Network for Greening the Financial System

Technical document

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

Executive and non-technical summaries

December 2023

Central Banks and Supervisors
Network for Greening the Financial System

Executive summary

While climate change poses an existential threat on its own, the scientific community readily acknowledges that it is only one aspect of nature-related risks (IPBES, 2019; Richardson et al., 2023). Widespread environmental degradation and the diverse forms of nature-related risks resulting from it can be understood through the concept of "planetary boundaries" (Rockström et al., 2009; Richardson et al., 2023), which designate the safe operating space for humanity across multiple processes that regulate the Earth system. Crossing these planetary boundaries could generate multiple risks for human (and non-human) populations (IPBES, 2019) as well as significant adverse impacts on the global economic and financial system, as increasingly acknowledged by economic and financial decision-makers including central banks and supervisors (NGFS, 2022).

This acknowledgement led to the establishment of the NGFS Task Force on Biodiversity Loss and Nature-Related Risks, whose purpose is to help mainstream the consideration of nature-related risks across all NGFS activities, along with climate-related risks. In September 2023, and relying strongly on previous evidence gathered with the support of external experts (NGFS-INSPIRE, 2022), the Task Force published its Conceptual Framework (NGFS, 2023a), which provides a common basis to understand, assess and address nature-related risks.

These different reports, alongside those produced by other stakeholders (e.g., TNFD, 2023a), stress that one of the most important next steps for financial actors – including central banks and supervisors – is to develop scenarios through which nature-related economic and financial risks can be better understood. By going beyond static assessments of dependencies and impacts or simple exposure analyses, dynamic scenario analysis can enable central banks and supervisors to envision different pathways that the world could take (e.g., the current trends of environmental degradation and the potential crossing of tipping points, or the introduction of policies to stop and reverse such trends), before assessing the macro-financial implications of these pathways – including those of systemic relevance. Building on the approach developed by the NGFS for climate-related risks (NGFS, 2023b), scenario analysis is therefore an essential tool to be mobilized by central banks and supervisors in their quest to monitor and support price and financial stability in the face of nature-related risks.

Against this backdrop, the NGFS Task Force on Nature was tasked with providing recommendations towards the development of scenarios for assessing nature-related economic and financial risks. The purpose of this Technical Document is to present such recommendations – i.e. not to actually develop the scenarios, which should be done in future work based on this report –, building on the literature assessed by the NGFS Team with the support of a group of external experts who provided inputs for different sections of the report. The recommendations of this Technical Document seek as much synergy as possible with the approach and methodologies of the NGFS scenarios developed for the purpose of assessing climate-related risks, while accounting for the specific features related to nature loss and the measures (policies and broader socioeconomic transformations) needed to reverse it.

This Technical Document is structured around two topics, corresponding to the two steps typically needed to conduct forward-looking risk assessments: (i) envisioning consistent narratives through which different hazards (i.e. potential sources of physical and transition risks) can be identified; and (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.

Developing narratives for nature-related scenarios is particularly challenging. Ecosystem functions and processes display an even higher degree of complexity than climate change, must be tracked across multiple metrics (at different scales) and exhibit nonlinear dynamics. These nonlinearities include the presence of positive and negative feedback loops within and among Earth system processes. For instance, climate change and biodiversity loss are interlinked through different Earth system processes (e.g., land-use changes drive both biodiversity losses and climate change), heightening the potential for physical risks. And while many responses to reverse biodiversity loss tend to mitigate climate change, some solutions aimed at mitigating climate change can exacerbate biodiversity loss (e.g., massive reforestation without due consideration for local ecosystems). Nature-related scenarios therefore need to be specific enough to account for such interactions and trade-offs, while remaining simple enough to be actionable by economic and financial stakeholders.

As a result, 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 (the "local-global tradeoff"). The more global the narrative of the scenario (e.g., envisioning a global price on a unique, aggregated biodiversity metric), the less it may capture local specificities that are essential to appreciate nature-related patterns; the more local and disaggregated the narrative of the scenario (e.g., a collection of case studies focused on a few regions and sectors), the less it may be able to create a common language and to inform how nature loss and related policies can generate global macro-financial impacts.

We therefore propose approaches to develop narratives of scenarios that could overcome this tradeoff, and consequently serve as starting points for the assessment of nature-related financial risks[1]. For physical risks (related to economic impacts generated by nature loss), we suggest two complementary frameworks, herein referred to as ESGAP (Environmental Sustainability Gap) and INCAF-Oxford. ESGAP is an index of environmental health, based on a systematic downscaling of the concept of planetary boundaries to the national level. The INCAF-Oxford framework is also an indicator-based approach centered on risks, based on an extensive review of potential hazards and shocks coupled with relevant datasets. For transition risks (resulting from a misalignment of economic actors with actions aimed at protecting, restoring, and/or reducing negative impacts on nature), we review eleven existing frameworks from which recurrent typologies of hazards can be better identified. We acknowledge that these approaches are only the beginning for developing scenario narratives, and can be enhanced with further work including better sectoral and regional calibration.

The quantification of macroeconomic (and ultimately financial) consequences of these nature-related hazards may require the use of specific models.[2] To this end, this Technical Document reviews a range of global macroeconomic and biophysical models and assesses their ability to: (i) integrate the outputs of the narratives – presented above – as inputs to the modelling exercise; and (ii) account for the transmission channels through which specific hazards (e.g., pollinator decline affecting the agricultural sector) can propagate in the economy (e.g., in the form of higher input costs for industry and decrease in final consumption).

Overall, we find that the models reviewed do not fully account for the most relevant nature-related hazards and their transmission channels toward significant macro-financial impacts, and were often not developed to do so. They are currently able to represent the economic impacts of only a sub-section of the potential physical and transition hazards identified previously, thereby not capturing a vast array of nature-related hazards that could emerge. Moreover, the models reviewed tend to underestimate the potential magnitude of the economic consequences of the nature-related hazards considered. One reason is that the models reviewed assume that the global economy is able to swiftly adapt to hazards through substitution, trade, and technology, thereby not allowing for nonlinear and irreversible physical hazards nor for transition policies that could generate structural economic change.

In light of the structural limitations of the examined models to assess nature-related financial risks, it is necessary to assess which alternative approaches can be used or developed. Particular focus should be placed on models that are able to both represent multiple hazards (or shocks) in multiple sectors and capture the indirect (cascading) impacts of these hazards throughout value chains.

To this end, and without excluding the possibility of exploring other approaches, we focus on the insights and limitations of Multi-Regional Input-Output (MRIO) tables and models. Input-Output tables trace the origin of direct and indirect inputs needed for the production of

1 While we acknowledge that physical and transition risks could interact and should be assessed jointly, we focus on them separately in this report for purposes of clarity and simplicity.

2 While we do not discard more qualitative approaches, these are not discussed in this report.

goods and services in a national economy, and display how this production generates profits, income and taxes. As a result, 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.

To provide an example of how MRIO models can be used to assess direct impacts of nature-related financial hazards and their propagation throughout sectors and countries, we conduct two case studies that connect some the narratives discussed above to MRIOs. They both show how a physical hazard (namely a drought in France) and a transition hazard (namely a policy aimed at reducing imported deforestation that would be implemented in a disorderly fashion) could generate multiple direct and indirect impacts, thereby potentially generating macrofinancially relevant impacts.

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' reactions to nature-related hazards 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.

In light of these findings, we provide a list of options aimed at moving forward with the development of quantified nature-economy scenarios and present their associated trade-offs (see Figure below). 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).

Overall, a 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 (including more qualitative approaches, not discussed here).

List of options for central banks and supervisors 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

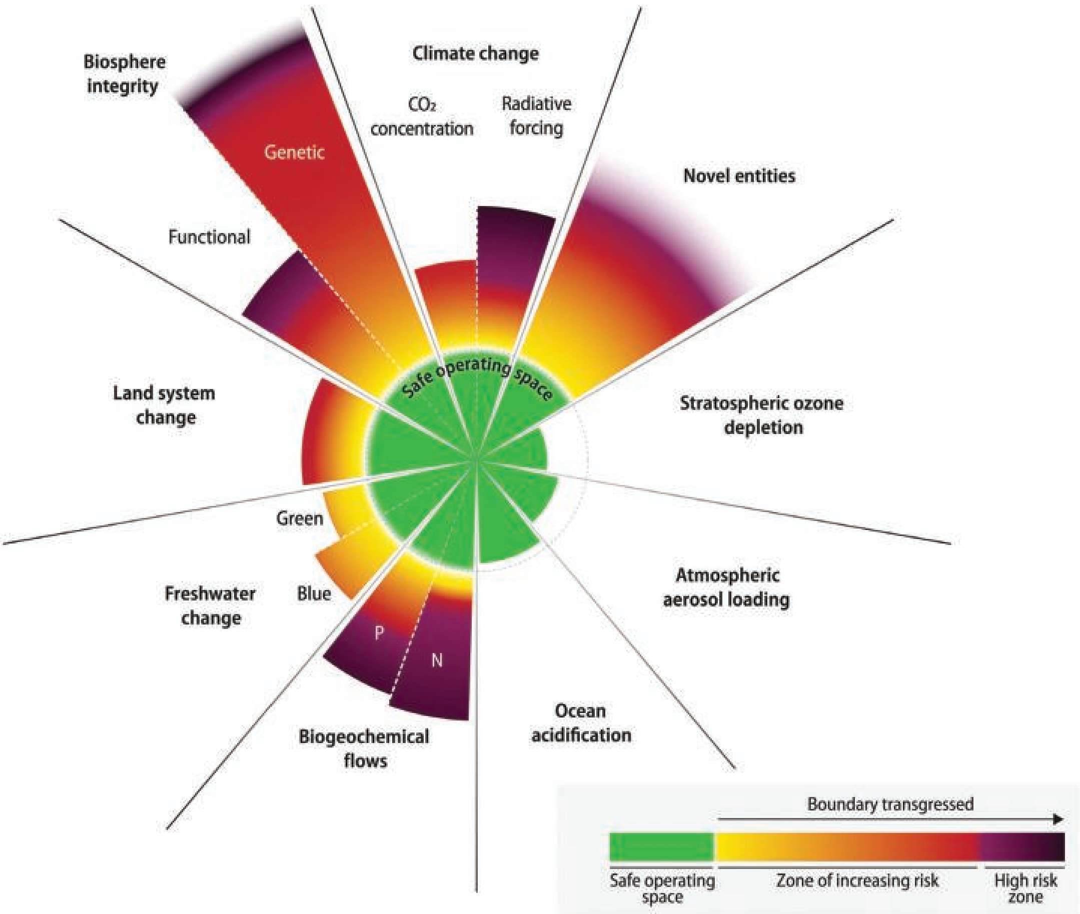
Non-technical summary

1. Background, goals and structure of the Technical Document

Nature, defined by the IPBES Conceptual Framework (Díaz et al., 2015) as "the natural world with an emphasis on the diversity of living organisms and their interactions among themselves and with their environment" provides human populations with ecosystem services (also known as nature's contributions to the people) that enable human life and well-being, as well as economic prosperity (NGFS, 2023a).

While climate change poses an existential threat on its own, the scientific community readily acknowledges that it is only one aspect of nature-related risks (IPBES, 2019; Richardson et al., 2023): Widespread environmental degradation, and the diverse forms of nature-related risks resulting from it, can be understood through the concept of "planetary boundaries" (Rockström et al., 2009; Richardson et al., 2023), which designate the safe operating space for humanity across multiple processes that regulate the Earth system. For instance, human activities are currently contributing to an unprecedented loss of biodiversity in human history, as the global rate of species extinction is between tens to hundreds of times higher than it has averaged over the past ten million years (De Vos et al., 2015; Pyron & Pennell, 2022). Beyond climate change and biodiversity loss, human activities contribute to other forms of environmental degradation related to freshwater availability and soil erosion, to name just a few. The latest available evidence suggests that humanity has now crossed six out of nine planetary boundaries (**Summary Figure 1**).

Summary Figure 1 **Planetary boundaries, or the need for a comprehensive approach to nature loss**



Source: Richardson et al., 2023.

Crossing these planetary boundaries could generate multiple risks for human (and non-human) populations (IPBES, 2019) as well as significant adverse impacts on the global economic and financial system, as increasingly acknowledged by economic and financial decision-makers including central banks and supervisors. Indeed, the Network of Central Banks and Supervisors for Greening the Financial System (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). As for climate change, nature loss can generate physical risks (resulting from economic impacts generated by nature loss) and transition risks (resulting from a misalignment of economic actors with actions aimed at protecting, restoring, and/or reducing negative impacts on nature).

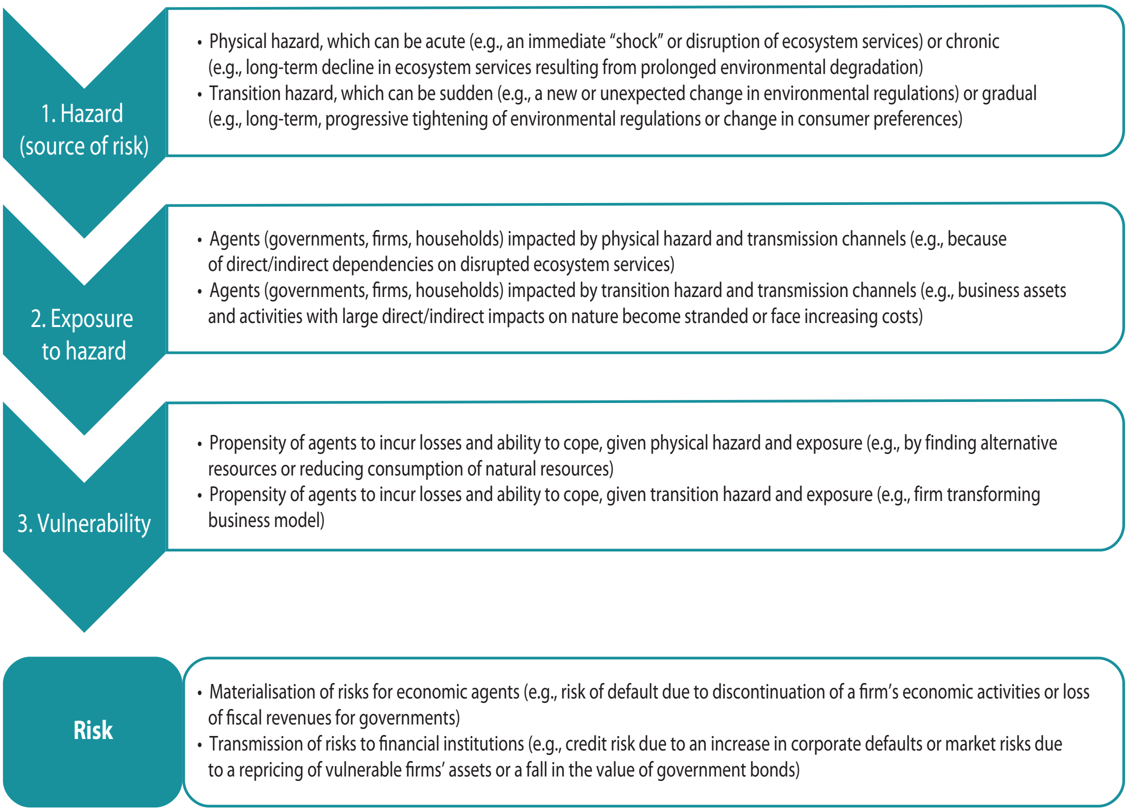
This acknowledgement led to the establishment of the NGFS Task Force on Biodiversity Loss and Nature-Related Risks (hereafter "the NGFS Task Force on Nature"), whose purpose is to help mainstream the consideration of nature-related risks across all NGFS activities, along with climate-related risks. In September 2023, and relying strongly on previous evidence gathered with the support of external experts (NGFS-INSPIRE, 2022), the Task Force set a milestone in the NGFS approach to nature-related risks with the publication of a Conceptual Framework (NGFS, 2023a). This conceptual framework report provides a common basis to understand, assess and address nature-related risks.

These different reports, alongside other players (TNFD, 2023a[3]), stress that one of the most important next steps for central banks and supervisors is to develop scenarios through which nature-related economic and financial risks can be better understood. Scenarios are plausible stories that can reveal relevant and potentially challenging information about how the future might unfold. In this way, they are an essential tool for strategic planning that can help to identify and account for critical uncertainties. Scenario analysis can enable central banks and supervisors to envision different possible pathways that the world could take (the current trends of environmental degradation and the potential crossing of tipping points, the introduction of policies to stop and reverse such trend, etc.), before assessing the economic, and eventually the financial implications – including those of systemic relevance – of these pathways.

In order to assess nature-related financial risks, it will be essential to develop scenarios that delineate the risk drivers (or hazards) that could emerge (i.e., the sources of physical and transition risks), as well as their direct and indirect impacts. The latter can be accomplished in part through the use of models to assess the potential exposure and vulnerability of different economic agents, sectors or regions to the hazards identified (see step 1 of **Summary Figure 2**). Until now, central banks have primarily assessed nature-related risks through static analyses. Research has sought to highlight potential exposures to shocks/hazards (see step 2 of **Summary Figure 2**), by focusing on impacts and dependencies of firms and the financial sector on nature.

3 Note that while consistency should be found across initiatives such as NGFS and TNFD, it is also important to remind that they have different objectives. For instance, the latter seeks to provide scenarios that are useful to individual firms and financial institutions, whereas the former – as discussed throughout this report – is more interested in understanding how different scenarios can generate macrofinancially-significant impacts.

Summary Figure 2 **The materialisation of risks as the consequence of hazard, exposure, and vulnerability**



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

Developing nature-related scenarios will enable central banks and supervisors to move beyond current static analyses of impacts and dependencies, or isolated case studies, which cannot provide a full picture of global macro-financial risks: Scenarios allow for specific vulnerabilities (step 3 in Summary Figure 2) and related risks to be assessed in a dynamic fashion. This can help to create a common language through which nature-related risks can be approached and assessed, while leaving room for further calibration and adaptation at the local scale (e.g., so that each central bank or supervisor can better account for specific features of the ecosystems or policies in its jurisdiction while acknowledging the global features discussed in this report).

Against this backdrop, the NGFS Task Force on Nature was tasked with providing recommendations towards the development of scenarios for assessing nature-related economic and financial risks.[4] The purpose of this Technical Document is to present such recommendations, building on the literature assessed by the NGFS Team with the support of a group of external experts who provided inputs for different sections of the report. This Technical Document also builds on previous NGFS reports, including the Conceptual Framework on nature-related risks (NGFS, 2023a) and previous work (most notably NGFS-INSPIRE, 2022), which explicitly call for the development of nature-related scenarios.

The recommendations of this Technical Document seek as much synergy as possible with the NGFS scenarios developed for the purpose of assessing climate-related risks (so as to minimize additional work and additional resources), while accounting for the specific features related to nature loss and the measures (policies and broader socioeconomic transformations) needed to revert it. Indeed, as summarized below and discussed extensively throughout the report, existing climate scenarios

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

and future nature scenarios will naturally overlap in many ways. Importantly, however, they can also diverge and even generate trade-offs, limiting the possibility for a single risk assessment framework.

This Technical Document is structured around two main topics, corresponding to the two steps typically needed to conduct any risk assessment: first, identifying the hazards that one could foresee (sources of physical and transition risks); second, identifying the methods and tools (e.g., models) through which the impacts of these hazards and the ability to mitigate them can be assessed. However, given the many challenges related to the second step, we split it into two parts: the assessment of widely-used models, and the need for new tools and approaches that can overcome the shortcomings of such models for the purpose of assessing nature-related risks. Importantly, the models and tools presented throughout the report are assessed solely on their ability to represent nature-related risks. For instance, models for which growth is an "exogenous" input and the elasticities of substitution between factors of production are high, will tend to underrepresent the material impacts of a nature-related hazard.

2. Developing narratives of scenarios – The challenge of identifying relevant physical and transition hazards (or sources of risks)[5]

As shown in Summary Figure 2 above, the essential first step to any risk assessment is to identify specific physical and/or transition hazards that can become sources of risks. 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, destabilization 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). Both these physical and transition hazards could have multiple impacts on the economy (although incomparably worse for unaddressed physical hazards) that need to be explored.

The identification of such physical and transition hazards (i.e. potential sources of risks) form the basis of what we call the narrative of the scenarios. The first task of this report is therefore to provide guidance regarding how central banks and supervisors (in particular) can develop narratives through which they can identify relevant physical and transition nature-related hazards. The output of such an exercise will then serve as an input to the risk assessment methodologies discussed in the following two sections, by assessing the extent to which existing models and tools can estimate the economic impacts of such hazards. While physical and transition risks could interact and should be assessed jointly, we focus on them separately in this report for purposes of clarity and simplicity.

However, developing such narratives of nature-related scenarios poses at least three significant challenges. First, ecosystem functions and processes – including their interactions with multiple socioeconomic processes – display a higher degree of complexity than climate change, with multiple metrics to be tracked (e.g., species abundance, genetic diversity, surface and underground water, etc.) and potential nonlinear dynamics at stake (due among others to positive and negative feedback loops within and among ecosystems)6. 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 are interlinked through different channels; while many responses to reverse biodiversity loss tend to mitigate climate change, some solutions aimed at mitigating climate change can exacerbate biodiversity

5 This topic is covered in Chapter 2 of the Technical Document.

6 Alongside the difficulty of accurately measuring ecosystem health, there are clear gaps in the data of existing metrics that hinder scenario developments. Data gaps also disproportionately affect the capacity of emerging market and developing economies to measure and manage nature-related risks (see Annex 7.1.1).

loss (e.g., massive reforestation without due consideration for local ecosystems). 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. While this is a challenge for modeling (as discussed below), it is also important to clarify in the development of narratives whether one assumes that the ecosystem service disrupted (in the case of physical risks) leads to irreversible consequences or not. For instance, does the narrative focus on global tipping points with multiple and irreversible consequences, or on very local issues (e.g., water shortage in one region) that are assumed to not significantly feedback into any other ecological systems?

As a result of these challenges, 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"). In other words, the goal of developing nature-related scenarios that can be used consistently by different players (including central banks and supervisors) across the world faces the following tradeoff: the more global and aggregated the narrative of the scenario (e.g., envisioning a global price on a unique metric to measure biodiversity impacts), 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 global macro-financial impacts.

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. We acknowledge that these approaches are only the beginning for developing scenario narratives, and can be completed with further work, including better sectoral and regional calibration as well as case studies.

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 aggregated metrics for identifying the distance between the current state and a "healthy" operating state for ecosystems. As such, it is a tool that can help identify which ecosystems and their environmental functions are more degraded than others, and thus more likely to collapse. It can thereby translate the broad concept of planetary boundaries into observable trends at the national level, while integrating the assumption (discussed above) 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 risks themselves rather than on ecosystem services, as most approaches do. This enables the identification of multiple potential hazards or shocks associated with nature loss in specific biomes (e.g., increased occurrence of storms due to the degradation of mangroves, increased potential for zoonotic diseases due to greater human encroachment in primary forests, etc.), based on scientific findings. These hazards can then be mapped *backwards* (to ecosystem services disrupted, natural assets and drivers of degradation along the impact chain) and *forwards* (to primary 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 sections).

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 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 existing 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.

In order to provide concrete examples of how these narratives can be used by existing models and tools, we use them as generic inputs to two case studies we conduct in Chapter 4 of the report: the first case study focuses on a potential drought (physical hazard) in France, and the second case study focuses on the impacts of an EU policy intended to limit deforestation (transition hazard) along global supply chains. The tools used and key results are discussed below.

Overall, our work indicates that it is possible to overcome the trade-off identified above, and develop narratives that are broad enough to create a common language across central banks and supervisors across the globe, while being specific enough (and lending themselves to further calibration) to be useful for a specific authority in a specific jurisdiction. That is, the complexity of nature-related trends cannot serve as not a sufficient reason for only using aggregated metrics, for conducting decontextualized or isolated case studies, or for simply ignoring the issue. This being said, we acknowledge that the approaches presented (ESGAP-SESi and INCAF-Oxford frameworks for physical risks, and our desk review for transition risks) would require more work to be fully implementable.

3. Review of modeling approaches of the economic impacts of nature-related hazards[7]

The quantification of macroeconomic and financial consequences of the nature-related hazards presented in the previous section may require the use of specific models (we do not discard more qualitative approaches but those are not discussed in this report). To this end, this section reviews a range of global macroeconomic and biophysical models and assesses their ability to: (i) integrate the outputs of the narratives presented in the previous section as inputs to the modelling exercise; and (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).

We evaluate six of the most commonly used modelling frameworks[8] that combine nature and macroeconomic aspects at the global level (so-called "nature-economy" models), including models used by the NGFS for its climate scenarios and different computable general equilibrium (CGE) models with nature-related components. The material for this assessment is composed of an "ID card" for each modelling framework, listing the most important characteristics of the models[9]. 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., enhanced 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 the sectoral and macroeconomic consequences resulting from physical or transition scenarios. This part of the analysis focuses in particular on the underlying assumptions of the economic models, and how these assumptions might minimise (or amplify) the economic impacts of physical or transition hazards. Our two main findings are the following ones.

7 This topic is covered in Chapter 3 of the Technical Document. The review of models conducted for this report does not aim to be exhaustive. In particular, some models may be of use in certain countries without being widely used in others.

8 The term "modelling framework" is used to emphasize that two or more models can be coupled and therefore assessed jointly.

9 Published as a standalone document alongside this Technical document: NGFS (2023), Review of global nature-economy models: Model "ID Cards".

First, we find that the six modeling frameworks assessed are currently able to represent the economic impacts of only a sub-section of potential physical and transition hazards identified in the previous section, thereby not capturing a vast array of nature-related hazards that could emerge. For physical risks: the loss of provisioning ecosystem services relating to food and timber production are the main hazards considered by the models assessed, followed by other provisioning services relating to fish and water. Most models reviewed do not comprehensively capture dependencies upon regulating and maintenance ecosystem services (such as the protection against floods, or air filtering), and none of the models capture dependencies on cultural services. For transition risks: land use change is the driver of nature loss represented by the models in the most detail, together with climate change. The models are able to assess the economic effects of a range of land-based policies and climate mitigation solutions, although the representation of technical change in agriculture remains far less developed than in the energy sector. Other drivers of nature loss and their related policies, such as direct overexploitation of resources and pollution, are more difficult to model in a spatially explicit way, and are partially represented by only a couple of models. The invasive species driver is not represented by any of the models reviewed.

Second, we find that the modelling frameworks we reviewed tend to strongly underestimate the potential magnitude of the economic consequences of the nature-related hazards considered (and were usually not developed to do so). The first main reason is that most of those models were primarily designed to estimate the impacts of economic trajectories on various aspects of the environment, and not the other way around. In fact, the models reviewed are typically calibrated to follow an exogenous path of GDP growth. The second main reason is that the models reviewed assume that the global economy is able to swiftly adapt to hazards through substitution, trade, and technology. For example, commonly used modelling assumptions, such as the ability to easily substitute inputs that become scarce (e.g., productive land) with others (e.g., labour or capital), tend to mitigate the economic consequences of any disruption in ecosystem services or any nature-related policy, no matter how well represented the transmission channels are.

Given the current limitations of these nature-economy models in representing the potentially severe economic impacts of nature-related hazards, we complement this model evaluation by focusing in depth on 14 "biophysical" models – taken from the ISIMIP models suite[10] – to better understand within-nature dynamics, while acknowledging that those models do not show economic impacts. Biophysical models are simulations of one or several (potentially interconnected) biological systems, which can be used to assess the influence of biological and physical factors on complex systems. With regards to physical risks, biophysical models could help link regulating ecosystem services (e.g., water regulation) to the provisioning services that directly impact the economy (e.g., agricultural yields), thereby better calibrating a shock in productivity of the agricultural sector in a macroeconomic 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.

Biophysical models, while often representing nature-related patterns with higher granularity and detail, generally lack economic and financial dimensions. As such, we conclude that these models can help better calibrate different narratives of scenarios, but they cannot on their own solve the challenges of the nature-economy models discussed above.

4. The possibility to use input-output tables and models to understand the propagation of nature-related hazards throughout value chains over a relatively short-term horizon[11]

In light of the structural limitations of the equilibrium-based macroeconomic models to assess nature-related financial risks, it is necessary to assess which alternative approaches can be used or developed. Particular focus should be placed on models that are able to both represent multiple shocks in multiple sectors and capture the indirect (or cascading) impacts of nature-related hazards throughout value chains.

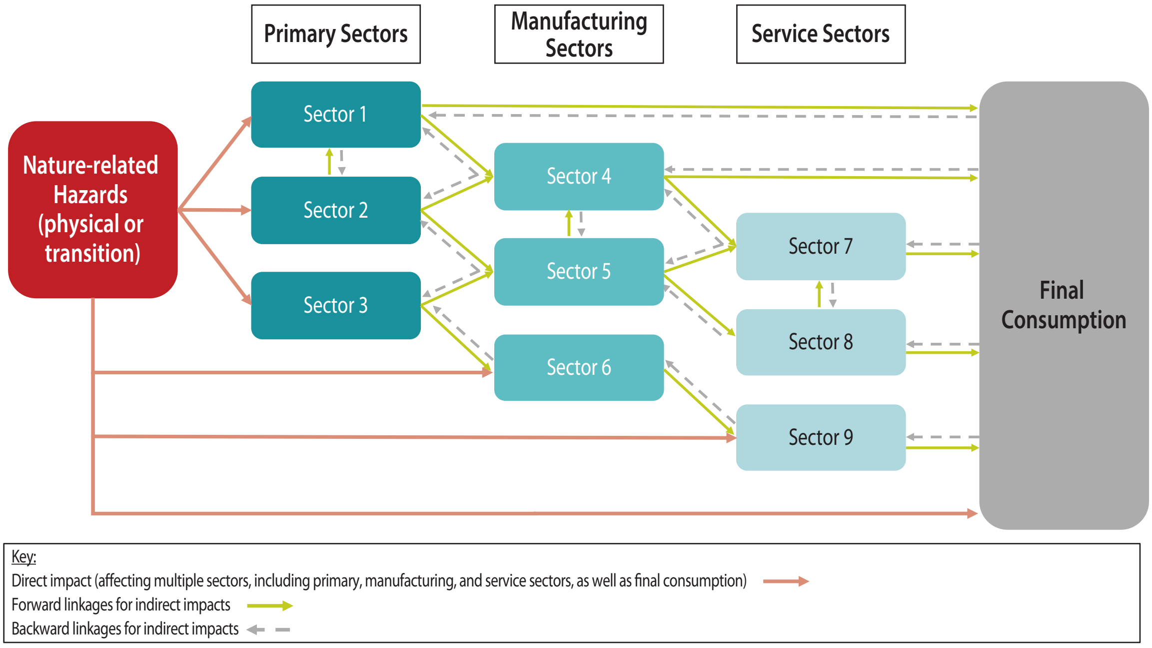
10 See: ISIMIP – The Inter-Sectoral Impact Model Intercomparison Project.

11 This topic is covered in Chapter 4 of the Technical Document.

To this end, and without excluding the possibility of exploring other approaches, we focus on the insights and limitations of Multi-Regional Input-Output (MRIO) tables and models. Input-Output (I-O) tables trace the origin of direct and indirect inputs needed for the production of goods and services in a national economy, and display how this production generates profits, income and taxes. The basic structure of an I-O table 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.

As a result, 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 (Summary Figure 3). Contrary to other models, MRIO models provide relevant information about indirect cascading effects caused by the stranding of a non-substitutable form of natural capital (due to a physical or transition hazard in a specific sector). This ability to capture non-substitutability can be understood as an application of the precautionary principle to risk management: in essence, MRIO tables and models can provide insights into what could happen in strongly adverse scenarios where economic agents cannot adapt to a large shock.

Summary Figure 3 **The propagation of nature-related hazards through the real economy, with forward and backward linkages between economic sectors**



Source: Authors' illustration.

MRIO tables and models can therefore be used without prior reliance on models, to appreciate in a more transparent and simple manner the potential direct and indirect impacts of a specific physical or transition hazard. While substantially less complex than most of the models developed to assess nature-related risks, MRIO tables have the advantage of providing central banks and supervisors (alongside other stakeholders) with a simple view of how specific hazards could generate both direct and indirect impacts throughout value chains, and therefore better identify potential points of vulnerability within the economic system.

MRIO tables and models can also be extended – still from a static or short-term perspective – to macroeconomic impacts in terms of GDP losses, employment, wages, net external financing, or any meaningful variable that can be matched to the regional and sectoral disaggregation of the initial MRIO data. In particular, an emerging body of research attempts to couple MRIO data and models with spatialized data, notably remote-sensing data. This path offers very promising developments to better assess nature-related risks in a way that allows for both inter-country comparability and spatial granularity.

To provide an example of how MRIO models can be used to assess direct impacts of nature-related financial hazards and their propagation throughout sectors and countries, we conduct two case studies which connect the narratives developed in Chapter 2 of the report (on Narratives) to MRIOs. The first case study – based on the INCAF-Oxford methodology described above – assesses the direct and indirect impacts of a physical hazard, namely a severe drought affecting France. The results indicate that the 111 French sectors directly affected by the drought scenario, are also highly interconnected (through both forward and backward linkages, as generically shown Figure 3 above) to many other sectors of the national economy, as well as rest of the European Union. Consequently, such a hazard could generate large economic cascading effects that would affect key agriculture, mining, manufacturing, and service sectors. Such disruptions may, in a worst case scenario, lead to the collapse of entire sectors, with cascading impacts to other countries. For instance, we find 14.8% of the European Union's current demand for these 111 sectors is exposed indirectly to this severe drought scenario. The second case study, focusing on a theoretical 'disorderly' transition risk, explores the impacts of a potential sudden European Union (EU) policy to ban non-deforestation-free products from Brazil[12]. Assuming (for the purpose of the case study) a 15% reduction on EU imports from the Brazilian sectors of Forestry, Agriculture, Livestock, and Mining, the case study highlights the potential for indirect effects to not only exacerbate the impact on directly affected sectors, but also the potential impact to other sectors of the Brazilian economy. Moreover, upstream impacts can significantly feedback into other countries. For instance, when looking at downstream effects, a value of 960 million EUR of EU imports is directly exposed to this theoretical transition shock.

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 nature-related hazards and, more broadly, changes in the structure of the economy. As such, MRIO tables and models are most adept at capturing impacts over the short- and medium-term horizon, a period during which structural economic changes are unlikely to take place, because these models provide a static picture of economic dependencies. We discuss several potential ways forward to overcome this issue, including by merging MRIO with other models – such as computable general equilibrium, stock-flow consistent models and technological development models – or by developing ad hoc quantitative and qualitative approaches to update technical coefficients of production. All of these potential solutions come with limitations and would need significant work before they can be used for the purpose of assessing nature-related financial risks.

The second main limitation of MRIO tables is their inability to provide information at the intra-sectoral level, which is particularly important for nature-related financial risks. Several ways forward are explored, including quantitative and qualitative assessments at the firm level and more systematic ways of conducting firm-level analysis, as well the possibility to increasingly rely on remote-sensing data. As for the previous limitation, all relevant solutions come with important caveats and will require considerable additional work.

12 Note that this case study assumes a disorderly transition, i.e. a scenario in which policies would be implemented rather abruptly and without careful consideration of how countries impacted (both Brazil and the EU in this case) could design mechanisms to avoid such impacts and therefore benefit from the transition. That is, assessments of transition risks do not question the need to conduct the ecological transition, and they can rather be seen as a useful tool to avoid potential risks that could emerge if the transition is not adequately planned and implemented and/or if economic actors are not prepared for forthcoming policies.

5. Options for central banks and supervisors aiming to assess nature-related economic and financial risks

In light of these findings, we provide a list of options aimed at moving forward with the development of quantified nature-economy scenarios and present their associated trade-offs (see Summary Figure 4).

These options are split between what central banks and supervisors can do in the short-term – provided that necessary data are available, and acknowledging that data availability can largely vary across countries – and what they could seek to explore as part of a long-term research program (e.g. between 3 and 5 years).

Summary Figure 4 **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

In the short term, 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.

Central banks and supervisors could also use some of the more traditional models described above, but with great caution (as they will almost automatically underestimate the economic impacts generated by nature-related hazards, for the reasons already discussed) and while assessing how the most problematic assumptions and features of such models 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 representations 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. When extended to the global level, these models represent multiple sectors and regions interacting and provide a more flexible and dynamic approach than the rigid IO 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 – including but not limited through research supported by central banks and supervisors – to improve usefulness of the models.

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. 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 biophysical and socioeconomic impacts caused by crossing a tipping point, future research 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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