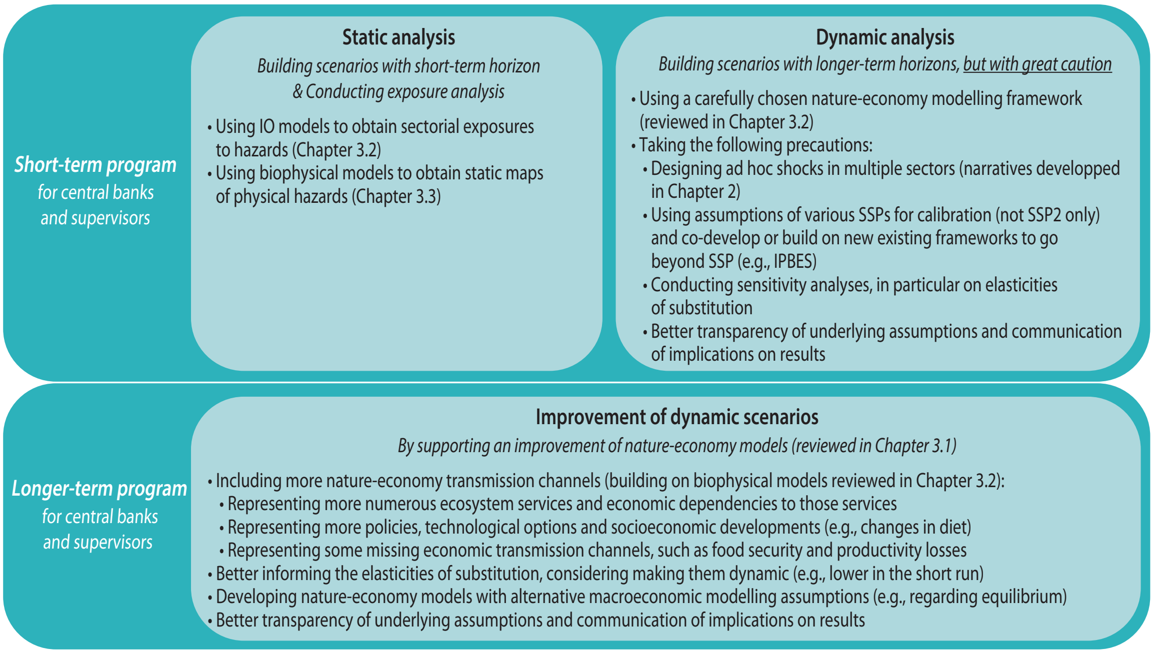
The two case studies presented in this chapter, focusing respectively on physical and transition risks, provide evidence of how MRIO models can be used to assess how nature-related financial hazards can generate direct impacts and indirect ones by propagating throughout sectors and countries.

However, input-output models are not exempt of limitations, with two main issues. First, the fixed nature of technical coefficients of production means that MRIO tables are not capable, on their own, to assess long-term dynamics, including agents' reaction functions to the initial impact and, more broadly, changes in the structure of the economy. Second, they are unable to provide information at the intra-sectoral level, which is particularly important for nature-related financial risks.

5. Conclusion and options for central banks and supervisors

In light of these findings, we provide a list of options aimed at moving forward with the development of quantified nature-related scenarios and present their associated trade-offs (see Figure 5.1). These options are split between what central banks and supervisors can do in the short-term and what they could seek to explore as part of a long-term research program (e.g., between 3 and 5 years).

Figure 5.1 **List of options for central banks and supervisors aiming to assess nature-related economic and financial risks**



Short-term program *for central banks and supervisors*

Static analysis

Building scenarios with short-term horizon & Conducting exposure analysis

- Using IO models to obtain sectorial exposures to hazards (Chapter 3.2)
- Using biophysical models to obtain static maps of physical hazards (Chapter 3.3)

Dynamic analysis

Building scenarios with longer-term horizons, but with great caution

- Using a carefully chosen nature-economy modelling framework (reviewed in Chapter 3.2)
- Taking the following precautions:
  - Designing ad hoc shocks in multiple sectors (narratives developped in Chapter 2)
  - Using assumptions of various SSPs for calibration (not SSP2 only) and co-develop or build on new existing frameworks to go beyond SSP (e.g., IPBES)
  - Conducting sensitivity analyses, in particular on elasticities of substitution
  - Better transparency of underlying assumptions and communication of implications on results

Longer-term program *for central banks and supervisors*

Improvement of dynamic scenarios

By supporting an improvement of nature-economy models (reviewed in Chapter 3.1)

- Including more nature-economy transmission channels (building on biophysical models reviewed in Chapter 3.2):
  - Representing more numerous ecosystem services and economic dependencies to those services
  - Representing more policies, technological options and socioeconomic developments (e.g., changes in diet)
  - Representing some missing economic transmission channels, such as food security and productivity losses
- Better informing the elasticities of substitution, considering making them dynamic (e.g., lower in the short run)
- Developing nature-economy models with alternative macroeconomic modelling assumptions (e.g., regarding equilibrium)
- Better transparency of underlying assumptions and communication of implications on results

Source: Authors.

While current models are not well-suited to assess the economic and financial impacts of nature-related hazards, tools and options exist to better assess nature-related risks.[54] **In the short term (and seeking alignment with other NGFS developments related to short-term scenarios), central banks could use input-output tables and models, biophysical models, or a combination of the two, which are static but offer greater coverage than current approaches.** This could enable central banks and supervisors to become more familiar with the identification of nature-related risks while they work on improving more complex models and assessing how they could be used jointly with MRIO tables. Such a task could be improved by regularly engaging with environmental authorities, among others to better calibrate initial hazards (as discussed in Chapter 2) and discuss results.

Still in the short-term, central banks and supervisors could use some of the global equilibrium-based (macroeconomic) modelling frameworks reviewed in Chapter 3, but with great caution: these models will almost automatically underestimate the economic impacts generated by nature-related hazards, for the reasons already discussed above, and any analysis which does use them should also assess how the most

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[54] Alongside modelling approaches, the NGFS could also focus more resources towards capacity building in the coming years, particularly for central banks and supervisors. Given the disproportionate impacts of environmental degradation and climate change in low- and middle-income countries, as well as their existing financial vulnerabilities (e.g., high levels of foreign indebtedness, fiscal constraints, etc.) capacity building will be crucial for effective risk management.

problematic assumptions and features of such models (for the purpose of assessing nature-related risks) can be modified. Creating ad hoc scenarios that change the parameters of the models, such as substitution elasticities, could be particularly useful in exploring the sensitivity of the results to different assumptions regarding the adaptability of the global economy to nature-related hazards. Additionally, more transparency on the uncertainties of significant model parameters and providing sensitivity analysis where necessary would be needed to improve the credibility and usefulness of the models to deliver policy-relevant insights.

As a longer-term effort central banks and supervisors should push the development of modeling frameworks that better account for interlinkages between nature and the economy to more effectively assess nature-related financial risks. A starting point would be to improve existing models by including more transmission channels. This could involve better representation of numerous ecosystem services and their economic dependencies, as well as more granular transition policies and technology options like organic farming and agroforestry (as currently developed with LPJmL in MAgPIE). Economic transmission channels such as food security and productivity losses should also be better incorporated, for example, by using a utility function with minimal calories to be consumed. Another area of improvement is exploring how elasticities of substitution could evolve in the short- and long-term and how they might differ across product classes.

Additionally, alternative macroeconomic modeling assumptions, such as non-equilibrium approaches, could provide a complementary perspective for capturing non-marginal impacts of severe nature loss that may be difficult to capture with existing equilibrium frameworks. For instance, the development of stock-flow consistent (SFC) models and SFC combined with input-output (IO) models could be particularly promising, as they represent multiple sectors and regions interacting and could provide a more flexible and dynamic approach than the rigid I-O approach. SFC-IO models also include the financial sector as a crucial driver of economic outcomes, which can help understand the feedback effects from finance to the economy and nature. However, the development of these models is currently at an early stage and needs to be accelerated to improve usefulness of the models. Central banks and supervisors cannot be at the forefront of such an effort but they can support it, including by calling for and taking part in multi-stakeholders scenario development.

In the longer-term, modeling frameworks should also incorporate certain crucial characteristics of nature loss, such as tipping points, although this is not a simple task. Tipping points are critical thresholds at which a small perturbation can significantly alter the state or development of a system. Current models and scenarios only include tipping points to a limited extent, but they can occur naturally or in the context of human-mediated climate change or nature loss. They may arise when there is limited substitutability of inputs to production processes or when the absorbing capacity of ecosystems is exceeded. The loss of a single ecosystem service can have cascading and compounding effects on multiple ecosystem functions and regions, leading to a decline in ecosystem resilience and, consequently, economic and financial resilience. While it may be impossible to account for all the socioeconomic impacts caused by crossing a tipping point, modelers could seek to better account for some of the complex interactions that can take place between biophysical processes (e.g., between soil systems and pollution flows).

Overall, a more comprehensive, methodologically-diversified and transparent approach to modeling the complex interplay between biophysical and economic systems is needed. The latter will enable central banks and supervisors (among others) to carefully use existing models and tools while remaining cautious about the climate and other nature-related risks that can be estimated from this, and open to emerging approaches.

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7. Annexes

7.1 Annexes for Chapter 1 Introduction

7.1.1 Bridging nature-related "data gaps"

Mitigating nature-related risks can be aided by gathering detailed knowledge about the current state and threats to biodiversity and ecosystems, with robust quality and comparable data. Research shows that the descriptions of species' geographical ranges and their temporal dynamics are fundamental biodiversity measures, and directly related to species' ecological relevance, population size, and extinction risk. However, there are obvious data gaps in the underlying data, as well as in the compilation, analysis, and effective use of data (including the tools and analytical methodologies for understanding the state of the environment) (UN, 2021).

Nevertheless, data can be useful for scenario analysis and for effective risk management. For instance, the identification of spatial patterns of biodiversity distribution is crucial for effective conservation and management strategies (Vargas et al., 2023). The largest the sample of spatial and temporal data, the least probable are potential biases and confounding factors. Moreover, the complexity and interactions between ecosystems, biodiversity, water systems, and oceans require data disaggregation, and therefore geospatial, and ecosystem-level data. Given the regional and local specificities of nature, ecosystems, and biodiversity, local data collection and analysis are also needed (Hochkirch et al., 2020).

At present, nature-related data gaps are significant, often disadvantaging key species and emerging markets and developing economies (EMDEs) (TNFD, 2023b). Emerging research shows data gaps in a variety of areas. Despite a rapid rise in data coverage, particularly in the last two decades, strong geographic and taxonomic biases persist. For example, despite increasing data collection for mammal species, data coverage remains lower than for other species, such as amphibians. Biodiversity data is also highly geographically biases: the most complete data coverage is found primarily within the United States, Europe, South Africa, and Australia. Only approximately half of nations have recently shown increasing, significant trends in coverage averaged across species (Oliver et al., 2021). Consequently, the number of species facing extinction may be much higher than previously thought (Borgelt et al., 2022). While in some cases, scientists have yet to track these species in the field, but in others the lack of data may reflect their already precipitous decline. The "data deficient" species are roughly twice as likely as "data-sufficient" species to be at risk of extinction. In addition, while soil biodiversity represents a major terrestrial biodiversity pool, supports key ecosystem services and is under pressure from human activities, it is found to have been neglected from many global biodiversity assessments and policies given the paucity of comprehensive information on soil biodiversity, particularly on larger spatial scales (Cameron et al., 2018). Other studies have assessed coverage gaps and biases on biodiversity data collection and techniques, often at the benefit of some regions (primarily North America and Europe), time periods, and species (Daru & Rodriguez, 2023).

Nature-related data standardisation and measurement initiatives have accelerated but need to expand on improving existing data and addressing data gaps. This will prove particularly key for EMDEs and low-income countries (LICs) when scenario analysis unfolds and intensifies data collection and assessment needs. The G20 Indian Presidency in 2023 put the issue in the agenda of the Sustainable Finance Working Group. Global and jurisdictional sustainability reporting frameworks, standards and approaches are underway to improve nature-related data, reporting and risk assessment (G20 SFWG, 2023). These include the Taskforce on Nature-related Financial Disclosures (TNFD), the International Sustainability Standards Board (ISSB), the Partnership for Biodiversity Accounting Financials (PBAF), the CDP, and regional initiatives such as in the European Union. The UN Biodiversity Lab supports country-led efforts to use spatial data and analytic tools to generate insight and impact for biodiversity conservation. In its input paper to the G20, the IUCN (2023) has made key recommendations to accelerate the improvements needed in nature and biodiversity data collection, standardisation, and assessment. Among these:

- Increasing the use of existing data tools. It includes promoting the use of the strongest data platforms and knowledge frameworks, and strengthening capacity building for national statistical offices, public finance institutions, and relevant line ministries to use nature-related data.

- Improving existing data and mobilizing financing towards this goal. The IUCN underlines that the assessment of the application of nature-related data to risk management of central banks and other financial regulators is a priority. More specifically, the IUCN recommends kickstarting the testing of existing datasets with financial regulators to improve data availability and reporting. Assessments on available metrics and indicators could be made at the level of commercial financial institutions to identify key areas of adjustment or further development of existing tools.
- Addressing data gaps across ecosystems and species. The IUCN recommends strengthening the two-way data flow between national and global processes for assessing nature-related data, developing case studies to strengthen the application of indigenous and local knowledge to biodiversity data generation and assessment, and promoting the participation of civil society and institutions in data governance structures.

7.2 Annexes for Chapter 2 on Developing Narratives to Assess Nature-Related Financial Risks

7.2.1 The ENCORE Database

The ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure) database was developed by the Natural Capital Finance Alliance jointly with UNEP WCMC (Natural Capital Finance Alliance, 2021). ENCORE assesses the interdependence of 86 types of production processes with 21 ecosystem services, which are themselves related to eight types of natural assets. The 21 ecosystem services are classified according to the Common International Classification of Ecosystem Services (CICES) (see **Annex Table 1**): 17 of the ecosystem services considered by ENCORE are regulation ecosystem services (16 biotic and one abiotic); the four remaining ecosystem services consist in two biotic provisioning services and two abiotic provisioning services (related to surface water and ground water). ENCORE does not include cultural ecosystem services and other relationships that are linked to more intangible forms of attachment to ecosystems or biodiversity.

Annex Table 1 **Ecosystem services covered by ENCORE**

Ecosystem Service	Type of ecosystem service
Ground water	Provisioning
Surface Water	Provisioning
Genetic materials	Provisioning
Fibers and other materials	Provisioning
Animal-based energy	Provisioning
Mass stabilisation and erosion control	Regulation and Maintenance
Climate regulation	Regulation and Maintenance
Flood and storm protection	Regulation and Maintenance
Filtration	Regulation and Maintenance
Dilution by atmosphere and ecosystems	Regulation and Maintenance
Water flow maintenance	Regulation and Maintenance
Water quality	Regulation and Maintenance
Soil quality	Regulation and Maintenance
Pest control	Regulation and Maintenance
Disease control	Regulation and Maintenance
Ventilation	Regulation and Maintenance
Buffering and attenuation of mass flows	Regulation and Maintenance
Bio-remediation	Regulation and Maintenance
Maintain nursery habitats	Regulation and Maintenance
Mediation of sensory impacts	Regulation and Maintenance
Pollination	Regulation and Maintenance

To measure the level of direct dependency of each production process on ecosystem services, ENCORE assigns dependency (or materiality) scores. Five dependency scores are available, from Very Low to Very High. The construction of the levels of dependency of each production process in ENCORE is the product of two factors: the degree of disruption to production processes if the ecosystem service were to disappear, and the expected ensuing financial losses. In ENCORE, the levels of dependency are not regionalised. This means that, for each ecosystem service, a production process occurring in one region is considered to have the same level of dependency as the same production process in another region.

7.2.2 *Examples of composite indicators for climate, environmental and nature-related risk*

Environmental Performance Index (EPI): Assesses a country's environmental performance based on various indicators related to environmental health and ecosystem vitality (https://epi.yale.edu/).

INFORM Index: Estimates the risk of countries to climate change and infectious diseases (https://www.undp.org/geneva/inform-index-risk-management).

Ocean Health Index: Evaluates the health of ocean ecosystems by combining indicators related to biodiversity, food provision, habitat integrity, and other factors (https://oceanhealthindex.org/).

Global Water Risk Index: Combines indicators related to water availability, water quality, and water-related vulnerabilities to assess the risk of water scarcity and pollution in different regions (https://www.wri.org/aqueduct).

Biodiversity Intactness Index: Measures the level of biodiversity intactness by combining indicators related to species populations, habitat loss, and conservation efforts (https://www.nhm.ac.uk/our-science/data/biodiversity-indicators/about-the-biodiversity-intactness-index.html).

Environmental Vulnerability Index (EVI): Assesses the vulnerability of countries to environmental risks, including natural disasters and other environmental stressors (https://gsd.spc.int/sopac/evi/index.htm).

Forest Landscape Integrity Index: Aligns indicators related to forest cover, fragmentation, and ecosystem health to assess the integrity of forest landscapes and their ability to provide ecological services (https://www.forestintegrity.com/).

Resource Efficiency Scoreboard: Evaluates resource use efficiency by combining indicators related to resource consumption, waste generation, and recycling rates (Resource Efficiency Scoreboard).

Air Quality Index: Combines indicators related to various air pollutants to assess air quality in different regions (https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database/2022).

Ecosystem Services Index: Combines indicators related to ecosystem services such as carbon sequestration, water purification, and pollination to assess the contributions of ecosystems to human well-being.

7.2.3 Transition Risk Narrative Frameworks

Annex Table 2 **List of Frameworks for Assessing Transition Risks**

Tool / framework	Description	Methodology	Key policy proposals / insights	Time-frame
Global Biodiversity Framework (GBF)	Kunming-Montreal Global Biodiversity Framework (GBF), agreed at the COP15 UN Convention on Biological Diversity, establishes global targets for biodiversity conservation. It includes four goals and 23 targets for achievement by 2030-2050 and establishes an ambitious policy framework for government and whole-of society action on nature. This hinges on a collective mission of halting and reversing biodiversity loss by 2030, by promoting conservation, restoration, sustainable use of nature, and equitable sharing of benefits, and a vision of "living in harmony with nature" by 2050. While CBD resolutions are non-binding, all 196 signature parties agreed at COP15 in Montreal to update their national biodiversity strategies and action plans (NBSAPs) to proceed with the implementation of the GBF at their jurisdiction level. By mainstreaming nature across policies and decision-making processes, signatories encourage the implementation of the GBF through regulatory and other measures by all actors of society.	Expert analysis and political considerations. The GBF evolved from earlier agreements to protect biodiversity, including the 1992 Earth Summit in Rio de Janeiro and the targets established by the 2011 UN Convention on Biological Diversity in Aichi. As with previous international agreements, the GBF was developed through political negotiations between signatory countries, based in part on a mix of expert analysis and scientific evidence, alongside stakeholder interest groups (firms, NGOS, etc.).	4 goals and 23 targets, among which include the following examples: [Target 1] Ensure [sufficiently participatory and/or effective management processes] to bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030, while respecting the rights of indigenous peoples and local communities. [Target 2] Ensure that by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity. [Target 3] Ensure the protection and effective conservation and management of at least 30% of the world's lands, inland waters, coastal areas and oceans by 2030. [Target 4] Ensure urgent management actions, to halt human induced extinction of known threatened species and for the recovery and conservation of species, in particular threatened species, to significantly reduce extinction risk, as well as to maintain and restore the genetic diversity within and between populations. [Target 7] By 2030, reduce by half both excess nutrients and the overall risk posed by pesticides and highly hazardous chemicals. [Target 14] Ensure the full integration of biodiversity and its multiple values into policies, regulations, planning and development processes, […] progressively aligning all relevant public and private activities, and fiscal and financial flows with the goals and targets of the GBF.	2030-2050

…/…

Global Biodiversity Framework (GBF)			[Target 15] Take legal and policy measures to encourage and enable business to regularly monitor, assess, and transparently disclose their risks, dependencies and impacts on biodiversity, including with requirements for all large and transnational companies and financial institutions along their operations, supply chains and portfolios in order to reduce biodiversity-related risks to business and financial institutions, and promote actions to ensure sustainable patterns of production. [Target 16] Cut global food waste in half and significantly reduce overconsumption and waste generation. [Target 18] Progressively phase out or reform by 2030 incentives, including subsidies that harm biodiversity by at least $500 billion per year, in a just and equitable way, and scale up positive incentives for the conservation and sustainable use of biodiversity. [Target 19] Mobilise by 2030 at least $200 billion per year in domestic and international biodiversity-related funding from all sources – public and private.	
Environmental Sustainability Gap (ESGAP)	The Environmental Sustainability Gap (ESGAP) framework is a tool that can be used to measure the environmental sustainability performance of nations. It provides a metric of analysis that links concepts of strong sustainability and critical natural capital to determine whether the essential functions of natural capital can be sustained in the long term. Generally applied via static index (SESi) and dynamic index (SESPi) **Strong Environmental Sustainability index (SESi):** an index built from 21 indicators of critical ecosystem functions' distance to standards of environmental sustainability. A 'snapshot' view as to whether countries currently meet science-based environmental standards for a wide range of environmental and resource topics.	In depth data collection from satellite accounts and from national accounting services, alongside scientific weighting of key indices to create a final index score.	The framework incorporates the non-substitutability between the different types of capital (i.e., natural, social, and economic) as well as the finiteness of the planet's natural resources and the constraints that these limits pose to economic growth. Thus, ESGAP adopts a strong sustainability vision in an effort to preserve "critical natural capital" for future generations. A simple framework for assessing ecosystem integrity. Already used in input-output frameworks (along with ENCORE) for assessing physical risks in New Caledonia (Comte et al. 2023), Vietnam (Nguyen et al. 2022), and South Africa (Hadji-Lazaro et al. *forthcoming*), notably in reports conducted by the Agence Française de Development (AFD). ESGAP SESi and SESPi can also be connected to other models. Most suitable for physical risks at this point. Can provide a first 'warning light' to serve as indicator for physical risk. Can also be used to develop guidance for more granular country-by-country analysis.	**ESGAP SESi:** Yearly metric. Historical and projected data dependent on data availability. **ESGAP SESPi:** Currently forecasted for European countries to consider coherence with 2030 sustainability goals. Possibility for considering historical trends (and projecting future trends) towards/away from 'good' environmental condition, dependent on data availability.

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Environmental Sustainability Gap (ESGAP)	**Strong Environmental Sustainability Progress index (SESPi):** an index developed to measure sustainability progress. Comprises the same 21 indicators of critical ecosystem functions as for SESi, but to measure whether, under current trends, standards of environmental sustainability will be reached by any chosen time horizon (e.g., in 2030 in a recent article on Europe[1]). Provides a sense of whether 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.			
Inevitable Policy Response (IPR)	IPR forecasts the possibility that governments will be driven to act decisively on climate change and nature loss – far more than they have thus far – thereby leaving private financial portfolios and public balance sheets exposed to potentially major transition risks. Forecasts suggest a generalised acceleration in policy responses, driven in part by increasing environmental disruptions, social costs, and growing public pressure for change. Policy responses may become "increasingly be forceful, abrupt, and disorderly leaving financial portfolios exposed to significant transition risk". Forecast Policy Scenarios for Climate and Nature (FPS + Nature) model the impact of the forecasted policies on the real economy and the environment up to 2050. Scenarios are based on assessments with leading experts on likely policy outcomes and projected technological changes. Attempts to consider the effects of policy responses and climate change on all major economic sectors, tracking changes to energy demand (oil, gas, coal), transport, food prices, crop yields, and rates of deforestation.	Policy implementation scenarios based on previous policy announcements (an upper bound for policy ambition), track record, historical trends, quality of governance (e.g, World Bank Worldwide Governance Indicator). IPR also surveys 200+ leading experts in national climate policy for views on policy action across major economies and emitting sectors. Value drivers fed into MAgPIE – a global partial equilibrium model that optimises land-use according to cropping patterns, yields and total costs – to determine major outcomes based on assumed policy, technology, market trends.	Policies are generally pursued at different rates according to institutional capacity, level of economic development, historical policy agreements, etc. These divide "early-mover" countries (generally high-income countries) from "late-mover" (generally lower-income countries). **Key policies:** **Protected areas** – Governments could act to safeguard nature by strengthening regulation to protect land. Current trends suggest 20% of total global land area could be protected by 2030, with international goals established at the CBD's COP 15 to protect 30% of land and sea by 2030 taking longer to implement. **Land restoration** – Governments may consider significantly increasing efforts to restore degraded ecosystems through national programmes, supplemented by private sector action. This could involve restoration on 4% of global land area by 2030. **Nature markets** – Formalisation of nature-related targets, creation of market infrastructure and corporate demand could support emergence of voluntary biodiversity credit markets initially at the local and regional scale, developing both independently and integrated with NBS-based carbon markets, with more focus on nature outcomes also having the potential to increase the "quality" of nature-based carbon credits.	Up to 2050

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[1] Usubiaga-Liaño, A., Ekins, P. Are we on the right path? Measuring progress towards environmental sustainability in European countries. Sustain Sci (2022). https://doi.org/10.1007/s11625-022-01167-2.

Inevitable Policy Response (IPR)	**Climate drivers** – The scenario also covers six other policy areas at the nexus of land use, climate and nature (carbon pricing, bioenergy, diets, deforestation, sustainable agriculture and food waste) demonstrating increasing action to raise taxes on carbon, reduce food waste, limit deforestation, etc. **Key findings:** **Food** – The price of deforestation-linked commodities increases, with sustainable yield improvements potentially keeping prices for staple crops stable over time. Policy action and the development of alternative proteins could bend the demand curve for ruminant meat, with production peaking by 2035, also influencing production of animal feed. **Energy** – Transition to low-carbon energy together with nature-related goals supports a shift to second-generation bioenergy that changes the countries and specific locations of biomass production. Increased demand for metals and minerals and some infrastructure expansion may need to be reconciled with increased land protection. **Nature-related goods, services and assets** – emerge as a new source of economic and financial value, driving the expansion of certified products, nature-based solutions and the emergence of new markets for biodiversity-rich land. New technologies designed to eliminate waste, reduce negative nature impacts and foster sustainability also emerge in tandem with the deepening of nature polices. **Supply chains** – Deforestation policies impact the production of tropical soft commodities as reputational, market access and liability risks could be passed down the value chain. **Global environment** – Planned policy action by governments would halt and reverse global biodiversity loss, potentially achieving 2000 levels of biodiversity intactness by 2045. Climate-related policies alone would be unlikely to improve biodiversity at a global scale and may only stabilise existing biodiversity loss.

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Science-Based Targets Network (SBTN), Science-Based Targets (SBT) for nature	Science-Based Targets Network (SBTN) is a network of 45+ organisations which develops methods and resources for establishing and implementing science-based targets (SBTs) for nature for both companies and cities. Its goal is for the world's major companies and cities to have adopted science-based targets to take action on water, land, ocean, and biodiversity by 2025. SBTs are defined as measurable, actionable, and time-bound objectives, based on the best available science, that allow actors to align with Earth's limits and societal sustainability goals. SBTs are designed to help organisations and cities to assess impacts and dependencies on nature and the environment and prioritise areas of action.	SBT setting and implementation occurs in a five-step process. (i) assessment of environmental dependencies and impacts via (direct) materiality screening and (indirect) value-chain assessment; (ii) interpretation of pressure and state of nature data and prioritisation of locations with the aim of addressing pressures; (iii) baseline data collection, target setting, and disclosure; (iv) action to meet targets; and (v) monitoring, verifying and reporting on progress over time.	SBTN aims to create a streamlined target-setting process for companies that enables progress towards multiple sustainability objectives in tandem. This provides complementarity between SBTs and other sustainability frameworks, standards, and regulations, including Science Based Targets Initiative (SBTi), the Taskforce on Nature-Related Financial Disclosure (TNFD), the Accountability Framework Initiative (AFi), the Alliance for Water Stewardship (AWS), the Natural Capital Protocol (NCP), the Biological Diversity Protocol (BDP), the Global Reporting Initiative (GRI), CDP, Organisation for Economic Co-operation and Development (OECD), United Nations (UN), International Organisation for Standardisation (ISO), ESRS/EFRAG and emerging EU requirements.	N/A
Taskforce On Nature-Related Financial Disclosures (TNFD)	TNFD offers a risk management and disclosure framework for organisations to identify, assess, manage and, where appropriate, disclose nature-related issues. The TNFD provides guidance on scenario analysis to help organisations understand risks and test the resilience of their strategy, given complex uncertainties. It allows individual organisations to explore the possible consequences of ecosystem service degradation, the ways in which governments, markets and society might respond, and the implications of these uncertainties for business strategy and financial planning. A 'toolbox' of tools and templates is provided to facilitate workshop-based scenario exercises by corporates, along with insights from four pilot tests. TNFD also provides an approach for identification and assessment of nature-related issues, called LEAP. This includes four phases, following an initial scoping of organisational priorities: **Locate** the firm's interface with nature; **Evaluate** dependencies and impacts; **Assess** risks and opportunities; and **Prepare** to respond to nature-related risks and opportunities and report.	Exploratory scenario providing qualitative storylines built around two critical uncertainties (closely linked to physical risk and transition risk). The TNFD proposes a workshop-based approach in 4 main steps: identifying the relevant driving forces, placing the business along the uncertainty axes, using scenario storyline descriptions, and identifying high-level business decisions. The TNFD suggests the use of tools and templates to guide the discussion by outlining clear and direct scoping questions. Ultimately, the question asked is "how the scenario exercise supports application of the TNFD framework, both in terms of disclosure and in terms of the LEAP approach for nature-related risk and opportunity assessment?". Allows for quantification of parameters and assumptions and quantification of scenarios through simulations of one or more models, or tools that provide variables to input into in-house models (Inevitable Policy Response + Nature etc.).	The TNFD presents 7 categories of driving forces (ecosystem interactions, dependencies, and impacts; finance and insurance; stakeholder and customer demands; regulators, legal and policy regimes; relevant technology and science; direct interaction with climate, and macro and microeconomy) that organisations can assess in order to define the most pertinent uncertainties. The TNFD proposes constructing scenario analysis around the two critical uncertainties of ecosystem service degradation (most closely correlated with physical risk and connected with climate change as a driver of nature loss), and alignment of market and non-market driving forces (most closely correlated with transition risk).	TNFD allows the organisation to define short-, medium- and long-term time frames, to understand how they align with the organisation's strategic planning horizons and capital allocation plans. Suggested to align with the GBF timeframe of 2030/2050: Set short-term plans for 'halting and reversing biodiversity loss' by 2030 and longer-term goals of 'living in harmony with nature by 2050'.

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Taskforce On Nature-Related Financial Disclosures (TNFD)	The TNFD's 2x2 critical uncertainties matrix provides four possible scenarios, each including a narrative of a plausible future of the world in which a company might find itself operating: **#1 Ahead of the game** Positive progress on carbon and climate accelerates the turn toward a policy and macro-prudential environment for nature-positive outcomes, but actual experienced loss from nature degradation is low. There are opportunities for organisations to lead, but also increasing scepticism of overreach on nature, given the lack of proof points about impact and risk, and the lack of visible opportunities in carbon neutral growth. **#2 Go fast or go home** In a nature-crisis environment where immediate and material business risks are broadly experienced, there will be threshold impacts that bolster the push for faster and more systematic action. Public attention and policy focus shifts toward nature as the master problem that subsumes carbon and climate. Macroeconomic disruption further compresses the time frame for action on nature, and investment in technologies for nature-positive outcomes skyrockets. **#3 Sand in the gears** Environmental assets are deteriorating fast, but politics and finance are too noisy, slow and bogged down in complexity to drive broad and systematic action. Organisations are incentivised to stopgap their most severe and acute business disruptions, and externalise the costs and negative consequences where possible. There are perverse incentives to overuse environmental assets in the short term. The developed–developing economy divide on benefits from environmental assets widens.

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Taskforce On Nature-Related Financial Disclosures (TNFD)	**#4 Back of the list** Nature falls down the list of priorities. Meaningful progress on carbon reduction becomes an even stronger magnet for finance, tech and corporate action because it seems relatively tractable, and a moderately effective – if indirect – way to make progress on nature issues. Organisations turn towards a strategy of reducing short-term harm to environmental assets and pull away from long-term planning as there seems to be no way of winning.			
Millennium Ecosystem Assessment (MA)	The 2005 Millennium Ecosystem Assessment (MA) developed a set of four scenarios to explore alternative development paths for world ecosystems and their services over the next 50 years and the consequences of these paths for human well-being. It proposes a methodology for developing qualitative narratives and modeling quantitative scenarios that integrate social, economic and environmental dimensions. It includes an analysis of global changes, alongside regional disaggregation of global patterns, and aims to reflect the deep uncertainties of long-range projections for key social and environmental variables, particularly acknowledging the possibility of multiple feedback effects and ecological regime shifts. Four scenario narratives of global trajectories: **Global Orchestration:** Depicts a worldwide connected society in which global markets are well developed. Supra-national institutions are well placed to deal with global environmental problems, such as climate change and fisheries. However, their reactive approach to ecosystem management makes them vulnerable to surprises arising from delayed action or unexpected regional changes. **Order from Strength:** Represents a regionalised and fragmented world concerned with security and protection, emphasizing primarily regional markets, and paying little attention to the common goods, and with an individualistic attitude toward ecosystem management.	The approach to scenario development used in the MA combines qualitative storyline development and quantitative modeling. The scenarios capture the aspects of ecosystem services that are possible to quantify, but also those that are difficult or even impossible to express in quantitative terms. Scenario narratives were developed through collective discussions within a scenarios working group. The scenarios were guided by a desire to understand the consequences of plausible changes in development paths for ecosystems and their services over the next 50 years and the consequences of those changes for human well-being. Participant experts sought to project possible developments based on (i) strategies that emphasise economic policy reform (reducing subsidies and internalizing externalities) as the primary means of management; (ii) strategies that emphasise local and regional safety and protection and that give far less emphasis to cross-border and global issues; (iii) strategies that emphasise the development and use of technologies allowing greater eco-efficiency and adaptive control; and (iv) strategies that emphasise adaptive management and local learning about the consequences of management interventions for ecosystem services.	Global cooperation and a focus on global public good improves overall human well-being, but it may have negative consequences for ecosystem services and some aspects of human wellbeing if local issues and inequalities of vulnerability and adaptability are not addressed. Over-emphasis on environmental technology and engineered ecosystems may contribute to sustainable development by allowing for greater efficiency and optimal control of ecosystems, but come with serious drawbacks. In particular, over-reliance in large-scale technological solutions brings major risks especially if drivers of ecosystem degradation are overlooked. Failure of technologies can engender devastating ecological surprises. Emphasis on adaptive management and learning at local scales may be achieved at the cost of overlooking global problems that may result in global environmental surprises with serious local repercussions. Strategies that focus on local and regional safety and stronger border enforcement that restrict trade and movement of people and goods might offer some benefits (e.g., security in the face of aggression, reduced risk of environmental pests, and diseases) but increases risks of longer-term internal and international conflict, ecosystem degradation, and declining human wellbeing. A globally compartmentalised, environmentally reactive world could mask worsening ecological and social disasters.	Up to 2050

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Millennium Ecosystem Assessment (MA)	**Adapting Mosaic:** Depicts a fragmented world resulting from discredited global institutions. It sees the rise of local ecosystem management strategies and the strengthening of local institutions. Investments in human and social capital are geared toward improving knowledge about ecosystem functioning and management, resulting in a better understanding of the importance of resilience, fragility, and local flexibility of ecosystems. **TechnoGarden:** Depicts a globally connected world relying strongly on technology and on highly managed and often-engineered ecosystems to deliver needed goods and services. Overall, eco-efficiency improves, but it is shadowed by the risks inherent in large-scale humanmade solutions.	Based on initial storylines, a team of modelers attempted to translate scenario narratives into quantifiable processes, where sufficient knowledge and data exists to allow modeling. Five global models were chosen to cover global social and environmental changes (IMPACT, WaterGAP, AIM, IMAGE, Ecopath/Ecosim) and two global models describing changes in biodiversity were chosen. Models were linked and run based on a set of indirect and direct drivers of changes in in ecosystem services.	Institutional development, feedbacks between local and global processes, and the risks entailed by the substitution of ecosystem services by human, social, or manufactured capital determine society's ability to cope with ecological surprises.	Up to 2050
Shared Socioeconomic Pathways (SSP)[1]	Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are typically used to derive scenarios of different climate policies to project future concentrations of greenhouse gas emissions. SSPs describe five different scenarios of trends in socio-economic development (economic growth, technology, demography, inequality, etc.) and global integration (cooperative development, increasing division, etc.). Five scenario narratives of SSP trajectories: **SSP1: Sustainability (Taking the Green Road):** Represents a world that shifts gradually toward a more sustainable path, emphasizing more inclusive development that respects environmental boundaries. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries, alongside improvements in education and health. Consumption is oriented toward low material growth and lower resource and energy intensity.	Since SSPs do not provide explicit indications of environmental policies, or the consequences of environmental damages – either for biodiversity or climate change – they serve mostly as a base for common understanding of likely potential qualitative outcomes. SSPs are therefore regularly coupled with specific climate and/or biodiversity policies to determine: how specific regulations, such as a ban on the sale of pesticides and fertilisers, may affect economic and environmental outcomes (referred to as "policy screening scenario narratives"); how to arrive at stated policy targets, such as the effort to keep global warming below 1.5 degrees Celsius (referred to as "target-seeking scenario narratives"). For example: Leclère et al. (2020) use a suite of land-use models and biodiversity indicators to assess whether – and how – terrestrial biodiversity losses can be reversed. The study combines results from several integrated assessment models (AIM, GLOBIOM, IMAGE, MAgPIE) to define the range of likely biodiversity outcomes for different policy interventions.	The vast majority of the available literature of biodiversity scenarios utilise narratives found in the Shared Socio-economic Pathway (SSP). See Maurin et al. (2022) for a review. For example: Leclère et al. (2020) propose a number of possible policies. They compare outcomes by testing how key variables respond to any one, or a mixture, of policy responses, including: Supply-Side interventions to increase crop yields, and increase trade of agricultural goods;	Up to 2100

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[1] Due to the number of studies using SSPs, we analyse its use in Leclère et al. (2020).

Shared Socioeconomic Pathways (SSP)[1]	**SSP2: Middle of the Road:** Depicts a world where social, economic, and technological changes do not shift markedly from historical patterns. Development, income growth, and environmental protections proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. **SSP3: Regional Rivalry (A Rocky Road):** Depicts a world in which resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. With little investment in technology and social policy, economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. **SSP4: Inequality (A Road divided):** Considers a world in which highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Social cohesion degrades and conflict and unrest become increasingly common. The globally connected energy sector continues to diversity with investment in both high-and low-carbon energies. Environmental policies focus on local issues around middle and high income areas.	Their study uses SSP2 as a baseline scenario to project outcomes based on 44 future drivers of expected habitat loss. They conduct six additional scenarios based on an SSP1 future which integrate ambitious conservation assumptions. These include different combinations of supply-side, demand-side and conservation efforts towards reversing biodiversity trends, alongside an Integrated Action Portfolio (IAP) scenario which includes all efforts.	Demand-Side interventions to reduce waste of agricultural goods from field to fork, and shift diets to a lower share of animal calories; and Increased Conservation policies to increase the extent and management of protected areas, and increase restoration and landscape-level conservation planning. The most ambitious scenario in the study depicts a mix of all supply side, demand side and conservation policies (including 40% increase in globally protected areas). This combination of policies provides the best results, allowing for biodiversity regeneration by mid-century within most models. However, mean-species abundance trends turn positive only after 2075, on average.	Up to 2100

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[1] Due to the number of studies using SSPs, we analyse its use in Leclère et al. (2020).

Shared Socioeconomic Pathways (SSP)[1]	**SSP5: Fossil-fueled Development (Taking the Highway):** This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated... The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world.			
WWF Biodiversity Risk Filter (BRF)	The Biodiversity Risk Filter is a spatially-explicit, corporate- and portfolio-level screening tool for determining biodiversity related risks. The tool is designed to allow companies to understand and assess the biodiversity-related risks of their operational locations and their suppliers, and to allow financial institutions to assess biodiversity-related risks for all companies in a given portfolio. The tool builds heavily on WWF's Water Risk Filter tool, which provides similar company-level and portfolio-level data for risk screening. The tools provide location-specific and industry-specific assessments of biodiversity and water-related risks. The tools aim to help companies and financial institutions to better prioritize where and on what to focus contextual responses as well as inform their biodiversity- and water-related stewardship strategies and target setting. BRF currently focuses on physical risks and reputational risks by analysing biodiversity-related dependencies and direct biodiversity impacts. Dependency and impact scores are measured for 33 different indicators with ranges from "very high" to "very low". Regulatory risk assessments will be incorporated in future versions of the BRF.	The current version of the online BRF tool consists of three key modules: The inform module, the explore module, and the assess module. The Inform and Explore Modules are combined to give a biodiversity risk assessment score in the Assess module. (i) the Inform Module provides an overview of the industry-specific dependencies on ecosystem services and impacts on biodiversity for 25 different sectors. The methodology is based on the ENCORE tool for dependencies and research from the SBTN for designating impacts. This module provides an indication of the industry's materiality and the impacts/dependencies of a portfolio or supply chain. (ii) the Explore Module is a collection of spatially-explicit maps of the importance and local integrity of biodiversity within a specific land and water-scape. These provide a geographically-situated biodiversity risk score according to 33 different indicators. (iii) The Assess Module contains a tailored physical and reputational risk assessment for which users need to input location-specific company and/or supply chain data in order to assess specific risks. Site-level risks are calculated according to location-specific and supply-chain risk calculations. For portfolio assessments, scores require location-specific data on revenue-streams, assets, corporate headquarters, etc. Site-level scores are then aggregated and weighted according to business and portfolio importance of a site.	Predominantly useful for assessing physical risks in its current state. Future versions will include 'regulatory' risks assessments. When combined with existing data on reputational risk, this could provide a measure for assessing transition risks. Offers a simple tool for analysing biodiversity risks at the corporate and sector level. Global in scope, yet integrates spatially-explicit data to keep track of location-specific dependencies and impacts. Aligns with work of other well-established organisations (TNFD, SBTN, etc.). For example, the SBTN team and WWF have created guidance on how the WWF Biodiversity Risk Filter can be used by companies and financial institutions at specific points in the SBTN target-setting process.	N/A

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WWF Always Environmentally Harmful Companies database	The WWFs classification of "Always Environmentally Harmful Companies" delineates economic activities, companies and sectors that have the highest negative environmental impacts and are considered to be universally and undeniably environmentally harmful in all cases. While the definition of "green" is open for debate, certain industries can be classified as always harmful for the climate and biodiversity and, therefore, as always contributing to financial risk. These include companies involved in coal, oil and gas and other forms of fossil fuel extraction, as well as cement manufacturers, mining and other deforestation-intensive companies (many of which are active in biodiversity hotspots). Such companies and sectors are invariably linked to climate and biodiversity crises. As such, their assets are likely to face threats due to (i) physical scarcity and increasing environmental damages brought on by harmful environmental changes, or (ii) new regulations which may "strand" these assets as the world transitions. These have the highest concentration of physical, transition and litigation risks, and therefore result in substantial threats for price and financial stability. Moreover, transition risks may arise through regulation of the financial sector, as financial institutions that are lending to companies involved in environmentally harmful activities may face far higher capital requirements to account for the long-term risks involved.	WWF suggests three ways in order to identify "always environmentally harmful": first through the level of economic activity, second through a company lens, and third, through a sectoral lens. The economic activity level distinguishes between those activities that cannot be retrofitted (such as solid fossil fuels) and ones with retrofitting potential (vehicle manufacture which solely relies on electric engines). This provides a more granular perspective on the transition risk, and could be the basis for adapting collateral frameworks and targeted refinancing operations so that always harmful activities are unable to benefit. The company level distinguishes between businesses expanding activities that can be labelled always harmful, those that are transforming but not fast enough, and companies that provide proof of their effective transformation. This could be used as the basis for targeted adaptations of asset purchase programmes excluding always harmful companies, increasing haircuts within the collateral framework or increasing the risk-weighting in the capital requirements framework. The sector level relies upon a more general risk analysis, useful for defining concentration limits or to modulate systemic risk buffers.	The overall exposure of the financial sector to the fossil fuel industry and activities related to deforestation are considered to be of the highest priority, as they are the core driver of GHG emissions and biodiversity destruction. These exposures present the highest financial risks. Financial institutions investing, underwriting or lending to sectors, companies or economic activities that are considered as 'always environmentally harmful' could face a number of new regulations: Higher regulatory capital requirements; Tighter liquidity requirements; Capital add-ons for concentration risk if they fail to reduce their exposure urgently; Higher systemic risk buffers according to their exposure to environmentally harmful assets and assets in particularly vulnerable regions. The WWF argues that, given the existence of always environmentally harmful companies: – Central banks and financial supervisors should jointly co-develop their own 'always environmentally harmful list' with scientific institutions and apply it to the monetary policy and financial regulation instruments to provide sufficient and significant credibility to financial institutions in their actions. – Central banks must stop investing in (e.g., through asset purchase programmes), and adapt their collateral frameworks for economic activities, companies and sub-sectors that are considered 'always environmentally harmful' and introduce a "green dual rate" – a discount interest rate on future refinancing encouraging clean energy production and energy efficiency renovations. – Central bank and financial regulation time horizons must be extended to 10-30 years to ensure that short term financial flows that may have major long-term consequences for losses and instability are treated as far higher risk. Once specific companies and sectors have been identified as "always environmentally harmful', it is possible to link these to existing models (e.g., multi-regional input output models) that account for economic interdependencies within a production network for scenario analysis.	N/A

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Nature Futures Framework (NFF)	The Nature Futures Framework (NFF) is a heuristic tool for identifying possible futures for nature and people. It seeks to open up a diversity of futures by exploring different value perspectives on nature. NFF aims to help integrate nature in policy-making and better link the efforts of scientists and regulators to diverse values for nature and people. Human-Nature value perspectives in the NFF are described through the lenses of Nature for Nature (NN), Nature for Society (NS), and Nature as Culture (NC) – The Nature for Nature (NN) perspective appreciates and preserves nature for what it is and does and maps to intrinsic and existence values of biodiversity (e.g., maintaining natural processes and function such as evolution and migration). The Nature for Society (NS) perspective focuses on instrumental values as in benefits that nature provides to people (e.g., supporting crop production and climate regulation). The Nature as Culture (NC) perspective values the relationships that nature and people co-create, not as separate entities but as an indivisible whole (e.g., preserving emblematic species, sacred landscapes, traditional knowledge). Following Kim et al. (2023), the NFF integrates (i) multiple value perspectives on nature as a state space where pathways improving nature toward a frontier can be represented, (ii) mutually reinforcing key feedbacks of social-ecological systems that are important for nature conservation and human wellbeing, (iii) indicators of multiple knowledge systems describing the evolution of complex social-ecological dynamics.	The Nature Futures Framework (NFF) is increasingly used as a foundation for thinking about positive futures for people and nature, and to help inform assessments of policy options across multiple scales (Pascual et al. 2023). The NFF places relationships between people and nature at its core. Because people relate to nature in multiple ways, there are a wide variety of desirable nature futures, with different goals and visions which can be synergistic or in conflict with one another. More recently, research has sought to explore how the NFF can also be applied in scenario development and modelling (Kim et al., 2023; Pascual et al., 2023). NFF can potentially be used to develop scenarios that highlight the interdependent effects of transition policies and how they relate to multiple values of nature. These value perspectives are conceptual tools to broaden and diversify stakeholders' visions for nature and people through exploring, mapping and combining a broad range of futures and interventions on gradients such as autonomy of nature, instrumental values and the importance of culture in shaping and being shaped by nature.	NFF can be used to develop scenarios that highlight the interdependent effects of transition policies and how they relate to multiple values of nature. This allows the framework to present possibilities that are not easily captured within standard economic or biophysical models. This includes alternative ways of relating to and within nature whose full social and ecological benefits cannot be easily measured or modeled (e.g., qualitative shifts from industrial agriculture to agro-ecology, protection of sacred natural landscapes and values, preserving indigenous knowledge and landscape management practices). The Nature Futures Framework can be used in exploring a much broader array of interventions, compared to previous environmental scenarios, integrating diverse values, roles and benefits of nature. Thus, it can be used to inform multiscale policy frameworks at local, national and global scales (e.g., CBD National Biodiversity Strategy and Action Plans, CBD National Reports, CBD Global Biodiversity Framework), helping to identify interventions, set targets, and monitor progress towards the goals. By taking on multiple value perspectives, the NFF is also able to highlight potential conflicts between people or groups of people who value different nature perspectives. This can produce transition risks via regulatory uncertainty, legal costs, reputational risks, socio-economic tensions, opportunity costs, and reduced international cooperation. These conflicts can lead to economic, social, and environmental consequences that have both direct and indirect financial implications.	None specified

7.3 Annexes for Chapter 3 on Modelling Approaches for Assessing Nature Scenarios

Annex Table 3 **Ecosystem services and their main economic dependencies represented in the reviewed models**

Ecosystem services covered		GTAP-InVEST	REMIND-MAgPIE	AIM/CGE and AIM/PLUM	IMAGE-MAGNET	MESSAGE-GLOBIOM	GCAM
Provisioning services	Surface- and Ground-Water provision	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** None	**Supply by nature:** Using LPJmL, models water availability and water cycles. **Economic dependency on the ecosystem service:** Only agricultural sector production is affected, as well as pollution of water by nitrogen leakage.	**Supply by nature:** not modelled (water availability is only used as initial data to downscale the land use with AIM/PLUM). **Economic dependency on the ecosystem service:** None	**Supply by nature:** Using LPJmL, IMAGE models water availability, quality and water cycles (river basin surface water only) and its impacts on yields **Economic dependency on the ecosystem service:** Only agricultural sector production is affected	**Supply by nature:** a full water cycle and its impact on crop yields is modelled in EPIC-IIASA (used by GLOBIOM) **Economic dependency on the ecosystem service:** Only agricultural sector production is affected	**Supply by nature:** Modelled for 235 water basins, as part of a coupled system with the economy, energy, land use and climate. Supply depends on precipitation, runoff, groundwater recharge and fossil groundwater, desalination cost, water subsidies, water rights, and water prices. **Economic dependency on the ecosystem service:** Both the production of the agricultural sector and of the energy sector are affected in case of a drop in water supply (leading to increasing water prices).
	(Food) crop provision	**Supply by nature:** depends on available land – crop growth is not modelled and yields of the agricultural sector are partly exogenous but can be affected by pollination (from InVEST). **Economic dependency on the ecosystem service:** multiple crop sectors (6) in the GTAP model: their productivity can be affected, hence affecting their production.	**Supply by nature:** modelled with a crop model (LPJmL) in which agricultural yields can be affected by several ecosystem services (climate, carbon cycle, water availability, nutrients). **Economic dependency on the ecosystem service:** multiple crop sectors (20) in the MAgPIE model: their productivity can be affected, hence affecting their production.	**Supply by nature:** depends only on available land – crop growth not modelled. **Economic dependency on the ecosystem service:** multiple crop sectors (6) in the AIM/CGE model: their productivity can be affected in an ad hoc way, hence affecting their production.	**Supply by nature:** modelled with a crop model (LPJmL) in which agricultural yields can be affected by several ecosystem services (climate, carbon cycle, water availability, nutrients). **Economic dependency on the ecosystem service:** multiple crop sectors (8) in the MAGNET model: their productivity can be affected, hence affecting their production.	**Supply by nature:** modelled with a crop model (EPIC) in which agricultural yields can be affected by several ecosystem services (climate, carbon cycle, water availability, nutrients). **Economic dependency on the ecosystem service:** multiple crop sectors (30) in the GLOBIOM model: their productivity can be affected, hence affecting their production.	**Supply by nature:** modelled by crop models or emulators (e.g., Persephone model) in which agricultural yields can be affected by several ecosystem services (water availability, land characteristics, climate). **Economic dependency on the ecosystem service:** multiple crop sectors (15) in the GCAM model: their productivity can be affected, hence affecting their production.

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Provisioning services	(Food) livestock provision	**Supply by nature:** depends on available land. **Economic dependency on the ecosystem service:** there are livestock sectors (2) in the GTAP model, that could (in theory) be affected.	**Supply by nature:** depends on available land and feed. **Economic dependency on the ecosystem service:** there are livestock sectors (5) in the MAgPIE model, and their production is affected.	**Supply by nature:** depends on available land. **Economic dependency on the ecosystem service:** there are livestock sectors (3) in the AIM/CGE model, and their production is affected.	**Supply by nature:** depends on available land and feed. **Economic dependency on the ecosystem service:** there are livestock sectors (6) in the MAGNET model, and their production is affected.	**Supply by nature:** depends on available land and feed. The RUMINANT model provides livestock yields. **Economic dependency on the ecosystem service:** there are livestock sectors (4) in the GLOBIOM model, and their production is affected.	**Supply by nature:** depends on available land and feed. **Economic dependency on the ecosystem service:** there are livestock sectors (3) in the GCAM-LAND model, and their production is affected.
	Fish provision	**Supply by nature:** Fisheries and Marine Ecosystem Model Intercomparison Project data (Lotze et al. 2019) models the impact of climate change on total catch biomass. **Economic dependency on the ecosystem service:** there is a fishery sector in GTAP, and its productivity is affected.	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** Exogenous demand trajectories for fish products are modelled. Supply not modeled.	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** there is a fishery sector in AIM/CGE, which could (in theory) be affected.	**Supply by nature:** not modeled (no fisheries in IMAGE. **Economic dependency on the ecosystem service:** there are fishery sectors (6) in MAGNET, which could (in theory) be affected.	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** None.	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** None.
	Timber provision	**Supply by nature:** depends on available land, but growth process of trees per se is not modelled. **Economic dependency on the ecosystem service:** there is a forestry sector in GTAP, and its productivity is affected.	**Supply by nature:** modelled with a crop model (LPJmL) in which forest yields can be affected by several ecosystem services (climate, carbon cycle, water availability, nutrients). **Economic dependency on the ecosystem service:** there is a forestry sector in the MAgPIE model: its productivity can be affected, hence affecting its production.	**Supply by nature:** depends only on available land – tree growth not modelled. **Economic dependency on the ecosystem service:** there is a forestry sector in the AIM/CGE model whose productivity can for example be impacted in an ad hoc way.	**Supply by nature:** modelled with a crop model (LPJmL) in which forest yields can be affected by several ecosystem services (climate, carbon cycle, water availability, nutrients). **Economic dependency on the ecosystem service:** multiple forest sectors (4) in the MAGNET model: their productivity can be affected, hence affecting their production.	**Supply by nature:** modelled with a forest model (G4M) in which forest yields can be affected by several ecosystem services (climate, carbon cycle, water availability, nutrients). **Economic dependency on the ecosystem service:** there is a forestry sector in the GLOBIOM model: its productivity can be affected, hence affecting its production.	**Supply by nature:** a forestry sector is modelled within GCAM (two types of managed forest land, hardwood and softwood) but not connected to a biophysical model modelling the process of tree growth – supply only depends on economic factors (expected profitability of deploying land in managed forests). **Economic dependency on the ecosystem service:** The production of the forestry sector (industrial roundwood, fuelwood, and residues) and associated prices can be affected (as well add the price of bioenergy for example).

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Provisioning services	Fibers provision	**Supply by nature:** same as food crops: growth not modelled, but productivity can be affected by pollination **Economic dependency on the ecosystem service:** there is a fibers sector (cotton) in GTAP, and its productivity is affected	**Supply by nature:** same as food crops: yields represented in crop model, also depending on available land **Economic dependency on the ecosystem service:** there is a fibers sector in MAgPIE, and its productivity is affected, hence affecting its production	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** None	**Supply by nature:** same as food crops: yields represented in crop model, also depending on available land **Economic dependency on the ecosystem service:** there are two fibers sectors (plant-based fibers, wool) in MAGNET, and their productivity can be affected, hence affecting their production	**Supply by nature:** same as food crops: yields represented in crop model, also depending on available land **Economic dependency on the ecosystem service:** there is a fibers sector (cotton) in GLOBIOM, and its productivity is affected, hence affecting their production	**Supply by nature:** fiber crop is represented in GCAM, just like food crops. **Economic dependency on the ecosystem service:** The fiber sector in GCAM, aggregating cotton and other fiber crops, is modeling similar to other crops. The productivity can be affected.
	Bioenergy	**Supply by nature:** not modelled. **Economic dependency on the ecosystem service:** None	**Supply by nature:** same as food crops: yields represented in crop model, also depending on available land **Economic dependency on the ecosystem service:** there is a bioenergy sector in MAgPIE (1st and 2nd generation biofuels), if its productivity is affected, so is its production.	**Supply by nature:** not modelled **Economic dependency on the ecosystem service:** there is a bioenergy sector in AIM/CGE, if its productivity is affected, so is its production.	**Supply by nature:** same as food crops: yields represented in crop model, also depending on available land **Economic dependency on the ecosystem service:** there are 6 bioenergy sectors in MAGNET (biogasoline, biodiesel, biofuel feedstock grains, biofuel feedstock sugar, biofuel feedstock molasses, biofuel feedstock oils, second generation biofuels). If their productivity is affected, so is their production.	**Supply by nature:** same as food crops: yields represented in crop and forest models, also depending on available land **Economic dependency on the ecosystem service:** there are "bioenergy sectors" in GLOBIOM. If their productivity is affected, so is their production.	**Supply by nature:** depends on available land and water (no modelling of vegetation growth) **Economic dependency on the ecosystem service:** GCAM has multiple bioenergy types (including purpose-grown energy crops – woody and herbaceous –, residual biomass, MSW, first-generation biofuels based on corn, soybean, oil palm, and other oil crops, and traditional biomass). If its productivity is affected, so is its production.
	Genetic material	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**

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Maintenance and regulation services	Pollination	**Supply by nature:** InVEST model relies on maps of pollinators to show impact of pollination (loss) on crop yields **Economic dependency on the ecosystem service:** through yields of agriculture sector (in GTAP)	**Supply by nature:** can model impacts on pollinator sufficiencies. **Economic dependency** Impact of lost pollinators on crop yields is under development.	**Supply by nature** **Economic dependency**	**Supply by nature:** IMAGE model derived a relationship between % of nature per grid cell and the % of pollinator dependent yield produced **Economic dependency on the ecosystem service:** could affect the yields of agriculture sector (in MAGNET – the connexion is currently being made by the modellers)	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**
	Climate regulation	**Supply by nature:** not modelled **Economic dependency on the ecosystem service:** The model on fisheries that is connected to GTAP represents the effect of ad hoc climate change scenarios on fish stocks. Apart from that, no climate damages or benefits on the economy.	**Supply by nature:** the effect of land use on GHG emissions and carbon storage are modelled in MAgPIE. The effect of GHG emissions on climate (temperatures, etc.) is then modelled with the MAGICC model. **Economic dependency on the ecosystem service:** LPJmL can model the impacts of climate change on agricultural yields, then affecting agriculture production in MAgPIE. In REMIND, a climate damage function can be directly applied to the macroeconomic output.	**Supply by nature:** the effect of land use on GHG emissions and carbon storage are modelled. **Economic dependency on the ecosystem service:** not modelled (there is no climate damage function nor sectoral effects of climate change).	**Supply by nature:** The effect of land-use on GHG emissions and subsequent effects on climate are modelled in IMAGE. **Economic dependency on the ecosystem service:** IMAGE (using LPJmL) can model the impacts of climate change (temperature and rainfall) on agricultural yields. It can then affect agriculture production in MAGNET. There is no climate damage function applied to the macroeconomic output nor to other sectors.	**Supply by nature:** the effect of land use on GHG emissions and carbon storage are modelled in GLOBIOM. The effect of GHG emissions on climate (temperatures, etc.) is then modelled with the MAGICC model. **Economic dependency on the ecosystem service:** The EPIC model that is linked to GLOBIOM can model the impacts of climate change on agricultural yields. There is no climate damage function applied to the macroeconomic output nor to other sectors.	**Supply by nature:** the effect of land use on GHG emissions and carbon storage are modelled in GCAM. The effect of GHG emissions on climate (temperatures, etc.) is then modelled with the Hector model. **Economic dependency on the ecosystem service:** Feedbacks of climate on yields for crops and forests is modeled using crop models or emulators (e.g., the Persephone model or response functions), which can be coupled with Hector. Energy production will also depend on climate (e.g. cooling and heating days). There is no climate damage function applied to the macroeconomic output. …/…

Maintenance and regulation services	Mass stabilisation and erosion control	**Supply by nature** **Economic dependency**	**Supply by nature:** could be represented using LPJmL, which models in particular the effect of soil composition (carbon, nutrients, etc.) on yields. **Economic dependency on the ecosystem service:** Could be captured through impact on crop yields in agriculture sectors (in MAgPIE)	**Supply by nature** **Economic dependency**	**Supply by nature:** IMAGE models topsoil erosion related to water and agricultural practices and its impacts on agricultural yields. **Economic dependency on the ecosystem service:** could affect the yields of agriculture sector (in MAGNET)	**Supply by nature:** could be represented using EPIC, which models in particular the effect of soil composition (carbon, nutrients, etc.) on yields. **Economic dependency on the ecosystem service:** Could be captured through impact on crop yields in agriculture sectors (in GLOBIOM)	**Supply by nature** **Economic dependency**
	Soil quality	**Supply by nature** **Economic dependency**	**Supply by nature:** using LPJmL, which models in particular the effect of soil composition (carbon, nutrients, etc.) on yields. Can also simulate level of soil erosion. **Economic dependency on the ecosystem service:** impact of soil erosion on crop yields in agriculture sectors is under development.	**Supply by nature** **Economic dependency**	**Supply by nature:** IMAGE models water-induced and human-induced changes in soil fertility and their impacts on agricultural yields **Economic dependency on the ecosystem service:** could affect the yields of agriculture sector (in MAGNET)	**Supply by nature:** could be represented using EPIC, which models in particular the effect of soil composition (carbon, nutrients, etc.) on yields. **Economic dependency on the ecosystem service:** would be captured through impact on crop yields in agriculture sectors (in GLOBIOM)	**Supply by nature** **Economic dependency**
	Flood and storm protection	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**	**Supply by nature:** in IMAGE, the GLOFRIS model represents the flood risk from climate change and provides expected value of affected GDP **Economic dependency on the ecosystem service:** not modelled (not connected to the macro model MAGNET)	**Supply by nature** **Economic dependency**	**Supply by nature** **Economic dependency**
	Water flow maintenance	**Supply by nature** **Economic dependency** *See "surface and groundwater provision"*	**Supply by nature** **Economic dependency** *See "surface and groundwater provision"*	**Supply by nature** **Economic dependency** *See "surface and groundwater provision"*	**Supply by nature** **Economic dependency** *See "surface and groundwater provision"*	**Supply by nature** **Economic dependency** *See "surface and groundwater provision"*	**Supply by nature** **Economic dependency** *See "surface and groundwater provision"*

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Maintenance and regulation services	Water quality	Supply by nature Economic dependency	**Supply by nature:** Using LPJmL, which models water availability and water cycles. **Economic dependency on the ecosystem service:** Not modelled.	Supply by nature Economic dependency	**Supply by nature:** LPJmL models water availability and quality and water cycles. **Economic dependency on the ecosystem service**	Supply by nature Economic dependency	Supply by nature Economic dependency
	Pest control	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	**Supply by nature:** IMAGE represents the presence of natural pest control based on land-use and land intensity. **Economic dependency on the ecosystem service:** Not modelled (e.g. not affecting crop yields)	Supply by nature Economic dependency	Supply by nature Economic dependency
	Disease control	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Dilution by atmosphere and ecosystems	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Filtration	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Ventilation	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Buffering and attenuation of mass flows	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Biore mediation	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Maintain nursery habitats	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency
	Mediation of sensory impacts	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency

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Cultural services	Tourism	Supply by nature Economic dependency	Supply by nature Economic dependency	Supply by nature Economic dependency	**Supply by nature:** IMAGE models suitability for nature based tourism, based on socioeconomic conditions and landscape attractiveness Economic dependency **on the ecosystem service:** Not modelled in MAGNET (but could be by affecting the production of the tourism sector?)	Supply by nature Economic dependency	Supply by nature Economic dependency
Additional ES represented					**Supply by nature:** Protection against fires Economic dependency **on the ecosystem service:** Not modelled		

Green = multiple and/or direct transmission mechanisms included (NB: assessment is relative to the other models).
Blue = incomplete compared to other models, or indirect mechanism.
Gray = not included.

Source: Authors.

Annex Table 4 **Drivers of nature loss and relevant mitigation policies represented in the reviewed models**

Direct drivers of biodiversity loss		GTAP-SEALS-InVEST	REMIND-MAgPIE-LPJmL	AIM/CGE and AIM/PLUM	IMAGE-MAGNET-GLOBIO	MESSAGE-GLOBIOM	GCAM
Land and sea use change	Expansion of cropland and pastureland (deforestation)	**Driver included** **Policies included:** protected areas, increase in yields to spare land, trade	**Driver included** **Policies included:** protected areas, increase in yields to spare land, trade, decrease in demand for meat – Under development: agroforestry management (in LPJmL)	**Driver included** **Policies included:** protected areas, increase in yields to spare land, trade, reduced waste in agricultural commodities, decrease in demand for meat, land restoration	**Driver included:** impacts on biodiversity (MSA) modelled in GLOBIO **Policies included:** protected areas, yield improvements, trade, subsidies, dietary shifts, REDD, payments for ecosystem services land use planning, different governance systems can be represented by adjusting exogenous scenario parameters	**Driver included** **Policies included:** protected areas, increase in yields to spare land	**Driver included** **Policies included:** protected areas, different agri management systems, decrease in demand for meat, increase in yields to spare land
	Expansion of managed forests (deforestation)	**Driver included** **Policies included:** as above	**Driver included** **Policies included:** as above plus afforestation policies	**Driver included** **Policies included:** as above	**Driver included:** impacts on biodiversity (MSA) modeled in GLOBIO **Policies included:** different wood production systems, management options, consumption shifts	**Driver included** **Policies included:** as above	**Driver included** **Policies included:** as above
	Expansion of cities	Driver not included Policies not included	**Driver partially included:** Urban land is in the model, but with exogenous expansion scenarios Policies not included	**Driver partially included:** Urban land is in the model, but no expansion endogeneous to the model Policies not included	**Driver partially included:** but only biophysical impacts modelled are disturbance effects from habitat fragmentation in GLOBIO. Urban expansion is endogenous, due to population and urban density curves Policies not included	Driver not included Policies not included	Driver not included Policies not included

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Land and sea use change	Fragmentation	**Driver not included:** No specific focus on sectors fragmenting habitat, e.g. transports (roads, rails), energy (dams), mining, etc., and no policies to limit fragmentation **Policies not included**	**Driver not included:** No specific focus on sectors fragmenting habitat, e.g. transports (roads, rails), energy (dams), mining, etc., and no policies to limit fragmentation **Policies not included**	**Driver not included:** No specific focus on sectors fragmenting habitat, e.g. transports (roads, rails), energy (dams), mining, etc., and no policies to limit fragmentation **Policies not included**	**Driver included:** impacts on biodiversity (MSA) modeled in GLOBIO **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**
	Land use intensification	**Driver partially included:** land-based intensification is a transition option to limit land expansion. Agricultural productivity increases are exogenous and adjusted in ad hoc scenarios. Impacts of intensification on biodiversity not modelled **Policies not included**	**Driver included:** intensification is modelled endogenously as land use allocation choice & as function of R&D investments. Impacts on biodiversity not modelled **Policies included:** Irrigated versus non-irrigated crop management systems, limits on CH4 and N emissions, agroforestry management option under development	**Driver partially included:** Model presents land-based intensification (crops) as a transition option – but it is not endogenous to agent behaviour. Impacts on biodiversity not modelled **Policies not included**	**Driver included:** intensification is modelled endogenously as land use allocation choice & as function of exogenous agri technical change. Impacts on biodiversity modelled through one-way connection to GLOBIO module **Policies included:** improved efficiency of nutrient use, improved irrigation efficiency, difference governance systems (ad hoc scenarios)	**Driver included:** intensification is modelled endogenously as land use allocation choice & as function of exogenous agri technical change. Impacts on biodiversity not modelled **Policies included:** nitrogen mitigation policies, water flow restrictions. Organic farming is possible in the model version for Europe	**Driver included:** intensification is modelled endogenously as land use allocation choice & as function of exogenous agri technical change. Impacts on biodiversity not modelled **Policies included:** restrictions on fertiliser uses, irrigated versus non irrigated crop management systems
	Sea use management intensification	**Driver partially included:** marine fisheries but this is limited to one aggregated fishing sector **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver partially included:** MAGNET models 6 fishery and aquaculture commodity sectors as extension of GTAP database. But these are not connected to biophysical fish stocks in IMAGE **Policies included:** production quotas	**Driver not included** **Policies not included**	**Driver partially included:** Fish is included in the food demand but its supply is not linked to a biophysical model **Policies not included**

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Land and sea use change	Land degradation	Driver not included Policies not included	**Driver included:** water-induced and human-induced changes in soil fertility (climate change). Pollinator loss and soil erosion feedbacks on land degradation currently under development **Policies included:** Under development: agroforestry management in LPJmL, limits on CH4 and N emissions	Driver not included Policies not included	**Driver included:** water-induced and human-induced changes in soil fertility **Policies included:** crop and livestock management changes, organic farming, more efficient production methods	Driver not included Policies not included	Driver not included Policies not included
Resource extraction	Rates of extraction of living materials from nature	**Driver included:** biomass crops for energy, fibre crops, forestry commodities, fishery extraction (one aggregated fishing sector) **Policies included:** protected areas, domestic/global forest carbon payment	**Driver partially included:** biomass crops for energy, forestry commodities **Policies included:** protected areas	**Driver partially included:** biomass crops for energy, forestry commodities **Policies included:** protected areas	**Driver included:** biomass crops for energy, fibre crops, forestry commodities, marine and aquaculture fishery extraction **Policies included:** production quotas (e.g. for fish), protected areas	**Driver partially included:** biomass crops for energy, forestry commodities **Policies included:** protected areas	**Driver included:** biomass crops for energy, fiber crops, forestry commodities, fishery extraction (one aggregated fishing sector) **Policies included:** protected areas, other taxes and subsidies, carbon prices
	Rates of extraction of non-living materials from nature (e.g. fossil fuels, metal, minerals)	**Driver partially included:** includes one aggregated natural resources commodity/sector – but extraction rates not explicitly modeled in relation to biophysical stocks Policies not included	**Driver partially included:** mining of coal, extraction of oil and gas are inputs to energy system module. No representation of other metals or mining **Policies included:** GHG emissions pricing, cap-and-trade, renewable energy and technology targets (focused on fossil fuels, no policies on metals and minerals extraction)	**Driver partially included:** mining of coal, iron, steel, non-ferrous products, unspecified minerals, extraction of oil and gas all included as resources or energy inputs to production function **Policies included:** GHG emissions pricing, cap-and-trade (focused on fossil fuels, no policies on metals and minerals extraction)	**Driver partially included:** extraction of surface coal, underground coal, oil, gas, uranium – in relation to available global reserves. No representation of other metals or mining **Policies included:** production quotas, protected areas, various GHG emissions reduction policies (focused on fossil fuels, no policies on metals and minerals extraction)	**Driver partially included:** mining of coal, extraction of oil and gas are inputs to energy system module. No representation of other metals or mining **Policies included:** GHG emissions pricing, cap-and-trade, renewable energy and technology targets (focused on fossil fuels, no policies on metals and minerals extraction)	**Driver partially included:** extraction of coal, oil, gas, uranium for energy module. Representation of other metals and mining is under development **Policies included:** production quotas, GHG emissions pricing, cap-and-trade (focused on fossil fuels, no policies on metals and minerals extraction)

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Resource extraction	Freshwater withdrawals	**Driver not included** **Policies not included**	**Driver included:** for withdrawals by agriculture (MAGPIE) and energy sector (REMIND) **Policies included:** Possibility to shift between irrigated and non irrigated crops. Protection policies of environmental flows.	**Driver included:** water demand from LPJmL model (exogenous) **Policies not included**	**Driver included:** water withdrawals for irrigation (LPJmL) and other sectors (household, manufacturing). Also models water availability and quality (LPJmL). Impacts on freshwater biodiversity calculated through GLOBIO-Aquatic linkage. **Policies included:** from IMAGE-LPJmL linkage – improved rainwater management, improved irrigation efficiency, increasing storage capacity and land-use related interventions	**Driver included:** water withdrawals for the energy sector (main model) and agriculture and domestic use (in water-nexus module) **Policies included:** limiting water flow requirements for ecosystem protection	**Driver included:** Water demand (withdrawals and consumption) is calculated for six major sectors: agriculture, electricity generation, industrial manufacturing, primary energy production, livestock, and municipal uses. For each sector, up to four types of water demand are represented **Policies included:** water subsidies (which can be differenciated by types of agents), and other price-based water policies such as river management. Fiscal and regulatory policies
Climate change	GHG emissions	**Driver partially included:** INVEST carbon sequestration module models climate impacts of scenarios, but only for CO_2, doesn't include emissions from agriculture & livestock **Policies included:** domestic/global forest carbon payment	**Driver included:** including CO_2, methane and others **Policies included:** various	**Driver included:** including CO_2, methane and others **Policies included:** various	**Driver included:** including CO_2, methane and others **Policies included:** various	**Driver included:** including CO_2 methane and others **Policies included:** various	**Driver included:** including CO_2, methane and others GHGs, short-lived species and aerosols **Policies included:** various
Pollution	NOx	**Driver not included** **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies included:** emissions factors can be changed in ad hoc scenarios to proxy for end-of-pipe abatement measures	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies included:** mitigation trajectories can be explored through link to GAINS model	**Driver included:** Air chemistry included in Hector, but impacts on biodiversity not explicitly modeled **Policies included:** price-based emissions constraints, emissions markets

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Pollution	SO_2	**Driver not included** **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies included:** emissions factors can be changed in ad hoc scenarios to proxy for end-of-pipe abatement measures	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies included:** mitigation trajectories can be explored through link to GAINS model	**Driver included:** Air chemistry included in Hector, but impacts on biodiversity not explicitly modeled **Policies included:** price-based emissions constraints, emissions markets
	PM2.5	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver partially included:** air pollutants from biomass combustion **Policies not included**	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies included:** emissions factors can be changed in ad hoc scenarios to proxy for end-of-pipe abatement measures	**Driver included:** but impacts on biodiversity not explicitly modeled **Policies included:** mitigation trajectories can be explored through link to GAINS model	**Driver included:** Air chemistry included in Hector, but impacts on biodiversity not explicitly modeled **Policies included:** price-based emissions constraints, emissions markets
	Mercury	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**
	Nitrogen/ nutrient runoffs	**Driver not included** **Policies not included**	**Driver included:** Nitrogen leakage in water is modelled **Policies not included**	**Driver not included** **Policies not included**	**Driver included:** N & P discharge to surface water in IMAGE. Impact on terrestrial and freshwater biodiversity modelled in GLOBIO **Policies included:** fertiliser use efficiency, production of N fixing crops, increased feed conversion efficiency, improved manure management, dietary changes	**Driver not included:** Only nitrogen emissions are calculated **Policies included:** nitrogen mitigation policies	**Driver not included:** Only nitrogen emissions are calculated **Policies included:** fertiliser use constraints
	Noise	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**	**Driver partially included:** disturbance effects from infrastructure development modeled in GLOBIO. **Policies not included**	**Driver not included** **Policies not included**	**Driver not included** **Policies not included**

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Pollution	Untreated urban and industrial wastewater	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	**Driver partially included:** urban waste water modules in the IMAGE nutrient module. But impacts on biodiversity are not modelled **Policies included:** construction of wastewater treatment plants, improved sanitation and sewerage system access	Driver not included Policies not included	Driver not included Policies not included
	Pesticides	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included
	Pharmaceutical residues	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included
	Plastics	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included **Policies partially included:** circular economy module enables modelling of recycling policies	Driver not included Policies not included	Driver not included Policies not included
	Dissolved metals	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included
	Oil spills	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included
	Salinisation	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included
	Invasive alien species	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included	Driver not included Policies not included

Green = multiple and/or direct transmission mechanisms included (NB: assessment is relative to the other models).
Blue = incomplete compared to other models, or indirect mechanism.
Gray = not included.

Source: Authors.

Annex Table 5 **– Examples of outputs from biophysical models**

Types of Biophysical Models	Examples of Outputs
Models for Biomes	• The impacts of land-use changes and deforestation on carbon assimilation and ecosystem health • The impact of changes in CO_2 levels on vegetation responses and the global carbon cycle, and the impacts of climate change on vegetation growth
Agriculture models	• The impact of environmental changes (e.g., land use, temperature, precipitation, CO_2 concentration) on vegetation dynamics and crop yields and productivity • The effects of pollution on agricultural productivity and soil fertility • The carbon sequestration rates by vegetation and soils
Water Models	• The changes in water availability, evapotranspiration rates, and runoff due to land use changes, producing global water risk maps, indicating water availability, stress indicators, and scarcity levels • The impacts of extreme events (e.g., droughts or floods) on water resources • The irrigation water requirements and intensity in different regions • The water demand by economic sectors, such as agriculture, industry, and domestic use and the associated need for water infrastructure investments like reservoirs, irrigation systems, or conservation programs
Models for Fisheries	• The impact of climate change, ocean acidification, overfishing and pollution on marine ecosystems and fish biomass • The impact of different scenarios, such as changes in fishing technology or the implementation of new fishing regulations
Biodiversity Models	• The impact of climate change and climate mitigation policies on biodiversity, especially species richness patterns • Which regions have high species richness
Model for Health	• The global excess deaths related to heat
Model for Fire	• Fire behavior and spread • The impacts of fires on vegetation and carbon stocks

Annex Table 6 **Options in the use of models, and associated trade-offs**

	Types of models	Input narrative	Output variables	Pros	Cons
OPTION 1 Quantify macroeconomic outcomes from restricted number of hazards	**Option 1.a.** **Single sector general equilibrium models linked with land-use partial equilibrium models** (REMIND- MAgPIE, MESSAGE- GLOBIOM)	Biophysical shocks/ transition policies	Macro-economic variables	Easy coupling between models, good experience of NGFS work by modelling teams Very aligned with NGFS work on climate (time horizon, macroeconomic hypothesis, etc.) Interactions of land-use policies and land-use change with climate policies and carbon sequestration Macroeconomic variables obtained	Few sectors interacting Impact from land-use policies only (cf. cons of option 2) Impact from land-use policies on macroeconomy is mediated by carbon price and bioenergy cost, so shocks in land-use modules likely to have very minor macro impacts as many transmission channels are lacking Strong dependency of macro results to GDP trajectory taken as input, preventing large macroeconomic shocks
	Option 1.b. **Multi-sector general equilibirium modles (e.g., CGE) models linked with "biophysical"or "economy-nature" models** (GTAP-InVEST, AIM/CGE, IMAGE-MAGNET)			Multiple sectors and regions interacting Macroeconomic variables obtained and sector-level variables (Theoretical) possibility to shock other sectors than land-use-related ones (i.e. agriculture and forestry), for example, tourism or chemicals-related sectors	Strong dependency of macro results to GDP trajectory taken as input High sensitivity to parameters, in particular substitution elasticities in production and utility functions (important uncertainties) More limited representation of land-use transition options than in land-use modules (cf. option 2) Few models allow to capture shocks in provision of ecosystem services, and for a restricted number of ecosystem services
	Option 1.c. **Alternative options (Input-output, IO-SFC, etc.) models linked with "biophysical"or "economy- nature" models**		Multiple sectors and regions interacting In Input-Output models: no or very little substitution between inputs by design In IO-SCF models: integration of the financial sector as an important driver of economic outcome		For input-output models: lack a dynamic aspects, mostly static analyses – may be more adapted to brutal (physical) shocks than to represent structural changes related to the transition IO-SFC models linked with nature models are in early stage of development

…/…

OPTION 2 Quantify economic and biophysical outcomes for agricultural and forestry sectors from a larger number of hazards.	**Land-use partial equilibrium models** (MAgPIE, GLOBIOM?).	Biophysical shocks/ transition policies.	Sectoral economic variables.	Transition policies related to land-use more detailed than in macro model. Links are increasingly made with biodiversity layers. Some sectoral economic variables obtained (food prices, food quantities).	Only transition aspects related to land-use are represented. Some aspects of the land-use transition are not depicted yet (e.g. agroforestry), strong focus on agriculture intensification, with no impact of fertiliser use. So far, they have not been used to explore the effect of physical shocks on food prices (but could be extended?). No macro impacts represented.
OPTION 3 Quantify biophysical consequences of a large number of hazards.	**"Biophysical"** (CWat, LPJmL, InVEST…) **or "economy- nature"** (IMAGE, GCAM) **models.**	Biophysical shocks/ transition policies.	Biophysical variables.	Numerous ecosystem services represented. Description of biophysical loops. Precise description of changes in management policies and subsequent impacts on ecosystems. Models already available with no coupling required.	No impacts on the economy.

7.4 Annexes for Chapter 4 on Using Input-Output Tables and Models to Understand the Propagation of Nature-related Hazards

7.4.1 Examples of literature using production network models (PNM) with a focus on second order effects

In order to account for the second order effects of a shock, researchers have looked at more general production functions which, for instance, allow the Domar weights to respond endogenously to shocks. Studying the second-order terms helps in understanding the non-linear impacts of a shock inherent in multi-sector models with production networks.

Baqaee and Farhi (2019) highlight the importance of second order effects in understanding the impact of shocks and show that the impact of such second order effects depends on the elasticity of substitution, amongst others. Negative shocks are amplified when sectors are complements and positive shocks are amplified if sectors are substitutes. The authors analyse a general class of economies with heterogeneous agents, arbitrary nested constant elasticity of substitution (CES) production structures, and multiple (and potentially sector-specific) factors of production. They derive a general formula describing the second-order impact on aggregate output of shocks in terms of non-parametric sufficient statistics: reduced-form general equilibrium (GE) elasticities of substitution and input–output multipliers.

Since the second order impact of a shock depends on the GE elasticity and the input-output multiplier, Hulten's first-order approximation is globally accurate if reduced-form elasticities are unitary and if the input–output multiplier is independent of the shock, which corresponds to assuming Cobb-Douglas models. Outside this special case, the Domar weights and more generally, the whole input-output matrix, respond endogenously to shocks, and the resulting non-linearities are shaped by the microeconomic details of the production structure. The intuition is that new Domar weights emerge in the economy after a productivity shock. By definition, this leads to a change in the derivative of the aggregate output production function. If the derivative changes it means that non-linearities are present.

Using a calibrated structural multi-industry model with realistic complementarities in production, Baqaee and Farhi (2019) quantify the effects of CES-induced non-linearities in production networks and show that such non-linearities amplify the effects of negative sectoral shocks while mitigating positive shocks. This is because the second-order term (second order derivative of the impact of a shock on aggregate output) is negative when sectors are complements and positive when they are substitutes. Baqaee and Farhi (2019) also discuss correlated shocks. This is particularly relevant when looking at nature-related shocks as it allows for the consideration of shocks affecting climate and nature simultaneously, two ecosystems at once or producers relying on several nature-related inputs. The authors show that the second-order effect of a common shock to two sectors is not simply the sum of the second-order impacts of the idiosyncratic shocks to each sector, and instead there are interactions between the two shocks.

In a more recent contribution, Baqaee and Rubbo (2022) reviews and synthesises some recent advances in the development of a flexible theoretical framework that can make sense of the vast amounts of the highly disaggregated microeconomic data that have become available in recent times. In particular, new datasets allow researchers to trace, at very disaggregated levels and high frequencies, the transmission, propagation, and amplification of shock and can be used to discipline disaggregated models.

Other papers have looked at factors influencing the impact of shocks in PNM. Dew-Becker (2022) describes the response of the economy to large shocks in a non-linear production network. The paper focuses on a sector's tail centrality, which quantifies the effect of a large negative shock to the sector. The paper then uses the results to analyse the determinants of total tail risk in the economy. Increases in interconnectedness in the presence of complementarity can simultaneously reduce the sensitivity of the economy to small shocks while increasing the sensitivity to large shocks.

Finally, Tintelnot et al. (2018) consider a quantitative model where domestic production networks coexist with international trade and where domestic firm-to-firm linkages can be endogenously rewired in response to international trade shocks. They find that allowing for the endogenous formation of the network in the model attenuates the costs of large negative trade shocks while amplifying the gains from trade following large positive ones.

To integrate nature shocks in a PNM, one option would be to assume that only one sector uses the natural inputs as a production factor, while all other sectors use this sector's output as an intermediate input for which they pay a price. Put differently, natural inputs do not have a price since they are not traded in the marketplace. However, they affect prices and quantities once they are sold onto another sector. When a nature-related shock occurs, the productivity of the sector that relies on the natural input experiences a negative shock. The effect of productivity shocks to the nature-reliant sector on aggregated output is thus given by the change in total output following the change in productivity in the nature-reliant sector.

Accounting for second order effects and in line with Baqaee and Farhi (2019), the impact is shaped by the structure of the production network in the economy, particularly by how all the other sectors in the economy use outputs from the nature-reliant sector as inputs to their production. This framework can easily be generalised into higher-dimensional notions of natural inputs by adding more sectors converting natural inputs into intermediate goods.

With such a framework one could show that exogenous fluctuations in ecosystem services can be a source of macroeconomic instability by rippling through supply chains and that ecosystem services loss can amplify productivity shocks to sectors.

However, it is important to note that this approach could suffer from significant limitations. As discussed above, Geerolf (2022) calls for a careful consideration over the model specification and calibration. PNM are static models and thus are not able to capture endogenous changes in elasticity of substitutions among traditional and natural inputs of production. Similarly, the literature has shown that the choice of the aggregation function largely affects the results. Moreover, given the lack of empirical evidence about the magnitude of the impact of the nature-related shocks and the substitutability of natural inputs, it should be clear that calibration of PNM models, as with any other economic model, is not straightforward.

7.4.2 Vector autoregression (VAR) and Structural vector autoregression (SVAR) models

Vector autoregression (VAR) statistical models are multivariate time series models that relate current observations of a variable with past observations of itself and past observations of other variables in the system. Structural VAR (SVAR) models impose additional constraints on a VAR to examine the causal relationships between variables. These models are used to understand the macro effects of a shock hitting the economy and how these effects evolve over time through impulse response function analysis. This might be particularly important in the case of nature-related shocks as it allows to distinguish, for instance, between permanent and transitory shocks.

A key element of SVAR models is that they impose structural restrictions to identify exogenous shocks. These restrictions are usually guided by theory and there are several possible identification strategies. SVAR models can also differ in terms of the units considered. Next to the traditional time series structure, there exist panel VAR (PVAR) models that extend the SVAR framework to panel data, where the observations are cross-sectional units observed over time. Panel VAR models allow for interdependencies and dynamic interactions between the variables across different units, providing a more comprehensive analysis of the data. Moreover, global VAR (GVAR) models can be used to look at effects in different countries. A GVAR model is a variation of the traditional SVAR model that incorporates international or global interdependencies among economic variables. It allows for the analysis of spillover effects and transmission channels across different countries or regions.

Next to the identification strategy, the estimation choice can play an important role in the evaluation of the impact of shocks. SVAR can be estimated both with frequentist and Bayesian techniques, where the second one allows to incorporate prior information about the relationship among the variables.

SVAR models have largely been used to investigate the impact of monetary policy shocks (Arias et al., 2019; Blanchard & Quah, 1989; Christiano et al., 1999; Gertler & Karadi, 2015; Jarocinski & Karadi, 2020; Sims, 1980;; Uhlig, 2005;) and financial indicators/uncertainty (Alessandri & Mumtaz, 2017; Bloom, 2009; Born et al., 2020; Ozdagli and Weber, 2017) on the real economy.

More recently, the literature has increasingly investigated the impact of different shocks on the macroeconomy using VAR models, including weather (Kim et al., 2022) and supply chain (Finck & Tillmann, 2022) shocks. Kim et al. (2022) provide an example by using a smooth transition VAR to capture the time-varying effects of weather shocks on the U.S. macroeconomy over the past sixty years. The findings suggest limited adaptation to increased severe weather in the U.S., at least at the macroeconomic level. To assess the economic significance of their estimates, they use the VAR model to compute variance decompositions. The impact of the weather shock is economically significant, in particular at the end of the sample. Finck and Tillmann (2022) introduce sign and narrative restrictions to identify the macroeconomic impact of specific supply chain disruption episodes for the euro area. They find that global supply chain shocks are a main driver of real economic activity and prices. An adverse supply chain disruption causes a drop in industrial production and increased consumer prices. A similar approach can be used to quantify the contribution to changes in macroeconomic variables of nature-related shocks.

SVAR models have also been used to analyse shocks to transition risk. In order to identify shocks to transition risk, Meinerding et al. (2023) use a coexceedance approach, which captures periods in which portfolio returns and climate related news index cross thresholds defined by the authors. These periods are used to identify the shocks. The authors then show the impact of transition risk shock on macro-financial variables using a BVAR. Meanwhile, Kanzig (2023) constructs a series of carbon policy surprises and use an external instrument SVAR to show that a tighter carbon pricing regime leads to higher energy prices.

Finally, SVAR models can be used to develop structural scenarios (Antolin-Diaz et al., 2021; Boer et al., 2021). A structural scenario is defined by combining restrictions on the path of future observables with a restriction that only a subset of the future shocks –the driving shocks– can deviate from their unconditional distribution over the forecasting horizon.

SVAR models could be adjusted in the following ways to study nature-related shocks: (i) nature- related time series could be introduced into the standard framework; (ii) nature-related identifying restrictions would then be imposed, and; (iii) the contribution of the shock to the observed variability could be studied.

However, it is important to keep in mind that using SVAR would fail to address many of the challenges related to identifying nature-related financial risks, as largely discussed throughout this Technical Document (see Chapter 2).

7.4.3 Assessing macrofinancial consequences of nature-related hazards through input-output analysis

Magacho et al. (2023)[55] have developed a methodology for analysing countries' dependence on key industries exposed to specific hazards (in our specific case nature related hazards), taking into account not only the direct impact of the hazard but also their productive interrelationship. It is possible to identify the countries most exposed in various dimensions (external, fiscal and socio-economic), due to the relative importance of their exposed industries. It is also possible to analyse which countries are most vulnerable in terms of their ability to switch from exposed industries to those considered resilient.

Following Miller and Blair (2009)[56], in order to obtain upstream indirect exposure, it is necessary to consider not only natural capital embodied in direct inputs, but also natural capital embodied in all inputs necessary to produce these direct inputs. One needs to obtain the Multiregional Leontief[57] matrix by considering that total production by industry and country. This is given by the summation of the column vector of intermediate inputs and the column-vector of final demand. The intermediate inputs are given by the multiplication of the technical coefficient matrix and the column-vector of total production.

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[55] Magacho, G., Espagne, E., Godin, A., Mantes, A., & Yilmaz, D. (2023). Macroeconomic exposure of developing economies to low-carbon transition. World Development, 167, 106231.

[56] Miller, R. E., & Blair, P. D. (2009). Input-output analysis: foundations and extensions. Cambridge university press.

[57] Leontief, W. W. (1936). Quantitative input and output relations in the economic systems of the United States. The review of economic statistics, 105-125.

To identify the downstream (or forward) exposure, i.e., those arising from the use of the goods and services produced by the industries under consideration, it is necessary to use the Ghosh (1958)[58] supply-side model, rather than the Leontief one mentioned above. The Ghosh model allows to identify by which industries an input is being used from the moment it is produced until its final use. Accounting for downstream exposure is therefore identifying the total nature indirectly associated with this input after its production.

Three different dimensions are considered in the analysis: external, fiscal and socio-economic. To assess external exposure, the net foreign currency income induced by exposed industries (exports adjusted for direct and indirect imported inputs used in production) is obtained as follows:

$$nx_{i,j} = ex_{i,j} \left(1 - im_{i,j}\right) \tag{1}$$

where nx_i is the net foreign currency income of industry *i* for country *j*, $ex_{i,j}$ represents exports from industry *i* to country *j*, and $im_{i,j}$ all (direct and indirect[61]) imported inputs necessary to the production of industry *i* in country *j*.

Exports are obtained directly from the input-output table, while imported embodied inputs are obtained as follows:

$$im = \imath^{\mathrm{T}} \left[A^{\mathrm{M}} \left(I - A\right)^{-1}\right] \tag{2}$$

with im the total vector of imported inputs, $\imath$ column vector of 1 ($\imath$ indicates the transpose), A is the multi-regional input-output matrix, and A^{M} is the same matrix with all domestic elements set to zero.

To estimate fiscal and socio-economic dependencies, the total output per sector that is directly and indirectly linked to exposed industries is estimated, then, on the basis of taxation, wages and employment per sector, the share of each of these variables linked to declining industries is deducted.

Firstly, total production unrelated to declining industries is as follows:

$$x_n = \left(I - A_n\right) y_n \tag{3}$$

with x_n total production in non-exposed industries, A_n is the multi-regional input-output matrix with all rows corresponding to exposed industries set to zero, and y_n is the final demand vector with all rows corresponding to exposed industries set to zero.

The share of variable k that is related to declining industries is written as follows:

$$s_k = 1 - \left(x_n^{\mathrm{T}} k\right) / \left(x^{\mathrm{T}} k\right) \tag{4}$$

7.4.4 Description of Input-Output Models

The basic structure of a MRIO model is composed of five main blocks of information concerning industries' intermediate consumption, value added by production, final demand, total output and additional information in the format of satellite accounts. Industries' intermediate consumption is represented by a squared matrix containing information at sectoral level of each country/region. If read vertically, each column displays which inputs a sector employs in its production process. Other factors that also contribute to the final value of the produced good, such as wages, taxes and consumption of fixed capital, are seen in the value added matrix, which is positioned under the intermediate consumption matrix. If read horizontally, each row shows which sectors purchase the output of a specific sector. What is not bought by other sectors is consumed directly by households, government or becomes investment; these values are displayed in the final demand matrix that is positioned on the right of the intermediate consumption matrix. Both the final demand and value added information can also be aggregated into a column vector and a row vector, respectively.

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[58] Includes direct inputs into the production process and all inputs required to produce these inputs (indirect).

A vector of total output can be calculated in two ways. By adding the columns of the intermediate consumption and value added matrices together, it is possible to obtain a vector of total inputs that displays total production value of each sector calculated from inputs. When all of its values are summed it represents the total output of the economy from a "supply-side perspective". Alternatively, if all the rows of the intermediate consumption and final demand matrices are added together, we can find the total output of the economy from a "demand-side perspective".

The additional information available in the satellite accounts is also organised in a matrix format which contains the same number of columns of the intermediate consumption matrix. The content of this matrix varies from MRIO table to MRIO table, but in general it displays information about employment and environmental footprints at the industry level.

In general, MRIO tables are able to produce a snapshot of the global economy, describing a static image of its organisation at sectoral level that comprises the global networks of production (forward and backward linkages) and consumption. As such, MRIO models can provide critical information for policy design about indirect cascading effects caused by a materialised physical or transitional nature-related financial risk in a specific sector, as well as the macroeconomic impacts of this materialised risk in terms of employment and GDP losses.

Each MRIO table can display different information at different levels of granularity. Consequently, there is no single "best MRIO table" available. The choice of which MRIO table should be employed depends on the goals of each analysis. Some of the MRIO tables available are described in **Table 4.1** in the main text.

7.4.5 Annex for Case study on physical risks: Assessing the direct and indirect impacts of a potential drought in France

Scenario Details and VaR Calculation

This annex presents a detailed overview of data and the step-by-step procedure to replicate the first case study of a severe drought affecting the French economy. Below, in **Annex Table 7** the direct shock in output loss calculated with the INCAF-OXFORD is presented in a disaggregated format for all the 163 sectors of EXIOBASE 3. The impact in both affected ecosystem services of "Dilution by atmosphere and ecosystems" and "Surface water" is separated.

Annex Table 7 – **Scenario Details and VaR Calculation**

	Dilution by atmosphere and ecosystems (M.EUR)	Surface water (M.EUR)
Cultivation of paddy rice	2.50308529	6.46630367
Cultivation of wheat	534.765877	1381.47851
Cultivation of cereal grains nec	450.22049	1163.0696
Cultivation of vegetables, fruit, nuts	1669.97931	4314.11323
Cultivation of oil seeds	233.6538	603.60565
Cultivation of sugar cane, sugar beet	72.5715857	187.476596
Cultivation of plant-based fibers	18.1462422	46.8777925
Cultivation of crops nec	362.706041	936.990605
Cattle farming	290.679769	1251.5379
Pigs farming	118.553629	510.439237
Poultry farming	241.747014	1040.8552
Meat animals nec	118.136306	508.642429
Animal products nec	8.02609377	34.5567926
Raw milk	385.539331	1659.96101
Wool, silk-worm cocoons	0,42308027	1,82159561
Manure treatment (conventional), storage and land application	0	0
Manure treatment (biogas), storage and land application	0	0
Forestry, logging and related service activities (02)	0	1074,53523
Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)	73,2812559	328,137179
Mining of coal and lignite; extraction of peat (10)	0	98,761864
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	0	57,4893635
Extraction of natural gas and services related to natural gas extraction, excluding surveying	0	24,9430836
Extraction, liquefaction, and regasification of other petroleum and gaseous materials	0	0
Mining of uranium and thorium ores (12)	0	0
Mining of iron ores	0	0
Mining of copper ores and concentrates	0	0
Mining of nickel ores and concentrates	0	0
Mining of aluminium ores and concentrates	0	8,55959702
Mining of precious metal ores and concentrates	0	0
Mining of lead, zinc and tin ores and concentrates	0	0
Mining of other non-ferrous metal ores and concentrates	0	0,88333742
Quarrying of stone	0	1372,45931
Quarrying of sand and clay	0	707,64835
Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	0	246,853105
Processing of meat cattle	716,806625	3086,25075
Processing of meat pigs	414,950953	1786,59438
Processing of meat poultry	655,085153	2820,50552
Production of meat products nec	1203,92801	5183,57891
Processing vegetable oils and fats	116,492053	501,563007
Processing of dairy products	1658,07815	7138,94759
Processed rice	13,3643898	57,5411227
Sugar refining	317,636218	1367,60039

Processing of Food products nec	3780,61339	16277,641
Manufacture of beverages	1240,68074	5341,81986
Manufacture of fish products	354,402755	1525,90075
Manufacture of tobacco products (16)	0	468,369259
Manufacture of textiles (17)	519,898557	2238,45212
Manufacture of wearing apparel; dressing and dyeing of fur (18)	328,368369	1413,80825
Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)	243,962351	0
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)	0	3044,14655
Re-processing of secondary wood material into new wood material	0	0
Pulp	0	0
Re-processing of secondary paper into new pulp	0	0
Paper	191,353054	823,881205
Publishing, printing and reproduction of recorded media (22)	0	0
Manufacture of coke oven products	0	16,8020647
Petroleum Refinery	0	3586,79538
Processing of nuclear fuel	0	0
Plastics, basic	0	0
Re-processing of secondary plastic into new plastic	0	0
N-fertiliser	3,26408034	5,6214717
P- and other fertiliser	22,9194102	39,4723176
Chemicals nec	89,005063	1226,29198
Manufacture of rubber and plastic products (25)	2859,03466	9847,78604
Manufacture of glass and glass products	0	503,843821
Re-processing of secondary glass into new glass	0	0
Manufacture of ceramic goods	0	0
Manufacture of bricks, tiles and construction products, in baked clay	174,7163	752,250734
Manufacture of cement, lime and plaster	1215,47049	5233,27573
Re-processing of ash into clinker	0	0
Manufacture of other non-metallic mineral products n.e.c.	252,149004	1085,64155
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	0	3599,06634
Re-processing of secondary steel into new steel	0	0
Precious metals production	24,801572	64,0707276
Re-processing of secondary precious metals into new precious metals	0	0
Aluminium production	0	634,396815
Re-processing of secondary aluminium into new aluminium	0	0
Lead, zinc and tin production	14,2678827	36,8586969
Re-processing of secondary lead into new lead, zinc and tin	0	0
Copper production	482,876126	1247,42999
Re-processing of secondary copper into new copper	0	0
Other non-ferrous metal production	31,5248699	81,4392472
Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	0	0
Casting of metals	700,458658	1809,5182
Manufacture of fabricated metal products, except machinery and equipment (28)	5094,21166	13160,0468
Manufacture of machinery and equipment n.e.c. (29)	5459,63552	14104,0584

Manufacture of office machinery and computers (30)	153,753784	397,197274
Manufacture of electrical machinery and apparatus n.e.c. (31)	1057,57173	2732,06031
Manufacture of radio, television and communication equipment and apparatus (32)	1924,15729	4970,73967
Manufacture of medical, precision and optical instruments, watches and clocks (33)	0	8747,93621
Manufacture of motor vehicles, trailers and semi-trailers (34)	8441,45905	21807,1025
Manufacture of other transport equipment (35)	1241,45488	6414,18353
Manufacture of furniture; manufacturing n.e.c. (36)	1802,13059	4655,50403
Recycling of waste and scrap	0	0
Recycling of bottles by direct reuse	0	0
Production of electricity by coal	0	839,891744
Production of electricity by gas	0	2088,41105
Production of electricity by nuclear	0	11428,0099
Production of electricity by hydro	0	1338,11044
Production of electricity by wind	0	0
Production of electricity by petroleum and other oil derivatives	0	391,221339
Production of electricity by biomass and waste	0	225,478129
Production of electricity by solar photovoltaic	0	2,15948514
Production of electricity by solar thermal	0	0
Production of electricity by tide, wave, ocean	0	31,8482445
Production of electricity by Geothermal	0	0
Production of electricity nec	0	75,8177602
Transmission of electricity	0	0
Distribution and trade of electricity	0	0
Manufacture of gas; distribution of gaseous fuels through mains	138,191347	594,99052
Steam and hot water supply	0	2266,59271
Collection, purification and distribution of water (41)	0	5520,06841
Construction (45)	0	7832,59627
Re-processing of secondary construction material into aggregates	0	0
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts and accessories	0	0
Retail sale of automotive fuel	0	0
Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)	0	0
Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)	0	0
Hotels and restaurants (55)	0	10038,7591
Transport via railways	0	8824,22047
Other land transport	1567,99458	8101,30534
Transport via pipelines	0	0
Sea and coastal water transport	0	2518,55596
Inland water transport	0	207,550375
Air transport (62)	0	1630,44267
Supporting and auxiliary transport activities; activities of travel agencies (63)	0	7434,34041
Post and telecommunications (64)	0	0
Financial intermediation, except insurance and pension funding (65)	0	0
Insurance and pension funding, except compulsory social security (66)	0	0
Activities auxiliary to financial intermediation (67)	0	0

Real estate activities (70)	0	78498,1546
Renting of machinery and equipment without operator and of personal and household goods (71)	0	0
Computer and related activities (72)	0	0
Research and development (73)	0	0
Other business activities (74)	0	0
Public administration and defence; compulsory social security (75)	0	0
Education (80)	0	0
Health and social work (85)	1263,62388	15233,6878
Incineration of waste: Food	0	181,658386
Incineration of waste: Paper	0	189,527449
Incineration of waste: Plastic	0	78,7617973
Incineration of waste: Metals and Inert materials	0	225,146122
Incineration of waste: Textiles	0	42,0700382
Incineration of waste: Wood	0	56,345201
Incineration of waste: Oil/Hazardous waste	0	215,749561
Biogasification of food waste, incl. land application	0	20,6278676
Biogasification of paper, incl. land application	0	2,36527033
Biogasification of sewage slugde, incl. land application	0	183,615172
Composting of food waste, incl. land application	0	116,038585
Composting of paper and wood, incl. land application	0	1,06639713
Waste water treatment, food	0	327,535893
Waste water treatment, other	0	573,594436
Landfill of waste: Food	0	112,204107
Landfill of waste: Paper	0	78,5996014
Landfill of waste: Plastic	0	24,0113268
Landfill of waste: Inert/metal/hazardous	0	312,67698
Landfill of waste: Textiles	0	15,8781031
Landfill of waste: Wood	0	47,7902733
Activities of membership organisation n.e.c. (91)	0	0
Recreational, cultural and sporting activities (92)	0	27427,4533
Other service activities (93)	150,712867	1038,2442
Private households with employed persons (95)	0	0
Extra-territorial organizations and bodies	0	0

Source: Authors.

The reduction in total output generated by the reduction in both ecosystem services is then aggregated for each sector. In other words, the values of columns 2 and 3 are summed. The result is a column vector (u) of 163 rows that indicate the total direct output loss per sector caused by the drought. If all the 163 values are summed, we obtain the total direct output loss.

The VaR (value-at-risk) for each sector can be calculated by dividing this column vector by a column vector of total output of the French economy. This vector can be obtained from EXIOBASE 3 as a subset of the total output vector for the year of 2022. Sectors are aggregated into larger sectors such as "agriculture" and "manufacturing".

The Leontief-Inverse and the Ghosh-Inverse Matrices for Backward and Forward Linkages Analysis

To obtain the total requirements matrix (Leontief-Inverse), that was employed for the backward linkages analysis, some parts of the EXIOBASE 3 MRIO table need to be manipulated. In particular, the (*Z*) matrix of intermediate consumption, the (*f*) column vector of final demand, and the (*x*) column vector of total output, are all required.

The first step is to obtain the (*A*) matrix of technical coefficients, which can be calculated by multiplying the intermediate consumption matrix (*Z*) by the inverse of the diagonalized output vector (*x*). The technical coefficients of production represent the quantity of direct inputs from other sectors needed to produce one unit of final product in the analyzed sector.

$$A = Z\hat{x}^{-1} \tag{1}$$

The (*L*) total requirements matrix (Leontief-Inverse) can be obtained from the relationship between total output, final demand, and technical coefficients of production:

$$x = (I - A)^{-1}f \tag{2}$$
$$L = (I - A)^{-1} \tag{3}$$

When read vertically, each coefficient of this matrix (*L*) represents the total output of a sector *i* that is needed by a sector *j* to produce one unit of final demand. In other words, the coefficients account for the direct and indirect inputs needed by a sector *j* to produce its final output.

While the total requirements matrix looks upstream in the production chain, the output inverse matrix (Ghosh-Inverse) can be employed to assess the downstream segment of the production chain. To obtain it, one should first calculate the (*B*) matrix of allocative coefficients by pre-multiplying the inverse of the diagonalized output vector (*x*) by the *Z* matrix:

$$B = \hat{x}^{-1}Z \tag{4}$$

The (*G*) output inverse matrix is found through the relationship between total output, allocative coefficients, and the value-added vector (*v*):

$$x' = v(I - B)^{-1} \tag{5}$$
$$G = (I - B)^{-1} \tag{6}$$

When read horizontally, each value in the *G* matrix indicates how important a sector is in providing direct and indirect inputs to other sectors of the economy.

Estimating the upstream impacts with MRIO Modelling

To calculate the upstream indirect impacts in the economy, consequential of a reduction in demand from the directly impacted sectors, we employ a Leontief Multi-Regional Input-Output Model. Based on Leontief's original works (Leontief, 1991 [1928], 1970; Leontief & Strout, 1963), this model works based on two main assumptions: (1) all sectors operate at constant returns of scale and (2) factors of production are complementary and not substitutable among each other. Although the second assumption may seem excessively restrictive at a first glance, it seems plausible to assume that sectors would not easily find substitutable inputs in the short-run, which makes this model ideal for short-run exposure and impact analysis.

The model is based on Equation 2 presented before. By combining it with equation 3 for simplification and taking the L matrix as fixed due to assumption number 2 we obtain:

$$\Delta x = L.\Delta f \tag{7}$$

With Equation 7 it is possible to calculate the upstream impacts of the severe drought impact in terms of total output loss. For this, the Δx component is replaced by the column vector (*u*) of total direct output loss. The result of this operation is a vector (*k*) of total output loss for each sector of the economy:

$$k = L.u \tag{8}$$

The sum of all values in k results in the value of 871.4 billion EUR total output loss presented in the case study. To isolate the indirect effects, one can subtract vector *k* by vector *u*. It is also possible to isolate the rows in vector *k* corresponding to the French sectors and get the impact in each sector or calculate the aggregated direct and indirect impact in output in France.

Assessing downstream exposure with MRIO modelling

Differently of upstream effects, downstream effects are not so predictable. The indirect effects take the form of supply constraints for the different sectors positioned downstream. Firstly, it is not possible to know beforehand how each sector would "pass the shock" forward. For instance, imagine a French sector k that supplies other 15 sectors directly. If this sector k receives a direct shock that results in a reduction of 10 M.EUR of output, how will this shock be divided among the downstream sectors? It is possible that all 15 sectors split the burden equally together with each one facing a reduction of 0.66 M.EUR of supply from sector k. But it is also possible that sector k decides to keep the same level of supply for 5 sectors and split the 10 M.EUR shock into 1 M.EUR reductions in supply for the other 10 sectors.

Secondly, all the sectors that will face a supply reduction could begin to import its supply from a foreign similar sector. Companies usually don't operate at 100% capacity and could raise their capacity in the short-run to provide at least part of the missing supplies to the exposed sectors. Moreover, in face of such a severe physical hazard, supply allocation decisions might be defined by governments in the short-run, favoring basic-needs goods, for example. Considering all these factors, the analysis of the downstream effects focuses on exposure rather than on output reduction.

The exercise to assess EU's final demand exposure to the French drought affected sectors employs the same Equation 7. The final demand (*f*) vector is altered so the original values for all EU sectors are kept the same and zeroes are applied to all other sectors. When plugged into Equation 7, the altered final demand vector (f_{EU}) allows us to analyze the quantity different sectors are directly and indirectly supplying EU's final demand.

$$x' = L.f_{EU} \qquad (9)$$

The results displayed in the case study can be obtained by isolating and aggregating the French sectors in the new x' vector.

The approach to evaluate sectoral exposure employed in the case study requires some manipulation of the (A) matrix of technical coefficients. First, the 111 impacted sectors were aggregated in the same way as at the beginning of the exercise, subsequently the aggregated agriculture sector was taken as an example. We will refer here to this group of agriculture sectors with the subscript "agg".

The sectoral approach presented focuses on the sectors downstream that are immediately ahead of the directly shocked sectors. For each sector in EXIOBASE 3 we look at its column in the (A) matrix of technical coefficients. The total sum of the sector's column represents the total direct inputs from other sectors that it needs to produce its output. The objective is to identify how much does the aggregated agriculture sectors represent in relation to the total direct inputs which each sector requires from other sectors. The formula for this operation is presented below:

$$\frac{a^{i,agg}}{\sum_{j=1}^{7987} a^{i,j}} = \text{Share of the aggregated targeted sector as direct inputs of sector i} \qquad (11)$$

The variable $a^{i,agg}$ is calculated by adding the values in each column that represent the agriculture sectors. The values in the resulting vector were transformed in percentage value to be presented in the case study.

7.4.6 Annex for Case study on transition risks: Assessing the potential impacts and exposure of an EU transition policy to ban Brazilian non-deforestation-free products

Scenario Details

This annex presents a detailed overview of the data and step-by-step procedure to replicate the second case study: the introduction of an EU policy to ban the consumption of non-deforestation-free products produced in Brazil. This annex is shorter than the first since parts of the methodology which are identical for both case studies are not repeated here. In this case study assumes a hypothetical 15% reduction in European Union imports for all Brazilian Forestry, Agriculture, Livestock, and Mining sectors.

The shock is composed of two parts. The first one is a reduction of 15% of the final demand for Brazilian Forestry, Agriculture, Livestock, and Mining sectors consumed in the EU. For this, EU's final demand for targeted Brazilian sectors is reduced by 15% in the original final demand vector in EXIOBASE 3. The second part is a reduction of 15% of EU's interindustry consumption from the Brazilian targeted sectors. This can be done by selecting the columns of all EU industries in the (*Z*) matrix of intermediate consumption and reducing by 15% the inputs coming from the Brazilian targeted sectors (select the rows of these targeted sectors).

Both parts of the shock are added to form a column vector (u) of total direct output loss per sector. In this vector, only the rows corresponding to the Brazilian targeted sectors will display values, while the remaining rows will be zeroed.

Estimating the upstream impacts with MRIO Modelling

Again, the indirect effects are analysed by looking separately at both the upstream and downstream effects. To estimate upstream effects the total requirements matrix (L) and Equation 7 are employed again. A similar Leontief Multi-Regional Input-Output Model is used and the hypothesis behind the model are the same. More details on how to obtain the L matrix and Equation 7, and on Leontief MRIO models and their hypothesis are found on Annex I. Equation 7 is reproduced below:

$$\Delta x = L.\Delta f \qquad (7)$$

With Equation 7 it is possible to calculate the upstream impacts of the EU policy in terms of total output loss. For this, Δf the component is replaced by the column vector (u) of total direct output loss. The result of this operation is a vector (k) of total output loss for each sector of the economy:

$$k = L.u \qquad (8)$$

The sum of all values in k results in the value of total output loss. To isolate the indirect effects, one can subtract vector k by vector u. It is also possible to isolate the rows in vector k corresponding to the Brazilian sectors and get the impact in each sector or find the aggregated direct and indirect impact in output in Brazil of 1.6 billion EUR. The results on the impact in other Latin American and EU sectors, are also obtained by isolating the rows in vector k that correspond to the sectors of those respective regions.

Building the Sankey plot

The Sankey plot displayed in the case study was built using data from the (Z) matrix of intermediate consumption. The columns corresponding to the Brazilian targeted sectors are aggregated and the values of the rows represent the amount of supply provided by each sector of the economy. R codes for building Sankey plots can be found here.

Estimating downstream indirect exposure

In this study, the downstream indirect effects only spread through the EU import channel. For instance, the effects of the policy are not expected to spread through downstream Brazilian sectors, as the policy only targets imports made by the EU. Following the arguments presented in Annex I, the analysis of the downstream effects focuses on exposure rather than on output reduction.

The data presented in the case study is found on the (Z) matrix of intermediate consumption and the (f) column vector of final demand. The values can be presented at sectoral or aggregated level.

To assess EU's final demand exposure to the Brazilian targeted sectors, we use the same technique employed in the first case study. In fact, even the same altered final demand vector (f_{EU}) is used, as the exposure analysis is also focused on EU's final demand exposure. When plugged into Equation 7, the altered final demand vector (f_{EU}) allows us to analyze the quantity different sectors are directly and indirectly supplying EU's final demand:

$$x' = L.f_{EU} \qquad (9)$$

The results displayed in the case study can be obtained by isolating and aggregating the Brazilian targeted sectors in the new x' vector. The total indirect EU final demand consumption can also be calculated by subtracting the total value in the x' vector by the total value of inputs imported for direct consumption by EU's final demand.

The analysis of the sectoral exposure for European sectors also follows the same steps carried out in the first case study. The rows representing the Brazilian targeted sectors are aggregated in the (A) matrix of technical coefficients. We refer to this aggregation of sectors with the subscript "tgt". For each sector in EXIOBASE 3 we look at its column in the (A) matrix of technical coefficients. The total sum of the sector's column represents the total direct inputs from other sectors required to produce its output. The objective is to identify the proportion agricultural sectors represent in comparison to the total direct inputs, from other sectors, required by each sector. The formula for this operation is the same presented in Annex I and is reproduced below again:

$$\frac{a^{i,agg}}{\Sigma_{j=1}^{7987} a^{i,j}} = \text{Share of the aggregated targeted sector as direct inputs of sector i} \qquad (11)$$

The variable $a^{i,agg}$ is calculated by adding the values in each column that represent the Brazilian targeted sectors. The values in the resulting vector were transformed in percentage value for the presentation in the case study.

7.4.7 The E3ME Model (Integrating FTT AND Multi-Regional Dynamic Model)

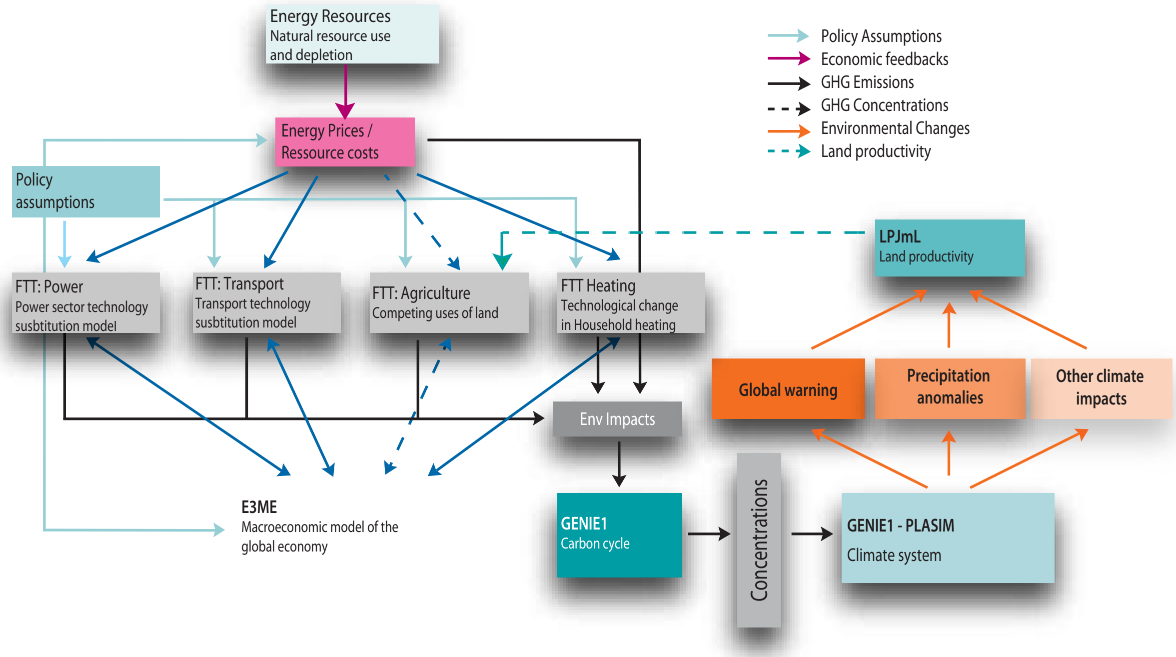
Overview

E3ME-FTT-GENIE is an integrated energy-technology-economy-climate simulation model used to assess the impacts of various types of policies, for various types of stakeholders including governments (EU Commission, national governments). The model specialises in, but is not exclusively used for, environmental, energy and climate policy, as well as labor markets. The model joins up an analysis of detailed technology diffusion dynamics for carbon-intensive sectors in FTT (Future Technology Transformations) with detailed and highly disaggregated macroeconomics in E3ME (Energy-Economy-Environment MacroEconometric model), and a fully-fledged climate and carbon cycle simulation of intermediate complexity in GENIE (Grid Enabled Integrated Earth system model). Of interest here are E3ME and FTT and the underlying detailed global energy system model. For a complete description of the model equations and dynamics, we refer the reader to Mercure et al. (2018a), including for a description of the climate simulation integration, which we omit here.

Macroeconomic evolution in E3ME

E3ME is a demand-driven macroeconometric model, based on a standard social accounting matrix with input-output relationships, bilateral trade relationships, and econometric equations describing the economic behavior of agents parameterised on time series from 1970 to the present. The model is disaggregated into 70 regions (including all G20 nations) and 43 (70) sectors of industry, for countries outside of the EU (inside of the EU). Econometric relationships are used to project the evolution of econometric variables up to 2070.[59]

Figure 7.1 **Components of E3ME-FTT-GENIE and their interactions**



Source: http://www.E3ME.com.

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[59] The model manual (Cambridge Econometrics, 2022) is available online. A detailed list of all equations in E3ME is given in Mercure et al. (2018a).

The model is demand-driven, which means that it does not operate on the basis of production functions nor utility optimisation. The model does not assume full employment of labor, physical and financial capital, but instead, assumes the existence of levels of resource use below full capacity (measured as unemployment and the output gap).

In contrast to standard general equilibrium models, the consumption of agents by product type is first determined econometrically on the basis of prices, disposable income, population, and patterns of expenditure. The input-output relationships are then used to determine final and intermediate production as well as the demand for investment goods. Investment is determined econometrically on the basis of past economic activity, prices of capital assets and levels of capacity use. Employment and hours worked is determined on the basis of economic activity. Imports and exports are determined on the basis of price differentials between domestic and foreign goods by sector.

Innovation is represented across the model through technology progress factors determined on the basis of cumulated past investment by sector. These indicators are integrated through various econometric equations, in particular domestic and export prices. The accumulation of capital in every sector is assumed to lead to production cost reductions, where the regression parameter is related to an effective sector-wide rate of learning-by-doing. Resulting price reductions determine the relative competitiveness of every sector-region.

GDP is calculated on the basis of the sum of value added across the economy, where intermediate and final production in every sector is endogenously determined from levels of consumption. However, for consistency with other models, sectoral output is calibrated in the baseline scenario to match OECD and national economic projections.

Energy sector module in E3ME

Particular focus is adopted in E3ME towards estimating energy demand in physical units, by type of energy carrier, for all sectors and types of fuel users, on the basis of energy balance time series from the International Energy Agency. The final demand for energy carriers is determined for 22 types of final energy users (including industrial users, transport and non-energy types of use) for 12 types of fuels (incl. oil, coal, gas, electricity, biofuels). This allows to accurately estimate greenhouse gas emissions in all scenarios. Econometric estimations of energy use are made on the basis of sectoral economic activity and substitution between sectors.

Technology diffusion in FTT

While the above approach for modeling total energy demand by energy carrier is comprehensive, which ensures matching known greenhouse emission levels, the use of elasticities of substitution is less than accurate for fuel users in which technological change is the major driver of substitution. Instead, it is well known that an approach involving technological diffusion processes is much more satisfactory and allows to reproduce observed data. Furthermore, for technological changes, while price differentials incentivise substitutions of technologies across fuels, the use of fuel is not just simply related to price differentials but depends on a complex process of technology adoption by agents and the survival of technological stocks and fleets.

The FTT model was created to represent the technological diffusion process in detail, on the basis of individual technologies currently available on the market, currently for power generation (Mercure et al., 2014), road transport (Lam & Mercure, 2021), heat (Knobloch et al., 2019) in buildings and steelmaking. This includes for example coal plants and solar panels for power generation, petrol and electric vehicles for road transport, gas boilers and heat pumps for household heating and so on. A current total of 88 technologies are represented (24 in power generation, 30 in road transport, 10 in household heating, 24 routes in steelmaking).

The model is a vintage capital model that essentially represents fleets of technological items that agents purchase or invest in, each of which age and depreciate over time, with a turnover determined by technology-specific survival functions (or rates of life expectancy). For instance, cars survive on average for 11 years while coal plants survive for 40 years. This suggests that over 25 years, the vehicle fleet turns over entirely, while technological change is slower in power generation.

Technological choice is represented on the basis of heterogeneous agents making comparisons between available technologies. The explicit assumption is made that the availability of technologies to agents is proportional to their prevalence in markets (the proportion of agents having access to technology A is proportional to the market share of that technology in markets). It is well known in sociology that agent investment or purchasing decisions are strongly determined by visual influence. This visual or peer influence effect is a way that agents have to reduce uncertainty when facing decisions to adopt new practices, and leads to the widely observed S-shaped profile of technological diffusion (Rogers 2010). Rates of technological uptake in FTT are calibrated against historically observed diffusion rates, ensuring consistency between history and projections.

The agent choice representation in FTT involves a comparison of a relevant levelised cost metric for each market (e.g., $/MWh in power generation, $ per km driven in road transport). Each technology is characterised by its particular learning-by-doing rate, which drives its cost down with cumulative investment. However, exogenous policies also influence rates of technological uptake, including technology-specific subsidies, the carbon price/tax, other taxes, bans and regulations as well as public/private procurement/investment.

Fuel use is determined on the basis of technological compositions in each FTT sector. E3ME supplies FTT with total demand by FTT sector (power, transport, heat and steelmaking currently), and in return, FTT supplies E3ME with prices, investment, fuel use by fuel type and public income or expenditure through policy initiatives.

The power model however does not model in detail the structure of electricity markets. The model has a representation of electricity storage, capacity factors, load bands and output allocation between different producing technologies according to auction by the network regulator. However, we have not carried out systematic studies of the different possible market clearing rules that could conceivably be adopted by regulators in different countries. We assume that electricity prices approximately reflect average costs of electricity production across the technology fleet in each country.

Fossil fuel asset module

Economic activity in fossil fuel production is strongly dependent on regional competitiveness in those sectors. This level of competitiveness is not straightforward to determine accurately from national accounts data. It is more effectively determined by using data on fossil fuel production by region. The model uses a detailed database of stocks of fossil fuels by region specified as distributed along a production cost variable. For oil and gas, this was determined using the Rystad database, which documents over 40,000 oil and gas assets worldwide. Coal reserves are determined similarly but given the ubiquity of coal resources worldwide at low extraction costs, the model uses less detailed data collected from various sources.

Rystad provides 2P reserves and resources for each asset along with a breakeven cost value. The model assumes that each asset produces if and only if it is profitable at each time period (this may or may not always be accurate, as stopping production when it is unprofitable poses challenges in some contexts). The model uses the Rystad data to determine which asset produces and which asset is idle according to the price of oil and gas, and thus searches through the database to determine the prices of oil and gas that clear the demand each simulated year. This means that for instance, in scenarios of peaking and declining oil demand, some oil wells stop production and become stranded where the breakeven cost is high (e.g., tar sands in Canada), while others remain in production until they are depleted where the breakeven cost is low (e.g., conventional oil in OPEC countries).

This calculation makes it possible to determine in detail production profiles for each E3ME country in each scenario, and these output profiles strongly affect economic activity for oil producers as it affects their exports and balance of trade. Conversely, this calculation indirectly influences oil importing countries as it redresses their trade balance through reduced imports. Thus, this model is a major source of structural change in the economy.

Climate policies and scenarios

As Espagne et al. (2023) demonstrate, it is also possible to use this model to make use of a number of policy instruments to simulate decarbonisation to limit climate change to well below 2°C. The policies are exclusively instruments that are common and used by governments worldwide, including: carbon taxes, fuel taxes, technology subsidies, public investments, fuel blend mandates, vehicle mandates, scrappage schemes.

In earlier work, it has been shown that in a model simulating non-linear technology diffusion processes such as in FTT, policies can produce complementarity effects where the overall outcome is more than the sum of the effects of the individual policies. Notably, carbon taxes and technology subsidies tend to work well with mandate policies (where manufacturers are required to market a proportion of low-carbon technologies), since mandates expand the choice options that consumers face, while the taxes or subsidies stabilise choices towards these new options. Taxes on their own work less well if choice is limited in which case consumers may be forced by circumstances to pay the taxes without changing their behavior. Mandates on their own work less well if the technologies pushed into the market fail to become cost competitive (Knobloch et al., 2019; Lam and Mercure, 2022; Mercure et al. 2014).

It is also noteworthy that technology compositions in different countries are generally completely different, which often means that effective policy mixes tend to vary depending on circumstances. Some countries are endowed with largely low-carbon electricity sectors, while other countries find themselves well ahead of others in terms of low-carbon technology compositions as a result of past policies.

Taking advantage of synergies explored in earlier work, and building on the policy mixes used in Mercure et al. (2021) and Nijsse et al. (2023), Espagne et al. (2023) constructed independent policy mixes in each of the 71 countries represented in the model. While they differ in each case, they build upon the following approach:

Cross-sectoral policies:

- Carbon price that gradually increases over time to around \$200/tCO2 in 2050 and covers the power sector and industrial activities, but not personal transport nor residential heat (as is currently the case in most countries).
- Energy efficiency regulations for curbing energy use in sectors not modelled in FTT

Power sector:

- Feed-in tariffs (or contracts for difference) for wind power, but no policy usually needed for solar
- Capital cost subsidies for technologies such as geothermal, hydro, carbon capture, nuclear and other low-carbon options
- We assume implicitly that market regulations change to allow renewables to receive fair remuneration (e.g., reforming marginal cost pricing where it exists)
- Ban and phase outs for coal plants by 2030, and for gas plants by 2040.

Road transport:

- Ownership/purchase taxes for conventional vehicles
- Subsidies on electric vehicles (we are not currently modelling hydrogen vehicles)
- Electric vehicle mandates in the early years to increase numbers on roads
- Biofuel blends
- Bans on conventional vehicles in 2030 or on dates announced in various countries
- We assume that charging infrastructure diffuses at the same pace as electric vehicles

Household heating:

- Heating fuel taxes
- Subsidies on heat pumps, solar heaters and other low-carbon options
- Mandates on heat pumps and other low-carbon options

Steelmaking:

- Public investment in hydrogen steel demonstration plants to attract private investment. This is modelled similarly to a mandate, in which industry is required to build capacity for low-carbon steel, part-funded by the public sector
- Capital cost subsidies
- We assume declining costs for hydrogen as inputs.

To generate a scenario of global decarbonisation, Espagne et al. (2023) then searched policy space and adjusted the stringency of the policies to achieve net-zero in countries in which such a pledge has been made (2050 for the EU, Japan and Korea, 2060 for China, 2070 for India), and adjusted the policy stringency for the rest of the world to achieve net-zero by between 2050 and 2060. The authors note note that there are very large numbers of equivalent policy mixes with which such emission reductions could be achieved in the model, but that carbon pricing on its own does not achieve those targets.

7.4.8 Remote-Sensing Data

In practice, different types of remote-sensing data exist, such as:

- **High-resolution imagery:** Advances in satellite technology have led to the availability of high-resolution imagery, which provides detailed information on land cover, habitat types, and vegetation patterns. This helps to identify and monitor specific habitats and their changes, helping to assess biodiversity loss. This data can be used to assess the health and economic value of specific habitats, such as forests, wetlands, or coastal areas, and provide estimates for economically relevant ecosystem services such as carbon sequestration, water purification, and even recreation potential.
- **Hyper-spectral imaging**: Hyperspectral sensors capture data in specific spectral bands, allowing for detailed characterisation of vegetation types and species composition. By analysing the unique spectral signatures of different plant species, researchers can assess changes in species diversity and identify areas at risk of biodiversity loss. This information can be used to measure crop nutrition and micronutrient content, easy disease detection and environmental stresses, estimations of yields, density, plant variety, vegetation types, timber volume, medicinal plants, etc
- **LiDAR (Light Detection and Ranging) technology**: LiDAR technology uses laser pulses to measure the distance between the sensor and the Earth's surface, providing detailed 3D information about vegetation structure. This allows the quantification of forest biomass, canopy height, and vertical structure, which are crucial indicators of biodiversity and habitat quality. Economic analysis can use this information to estimate to help understand the implications of deforestation and degradation, including the loss of timber resources, the reduced carbon sequestration capacity, and the increased vulnerability to natural hazards, especially forest fires, and the probability of spread of diseases vectors.

Annex Table 7 below provides a list of key satellite missions including their meta-information such as time and spatial resolutions, and accessibility, and links to the data.

Annex Table 8 **Satellite missions for measuring biodiversity loss**

Mission	Indicators	Spatial resolution	Time resolution	License	Website
ALOS PALSAR	Forest structure, biomass, land cover	6-100 m	2006-2011	Free and open access	www.eorc.jaxa.jp
COSMO-SkyMed	Land cover, land use change, forest monitoring	1-100 m	2007-present	Data availability to be determined	www.asi.it
EnMAP	Hyperspectral data for environmental monitoring	Spectral resolution: <10 nm. Spatial resolution: 30 meters	Planned mission (2022)	Data availability to be determined	www.enmap.org
Gaofen-1	Land cover, land use change, vegetation indices	2 m	2013-present	Data availability to be determined	www.cnsa.gov.cn
GeoCARB	Carbon dioxide (CO_2) and methane (CH_4) concentrations	Spectral resolution: 0.4 nm. Spatial resolution: 6-10 km	Planned mission (2023)	Data availability to be determined	geo.carb.onera.fr
GIMMS	Land cover change, ecosystem functioning	8 kilometers	1981-2015	Free and open access	daac.ornl.gov
Global Ecosystem Dynamics	Vegetation productivity, leaf area index	1 kilometer	1981-present	Free and open access	lpdaac.usgs.gov
Global Forest Watch	Forest cover change, deforestation, degradation, forest fragmentation	Varies depending on source	Varies depending on data availability	Varies depending on the data source and organisation	www.globalforestwatch.org
Hyperion	Hyperspectral data for environmental monitoring	30 m	2000-2017	Free and open access	eo1.usgs.gov
IKONOS	Land cover, land use change, vegetation indices	1 m	1999-2015	Commercial use restrictions apply	www.maxar.com
Landsat	Land cover and land use change, vegetation indices, forest cover	30 meters (visible, NIR)	1972-present	Free and open access	landsat.usgs.gov
MODIS	Vegetation indices, land surface temperature, fire occurrence	250-500 meters	2000-present	Free and open access	modis.gsfc.nasa.gov
NASA Earth Observing System	Various remote sensing instruments and data products	Varies depending on instrument	Varies depending on data availability	Varies depending on the data product and organisation	earthdata.nasa.gov
PlanetScope	Land cover, land use change, vegetation indices, deforestation monitoring	3-5 meters	2016-present	Commercial use restrictions apply	www.planet.com
PROBA-V	Vegetation indices, land cover, land use change	100 m	2013-present	Free and open access	proba-v.vgt.vito.be
RapidEye	Land cover, land use change, vegetation indices, deforestation monitoring	5 meters	2009-2020	Commercial use restrictions apply	www.planet.com
Sentinel-2	Land cover, land use change, vegetation indices, forest cover	10-20 meters	2015-present	Free and open access	sentinel.esa.int
Suomi NPP VIIRS	Vegetation indices, night-time lights, fire detection	375 m (visible and NIR bands)	2011-present	Free and open access	jointmission.gsfc.nasa.gov
WorldView-3	Land cover, land use change, vegetation indices	31 cm	2014-present	Commercial use restrictions apply	www.maxar.com

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BANQUE DE FRANCE
EUROSYSTÈME

NGFS
Secretariat