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THE INSPIRE SUSTAINABLE CENTRAL BANKING TOOLBOX
Policy Briefing Paper 11

# Building blocks for central banks to develop nature scenarios

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## Summary

Models and scenarios are increasingly being adopted by central banks and financial supervisors as a tool to support the assessment of climate risks, but existing scenarios currently do not sufficiently incorporate broader environmental risks, such as nature-related risks, into such assessments.

Nature scenarios are used in models to describe plausible future developments of all elements of nature, the development of socioeconomic variables and policies, and the interactions between them. A significant drawback is that outputs from nature–economy models and scenarios cannot readily be used by the financial sector.

In reviewing a selection of models currently used in economic and nature loss assessments, five key issues emerge for model and scenario development: input data needs; model assumptions; uncertainty around nature–economy interactions; the choice of global or local scenarios; and usability for financial institutions. While there are ways to address some of these challenges, more research is required to operationalise the solutions.

Overcoming these challenges could enable the introduction of more targeted monetary policies and prudential policies, and more effective financial sector risk management. It could also contribute towards shifting financing away from nature-harming investments.

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This paper is part of a toolbox designed to support central bankers and financial supervisors in calibrating monetary, prudential and other instruments in accordance with sustainability goals, as they address the ramifications of climate change and other environmental challenges. The papers have been written and peer-reviewed by leading experts from academia, think tanks and central banks and are based on cutting-edge research, drawing from best practice in central banking and supervision.

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## 1. Introduction

Central banks and financial supervisors around the world are increasingly recognising the relevance of nature-related risks – financial or economic risks posed by natural processes – and acknowledge that they could have significant macroeconomic and financial stability implications (NGFS, 2022a). In response, central banks and financial supervisors have taken many measures to address biodiversity-related financial risks (Almeida et al., 2022), including conducting impact and dependency analyses and incorporating nature-related risks into supervisory expectations and risk management frameworks. The Network for Greening the Financial System (NGFS) has also launched a taskforce to "mainstream the consideration of nature-related risks across the various NGFS streams of work in the coming years" (NGFS, 2022b).

To assess and manage nature-related financial risks, models and scenarios that capture the complex interlinkages between nature, the economy and the financial sector are needed. Financial institutions will need to use scenarios as part of revised risk management practices as they may face higher default risks in their lending portfolios if they do not properly account for environmental dependencies and impacts. Similarly, central banks and financial supervisors will need better models and scenarios to account for systemic risks arising from these dependencies and impacts of environmental degradation on the real economy (through firms) and the financial system (through banks and non-bank financial institutions).

"To assess and manage nature-related financial risks, models and scenarios that capture the complex interlinkages between nature, the economy and the financial sector are needed."

However, existing global nature scenarios are fragmented, and there is a persisting knowledge gap on how the current generations of nature–economy models can be applied for nature-related financial risk assessment. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) provides an overview of use cases and available scenarios for assessing the relationship between nature and the economy (IPBES, 2016). More recently, with a focus on transition risk assessment, Maurin et al. (2022) reviewed global and quantitative biodiversity scenarios, proposing a framework for scenario design.

This paper builds on this work, aiming to improve the understanding of the current generation of models and scenarios on nature–economy interactions in light of their applicability for analysing nature-related financial risks. It discusses key criteria that methodologies for assessing nature-related risks should satisfy if they are to provide useful guidance for the financial sector, and highlights areas where further research is needed.

### 1.1. The growing importance of nature-related risks for the financial sector

Nature has declined at unprecedented rates across the globe in recent decades, posing serious potential economic and financial risks. If immediate action is not taken to prevent nature loss,[1] an accelerated deterioration of ecosystems is anticipated, with potentially severe consequences for the economy and financial system. It is now understood that the economy both depends on and impacts nature, as posited by the 'double-materiality' framework (Täger, 2021). This approach is based on the understanding that firms rely on natural capital assets (the world's stocks of natural resources including geology, soil, air, water and all living things) to produce goods and services in the economy while, at the same time, the nature-harming activities of firms themselves contribute to the decline of nature, reducing the availability of ecosystem services – broadly defined as a range of material and non-material benefits that humans obtain, directly and indirectly, from nature and that sustain and fulfil human life (Millennium Ecosystem Assessment, 2005).

Financial institutions that lend to, invest in and insure these environmentally damaging economic activities are thus also affected by changes to the quality or quantity of

[1] Nature loss refers to the degradation, destruction, pollution or extinction of any element of the biophysical environment, e.g. climate, biodiversity or water.

ecosystem services. The decline of pollinators is one example: pollination supports 75% of global food crop types, with the annual market value of crops dependent on animal pollination ranging from US$235 billion to US$577 billion (Power et al., 2022). Avoiding systemic consequences from environmental degradation, including nature loss, calls for urgent and transformative changes to economic and financial systems (IPBES, 2019), which has far-reaching implications for central banks and financial supervisors (Almeida et al., 2022).

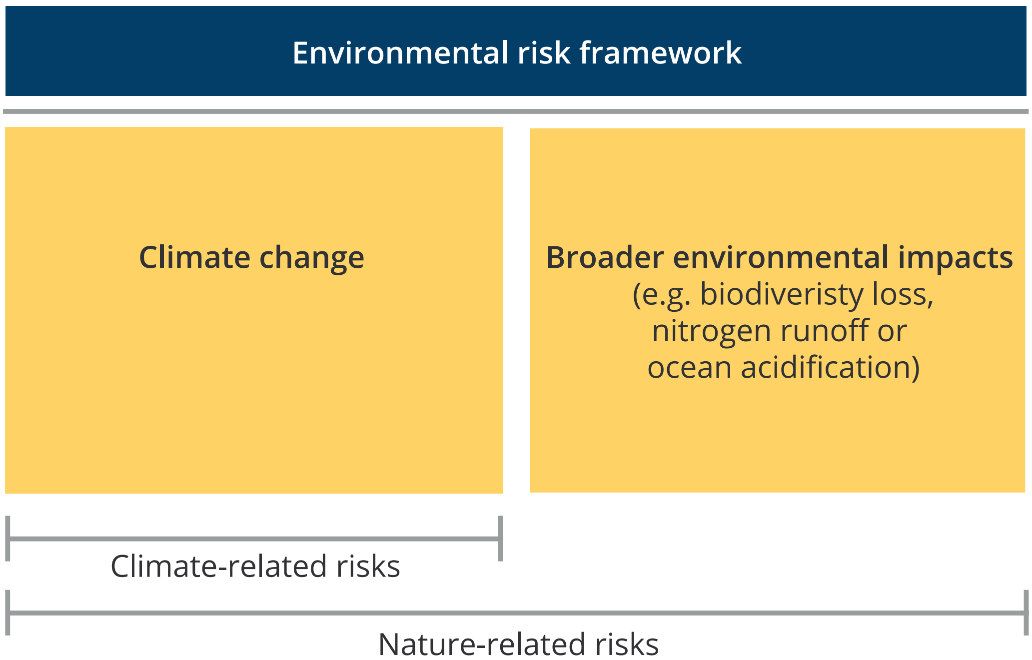
"Nature loss is more localised and context-specific than climate change, with many sectors of the economy being directly or indirectly involved in the degradation of nature."

Analysing nature-related risks as a whole poses greater challenges compared with focussing only on climate-related risks, even though they share similar characteristics in terms of likely impacts on economies and financial systems. Nature-related risks are those financial or economic risks posed by any natural process, including climate change, biodiversity loss, water stress and soil quality (and all the features, forces and processes that occur as a result of a combination of these with other natural phenomena). Both nature- and climate-related risks can manifest in ways that have physical, transition or systemic implications. However, there are some differences. For example:

- Nature-related risk, comprising the entire biophysical environment,[2] is multidimensional and cannot be reduced to a single metric whereas units of carbon emissions, or $CO_2$-equivalent, can be used when measuring climate risk.
- Nature loss is more localised and context-specific than climate change, with many sectors of the economy being directly or indirectly involved in the degradation of nature.
- While there is growing understanding and action on issues related to climate-related risks among the financial sector, particularly central banks and financial supervisors, there is still a lack of awareness when it comes to understanding broader nature-related risks and the interactions between nature and climate.

These aspects make it more challenging to understand the issues surrounding nature loss and to identify solutions, compared with climate change.

**Figure 1. Breakdown of environmental, climate and nature-related risks**




*Source: Authors' adaptation based on the framework developed by the World Bank and Bank Negara Malaysia (BNM) (2022).*

[2] The biophysical environment includes living things ('bio-'), such as plants and animals, and non-living things ('-physical'), such as rocks, soils and water. The biophysical environment is made up of four parts: the atmosphere; hydrosphere; lithosphere; and biosphere. In this paper, 'biophysical environment' is used to refer to 'nature', and the terms are used interchangeably.

### 1.2. Methodologies: using models and scenarios

To manage nature-related risks, central banks, financial supervisors and the financial sector as a whole need tools to better understand them. This requires the development of methodologies and metrics that translate nature-related risks into economic and financial indicators familiar to the financial sector. Given the forward-looking but highly uncertain characteristics of nature-related risks, models and scenarios play a crucial role in assessment and evaluation. Creating a set of severe but plausible scenarios that describe how risks may evolve in the future can help to avoid the underestimation of risks or missing out on potential opportunities, such as higher yields and lower costs from more sustainable and efficient resource use. The scenarios would set out future pathways to nature loss generated by the continuation of current economic activities and support central banks and financial supervisors to introduce policies to better manage nature-related risks and uncertainty.

Scenario-based approaches are already used in the context of climate-related risks but are yet to incorporate broader nature-related risks. The NGFS climate scenarios provide a common reference point for understanding how the physical impacts arising from climate change ('physical risk') and potential changes to climate policy and technology ('transition risk'), as well as other socioeconomic factors, could result in different future outcomes. The third and latest iteration of the NGFS climate scenarios attempts to improve on the previous by providing updates to the country-level climate commitments (made at COP26) and GDP and population pathways, and by including projections of the potential losses from two types of extreme weather event (floods and tropical cyclones). However, nature remains largely absent. It should be noted that a new taskforce by the NGFS on nature-related financial risks is addressing this issue.

"Without considering broader environmental risks such as biodiversity loss, nitrogen runoff and ocean acidification, scenarios would underestimate the overall risk."

Current nature scenarios have limitations, including an inability to capture the complexity of climate–nature interactions. It is well understood that climate change is one of the key drivers of nature loss (see e.g. IPBES, 2019), and that nature loss exacerbates climate change (Power et al., 2022). The climate–nature feedback effect is evident in the case of forest removal, which is not only harmful for biodiversity,[3] given the importance of forests as a natural habitat, but also because their removal can lead to climate risks given their important roles in storing carbon and providing protection against flood and storm events. There are also climate–nature trade-offs to consider. For example, renewable technologies require the mining of minerals and metals which could result in nature loss (e.g. through deforestation) and pollution pressures (e.g. through discarding harmful waste into water sources). Without considering broader environmental risks such as biodiversity loss, nitrogen runoff and ocean acidification, scenarios would underestimate the overall risk by disregarding the feedback effects and trade-offs between climate and nature.

Furthermore, the top-down approach taken in designing these scenarios limits their usability for financial institutions, who have specific requirements such as firm-level information (e.g. on risks and impacts for individual firms). Existing nature scenarios could be improved by incorporating considerations of the broader biophysical environment (e.g. biodiversity loss, land-use change, ecosystem services) as well as firm-level information.

### 1.3. Drivers of nature-related risks

To develop scenarios that are useful for economic and financial actors, it is important to understand the different drivers of nature-related risks. Nature-related risks and impacts can translate into physical or transition risks for firms, central banks and the financial sector as a whole (CISL 2021; Almeida et al., 2022; NGFS 2022a). Physical risk stems from environmental degradation that affects the resources required for firms'

[3] Biodiversity is defined by the Convention on Biological Diversity as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems" (CBD, 2006).

production needs or that ensure the functioning of their operations. For example, it is estimated that more than three-quarters of global crop production depend, to some extent, on animal pollination (FAO, 2016). Meanwhile, firms contributing to environmental degradation are exposed to transition risk, as they can be affected by incoming regulation to limit pollution (of water or air) or the expansion of activities (e.g. by protecting land or seas), or by changes in consumer preferences, such as the growing popularity of meat-free diets and demand for palm-oil-free products. The Kunming-Montreal global biodiversity framework, adopted at COP15 in December 2022, could increase transition risk: one of the targets is to increase the share of protected areas of land and sea to 30% by 2030. Transition and physical risks can negatively impact business operations and profitability, and thus the ability to repay lenders, resulting in market and credit risks for financial institutions.

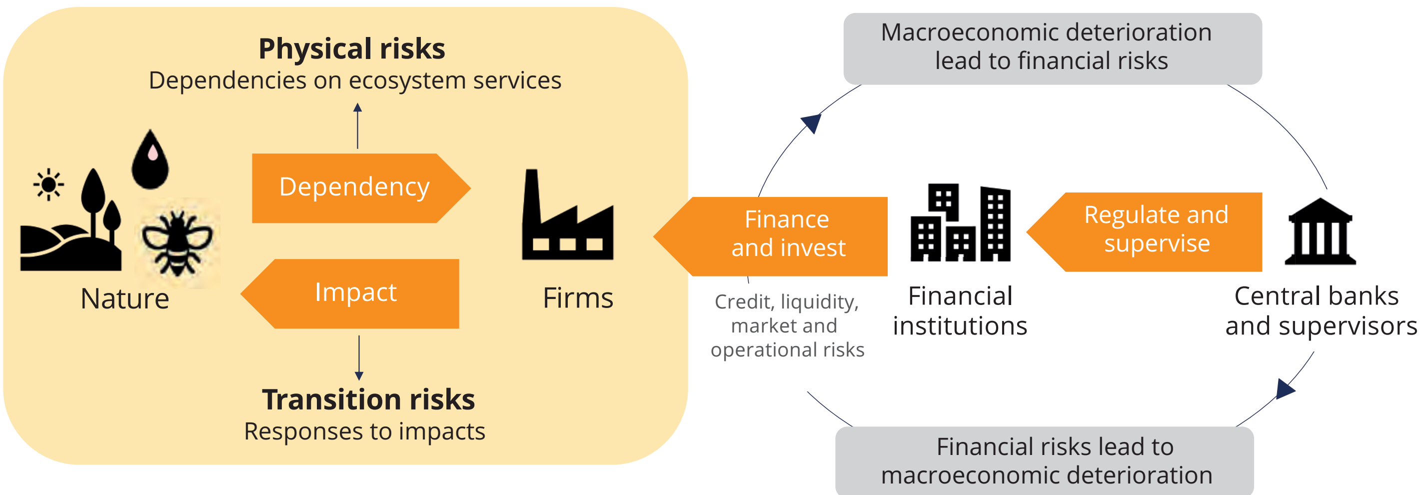
At the systemic level, cascading impacts across supply and value chains could transmit the negative impacts of an individual firm's economic activities to the broader economy. For example, a manufacturing firm polluting a water source such as a river could impact the output of agricultural firms that depend on high quality water from this source for crop irrigation. Given the scale and pace of nature deterioration, multiple localised impacts are possible, and this could eventually accumulate into systemic risks with implications for financial stability (see Figure 2). Ideally, scenarios would capture the future development of the impact of economic activities on nature, policies to limit environmental degradation, societal preferences and the impact of nature degradation on economic activities. Feedback effects such as the interaction between exposure and impacts and supply chain linkages should also be captured.

"Given the scale and pace of nature deterioration, multiple localised impacts are possible and this could eventually accumulate into systemic risks, with implications for financial stability."

## 2. Taking stock of existing nature–economy models

The growing awareness that nature loss will become an increasingly important economic and financial risk means that nature scenarios and tools, such as nature–economy models, will need to be developed to assess and manage these risks. Nature–economy models are models that include both an economic and a nature-related component. This means they can potentially capture the feedback effects between economic activities and the environment.

### Figure 2. Exposure and impact dynamics at firm- and economy-wide levels




*Source: Authors' adaptation based on Almeida and Dikau (2022).*

### 2.1. Applying models and scenarios to nature-related risk

Models and scenarios are distinct from one another but complementary: scenarios describe possible futures resulting from different drivers and policy changes while models translate scenarios into projected consequences for nature, the economy and the financial sector (IPBES, 2016). Models and scenarios can help decision-makers understand the consequences of a range of policy decisions. Scenarios are used to describe possible future developments of the economy, policy, society or ecosystem (e.g. shared socioeconomic pathways [SSPs]) and can be both qualitative and quantitative. Scenarios can be used to design the path to achieving a given target, with stated variables describing biophysical components such as biomass, species richness, functional diversity or habitat structure. Models are tools to quantitatively describe system dynamics and economic behaviour. They aim to outline and assess the ecosystem functions[4] and biophysical processes such as water cycles and biodiversity that underlie the supply of services to people, or the impacts of economic activities on the environment. Models often use scenarios to project how changes in specific drivers translate into consequences for nature and ecosystem services and to understand future nature-related risks. This enables the generation of potential pathways by assessing the spatial or temporal dynamics of economic drivers that could directly or indirectly affect stated variables under policy or resource constraints. As such, combined scenarios and models simulate the future development of economies under specific assumptions.

"Scenarios describe possible futures resulting from different drivers and policy changes while models translate scenarios into projected consequences for nature, the economy and the financial sector."

Nature-related models have different scopes and objectives: some capture the physical impact of economic activities on nature loss while others translate nature loss into economic impacts. Meanwhile, models of ecosystem services translate the state of ecosystems (e.g. the type of land use or the stock of fish) into spatially explicit ecosystem service flows for the economy (e.g. pollination or fish provision), which can be expressed in biophysical or economic terms.

Scenarios can feed into many different types of models (IPBES, 2016), with structural models potentially the most useful for understanding long-term developments. This is especially necessary when future outcomes may differ from historical observations, as is the case with the ongoing processes of climate change and nature loss. At least three broad categories of model can be identified (Low and Meghir, 2017):

- **Fully specified models** make explicit assumptions about the behaviour and objectives of economic agents, the economic system and the evolution of ecosystem services. This enables the models to describe the feedback effects between economic activities and ecosystem services. Accordingly, future relationships can be described in the absence of (or with limited) historical data.[5] These models are thus useful when there is a high degree of uncertainty about the future, making them relevant in the context of nature given that ecological dynamics are characterised by uncertainty, non-linearity and tipping points (Bretschger and Vinogradova, 2019; Leclère et al., 2020; Doelman et al., 2022).
- **Data-driven models** aim to understand the relationship between economic activities and ecosystem services based solely on historical observations. Data-driven models can be useful to assess localised nature loss impacts in a historical context, for example the Aral Sea (Micklin, 2007) or the Dust Bowl in the US (Hornbeck, 2012; see also: Newbold, 2015; Palmer et al., 2022).
- **Partially specified models** combine the two above approaches, identifying restrictions imposed by empirical evidence or theory (Kim et al., 2018; Antolin-Diaz et al., 2021; Boer et al., 2021; Chudik et al., 2021). Given the reliance on both historical data and assumptions about the relationship between ecosystem services and economic activities, this combined approach can also be useful in a context of uncertainty about the future, which applies to the dynamics of nature loss.

[4] Ecosystem functions are "the physical, biogeochemical, and ecological components, processes and outputs of ecosystems that are driven by multiple controls, such as abiotic and climatic factors, ecosystem structure, biodiversity, human disturbance and land management" (Duncan et al., 2015).

[5] It should be noted that most of those models still rely on historical data to estimate or calibrate model parameters.

### 2.2. Assessing the suitability of nature models

Models and scenarios can be assessed against a set of criteria to understand how their results can be translated into relevant financial indicators for the financial sector, including central banks and financial supervisors. Climate- or nature-related risk assessment is usually composed of several steps, from an exposure analysis and the development of severe but plausible scenarios, through to the economic and financial impact assessment. However, current nature-related models and scenarios typically produce economic outcomes at most. While economic indicators (e.g. GDP) are important inputs for financial risk assessment, they cannot directly be used for the assessment of nature-related risks.

Table 1 presents 18 criteria with which to review the applicability of five available approaches for nature-related financial risk assessment. The models reviewed are: GLOBIO; Globiom; IMAGE; REMIND; and the World Bank's GTAP-AEZ-INVEST model (referred to as the 'World Bank model').[6] Table 1 is grouped into three categories. The first relates to the model itself and looks at the economic or biophysical output, the inputs needed, granularity and coverage, and the ability to account for biophysical feedback effects. The second category examines the scenarios adopted, including, for example, the time horizon used and the model's ability to incorporate uncertainty. The third category relates to the usability of these approaches for the financial sector.

"Five key criteria support an assessment of which models and scenarios are most suited for use in assessments of nature-related risk."

The five models reviewed are all fully specified models but can be further categorised into three types: biodiversity models; partial equilibrium models; and general equilibrium models. With the exception of GLOBIO, all models can also be described as integrated assessment models (IAM) as they include an economic and nature-related module. The models differ widely with respect to the applied methodology and outputs they deliver. With the exception of the GLOBIO model, all models analysed provide outputs that are familiar to the financial sector, particularly for risk assessment (e.g. GDP). Some models provide a more granular or explicit representation of biophysical processes but with outputs that are less readily applicable for financial sector use. For instance, GLOBIO's output is a location-based measure of species losses.

We have identified five key criteria to support an assessment of which models and scenarios are most suited for use in assessments of nature-related risk: (i) input data needs; (ii) model assumptions; (iii) treatment of uncertainty around interactions between nature and economic activity; (iv) global versus local scenarios; and (v) usability for the financial sector.

#### Input data needs

All models require different input data to calibrate the assumed relationships and to generate outputs. The five models reviewed have large data input needs in terms of spatial and temporal granularity, which means that data limitations could impact the quality of the assessment. For instance, GLOBIO relies on spatial data for infrastructure, fragmentation and land-use change, climate change, nitrogen deposition, hunting and road disturbance. Globiom requires grid-cell information on land-based ecosystems. IMAGE and REMIND require time series data on population, economy, policy, technology, lifestyle, resources, climate and others. The World Bank model uses inputs from other models: specifically, it relies on spatial data on land use and data on state of the select ecosystem services from InVEST,[7] and sectoral disaggregated economic data from GTAP. Moreover, all the models need inputs about future GDP trajectories and demography (e.g. from the SSPs), policies, technology development and preferences to run scenarios.

[6] This list is not exhaustive, and many other models exist. However, these particular models were chosen due to their relevance and to provide an overview of the variety of existing approaches.

**Model assumptions: agents' behaviour and biophysical and economic development**
Key model assumptions relate to agents' behaviour, the developments of the biophysical environment, the economy, and the interactions between them. These assumptions differ between models, affecting the assessment. All models reviewed that include an economic module (i.e. all except GLOBIO) assume utility-optimising agents, and are either partial equilibrium models (e.g. Globiom) or general equilibrium models (e.g. REMIND and the World Bank model).

Models can assume static or dynamic optimisation. In static (intra-temporal) optimisation, a single value is generated for each time period, allowing for a comparison to be made over two (or more) periods of time. By contrast, in a dynamic (inter-temporal) setting, an optimal time path is generated by the model, allowing assessments to be made over time. This has implications for the analysis as dynamic models are able to explore the pathways that result from interacting socioeconomic and biophysical factors that drive long-term dynamics in the development of nature and the economy. For example, the World Bank Model is 'comparative static', comparing data at two static time points, while the IMAGE and REMIND models are dynamic.

None of the economic models reviewed explicitly incorporates the financial sector, and the granularity of trade and supply chain relationships varies considerably across models. The World Bank model covers 137 countries and 65 commodity sectors, while Globiom, REMIND and IMAGE have a more aggregated structural set-up (e.g. Globiom covers 37 regions) and cover fewer economic sectors, focussing in particular on agriculture and energy.

"None of the economic models reviewed explicitly incorporates the financial sector, and the granularity of trade and supply chain relationships varies considerably."

All the models reviewed make assumptions about possible future developments of the biophysical environment, for example land-use change,[8] climate variables or ecosystem services. IMAGE, REMIND and the World Bank models also include assumptions about possible future policy scenarios. All the scenarios reviewed assume GDP trajectories, demography (e.g. from SSP), policies, technology development and preferences as input data. However, the impact on economic growth is limited due to the exogeneity of assumptions. If a scenario considers ambitious conservation and climate change mitigation measures, there is no effect on the exogenously determined GDP trajectories. For example, even if a fossil fuel-intensive development pathway with strong consequences on carbon emissions and biodiversity loss is taken (e.g. the SSP5 trajectory), the exogenously assumed productivity and resulting GDP growth rate may disguise the impact of damages that could result from strong climate change and nature loss.

**Treatment of uncertainty around the interactions between the biophysical environment and economic activity**
The models reviewed differ in terms of their coverage of biophysical feedback effects, namely the interaction between the state of different ecosystems (e.g. the impact of forest quality on water cycles). These dynamics are characterised by strong uncertainty given the complexity and forward-looking characteristics of nature loss (i.e. historical data is of limited use). Only two models (Globiom for emissions and land use, and IMAGE for land, atmosphere and ocean) capture feedback effects within the biophysical environment. But even in these models, only a limited number of ecosystems are considered. Meanwhile, the nature–economy interaction is mostly described through land-use models, and thus does not consider other important ecosystem functions (e.g. provision of freshwater). GDP impacts emerge from relative price changes as ecosystem services deteriorate (e.g. in the World Bank model), whereas the degree of assumed substitutability of those services (e.g. via trade, or being able to switch to other input factors) has important implications

[7]InVEST is a model that can be used without necessarily being combined with GTAP-AEZ.

[8]The process by which human activities transform the natural landscape, referring to how land has been used and usually emphasising the functional role of land for economic activities (Paul and Rashid, 2017).

for the impact assessment. None of the models reviewed are able to capture both non-linearities and endogenous tipping points, which could be important drivers of severe risk materialisation.

**Global versus local scenarios**

Nature loss and pollution are more localised in their impacts than climate change, and nature scenarios need to be able to capture this location-specific characteristic. This requires the development of many alternative scenarios, as the external validity of findings based on localised scenarios would be limited only to those specific locations. However, local scenarios may not be able to capture global feedback effects and could lead to an underestimation of impacts. Which scenario is chosen would thus depend on the context of its use.

All of the reviewed models rely on a top-down approach for the scenario design (e.g. by relying on global socioeconomic pathways such as the SSPs) and can be calibrated at global and local or national levels. These top-down scenarios assume GDP trajectories, demography, policies, technology development and societal preferences as input data.

**Usability for financial institutions**

Central banks, financial supervisors and financial institutions are already aware of and have used climate scenarios, in climate stress test exercises for example, but familiarity with nature scenarios is limited due to their complexity and lack of financial-related outputs. While all the models reviewed can be freely accessed, their use requires specific expertise which might be lacking within financial institutions. For models and scenarios to be usable for the financial sector, outputs would need to be translated into a financially relevant indicator such as value-at-risk or probability of default. While none of the models reviewed provides this type of output, all of them (with the exception of GLOBIO) are able to produce a measure of GDP change that can be indirectly used by financial institutions. The use of nature scenarios by financial sector participants can help to properly account for broader environmental risks in the financial system and ensure financial stability (see Table 1 overleaf).

This analysis indicates that while nature–economy modelling methodologies are already available, they only partially satisfy the criteria identified, and direct usability for the financial sector is limited. Applying them to nature-related risk assessment requires additional steps to be taken – both by the modelling community and by central banks, financial supervisors and the financial sector as a whole. All five models provide relevant information for nature-related risk assessments, some focusing more on biophysical interaction and others on economic outputs such as GDP. There is room for improvement, specifically relating to the scope of nature–economy relationships covered (e.g. the number of ecosystem services), dynamics and feedback effects within the nature–economy sphere, and globally comparable scenarios. Furthermore, all models require substantial technical expertise and capacity to run and operate, which would benefit from a unified platform (e.g. the NGFS climate scenarios) to provide financial sector participants with readily available and meaningful outputs.

"While all the models reviewed can be freely accessed, their use requires specific expertise which might be lacking within financial institutions."

### Table 1. Stocktake of a selected sample of nature–economy models and scenarios

| | **GLOBIO** (Netherlands Environmental Assessment Agency [PBL]) | **Globiom** (International Institute for Applied System Analysis [IIASA]) | **IMAGE** (PBL) | **REMIND** (Potsdam Institute for Climate Impact Research [PIK]) | **World Bank model** |
|---|---|---|---|---|---|
| **Model** | | | | | |
| **Type** | Biodiversity model | Partial equilibrium model of land-use change (bottom-up) | Integrated assessment model | Integrated assessment model (Ramsey-type growth economic module) | Land-use enhanced computable general equilibrium (GTAP-AEZ) combined with ecosystem service model (InVEST) |
| **Goal** | Measures the average population level response to different stressors across a range of species | Analyses the competition for land use between agriculture, forestry and bioenergy | Captures the global dynamics among societies, biosphere and atmosphere | Calculates the trade-off between investment and energy needs given a set of economic and biophysical constraints | Calculates the economic costs of loss in ecosystem services |
| **Scope** | Biophysical outcome | Economic outcome (in land-based sectors) | Economic and biophysical outcomes | Economic and biophysical outcomes | Economic and biophysical outcomes |
| **Outputs** | Location-based species loss (Mean species abundance [MSA]) | Land-use change | Impacts on climate change, land-use change, biodiversity loss, modified nutrient cycles, and water scarcity | Optimal economic and energy investment | Land-use change, GDP, sectoral disaggregated value added |
| **Input data needs** | Spatial data on infrastructure, fragmentation and land-use change, climate change, nitrogen deposition, hunting and road disturbance (projected in meters) | Grid-cell information on land-based ecosystems | Time series data on various drivers (e.g. population, economy, policy, technology, lifestyle, resources, climate) | Time series data on various drivers (e.g. population, economy, policy, technology, lifestyle, resources, climate) | Spatial data on land use, and the state of select ecosystem services (InVEST), sectoral disaggregated economic data (GTAP) |
| **Data sources** | MSA maps | Gridded representation of land use (FAOSTAT) | Various sources (UN, GTAP database, World Bank, Food and Agriculture Organization [FAO]) | Outputs from other biophysical and land-use models (e.g. MAGICC and MAgPIE) | InVEST and GTAP database |
| **Sectors** | N/A | Agriculture (including livestock), forestry and bioenergy | Energy, agriculture, land use | Energy and non-energy sectors | 65 commodity sectors, including agriculture, forestry, fisheries and related industries |
| **Regions** | N/A | 37 aggregated economic regions | 26 regions | 12 regions | 137 regions |

*cont.*

### Table 1. Stock-take of a selected sample of nature–economy models and scenarios

| | GLOBIO (Netherlands Environmental Assessment Agency [PBL]) | Globiom (International Institute for Applied System Analysis [IIASA]) | IMAGE (PBL) | REMIND (Potsdam Institute for Climate Impact Research [PIK]) | World Bank model |
|---|---|---|---|---|---|
| **Model** | | | | | |
| **Can be calibrated at global and local level** | Yes | Yes | Yes | Yes | Yes |
| **Biophysical feedback effects** | No | Yes – between land use and emissions | Yes – between land, atmosphere and oceans | No | No |
| **Uncertainty** | Data, parameters and modelling uncertainty | | | | |
| **Scenario** | | | | | |
| **Scenario adopted** | Land-use change scenarios (based on IMAGE) | Land-use change scenarios | Climate and policy scenarios | Climate, land-use and policy scenarios | Partial ecosystem collapse and policy scenarios |
| **Input data needs for scenarios** | GDP trajectories and demography (e.g. from SSP), policies, technology development and preferences | GDP trajectories and demography (e.g. from SSP), policies, technology development and preferences | GDP trajectories and demography (e.g. from SSP), policies, technology development and preferences | GDP trajectories and demography (e.g. from SSP), policies, technology development and preferences | GDP trajectories and demography (e.g. from SSP), policies, technology development, preferences and ecosystems (wild pollination, timber provision and fisheries) |
| **Time horizon** | Any (depending on the model with which it is combined, mostly IMAGE) | 2000 to 2030, 2050 and 2100 (10-year time step) | 2050 or 2100, with annual or 5-year time step | 2100 with a 5-year time step | 2022 and 2030 (the timeframe is for illustrative purposes only – the World Bank Model is a comparative static model) |
| **Uncertainty** | Subject to uncertainties in the climate, demographic and economic scenarios used | | | | |
| **Usability** | | | | | |
| **Open access** | Yes | Yes | Yes | Yes | Yes |
| **Output directly relevant for the financial sector** | No | GDP, agricultural sector outcomes | GDP, energy and agricultural sector outcomes | GDP, energy sector outcomes | GDP |
| **Applications** | Schipper et al. (2019) | Frank et al. (2018) | Doelman et al. (2022) | Luderer et al. (2019) | Johnson et al. (2021) |

## 3. Discussion: challenges and implications

As presented in Section 2, there are existing models and nature scenarios that can be used to better understand nature-related risks, albeit imperfectly. As is the case with other models and scenarios, including those used for climate considerations, it is unlikely that a perfect tool can be built. The added complexities of measuring and modelling biophysical aspects, including nature–economy interactions and the existence of tipping points, make this task even more challenging. The assessment criteria outlined in Section 2 – in particular the five priority criteria – help to identify where these challenges lie, and these are discussed further below, along with the additional challenges of tipping points and compounding risks.

“The assumed substitutability of nature with human-made capital and the input factors for economic production could have significant implications for the economic impacts of nature loss.”

### 3.1. Input data needs

Models and scenarios require large data inputs, and for a number of reasons, it is difficult to locate, understand and use existing data. First, nature-related data only captures geo-specific physical impacts and is not easily matched with firm-level information, including on supply chains (although notable progress is being made in this area; see for example Wieland et al., 2022). Second, data is held in various locations (e.g. research institutions and universities, different government ministries and environmental agencies, international organisations, NGOs and the private sector) rather than compiled in one database, which makes it difficult and time-consuming for financial sector participants to locate and use the data. Third, the financial sector has a limited understanding of available nature-related datasets and their application, resulting in inertia with regard to assessing nature-related risks. Fourth, time series datasets for environmental-related data are not always available or do not have the desired coverage. Finally, poor data quality can directly contribute to model uncertainty.

### 3.2. Model assumptions

The choice of assumptions about the behaviour of economic agents, biophysical and economic development, and the parameters used in the models are key drivers of model outcomes. In general, models are based on assumptions about economic and social dynamics, and these can differ between models. For example, there could be different assumptions about the behaviour of agents, specification of production functions,[9] or the pattern and drivers of economic growth.[10] While the models reviewed in Table 1 make broadly similar assumptions on socioeconomic trajectories, they differ in how these trajectories are taken into account (notably the interactions between human, land and climate systems) and in the choice of parameters used. These assumptions can influence the outcome of the assessment. For instance, the assumed substitutability of nature with human-made capital (i.e the ‘weak sustainability approach’ described by Dietz and Neumayer, 2007) and the input factors for economic production could have significant implications for the economic impacts of nature loss.

Another related issue is the limited representation of feedback effects between aspects within the biophysical environment and economic activities in current models (Maurin et al., 2022). Furthermore, the scope and detail of representing several segments of the economy, the financial sector and nature – and their interactions – differ across models. For example, most models do not explicitly consider the financial sector, which due to its dynamic interaction with the real economy could be either a risk amplifier or an enabler for green investments (Battiston et al., 2021). These aspects are particularly relevant in the case of nature, as disregarding them might lead to an underestimation of potential negative or positive outcomes. It is important to recognise such caveats and limitations when interpreting results and outcomes.

[9]For example, a Cobb-Douglas production function which assumes constant returns to scale and a certain elasticity of substitution among input factors.

[10]For example, conditional convergence among countries or the fact that economic growth assumptions are only to a limited extent affected by the level of ambition of scenarios.

## 3.3. Uncertainty

### 3.3.1 Nature–economy interactions

Uncertainty underscores models and scenarios of nature–economy interactions as it is not possible to infer how they will develop from past observations. Model uncertainty is amplified in nature–economy assessments given the uncertainty around data inputs, model specification and biophysical and economic developments. Models are also characterised by structural and methodological uncertainty; that is, an incomplete knowledge of the parameters and functional relationships between variables (e.g. the impact of climate change on crop yields and local climate change). An additional layer of complexity is added by the non-linearity of nature (Whiteman et al., 2013) and the feedback effects of biophysical processes that are currently omitted in most models but could have large impacts (Lade et al., 2020; 2021). In addition, existing models generally use the mean of the probability distribution of projected impacts, neglecting the low-probability, high-impact tails of the distribution (Weitzman, 2009; Ackerman et al., 2010; Marten et al., 2012), which could lead to an underestimation of the overall risk posed by nature degradation. Meanwhile, scenario uncertainty results from uncertainties in future scenario drivers, policy targets and societal trends including population, economic growth, technology, policy targets and societal preferences.

> "A key aspect of model and scenario uncertainty is the consideration of tipping points, but current models and scenarios only include them to a limited extent."

### 3.3.2. Tipping points

A key aspect of model and scenario uncertainty for nature assessments is the consideration of tipping points, which current models and scenarios only include to a limited extent. Tipping points refer to a critical threshold at which point a tiny perturbation can qualitatively alter the state or development of a system (Lenton et al., 2008).[11] They can occur naturally but are commonly discussed in the context of human-mediated climate change or nature loss. Tipping points could emerge when there is limited substitutability of inputs to production processes or when the absorbing capacity of ecosystems is exceeded (Folke et al., 2004; Bretschger and Vinogradova, 2019; Franklin and Pindyck, 2018). Biophysical tipping points (e.g. eutrophication[12] or desertification) could trigger large, abrupt and persistent changes in the structure and function of ecosystems, or lead to socioeconomic changes. Such events could fundamentally alter the dynamics of the relationship between economy and nature. For example, if agricultural land becomes less fertile and no longer meets the necessary conditions for crop production, mass migration of populations might be triggered. Currently, most nature–economy models do not factor in the non-substitutability of natural capital. Model assessments could therefore be based on overly optimistic assumptions, particularly in the context of ecosystem collapse (Dietz and Neumayer, 2007).

### 3.3.3. Compounding risks

Uncertainty also arises from a lack of understanding of cascading and compounding impacts. The impact of nature loss might exceed the direct impact faced by individual firms, depending on the elasticities of substitution. Indirect impacts could emerge via supply chain networks, where the impacts of nature loss could cascade through the economic system. Likewise, financial sector linkages could play a role in amplifying potential financial risks, especially if banks with a high exposure to a highly affected sector are systemically relevant for the financial system. Not accounting for these indirect impacts increases the uncertainty of actual risks arising from nature loss.

The loss of one ecosystem service could lead to cascading and compounding effects on various ecosystem functions and across multiple regions, resulting in a loss of ecosystem resilience and, in turn, economic and financial resilience (Power et al., 2022).

[11] In the context of biophysical systems, tipping points can be understood as leading to "abrupt and possibly irreversible shifts between alternative ecosystem states, potentially incurring high societal costs" (Dakos et al., 2019).

[12] Eutrophication refers to the increase of plant and algae growth in estuaries and coastal waters as a consequence of enrichment with nutrients. If too many nutrients are added, this could kill the inhabiting species and bring those waters to the brink of collapse.

For example, early-stage analysis finds that while 42% of the value of securities held by French financial institutions comes from issuers that are highly dependent on one or more ecosystem service, when indirect dependencies are taken into account, all issuers of securities in the portfolio studies were found to be at least partly dependent on all ecosystem services throughout their value chains (Svartzman et al., 2021). Meanwhile, nature and climate could also interact to create further compounding risks (Almeida et al., 2022), and this relationship is yet to be considered in the current suite of nature scenarios.

### 3.4. Global versus local scenarios

The trade-offs that arise as a result of choosing either local or global assessments pose an additional challenge in the formulation of effective nature scenarios. The geographical heterogeneity that characterises nature-related impacts and exposure requires scenarios that are context-specific. Local scenarios are more likely to accurately capture the dynamics of a local ecosystem, albeit at the expense of a lack of generality and potentially missing systemic impacts. Models can estimate local environmental risks and impacts but it is difficult to prove the external validity of these results. For instance, tipping points for ecosystem services can be estimated in specific contexts (Palmer et al., 2022; Dietz et al., 2021), but it is unclear to what extent the threshold values identified can be applied to ecosystem services in different locations.[13] On the other hand, models working on a global scale enable visualisation of the linkages between firms around the world. In a globalised world, it is important to understand the impact of a product or process on nature throughout its entire value chain, particuarly which stages of production have the greatest negative impact. This would improve the understanding of the risks involved in the production process.

“While it is unlikely that perfect and complete biophysical data will become available, ecosystem-specific data readily exists and can be used now for financial decision-making.”

### 3.5. Usability for the financial sector

Beyond the issues within the models and scenarios themselves, there is a lack of capacity within the financial sector to use them effectively and a mismatch between the structure of scenarios and the needs of the financial sector. The lack of expertise and capacity within the financial sector prevents models and scenarios being used to their full potential. Meanwhile, the top-down approach adopted by scenarios does not reflect the granular approach the financial sector needs. While information useful for macroeconomic and financial assessments can be derived from scenario analysis, model and scenario outputs often cannot be directly used to make financial decisions as existing models do not specifically provide indications of physical and transition risk. Financial institutions and financial regulators may lack the expertise or capacity to convert the outputs of existing models and scenarios into financial risk measures.

## 4. Recommendations for designing nature-related scenarios

The review of models, identification of key criteria and discussion in Sections 2 and 3 provide a starting point for evaluating nature scenarios. This section recommends some concrete steps that the financial sector can take to address the shortfalls identified.

**Better understanding and mastery of existing data, coupled with advances in data availability, usability, granularity and quality, can improve the performance of nature models.** A myriad of nature-related data already exists, including some granular and high-frequency level datasets on water, deforestation and biodiversity, and there are already attempts to systematically organise existing information by the TNFD knowledge bank, for example. While it is unlikely that perfect and complete biophysical data will become available, ecosystem-specific data readily exists and can be used now, including for financial decision-making. Meanwhile, advances in data collection and technology, such as progress in geospatial analysis,

[13]This is despite some recent advancements. See, for example, Lade et al. (2021).

has already improved, and is expected to further improve, data availability related to both the quality of ecosystems services and asset-level location. Furthermore, the adoption of environmental accounting could enrich the body of data on firms' impacts on nature (as captured in the World Bank's 'Changing Wealth of Nations' database, for example). These improvements can support the analysis of firms' exposure to and impact on ecosystem services. Building capacity among financial sector participants, including central banks and financial supervisors, to locate and utilise this existing nature-related data could improve risk management practices.

**Assumptions are unavoidably part of any model and scenario, but allowing for wider model heterogeneity and exploring the complementarities between models with different assumptions can improve understanding of nature-related risks and impacts.** In order to investigate the extent to which results are driven by model-specific assumptions, a suite of distinct model types can be used. For instance, Stock Flow Consistent (SFC) models or Agent Based Models (ABM) usually rely on different economic model assumptions to their Computable General Equilibrium (CGE) counterparts, making a model comparison specifically useful. SFC models and ABMs usually do not rely on an underlying optimisation framework but are rooted in a system dynamic setup. The strength of SFC models is the explicit representation of financial and economic sector interaction as interconnected balance sheets (Monasterolo and Raberto, 2018). SFC and ABM models can represent emerging non-linear behavioural patterns, which could be particularly suited to the characteristics of nature loss. On the other hand, CGE models allow a high sectoral disaggregation of impacts, while Integrated Assessment Models (IAM) have very detailed representations of the relationships between the economy, land use and energy.

Similar considerations apply to assumptions used for the biophysical modules. Different biophysical models provide varying representations of biophysical processes, in terms of the ecosystems they focus on and the level of granularity used. For instance, the GLOBIO model can produce greater detail on location-based species loss whereas the IMAGE models produce more detail on land-use change (especially when coupled with the MAgPIE model). Different models can address different questions, but some might also be able to address the same questions through different approaches. Therefore, utilising different models and comparing their results might be a way to reduce model uncertainty. While the comparability of results might be limited, comparing the different drivers of the results across model classes could provide relevant insights.

"Structural uncertainty can be addressed to some extent by introducing thresholds or non-linearities, for example."

**To address issues surrounding model and scenario uncertainties, multi-model ensembles and sensitivity analysis can be used.** By considering different combinations of models and parameters, and by conducting a sensitivity analysis, it is possible to establish the full range of model behaviours and to determine the importance of each source of uncertainty (Kim et al., 2018; Leclère et al., 2020; Doelman et al., 2022). Structural uncertainty can be addressed to some extent by alternative model formulations: by introducing thresholds or non-linearities, for example. In addition, comparing results from a range of different models can be useful to account for a more diverse range of outcomes. By creating wider ranges of possible outcomes, sensitivity analysis can help reduce the risk of errors in the original assumptions for the baseline analysis. Sensitivity analysis can also inform users (such as policymakers) about the importance of each of the various elements in determining the final output, allowing them to understand which variables are the key drivers of outcomes and enabling better policy interventions.

**To address uncertainties related to nature–economy interactions, tipping points and compounding effects could be introduced.** The current generation of models cannot capture the endogenous emergence of global tipping points, non-linearities or compounding effects, but – while it is challenging – there are ways to gain insight into their potential effects. For example, assumptions can be made about the thresholds at which the tipping points might happen, and stylised representations of compounding effects could be developed. Introducing endogenous tipping points and accounting for compounding effects may never be perfected, but for now, it is useful to apply ecosystem collapse scenarios to gain insight on the tails of the distribution of potential impacts (see Johnson et al., 2021). Although arbitrary, the introduction of such thresholds could be used to simulate how the outcomes would change under drastically different assumptions about the development of ecosystem services.

**The choice of whether to adopt global or local scenarios entails trade-offs.** Nature-related impacts and pressures are more localised and context-specific than for climate. A firm's impacts and dependencies on nature are location-specific and will be affected by changes in the biophysical environment in which it operates. Using a global approach when developing scenarios would therefore be less relevant to local users. However, using highly localised scenarios might not enable relevant global feedback effects to be captured, providing only a partial understanding of risks and impacts. Thus, scenarios must be flexible enough to be used at both the global and local level.

**Central banks, financial supervisors and the financial sector as a whole will need to develop the necessary skills to understand how to choose and use models and scenarios suited to their objectives.** For instance, users within financial institutions might be interested in the implications of the collapse of a specific ecosystem service or may need models and scenarios that focus on specific sectors or sub-sectors that they are most exposed to. Ideally, scenarios for financial institutions would take a bottom-up approach in order to include firm-level information that would enable the identification of best-in-class (i.e. low-risk) firms. This would justify financial institutions focussing on a small number of variables to be analysed in great detail while treating several variables exogenously in the assessment. The trade-off for these smaller models is that they might oversimplify the description of relationships, but on the other hand, they enable more general dynamics in the variables of interest to be modelled. Central banks and financial supervisors might be more interested in understanding the financial stability implications of nature-related risks, for example where individual defaults lead to systemic default. Financial supervisors may also place more emphasis on double materiality to account for systemic risks that could arise from impacts and dependencies. For these purposes, central banks and financial supervisors may consider using models that include many sectors and connections and account for a wide range of endogenously-determined variables. However, this would come at the cost of reduced granularity in the assessment, harder to solve models and reduced flexibility in the choice of the parameters. It is therefore important to be clear about the specific purpose and application of the model.

"Ideally, scenarios for financial institutions would include firm-level information to enable the identification of low-risk firms."

## 5. Conclusion

While multiple models of nature–economy interactions are already available, considerable methodological gaps exist and an assessment of risks from the financial sector's impacts and dependencies on nature is needed. A multitude of nature–economy models already exist, benefitting from recent improvements in data quality and availability and computational capacity – improvements that are expected to continue. Biophysical models usually have a specific focus, on species loss and land-use change, for example, and provide outputs that are difficult to translate into indicators that the financial sector can use for financial risk management. Nature–economy models (e.g. IAMs or the World Bank's GTAP-INVEST model) bridge this gap by providing outputs such as GDP that can be used by the financial sector. Yet challenges and caveats persist for the current generation of nature–economy models and these require further research.

We have identified five challenges, relating to: input data needs; model assumptions about agents' behaviour and biophysical and economic development; treatment of uncertainty around biophysical environment and economic interactions; global versus local scenarios; and usability for financial institutions. These challenges will have to be overcome to improve the assessment of nature-related risks. The usability of biophysical data is still limited while model assumptions, as an important driver of the results, should be better leveraged according to the relative advantages of different approaches. Uncertainty around nature–economy interactions remains a key challenge, but this uncertainty can be mitigated by using multi-ensemble models and sensitivity analysis. Both global and local scenarios are needed for various future developments including policy implementation, ecosystem degradation and economic development, but trade-offs must be understood. Finally, any progress on these dimensions has to be accompanied by increased capacity among financial sector participants, particularly for risk management.

Given the complexity of modelling and scenario development and the urgency of nature-related risks, it is important that aiming for perfection does not impede good progress. While they carry certain caveats, existing exposure analysis can provide useful insights. They show that the financial sector's dependencies and impacts on nature is generally high and that the key sectors with particularly high impact are agriculture, forestry and mining. They also show that exposure to certain ecosystem services, such as freshwater provision and climate regulation, is particularly high. These provide relevant insights on where the potential to reduce damage to nature is highest, and which ecosystem services should be included in nature scenarios. Meanwhile, global nature-economy model assessments (such as those conducted by Johnson et al., 2021), already indicate that nature loss could be material for the economy.

Moving from exposure analysis to a comprehensive nature-related risk assessment could enable the introduction of more targeted and effective financial sector action. Improving models and scenarios would enable more granular analysis of the potential financial risks of nature loss which would in turn enable a more targeted and context-specific regulatory and supervisory response. The financial sector could use those insights to adapt their risk management practices, ultimately shifting financing away from nature-harming investments.

"Moving from exposure analysis to a comprehensive nature-related risk assessment could enable more targeted and effective financial sector action."

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