Environmental *Change* Institute

eci

UNIVERSITY OF OXFORD

The Green Scorpion: the Macro-Criticality of Nature for Finance

Foundations for scenario-based analysis of complex and cascading physical nature-related financial risks

Published as Oxford-NGFS Occasional Paper

Nicola Ranger, Jimena Alvarez, Anna Freeman, Thomas Harwood, Michael Obersteiner, Estelle Paulus and Juan Sabuco

December 2023

Resilient Planet Finance Lab

Citation

Ranger, N., Alvarez J., Freeman, A., Harwood, T., Obersteiner, M., Paulus, E. and Sabuco, J. (2023). The Green Scorpion: the Macro-Criticality of Nature for Finance – Foundations for scenario-based analysis of complex and cascading physical nature-related risks. Oxford: Environmental Change Institute, University of Oxford.

Acknowledgements

This work was co-funded by INSPIRE, the NERC Integrating Finance and Biodiversity for a Nature Positive Future programme (Integrating Nature Climate Scenarios and Analytics for Financial Decision-making project, INCAF) and the Oxford Martin Systemic Resilience Programme, and benefitted from nature risk analytics supported by Climate Arc as part of the Resilient Planet Finance Lab at the Environmental Change Institute. The work was commissioned as a contribution to the work of the Task force on biodiversity loss and nature-related risks (Task force Nature) of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS). We express our sincere thanks to Romain Svartzman*, Jeffrey Althouse* and Marie Gabet* of the Banque de France and Serafín Martínez Jaramillo, Banco de Mexico, and all the members of the NGFS Task force Nature for their guidance and inputs on this research, and Akaraseth Puranasamriddhi and Emma O'Donnell of the Environmental Change Institute for research assistance. We also express gratitude for the wider ongoing collaborations and discussions as part of the NERC-funded INCAF project that this research has benefitted from, including the University of Reading (Tom Oliver, Anne Verhoef, Rowan Sutton and Helen Killick) and UK Centre for Ecology and Hydrology (Paula Harrison, Mike Perring*, James Bullock, HyeJin Kim), the Green Finance Institute (Helen Avery, Ingrid Holmes and Rhian-Mari Thomas), National Institute for Social and Economic Research (Ian Hurst, Iana Ladze, Stephen Millard and Patricia Sanchez Juanino), TNFD (David Craig, Emily McKenzie, Tony Goldner, James d'Ath and the rest of TNFD Secretariat), Defra (Neha Dutt, Louise Baker and Saad Qayyum), UNEP WCMC (Joanna Wolstenholme, Sebastian Bekker and James Vause), the Bank of England* (Theresa Löber, Chris Faint, David Swallow, Danae Kyriakopoulou, David Gayle, Maria Flatman, Ines de Sousa Almeida and Annabel Williamson), Financial Conduct Authority (Carlos Martin Tornero), the members of the UK Climate Financial Risk Forum (including Billy Suid, Liam McNamara and Sandy Trust*) and Elena Almeida (now London School of Economics and Political Science). Thank you in particular to those colleagues who kindly provided review comments on this draft [*]. This INSPIRE (research, publication, project, website, report, etc.) is funded by the Gordon and Betty Moore Foundation through The Finance Hub, which was created to advance sustainable finance. The views expressed represent those of the authors. Photo by Leon Pauleikhoff on Unsplash.

The *'Green Scorpion'* naming reflects the *'sting in the tail'* of nature-related financial risks, the need to explore cascading and tail-risks and the risk amplification of climate change by nature. **This paper is published as an NGFS-Oxford Occasional Paper alongside NGFS (2023a) available at:** https://www.ngfs.net/en/the-green-scorpion-macro-criticality-nature-for-finance

Funders

UKRI Natural Environment Research Council · Integrating Finance & Biodiversity · INSPIRE · Oxford Martin School · climate arc

Contents

Executive Summary

The erosion of natural capital linked with biodiversity loss and environmental degradation generates significant and long-term risks to society, the economy and therefore financial institutions (FIs), from increasing the risk and impacts of pandemics, floods and droughts, to undermining water quality and supplies, soil erosion, damaging agricultural production and risks to human health. More than half of global gross domestic product (GDP) is dependent on nature and its services, yet it could also be argued that there is no economy (or indeed, life) without these critical services, such as water, clean air and food. Human activities, such as land-use change, overextraction and pollution, are degrading this foundation to social and economic well-being; the 2019 Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), for example, concluded that fourteen of the eighteen critical ecosystem services assessed had declined since the 1970s. Indeed, the degradation of natural assets such as forests and soils acts as a risk multiplier on climate change and vice versa.

History, as well as the science, point to the potential scale of the impacts; yet a challenge for financial institutions is that the toolkit, and underpinning data, needed to account for these risks in decision making, is currently limited. Most studies to date have considered only direct risks to particular sectors and geographies. Yet, we know from analyses of climate risks that the largest risks are likely to emerge from the non-linear interaction of risk drivers, leading to complex, cascading and compounding risks. Indeed, the majority of studies by Central Banks to date have focussed on dependencies (exposures) not risk and do not account for these cascading risks. This means that studies to date have potentially significantly underestimated the scale of the risks. Indeed, nature and climate risks interact and compound, leading to even greater risks. For example, degradation of soil quality can increase the impacts of drought leading to even larger impacts on food production; while removal of forests can increase flood risk. Climate change can amplify impacts on nature; for example, fisheries impacted by overfishing and ocean acidification. The strength of the interplay between climate and nature leads us to conclude that within risk assessments, both must be considered in parallel to avoid underestimates and further that the potential for tipping points and cascading risks cannot be ignored in scenarios. The wider cascading impacts are challenging to predict and include political instability and civil unrest.

The urgency of action globally to protect and restore biodiversity and natural capital is clear and well accepted and financial institutions and Central Banks have a crucial role to play. The policy direction is now clear. The Kunming-Montreal Global Biodiversity Framework (GBF) - the equivalent of the Paris Agreement for climate change - was adopted in 2022 and set an ambitious pathway toward the global vision of a world living in harmony with nature by 2050, with four goals for 2050 and 23 targets for 2030. How financial institutions price and allocate capital within the economy will play a key role in achieving these goals. The GBF will be a an increasingly strong driving force for action, in the same way as the Paris Agreement has been on climate. This itself creates transition risks but also significant opportunities for proactive financial institutions.

Today, nature risks are not priced into financial markets and are not accounted for in the scenarios used by financial institutions, Central Banks and supervisors to date, leaving the financial system exposed to potential systemic risks, as well as contributing to the misalignment

of capital flows with societal goals. The uncertainty and lack of pricing of this risk is a market failure which means that the way capital is allocated in the economy is not aligned with GBF goals and is flowing to activities that generate risk unintentionally. We demonstrate here that nature-risks can be even more immediate than physical climate risks and indeed act as risk amplifiers on climate change. Better measurement, management and pricing of these risks is an important step for financial resilience and underpins the transition to a nature-positive future, albeit is not alone sufficient without wider policies and action. For Central Banks, there is also a need to identify and address any systemic or structural issues such as regulatory gaps, inadequate oversight or the potential for speculative bubbles that may contribute to financial instability and provide guidance to firms to minimise conditions that could lead to such a crisis.

The main objective of this report is to draw upon the science and economics of nature to help develop the scenario approaches for nature-related financial risks needed to assess the macro-criticality of nature for financial institutions, and inform action by Central Banks and financial institutions, and couple this with a preliminary assessment of the relative scale of risks across countries. Different applications require different types of scenarios. For example, for prudential regulation of Central Banks and supervisors, the main focus of this report, and relatedly setting capital requirements of financial institutions, there is a need to explore plausible yet more extreme scenarios. Our focus is on physical nature-related financial risks; that is, those associated with physical changes in nature and the ecosystem services it generates for our societies and economies. To design a scenario approach, we take as a starting point the conceptual framework proposed by the NGFS and the scenario and risk assessment guidance of the Taskforce on Nature-Related Financial Disclosures (TNFD), learn from climate financial risk assessment, and develop a set of principles and a framework for assessing the macro-criticality of nature-related risks based on the science and economics. This is supported by new research on risk transmission channels from nature to finance including through an analysis of more than sixty historical analogues. The output is an inventory of almost eighty potential nature-related physical risk shocks (hazard-primary economic receptor pairs) that can form the basis to scenario development. A further innovation in this report is the shift from dependency to risk. We present a new preliminary risk screening approach for FIs, Central Banks and supervisors and demonstrate how risks can be quantified for five potential risk dimensions (pollination, ground water, surface water, air quality and water quality (pollution)).

Our preliminary analyses clearly demonstrate the macro-criticality of nature-related risks for society, economies and the global financial system. The approach developed in this report is primarily aimed at comparing risks across sectors and countries, however the values at risk that emerge are substantial. Water-related risks are dominant and could constitute 7 – 9% of global GDP (5% VaR – Value at Risk), with significant impacts on the manufacturing sector. Risks to agriculture are also significant, estimated at around 14 – 18% of output at risk from water-related risks and potentially 12% of output at risk related to pollinator decline. These direct impacts could be amplified by cascading feedbacks across markets, and act as a risk multiplier on climate change, leading to significant impacts on people and economies, as well as the global financial system. It is important to note that in this study, we look at only five ecosystem services; subsequent work will provide analyses for all twenty services identified in the ENCORE database. As such, these estimates should be treated very much as a lower bound.

The research motivates further work by Central Banks, as well as governments and financial institutions, to assess risks and identify actions to mitigate them. There is a clear rationale for precautionary action by Central Banks to assess these risks and identify where actions are required to mitigate them. In addition, a clear role for the NGFS in supporting further research and development in this area and providing technical assistance to its members to develop appropriate scenarios.

1. Introduction

Nature[1]-related financial risk assessment is in its infancy, yet its potential importance in terms of both financial stability and nature recovery is increasingly recognised. More than half of global gross domestic product (GDP) is dependent on nature and its services, 44 USD Trillion (WEF, 2020), yet it could also be argued that there is no economy (or indeed, life) without these critical services, such as water, clean air, fertile soils and food. The 2019 Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) concluded that fourteen of the eighteen ecosystem services ('categories of Nature's contribution of people') that were assessed had declined since the 1970s, while outputs of food and other products had risen (IPBES 2019) (Figure 1). It further concluded that "*nature across most of the globe has now been significantly altered by multiple human drivers, with the great majority of indicators of ecosystems and biodiversity showing rapid decline*". These drivers include land-use change, pollution, extraction and climate change. Indeed, climate change and nature are intimately interlinked, with degradation of natural assets such as forests and soils acting as a risk multiplier on the impacts of climate change and vice versa (Pörtner et al. 2022). The erosion of natural capital generates significant and long-term risks to society and therefore financial institutions, from increasing the risk and impacts of pandemics, floods and droughts, to undermining water quality and supplies, damaging agricultural production and creating risks to human health. History, as well as the science, point to the potential scale of the impacts.

These risks are not currently priced into financial markets and are not accounted for in the scenarios used by financial institutions, Central Banks and supervisors to date for prudential risk management, leaving the financial system exposed to potential systemic risks. The uncertainty and lack of pricing of this risk also means that the way capital is allocated in the economy is not 'efficient' with finance flowing to activities that generate risk unintentionally. Better measurement, management and pricing of these risks is an important step for financial resilience and underpins the transition to a nature-positive future, albeit is not alone sufficient without wider policies. For Central Banks, there is also a need to address any systemic or structural issues such as regulatory gaps, inadequate oversight or the potential for speculative bubbles that may contribute to financial instability and provide guidance to firms to minimise conditions that could lead to crisis. Understanding the risk is the first step to informing action.

[1] In this report, we use the term nature to describe the natural world and its living organisms (Box 1).

How material are these risks to financial institutions, when compared with climate change and other risks? To address this question, we need to develop analytics and scenarios to understand the potential scale of the risks, their timescales and distributions. In terms of assessing and managing nature-related financial risks, Central Banks and financial institutions are arguably where they were around five to ten years ago with climate change risks. That is, making the first assessments of the potential financial risks related to nature loss, in order to take decisions on what additional analyses and measures may be required. Indeed, the scientific evidence base on economic impacts of biodiversity loss and environmental degradation is less well developed than for climate. Most studies by financial institutions to date have considered only risks to particular sectors and geographies. Yet, we know from analyses of climate risks that the largest risks are likely to emerge from the non-linear interaction of risk drivers, leading to complex, cascading and compounding risks (Ranger, Monasterolo, Mahul, 2022). This report focusses on building the foundations for analysing such risks to assess the macro-criticality of nature.

Scenario analysis and stress testing is an important tool used by financial institutions to assess future risks under uncertainty. Scenarios have become a common tool used for climate financial risk assessment over recent years; with the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) now on its fourth iteration to date (November 2023). Arguably, the challenges of scarcity of data, gaps in the evidence base on the dependencies of economic sectors on nature, limitations of models, lack of capability within financial institutions and uncertainties in risk estimation are even greater for nature than for climate. Under such conditions of uncertainty, well-grounded but simple, flexible and transparent approaches can sometimes be more useful and effective than more complex approaches. The objective of this report is to draw upon the science and economics of nature to help develop such approaches, with a particular emphasis on building the foundations for assessing more complex, multi-sectoral and multi-dimensional risks.

Our focus in this report is on physical nature-related financial risks; that is, those associated with physical changes in nature and the ecosystem services it generates for our societies and economies. While for transition risks, some narrative scenarios have been published (e.g. IPR 2023), for physical risks there is no systematic assessment or collection of relevant narrative scenarios for financial risk assessment. We further note that the main focus of this report is on direct anthropogenic drivers of nature-related risk aligned with IPBES[2].

This technical report aims to build upon the work of Central Banks and supervisors, financial institutions, the NGFS and the Taskforce on Nature-Related Financial Disclosures (TNFD) to date on nature-related financial risks. It learns from the approaches of NGFS on climate scenarios to set out a preliminary framework for the assessment of risks and the generation of nature-related scenarios for financial risk assessment.

[2] We do not consider natural-drivers, such as volcanoes and earthquakes.

Figure 1. Global trends in the capacity of nature to sustain contributions to good quality of life from 1970 to the present (Source: IPBES 2019). Full descriptions of areas of nature's contribution to people in Annex 1.

Box 1: What do we mean by nature, financial risks and other terms used in this report?

All definitions used in this report are consistent with those defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (the equivalent of the Intergovernmental Panel on Climate Change, IPCC). In most cases, these are consistent with those used by the Taskforce on Nature-Related Financial Disclosure (TNFD 2023).

Nature, is defined as *"the natural world with an emphasis on living organisms"* and includes biodiversity, ecosystems and the biosphere. This definition is used whilst acknowledging that it *"embodies different concepts for different people"* (IPBES, 2019, p. xiv).

Biodiversity is defined 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, 1992).

Ecosystem services "*The benefits (and occasionally disbenefits or losses) that people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; and cultural services such as recreation, ethical and spiritual, educational and sense of place*". UNEP WCMC defines 21 ecosystem services (see Annex C), whereas IPBES defines eighteen categories of Nature's Contribution to People (NCPs) (Table 1).

Nature's contribution to people (NCP) (Table 1) "*are all the contributions, both positive and negative, of living nature (i.e., all organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life.*" (IPBES, 2019, p. 1046).

Natural capital "*A concept referring to the stock of renewable and non-renewable natural resources (plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits to people". Within the IPBES conceptual framework, it is part of the nature category, representing an economic-utilitarian perspective on nature, specifically those aspects of nature that people use (or anticipate to use) as source of Nature's contributions to people*" (IPBES, 2019).

Nature-related financial risks (NGFS, 2023) "*risks of negative effects on economies, financial institutions and financial systems that result from: i. the degradation of nature, including its biodiversity, and the loss of ecosystem services that flow from it (i.e., physical risks); or ii. the misalignment of economic actors with actions aimed at protecting, restoring, and/or reducing negative impacts on nature (i.e., transition risks)*".

Source: IPBES Glossary[3] (unless otherwise stated)

The following section reviews the science and economics of nature risks and the conceptual frameworks proposed for finance to date, and draws upon lessons from climate change, to define

[3] IPBES Glossary of terms used in this report: https://www.ipbes.net/glossary?page=1

a set of principles for scenario development. Section 3 then presents our proposed approach to risk assessment and scenario development and produces an inventory of potential nature-related physical risk scenarios based upon the literature and analyses of historical analogues. Section 4 demonstrates how risks can be quantified for five potential risk dimensions (pollination, ground water, surface water, air pollution and water quality). Section 5 offers a stepwise approach to developing scenarios using the inventory and provides an application to compounding heat, water scarcity and pollution impacts in France. The final section concludes with recommendations on next steps. In this report, we align with the TNFD (2023) and NGFS (2023) as far as possible, and go further, including defining a typology of nature-climate shocks and associated scenarios based on them and developing and testing a preliminary risk screening methodology.

This report responds to a specific set of questions defined by the NGFS Task force Nature:

- What can be learnt from the literature and existing work on climate and nature scenarios that could form a basis for integrated climate-nature scenarios for Central Banks? (Section 2)
- What would a typology of climate-nature shocks look like? (Section 3)
- Can we develop a simple data-driven approach to screen key potential nature-climate shocks to help prioritise which should be considered by a country, according to different countries' characteristics? (Sections 4 and 5)

2. Characterising Nature-Related Risks and the Implications for Analytics and Scenarios

2.1 The science and economics of nature-related risks

"Nature across most of the globe has now been significantly altered by multiple human drivers, with the great majority of indicators of ecosystems and biodiversity showing rapid decline"; this was the clear conclusion of the 2019 IPBES Global Assessment Report. The dominant drivers over the past 50 years have been changes in land and sea use, direct exploitation of organisms, climate change, environmental pollution, and invasion of alien species. It is well established that *"globally, land-use change is the direct driver with the largest relative impact on terrestrial and freshwater ecosystems, while direct exploitation of fish and seafood has the largest relative impact in the oceans… Climate change, pollution and invasive alien species have had a lower relative impact to date but are accelerating"* (IPBES, 2019). Land-use change is driven primarily by agriculture, forestry and urbanisation and includes deforestation, which is of particular concern given the vital regulating role that forests play (Pörtner et al. 2022). The unsustainable use of the Earth's resources is underpinned by a set of demographic and economic drivers that have increased, and interact in complex ways, including through trade (IPBES, 2019).

Statistics on the current state of biodiversity loss and nature degradation are alarming: the extent and condition of ecosystems has declined in 50% natural ecosystems, including more than 85% of wetland area lost, and an average of 25% species are at risk of extinction (IPBES, 2019). Globally, more than three quarters of the categories of ecosystem services defined by IPBES *("nature's* *contributions to people*"), those considered vital to people, culture and economies, such as clean air, water, food and energy, have shown a decrease over the last 50 years (IPBES, 2019). The immediacy, urgency and potential scale of the impacts of these trends are made clear in the latest assessment of the planetary boundaries framework (Figure 2, Richardson et al. 2023), which shows that now six of the nine *'planetary boundary'* thresholds – those essential to sustain lives and livelihoods - have been breached, including climate change, land and freshwater system change, biochemical flows, novel entities (e.g. plastics). The remaining are close to being breached, for example ocean acidification is expected under climate change.

The economic implications are significant. Similar to physical climate risks, these risks can be **acute** (i.e. shocks such as forest fires or pests affecting a harvest) and/or **chronic** (i.e. gradual changes such as pollution stemming from pesticide use) (INSPIRE and NGFS, 2022). Also, like physical climate risks, the immediacy of the risks is clear. For example, IPBES in 2019 concluded that land degradation has reduced productivity in 23 per cent of the global terrestrial area, and between $235 billion and $577 billion in annual global crop output is at risk as a result of the loss of pollinators. Loss of coastal habitats and coral reefs reduces coastal protection, which increases the risk from floods and hurricanes to life and property for the 100 million to 300 million people living within coastal 100-year flood zones.

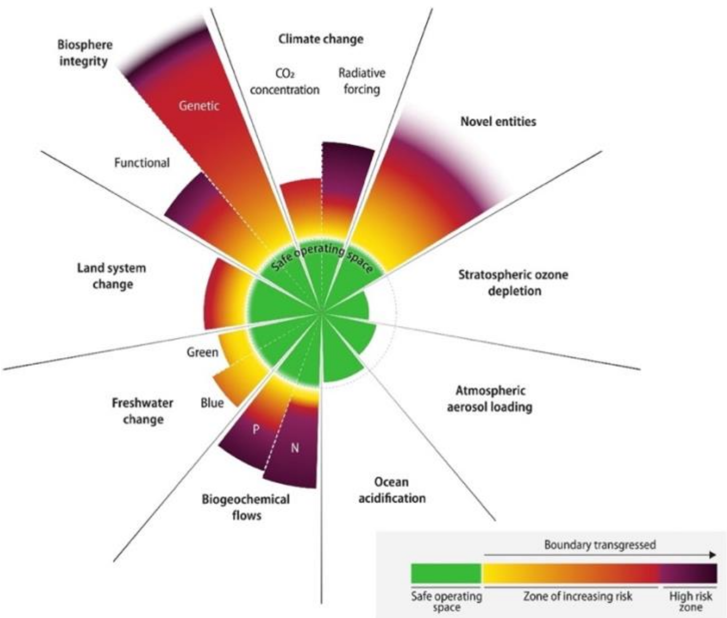


Figure 2: Current status of control variables for all nine planetary boundaries. The green shaded polygon represents the safe operating space. Source: Richardson et al. (2023)

The UK Government's recent review of the Economics of Biodiversity (Dasgupta 2021), in particular highlighted the significant impacts of these changes on people and the economy, many of which are already being observed: *"Our unsustainable engagement with Nature is endangering the prosperity of current and future generations"*. Looking forward, it is well established that *"biodiversity and nature's regulating contributions to people are projected to decline further in most scenarios of global change…, while the supply and demand for nature's material contributions to people that have current market value (food, feed, timber and bioenergy) are projected to increase"* (IPBES, 2019).The NGFS and INSPIRE Study Group on Biodiversity and

Financial Stability concluded that[4] *"biodiversity loss is a potentially significant threat… economic activity and financial assets are dependent upon the ecosystem services provided by biodiversity and the environment: this raises the prospect of physical risks to finance if these services are undermined" (INSPIRE-NGFS 2022).*

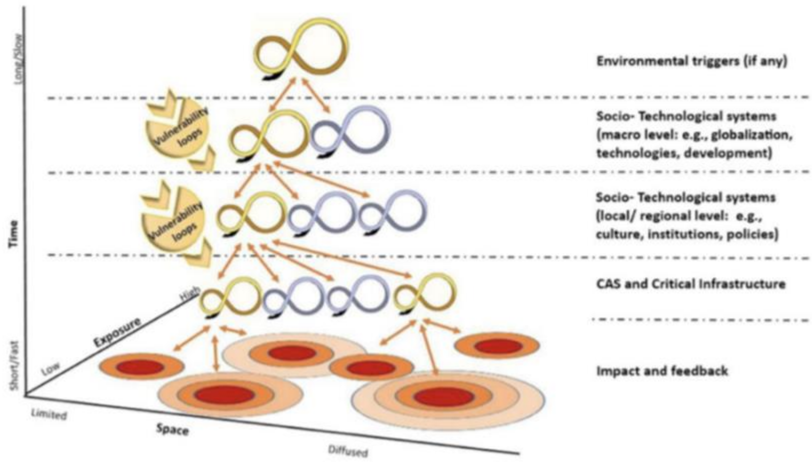


Figure 3: Illustration of complex feedbacks between systems that can generate systemic risks. CAS = complex adaptive systems. Source: Pescaroli and Alexander (2018)

While a substantial literature exists on the economic value of biodiversity and natural capital and the services they provide, the (related) literature on the economic and financial risks associated with biodiversity loss and the degradation of ecosystem services is more nascent, particularly in terms of firm- or sector-level performance. In addition, those studies that exist have focussed on direct risks to specific ecosystem services and sectors (e.g. Table 1 below and references therein). Yet, our nature-climate-economy system is a complex system, and it is well known that complex systems behave non-linearly, with unexpected outcomes and thresholds that can amplify shocks and lead to quasi-irreversible effects locally (Figure 3). For example, soil salination due to clearing land for agriculture can erode soil quality until a threshold is breached, whereupon agricultural productivity can collapse. In Western Australia, for example, the lost agricultural productivity from salinity damage is estimated to be worth at least $519 million per year (Government of Western Australia, 2022). In addition, the negative impacts of environmental change in one country can transmit globally through natural systems (water systems, climate) and human systems affecting people and economic output in other countries via global supply chains and trade. The IPCC in 2022 concluded that the interconnectedness of systems globally establishes pathways for the transmission of risks through trade, finance, food and ecosystems, exacerbating existing stressors and constraining adaptation, generating larger and more complex risks to agriculture, water, health, people and economies (Pörtner et al. 2022).

[4] We note that the study group also considered transition risk, for example, the report goes on to say that "…economic activity and financial assets in turn have impacts on biodiversity and could therefore face risks from the transition to a nature positive global economy".

Studies of climate tipping points (e.g. Lenton et al. 2019) underscore the interdependencies between climate and nature risks and point to the potential for rapid changes in the Earth's systems that can have major, knock-on impacts across human systems globally. For example, at least three of the nine major climate tipping points identified in Lenton et al. (2019) are directly linked with systems under threat through biodiversity loss and environmental degradation (the Amazon rainforest, coral reefs and Boreal forests), suggesting the potential for nature-related risks to increase the likelihoods for rapid changes in global climate or heighten the impacts and so cause severe and potentially irreversible social and economic impacts. The recent NGFS report on compound risks, highlights that ignoring the potential for cascading and compounding risks in scenario analysis can lead to a severe underestimation of losses (NGFS, 2023b).

For this reason, we conclude that scenarios that do not consider the potential for cascading and compounding nature-related risks are inadequate and will significantly underplay the risks.

Despite the imminent and substantial threats to nature and its services, approaches to *quantify* the potential financial and economic impacts of nature loss, and to *model and project* future impacts under different scenarios of socioeconomic change, is arguably less advanced than for climate change; which itself retains many knowledge gaps and uncertainties. This means that such projections come with uncertainties and need to be interpreted accordingly. Nature-related risks are multi-dimensional, location-specific and complex, with different drivers (e.g. loss of pollinators, pollution, changing land use, zoonotic diseases) affecting the economy in different ways but also interacting and compounding at the sector or local level. Models inevitably reduce the complexity through for example, only representing certain drivers, sectors or transmission channels, yet this can mean that important feedbacks are excluded. Ferrier et al. (2016) note the particular challenge in representing the complex feedbacks inherent in nature-related risks and the need to better link models across disciplines: *"Links between biodiversity, ecosystem functioning and ecosystem services are only weakly accounted for in most assessments or in policy design and implementation… scenarios and models of indirect drivers, direct drivers, nature, nature's benefits to people… need to be better linked in order to improve understanding and explanation of important relationships and feedbacks between components of coupled social-ecological systems."* These issues are amplified when one begins to model the economic and financial implications, which requires understanding complex processes of price and demand dynamics, substitutability, financial contagion, innovation and behavioural responses across consumers, producers, corporates, trade, investors and governments. In addition, and most importantly, there are large gaps in the availability and accessibility of the data required to develop, calibrate and validate models, including related to nature (Figure 4) and also a paucity of empirical evidence of the economic impacts of past shocks. Risks are highly specific to individual countries and local communities, driven by a large and diverse number of interrelated and interacting factors that are unique to the local ecological, social, economic context, so these issues pose challenges for financial risk assessment.

The following section builds upon this analysis of the science, economics and modelling to propose a set of principles for scenario analysis for nature-related financial risks, beginning with a review of existing conceptual and scenario frameworks and methodologies adopted in past studies.

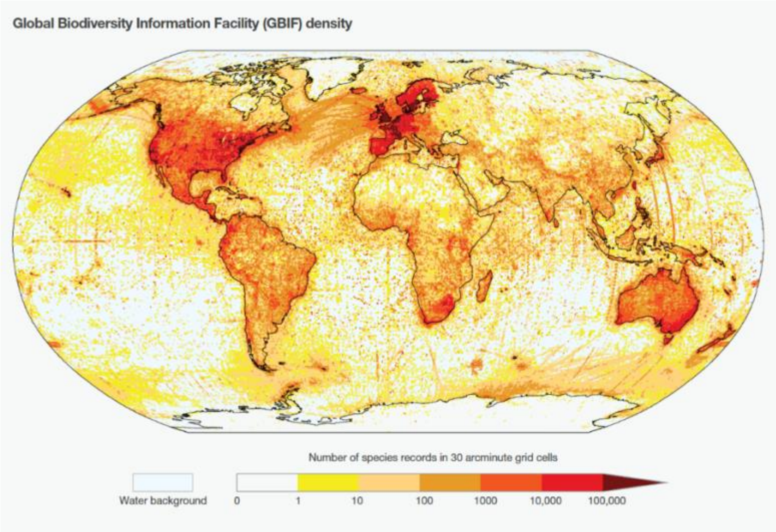


Figure 4: Example of spatial bias in the availability of biodiversity data. Source: Ferrier et al. (2016)

2.2. Toward a scenario framework for nature-related financial risks

2.2.1. Review of existing risk and scenario analyses and frameworks

No comprehensive set of scenarios exists for physical nature-related risks to date equivalent to those, for example, of the NGFS climate scenarios. However, several components of such a set are beginning to emerge, for example the physical risk elements included within the Inevitable Policy Response FPS + Nature scenarios (IPR, 2023), five scenarios for Africa of FSDA (2022), the three scenarios for a partial collapse of ecosystems explored in Johnson et al. (2021)[5] and the transition-focussed narrative scenarios for the food and agricultural sector of WBCSD (2023) (see Annex 2). Of these, Johnson et al. (2023) quantifies physical nature risks globally, estimating a global GDP in 2030 contraction of $2.7 trillion (-2.3 percent), compared with the baseline scenario where no ecological tipping points are reached. These estimates should be considered a lower bound given the narrow set of risks considered. FSDA (2022) takes the projections from Johnson et al., and combines this with other scenario information, and calculates risks to financial portfolios in Africa, for example finding between -2 percent and -5 percent impact on agricultural asset values by 2030.

Our goal in this paper, as requested by the NGFS Task force Nature, is different, in that we are tasked to explore the feasibility of developing a comprehensive scenario framework for physical climate risk that is more analogous to and compatible with the NGFS climate scenario framework (as of 2023). That is, an underpinning global framework for scenarios and set of high-level narratives that could form the basis of scenario development for any country. At the time of writing, several frameworks for nature-related risks and scenarios are beginning to emerge, including NGFS (2023), TNFD (2023) and OECD (2023), building upon earlier frameworks such as F4B

[5] Three ecosystem collapses explored are: wild pollination collapse; marine fisheries collapse; widespread conversion of tropical forests to savannah. Johnson et al. also develop one 30:30 transition scenario.

(2021)[6], CISL (2020)[7] and INSPIRE and NGFS (2022).[8] We note that there are some inconsistencies in the frameworks, which is reflective of the nascent stage of the field. For example, OECD (2023) focusses on biodiversity-related financial risk whereas the NGFS conceptual framework focusses on nature-related financial risks and includes climate (NGFS, 2023). We also note that much of the focus to date has been on frameworks for risk assessment, rather than scenarios, with TNFD (2023) going further in providing specific guidance on scenario development.

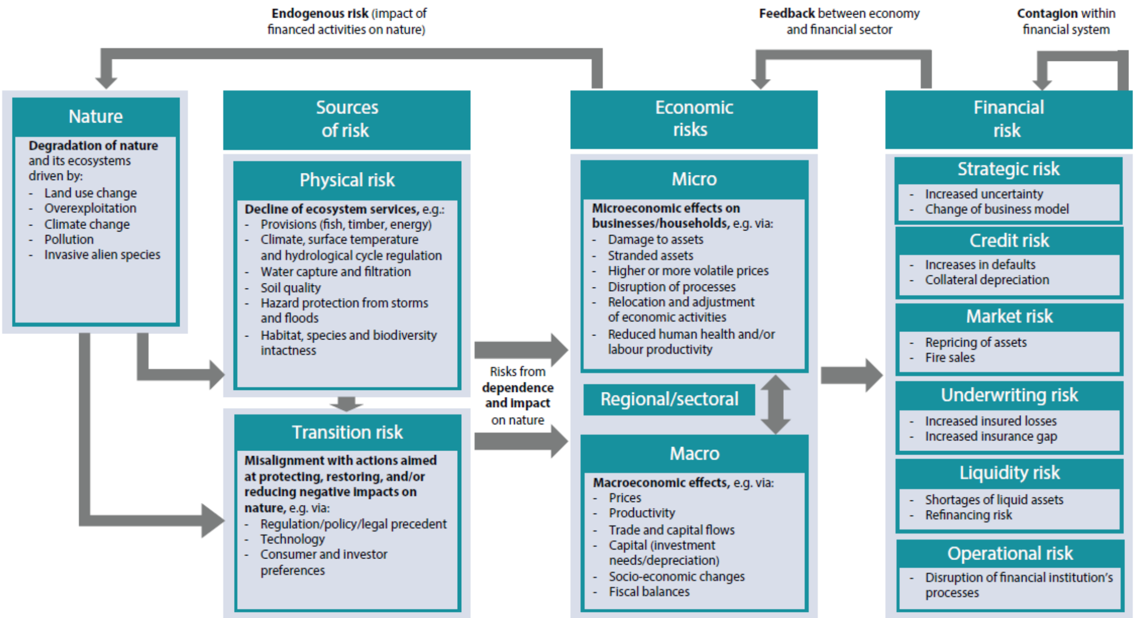


Figure 5: Transmission channels for nature-related risks. Source: NGFS (2023), p.8 (adapted from Svartzman et al. (2021))

Importantly, different applications require different types of scenarios. For prudential regulation of Central Banks and supervisors, for example the main focus of this report, and relatedly setting capital requirements of financial institutions, there is a need to explore more extreme scenarios. For example, Solvency II regulation in Europe requires insurers' financial resources to ensure that the chance of an insurer being unable to pay claims during any one year is no more than 1-in-200 (0.5%) (EU, 2021). Assessing such risks requires consideration of scenarios of events that might occur with 0.5% annual probability. The European Banking Authority guidelines on scenario use for stress testing recovery plans (EBA 2014) call for a focus on scenarios *"based on events that are exceptional but plausible"*, ensure coverage of *"a systemwide event, an idiosyncratic event and a combination of system-wide and idiosyncratic"*, where a systemwide event is defined as an *"event that risks having serious negative consequences for the financial system or the real economy"*. Whereas scenarios for business strategy development will likely consider more baseline 'most

---

[6] https://www.naturefinance.net/resources-tools/the-climate-nature-nexus-1/

[7] https://www.cisl.cam.ac.uk/files/integrating_climate_and_nature_the_rationale_for_financial_institutions.pdf

[8] https://www.ngfs.net/sites/default/files/medias/documents/biodiversity_and_financial_stability_exploring_the_case_for_action.pdf

likely' scenarios. This motivates the focus of this report on shocks, and also the near-term focus such that results are directly relevant to stress testing and scenario analysis today.

Figure 5 maps the transmission channels from nature to finance in the NFGS Conceptual Framework published in 2023. This is analogous to the equivalent figure for climate-related financial risks (NGFS 2021). From NGFS (2023), we adopt our definitions of **physical risk** ("*stemming from nature degradation and loss of ecosystem services")* and **transition risk** ("*stemming from a misalignment of economic actors with actions aimed at protecting, restoring, and/or reducing negative impacts on nature*") (Figure 5). In line with NGFS (2023), in this paper we consider liability risk as transversal across physical and transition risk. Importantly, as shown in Figure 5, these risks drive impacts at both the macro- and micro-scale that can impact on the financial sector through multiple channels (strategic, credit, market, underwriting, liquidity and operational risks). These risks can create contagion within the financial system and feedbacks to the real economy, similarly to climate-related risks. Studies have shown that these feedback and contagion effects can significantly amplify the scale of financial risks (Battiston et al. 2021b,c).

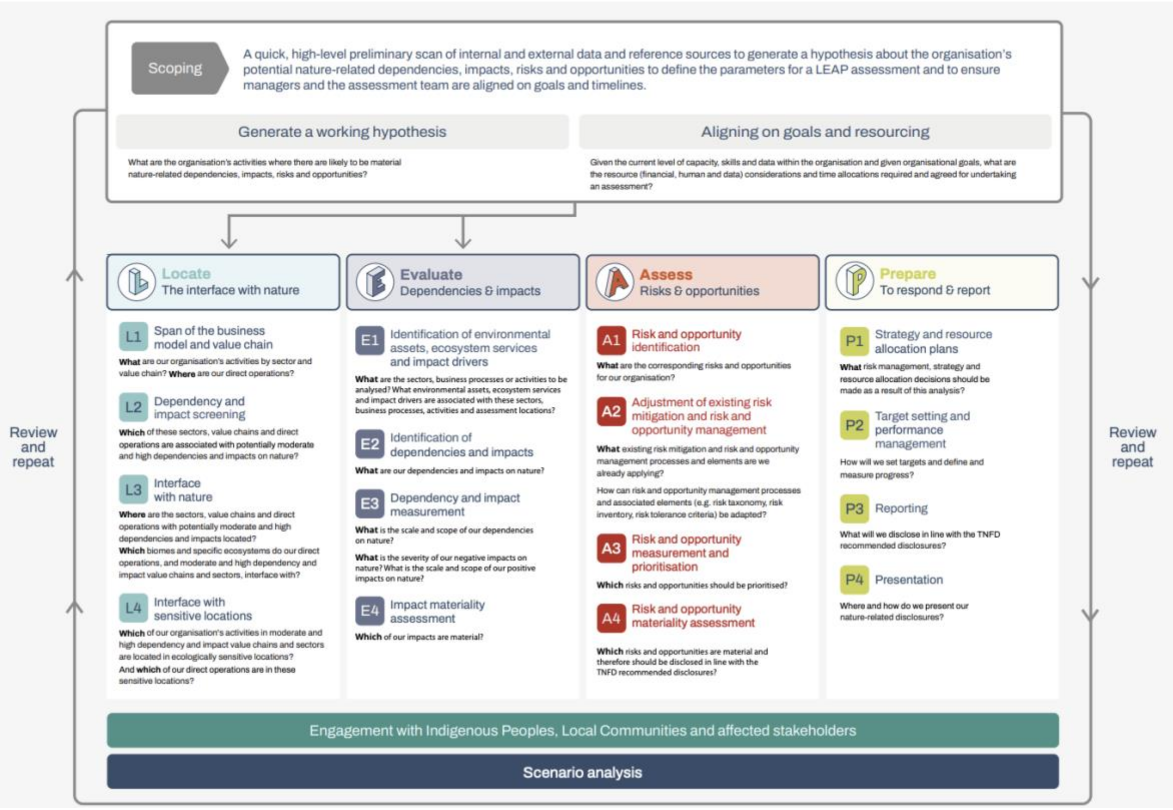


Figure 6: TNFD LEAP (Locate, Evaluate, Assess and Prepare) Approach (TNFD 2023)

In terms of the risk assessment itself, the predominant framework is the TNFD LEAP approach (Figure 6)[9], which has been piloted by more than 200 organisations. This includes four steps, locate, evaluate, assess and prepare. TNFD also recommends a number of tools to assess risks, including the ENCORE database and toolkit, which has been used in all of the studies by Central

[9] https://tnfd.global/publication/additional-guidance-on-assessment-of-nature-related-issues-the-leap-approach/

Banks to date (NCFA & UNEP-WCMC 2018)[10]. NGFS (2023) introduces a "principle-based risk assessment framework", largely consistent with TNFD, consisting of three phases: I) identification of sources of risk (physical and transition); II) assessment of economic risk; III) assessment of risks "to, from and within" the financial system. The scenarios explored in this report largely focus on the first two, and we note the evidence of potential amplification efforts of feedbacks within the financial system (e.g. Battiston et al. 2021a, b). As in LEAP, Phase I includes guiding questions which start from dependencies and impacts exposure identification and move to highlight the importance of location specificity, developing a forward-looking view (e.g. scenarios), systemic dimensions (e.g. cascading, compounding effects and contagion) and the interlinkages between climate and nature. Phase II includes guiding questions to identify direct and indirect effects, interactions between micro and macro level effects (both regional and sectoral) and vulnerability through substitution (both geographical and technological) stressing on the time dimension in assessing it. Phase III includes guiding questions on risk transmission between economic and financial systems, contagion within the financial system and endogenous risk.

To date, studies of nature-related financial risks have been conducted by the Central Banks of the Netherlands (van Toor et al., 2020), France (Svartzman et al., 2021), Brazil (Calice et al., 2021), Malaysia (WB & BNM, 2022) and Mexico (Martínez and Montañez, 2021) and for the Euro area (Boldrini et al. 2023). Each study is different, but at their core all of these studies to date have shared a common approach based on ecosystem service dependencies; that is, assessing the dependencies of output from different economic sectors on the provision of a specific ecosystem service. Arguably, they do not quantify risk in a way compatible with standard approaches recommended, for example, by financial regulators and supervisors for climate and non-climate risks (e.g. Adrian, 2020) or the climate risk community (e.g. IPCC 2014). Specifically, they provide analysis on to what extent a sector or portfolio is *exposed* to the variations in the provision of an ecosystem service (with a greater or lesser level of detail), but they do not capture the likelihood or potential magnitude of a loss of provision (*hazard*) or to what extent a specific level of loss (if it occurred) would translate into a physical loss of output (*vulnerability*, for example, in the form of a '*damage function*'). The results could, therefore, be considered an upper bound estimate of the potential scale of the risk. FSDA (2022) also does go further in assessing financial risk to African financial markets (Zambia, Egypt, Kenya, Ghana, Mauritius and South Africa) in terms of losses to asset values. For the NGFS, to fully assess nature-related financial risks in a way consistent with regulatory approaches, there is a need to shift from dependency to risk. Table 1 reviews recent studies that have accessed economic or financial risks to different sectors, however we note the paucity of simulation and empirical literature on the economic impacts of nature-related shocks.

Table 1: Selection of recent quantitative studies on financial implications of nature-related risks

Sector	Geography	Impacts/Results	Sources
Water (driven by increased water	UK	An exploratory analysis was performed to gauge the impact of three months without access to water – the chosen scenario – on the credit risk of the bank's corporate loan	CISL and HSBC (2022)

[10] See also review of risk exposure methodologies in INSPIRE and NGFS (2022) Appendix 3

demand and water stress)		book." (p. 6) *"The sample's RWA [Risk weighted assets] increases by* ***~20 per cent*** *in the year immediately following the shock. Most of the companies in the sample are subject to a downgrade of internal rating of at least 1 notch, with cases of extremely severe downgrades also occurring. The credit risk of a significant share of companies in the sample moves from investment grade to speculative grade*	
Global GDP (Pollination, Timber and Fisheries)	Global	$2.7 trillion loss in 2030 linked to partial ecosystem collapse scenarios for timber, pollination and fisheries, equivalent to 2.3% global change in GDP. For pollination, crop output declines 9% and $400 billion by 2030	Johnson et al. (2021)
Agriculture (driven by extreme weather, land use change and price shocks)	Global	Individual firms at the centre of the global food supply system could lose **up to 26% of their value by 2030**, with a sector average hit of over 7%.	UN Climate Change High Level Champions (2022)
Agriculture (water-related stranded assets)	Global	**69% of listed equities** reporting via CDP state that they are exposed to water-related risks that could generate a substantive change in their business" (p. 4). "Research carried out by the International Food Policy Research Institute (IFPRI) suggests that current business-as-usual water management practices and levels of water productivity will put at risk **US$63 trillion**, or 45%, of the projected 2050 global GDP, equivalent to 1.5 times the size of today's entire global economy" (p. 6). The maximum potential financial impact was estimated at **US$225 billion**, while the cost of response was US$119 billion" (p. 8) "US$13.5 billion already stranded and over US$2 billion at risk on major infrastructure projects" (p. 10).	CDP & Planet Tracker (2022)
Agriculture (Pollination)	Global	Short-term global pollination services are valued at a range midpoint of **USD 1 trillion.**	Lippert et al. (2019) Paudel et al. (2015)
Agriculture (declining natural capital with multiple causes)	Global	Under the extreme loss of natural capital scenario, the 0.5 percent VaR could almost double from USD 6.3 trillion to USD 11.2 trillion of invested stock in agriculture, i.e. a 0.5 percent chance of the annual loss being more than **USD 11.2 trillion**.	Caldecott et al. (2013)
Fisheries (Corals)	Global	Estimated ecological asset value of **$10 trillion.**	Hughes et al. (2020)

Food (Multiple breadbasket failure)	Global	Based on a systematic literature review, historically, synchronized crop-production losses have led to a global production deficit of as much as **20%**. Simultaneous breadbasket failures increase local and global food prices and undermine food security, particularly in import-dependent low-income regions. Historically, simultaneous losses in major producing countries affected global production instability, leading to a global production deficit of 20% in maize in 1983, 14% in soybean in 1976, 8% in rice in 2002, and 7% in wheat in 2003. Looking forward, increasing risk of simultaneous failure of wheat, maize and soybean.	Gaupp et al. (2020) Mehrabi &Ramankutty (2019) Kornhuber et al. (2023) Janetos et al. (2017) Hasegawa et al. (2022)
Food and water linked to increase in extreme weather events (climate change)	Global	A hypothetical but plausible scenario of increase in extreme weather due to climate change leading to a breadbasket crop failure and significant global food and water shortages. Estimated **$5trillion global economic loss over 5 years** ($3 trillion for lowest severity scenario and $17.6 trillion in the most extreme scenario). The <u>expected</u> loss (the sum product of loss and probability of event) estimated at $711 billion.	Lloyds of London and CCRS (2023)
Health (Air pollution and wildfires)	USA Australia	Smoke from 22 Southern California wildfires in 2007 led to excess hospital admissions with an associated health care cost of **$3.4 million.** Australian bushfire season in 2019-2020 led to health care costs of **AUS$1.95 billion**. Effect of PM2.5 on mortality in the Medicare population and estimate the annual mortality cost of wildfire smoke is just over **$6 billion.**	Bayham et al. (2022) (and references therein)
Wildfires	California	Wildfire damages in 2018 totalled **$148.5 (126.1–192.9) billion** (roughly 1.5% of California's annual gross domestic product), with $27.7 billion (19%) in capital losses, $32.2 billion (22%) in health costs and $88.6 billion (59%) in indirect losses (all values in US$). Total losses in the United States were $88.6 billion—more than 0.4% of the nation's gross domestic product (GDP) that year. Of this total, $42.7 billion (48.2%) of the indirect losses occurred in California, and $45.9 billion (51.8%) occurred in other parts of the United States via production and consumption supply chains connected to California.	Wang et al. 2022

A further advancement required from those analyses of Central Banks to date, is to shift to the use of scenarios. Given that the studies by Central Banks to date have mostly focussed on exposures, work on future nature-climate scenarios is at a nascent stage. Scenarios explicitly recognise that the future will not look like the past and will be influenced by many factors that cannot be predicted precisely. In most jurisdictions therefore, financial regulators and institutions use scenarios to stress test their resilience against uncertain but plausible futures.

TNFD (2023)[11] provided an initial toolkit (guidance) for the generation of scenarios for nature-related risk (and impact) assessment. It described that *"scenarios are a set of plausible descriptions or narratives about how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and critical uncertainties. They are used to provide a view of the implications of developments external to the organisation and inform actions by the organisation".* It particularly advocates for the use of exploratory scenarios, which describe a range of critical uncertainties and set out plausible futures, rather than normative scenarios that start with a preferred/desired outcome and work backwards. It also recommends the use of qualitative scenarios that allow for targeted quantification to be layered in, and a versatile and adaptable building blocks approach, with a set of standardised elements that can be used to develop customised scenarios. These recommendations are consistent with the wider literature on scenario analysis in conditions of uncertainty, as well as within guidance, for example, of the International Sustainability Standards Board (ISSB, 2023). Such narrative scenarios were a starting point for those studies noted above (and summarised in Annex 2). These approaches are adopted here as a basis to the approaches developed in this paper.

A further important contribution of TNFD (2023) is its critical uncertainties matrix (Figure 7). TNFD identify two critical uncertainties to be explored through scenarios: the degradation of ecosystem services (physical risks) including the connection with climate change; and the alignment of market and non-market driving forces, which is linked to transition risk and includes the impacts of both nature-related and climate policy. Based on this, TNFD propose four critical narrative scenarios for consideration (Figure 7) and provides qualitative case studies demonstrating how they can be developed by corporates through participatory processes.

[11] https://tnfd.global/wp-content/uploads/2023/09/Guidance_on_scenario_analysis_V1.pdf?v=1695138235

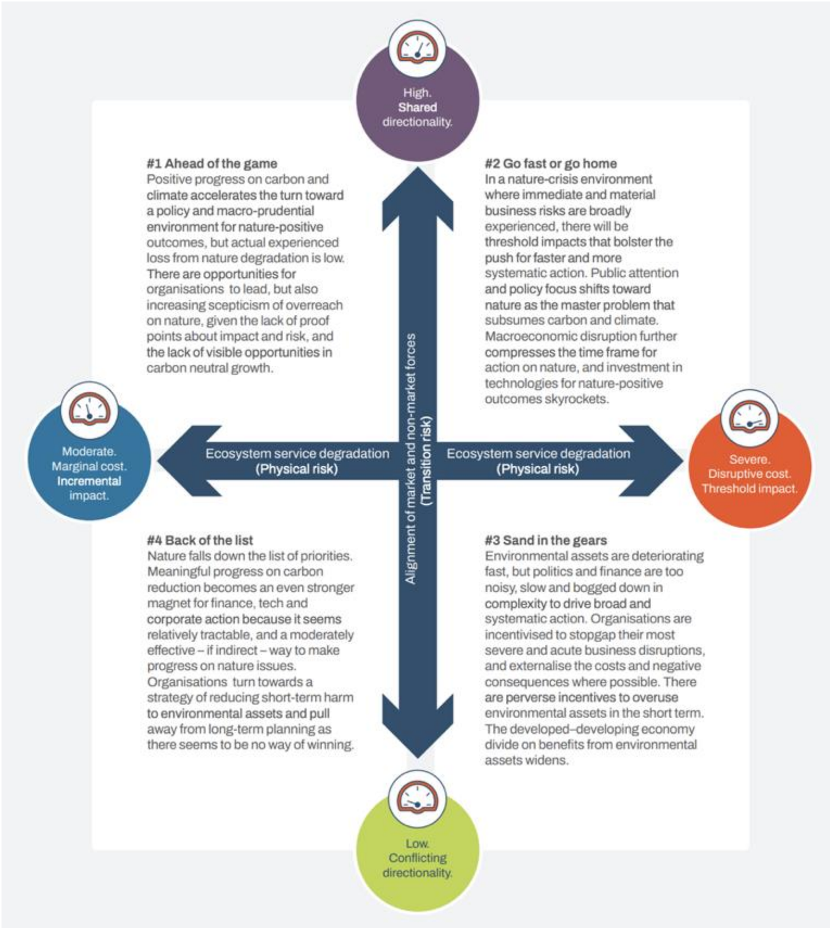


Figure 7: TNFD Critical Uncertainties Matrix and Associated Scenarios. Source: TNFD (2023)

2.2.2. Foundations to Scenario Development for Financial Institutions

2.2.2.1. Lessons from existing approaches within climate and nature

Unlike for climate change, there is no well-established, consistent, global framework and coordinated initiative for modelling and scenario development, equivalent to the World Climate Research Programmes' (WCRP) Climate Model Intercomparison Project (CMIP), the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), Representative Concentration Pathway (RCPs) and Shared Socioeconomic Pathways (SSPs). These consistent frameworks and modelling efforts for climate have been a critical underpinning of economic and financial research of the impacts of climate change and have enabled the development of frameworks and relevant scenarios for climate financial risk assessment (NGFS 2021, 2022). The NGFS to date is on its fourth iteration of scenarios; while these have evolved significantly over subsequent iterations, the CMIP and ISIMIP data and RCPs and SSPs continue to be at their core, particularly for long-term scenarios.

There are efforts in the IPBES community to develop consistent approaches to risk assessment, models and scenarios (IPBES 2016). Arguably, those frameworks that do exist in the nature community, such as the National Ecosystem Assessment framework and the Nature Futures

Framework (Lundquist et al. 2023), while providing an important underpinning to analysis, do not yet bring the coherence and consistency of the climate frameworks noted above. This means there is a wider gap to fill in going from the science to scenarios appropriate for financial risk assessment than in the case of climate. Compared with climate change, there is also a less well-developed underpinning evidence base and modelling on the economic implications of nature loss. A recent review on global biodiversity scenarios to assess socio-economic impacts (Maurin et al., 2022) concluded that the exploratory scenario in Johnson et al. (2021) is the only "suitable" for physical risk assessments. Yet, the Johnston et al. (2021) Nature-Economy model, while arguably being the most comprehensive global economic model-based analysis to date, includes only three physical risks: pollination services, risks to timber and degradation of fisheries (Annex 2). This is reflective of the wider literature and suite of models for nature-related impact assessment, which tend to focus on a limited set of risks and largely ignore compounding effects, including the compounding impacts of climate change, and so if used within financial risk assessment (as in FSDA 2022) are likely to significantly underplay the impacts of nature loss.

One important reason for the relative nascent stage of nature-economy-finance modelling could be that the demand for this risk-based information from governments, corporates and financial institutions is more recent. For example, the Taskforce on Nature-related Financial Disclosures was announced in July 2020, five years after the launch of the Taskforce on Climate-related Financial Disclosures (TCFD) in 2015. In addition, the Kunming-Montreal Global Biodiversity Framework was agreed in only 2022. As noted above, the requirements for financial institutions are different from other applications requiring the development of new approaches. On nature, we need to replicate the decade of work on climate financial risks (rapidly) but we are working from a lower base.

So, what can we learn from climate, given that models and scenarios there are more developed?

Nature-related risks do share some common characteristics to climate risks (Table 2), so there are important lessons that can be learnt from the frameworks and approaches to climate scenario analyses conducted by Central Banks and FIs to date. Risks can similarly manifest over time (chronic risks) or as shocks (acute risks), with the most significant financial risks likely associated with acute shocks. The transmission channels for both climate and nature exhibit non-linearities and complexity that can limit predictability as well as create tipping points and irreversibility at local and global scales. As discussed in Section 2, different drivers and risks interact strongly at all scales with complex local and global feedbacks. They can transmit either through domestic impacts (e.g. reduced regulation of local flood risk) or internationally (e.g. changing terms of trade or commodity prices). A growing body of literature highlights the importance of accounting for this for climate scenarios and models (Ranger et al. 2021, 2022, Exeter-USS 2023, Trust et al. 2023) and the same is true for nature. The current NGFS scenarios do not incorporate such risks to date, and the NGFS itself has identified this as a significant gap (NGFS 2023). Similarly, several authors have now highlighted that the integrated assessment modelling (IAM) approaches that have been the workhorse of the NGFS scenarios have severe limitations in their ability to capture acute risks and these feedbacks. The limitations of IAMs for physical climate risk modelling are well documented (Ranger et al. 2022). The NGFS and Financial Stability Board in their 2022 review of progress on scenario analysis to date noted these issues: *"many respondents highlight that measures of exposure and vulnerability are likely understated. One of the reasons is that, in many cases, metrics are not capturing second-round effects, potential climate non-linearities… many exercises also did not consider other potentially large sources of risk, such as those stemming* *from an abrupt correction in asset prices… The scarcity of available data and modelling limitations and uncertainties are other key reasons mentioned by authorities to suggest that these preliminary results might significantly understate actual climate-related risks and impact*" (NGFS-FSB 2022). The same conclusion was reached in Ranger et al. 2023, which interviewed banks and insurers participating in the 2022 Bank of England scenario exercise (CBES).

Given this, we strongly propose that any framework for nature-related scenarios must represent acute shocks and complex, cascading and compounding risks to avoid the severe underestimation of physical risks. The TNFD proposed narrative approaches provide a good foundation, upon which we build in this paper.

There are also important differences between climate and nature risks. Unlike global climate change, importantly, the impacts of biodiversity loss and damages to ecosystem services can be more directly local and much faster acting, as well as to some extent global and accumulative. For climate change, while the impacts are felt locally and are highly variable across countries, a tonne of carbon emitted from Europe will have the same impact globally as a tonne emitted from Southern Africa and those impacts can be delayed and emerge over timescales of decades to even centuries in some cases (e.g. ice sheets). This is not the case for nature. For nature, the impacts of human activities on biodiversity and ecosystem services can be more localised and immediate and unique to the location, as well as indirect and long-term. For example, the removal of a hectare of forest in Europe could have a very different impact (both globally and locally) to the removal of a hectare from Southern Africa and those impacts may be seen immediately on local climate and flood risk, as well as nature, in addition to the long-term global impacts on the climate through the removal of carbon sinks.

Nature-related risks are also subject to local thresholds and tipping points where biodiversity and ecosystem-services can shift rapidly with significant social and economic impacts, both locally and globally. This means that scenarios for nature-related financial risk assessment will need to be much more locally specific and calibrated locally, representing the specific circumstances of natural assets and their linkages with people and the economy at a micro and macro-scale. This means it could be more difficult to define a set of locally relevant central nature-related risk scenarios that can be applied to all countries, similar to the NGFS climate scenarios.

For Central Banks and supervisors, a new approach to scenario development is needed that combines the benefits of global scenarios (like those of the NGFS on climate) with the local specificity required to inform decision making related to nature risks and impacts.

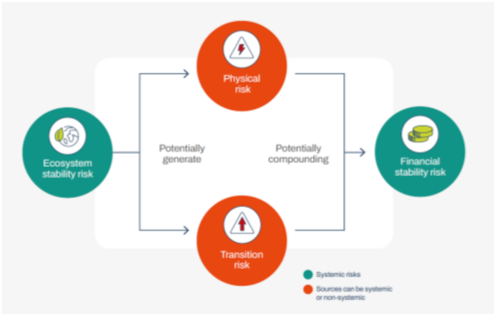
Importantly, it is vital to note that, while here we are comparing nature and climate risks, in reality both are and will manifest concurrently with strong interplay between the two from local to global scales. The risks and impacts materialise from many of the same sectors and action and outcomes are fully interdependent. Therefore, we would argue, consistent with INSPIRE-NGFS (2022) that it is strongly inadvisable to conduct scenario analysis without considering nature and climate changes and policies together. The following sub-sections proposes a set of principles that guide the scenario approach developed in this paper.

Table 2 - Characteristics of climate-related and nature-related physical financial risks. While climate and nature are interlinked and we conclude should not be considered separately, it is important to understand the differing characteristics of these risk drivers from a financial perspective given the implications for risk assessment and management.

Characteristics	Climate-related physical financial risks	Nature-related physical financial risks
Driver	Global, Increasing GHG emissions and changes in natural sinks directly attributable to human activities.	Local (albeit could occur as a global trend). Wide range of drivers directly attributable to human activities.
Acute and chronic	Both acute (shocks) and chronic (gradual) impacts	Both acute (shocks) and chronic (gradual) impacts
Diversity of impacts	Wide range of potential impacts on natural and human systems	Range of potential impacts on natural and human systems is arguably even wider and more direct than for climate change, including changes in genetic materials for medicines etc.
Timescales	Immediate but time delay before the physical impacts of GHG emissions fully manifest	Impacts of nature degradation can be immediate or can build up over time
Spatial scales and localisation	The impacts of rising GHG concentrations are global, albeit are spatially heterogenous and determined by a combination of local nature and socioeconomic factors (including nature loss)	Impacts of nature degradation are local, and determined by local natural and socioeconomic factors, however can also have a global impact, due to connections across natural and social systems
Linearity, uncertainty and predictability	The relationship between climate change and local and global physical climate risks can be strongly non-linear, with potential for compounding and cascading risks that can amplify local effects, making prediction difficult	The relationship between nature and related local and global physical nature risks can be strongly non-linear, with potential for compounding and cascading risks that can amplify local effects, making prediction difficult
Thresholds and tipping points	Climate change can drive tipping points in nature and socioeconomic systems with extreme impacts	Nature degradation can drive tipping points in natural and socioeconomic systems with extreme impacts
Climate-Nature Risk amplifiers	Nature degradation and associated socioeconomic vulnerabilities are risk amplifiers of climate risks	Climate change, natural climate variability and socioeconomic vulnerabilities are risk amplifiers of nature risks
Status of modelling	Integrated assessment models for climate are well known to capture only a fraction of potential physical climate risks. Models include many sources of uncertainty and collaborative efforts such as ISIMIP play an important role in helping to ensure model comparability,	Integrated assessment models for nature are at a nascent stage, capturing only certain processes and so likely underplay the risks. Projections that exist are uncertain. Model comparability is challenging due to lack of structured comparison efforts analogous to ISIMIP.

Box 2: Defining Nature-Related Systemic Risk

The TNFD defines an additional category of nature-related financial risk called ‘stability risks’, which is defined as “risks to an organisation that arise from the breakdown of the entire system, rather than the failure of individual parts. These risks are characterised by modest tipping points combining indirectly to produce large failures, where one loss triggers a chain of others, and prevents the system from reverting to its prior equilibrium” (TNFD, 2023, p. 35). This report describes how nature-related financial risks are non-linear and complex, with the potential to compound and cascade, leading to major impacts. TNFD classifies systemic risks into two categories: ecosystem-stability risk and financial stability risk, where the instability or collapse of ecosystems can generate both physical and transition risks that can in turn potentially compound to generate financial stability risk.



TNFD definitions of physical, transition and stability risk (TNFD 2023)

This direct consideration of the potential for instability is critical to both macro-prudential and wider policies, and is an important contribution from TNFD to the wider thinking on both climate change and nature risks. It is analogous to definitions of systemic risk from other fields including finance. For example, Schweizer and Renn (2019) define systemic risk as an “event that can trigger a severe instability or collapse of an entire economy with significant economic losses and developmental impact”. IMF (2019) use the definition “a risk of disruption to financial services that is (i) caused by an impairment of all or parts of the financial system and (ii) has the potential to have serious negative consequences for the real economy”. Key characteristics of systemic risks include high complexity, transboundary and global nature including cascading risks, non-linearity and tipping points and a stochastic relationship between triggers and impacts (NGFS 2023, Ranger et al. 2021, Schweizer and Renn 2019).

2.2.2.2. Principles for analytics and scenario development

As outlined in the previous sections, the characteristics of nature-related drivers and risks pose challenges for traditional risk assessment and for the development of consistent scenarios across countries, analogous to those of the NGFS for climate change. Given these characteristics, we draw the following principles for the development of analytics and scenarios for nature-related financial risks for Central Banks and Supervisors:

i. **A new approach to analytics and scenario development is required that is able to capture a wide range of possible risk transmission channels in a consistent way and explicitly**

represent the potential for cascading risks, systemic shocks and tail risks: The NGFS climate scenarios (NGFS 2023c) have been instrumental in guiding climate scenario analyses around the world but are known to underestimate physical climate risks due to the limited scope of impacts covered and lack of representation of shocks and tail-risks (NGFS-FSB 2022, Ranger et al. 2022). To date, these approaches have been largely based on integrated assessment models (IAMs), as described above. In the case of nature-related risks, we argue that the complex nature of the potential shocks, as outlined above, means that a new approach is needed that can explicitly capture the wide-ranging risk transmission channels for nature-related shocks and stresses and the potential for local and global tipping points. This includes explicit consideration of where nature-related drivers and risks could generate cascading systemic or stability risks that are vital for macro-prudential policy (Box 2). We argue that this requires a different approach to be undertaken by the NGFS for the climate scenarios and could not be achieved, for example, by simply adding an additional component to existing global IAMs or the existing NGFS climate scenarios[12]. For Central Banks, there is a need for a typology of nature-related risks and (from this) a basic set of 'template' scenarios covering all the key dimensions of risk that can be used to generate scenarios.

ii. **The approach to generating analytics and scenarios for nature-related risks must be capable of representing the strong localisation of nature-climate risks, the local vs global dynamics and the multiple dimensions of nature-climate risks.** A recommended approach is, rather than attempting to provide scenarios for all countries (as with climate), for an organisation like the NGFS to provide guidance and a toolkit of 'building blocks' of scenarios to Central Banks and Supervisors to enable them to develop their own locally relevant scenarios. Alongside this, a set of global scenarios could be suitable for assessing global-level shocks. This can be complemented with a simple tool to help Central Banks and supervisors identify where the most financially material risks may emerge, and so prioritise their development of scenarios. The challenge of strong heterogeneity of risks, and the potential for rapid amplifying feedbacks was recognised in the NGFS conceptual paper on short-term scenarios and motivated a narrative-based approach: *"Given the global nature of NGFS scenarios, there could be substantial geographical and sectoral heterogeneity in these assumptions, depending on the economic structure and level of economic development" (NGFS 2023d).*

iii. **Using narrative scenarios first.** Given the complexity and local specificity of nature-related risks, we recommend a scenario approach that begins with the exploration of narrative scenarios, in line with the TNFD guidance (TNFD 2023). As noted by Schinko et al. (2017) in the context of deep uncertainty, models and scenarios that allow to "explore rather than predict" can better help understand the drivers of individual and system-level responses to shocks in comparison with forecasting models. To account for deep uncertainties, scenario generation exercises will often include model-based projections alongside narrative and partially-quantified scenarios developed through expert judgment and the best available

[12] Arguably, nature needs to be embedded within fully coupled earth system models and the SSPs

science (Jack et al. 2020). This approach is consistent with the standard requirements for stress testing and vulnerability assessment by many Central Banks (e.g. IMF 2019).

iv. **Climate and nature need to be fully integrated; any scenario framework should consider the interconnections and feedbacks.** Climate and nature-related risks are fully interconnected (Pörtner et al. 2021) and a failure to represent this in analytics, scenarios and models, particularly at the global and national (macro) scale, could lead to substantial underestimates of the risks from both. As such, any scenario framework should consider the potential interconnections and feedbacks from the outset. At a more micro-scale or for hazard-specific studies, a pragmatic approach is needed with the inclusion of those factors that are material (consistent with standard approaches to risk management). For example, a study on the impacts of flooding on mortgages might conclude that nature-related risks are immaterial compared with climate change risks; whereas, studies on agri-foods sectors could likely conclude that both climate and nature-related risks are both very material.

v. **Including short-term scenarios.** Some of the risks associated with biodiversity loss and the degradation of nature can often be immediately felt, while others will emerge over the medium to long-term. As underlined by the IPBES Global Assessment Report in 2019 and other evidence, the impacts of human activities on nature are already manifesting around the world in many different ways; there is no low physical risk scenario (i.e. there is no scenario in the near-term where physical risks are low due to the existing and historical degradation of natural systems). It is therefore vital that Central Banks, supervisors and FIs consider short-term scenarios of physical nature-related risks, and fully integrate them when developing approaches to short-term climate scenarios (NGFS 2023d).

We note that developing such scenarios will require an investment in further research, but also technical assistance and capacity building to Central Banks. This could be an important future role for the NGFS in supporting its members to conduct nature-related risk assessments.

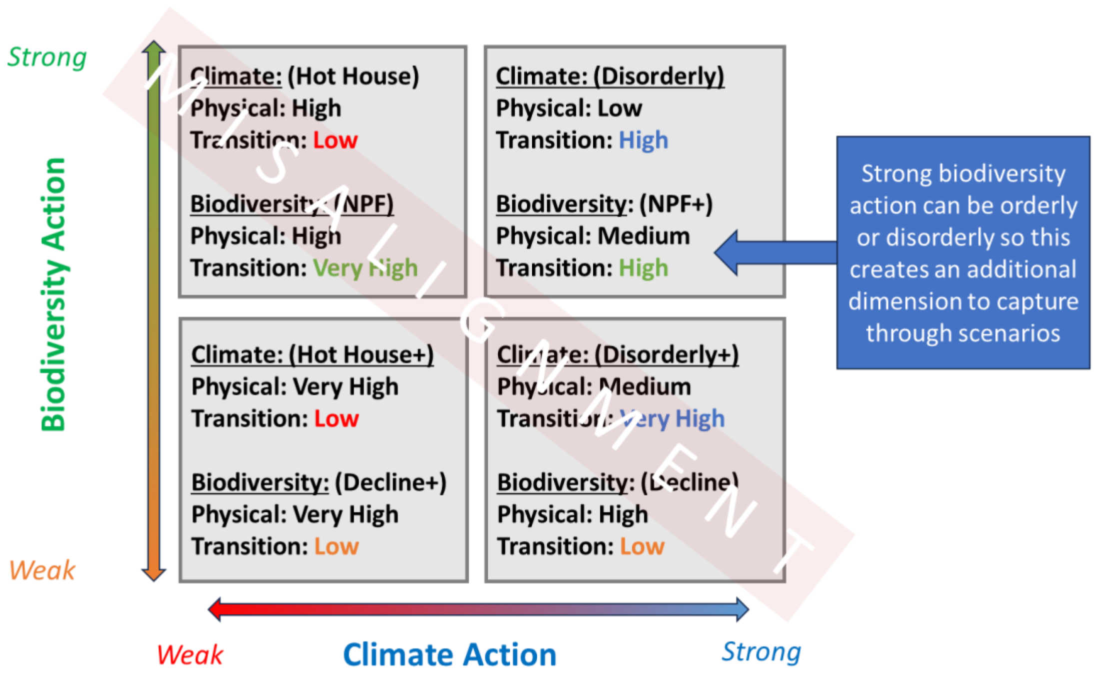
2.2.3. Proposed approach to scenario development

Existing frameworks and guidance such as TNFD (2023) and IPR (2023) provide detailed analyses of potential pathways of changes in policies, practices, market sentiments, demand and technologies, and in the case of IPR (2023) these are used to generate detailed narrative scenarios. However, the emphasis of these narratives is on policy changes relevant to transition risks and setting the potential scale of physical risks. What is missing is any detailed exposition of what types of physical nature-related risks are possible, and how such information can be used to shape the physical nature-risk aspects of scenarios. This is our focus in this report.

An important question considered in this report is; given that nature-related related risks are so location-specific, is it possible to generate a set of global scenarios analogous to the NGFS climate scenarios? And if not, what global public good resources (analogous to the NGFS climate scenarios) could be supplied that would (a) help to ensure greater consistency in approaches across disciplines and so greater comparability; and (b) contribute to improved accessibility of high quality and relevant scenarios across countries. Given the complexities outlined in this paper, it is clear that it would not be appropriate to provide a deterministic one or two nature scenarios as a 'bolt-on' to the climate scenarios, or indeed, generate such a scenario through a singular added damage function to the existing IAMs being used to generate climate scenarios. Such an approach would inevitably lead to significant under representation of risks.

Box 3: INCAF conceptual framework for integrated nature-climate scenario development

The Integrating Nature Climate Scenarios and Analytics for Financial Decision-making (INCAF) project aims to bring together the climate, nature and finance communities to develop a framework to capture nature and climate risks in an integrated and relevant way, analogous to the original NGFS climate scenario framework. An important question in constructing scenarios from the building blocks emphasised in this paper, is how to ensure the scenarios used span the space of plausible future outcomes, and how they can be appropriately combined with climate and transition risk scenarios. The initial proposed framework maps the scenario space using two axes: the "Climate action" x-axis which ranges from weak (left) to strong (right) and the "Biodiversity action" y-axis which ranges from weak (bottom) to strong (top). This creates four quadrants, within which physical and transition risks are defined for both climate and biodiversity[13]. A new element to be captured in this framework is the potential for 'misalignment' between climate and nature-related societal action either globally or nationally. For example, strong action on climate but weak action on nature increases climate-related risks. It is also possible to have strong nature-related action locally but weak globally, adding an additional dimension to risk to be considered. The four world quadrants are explained below.

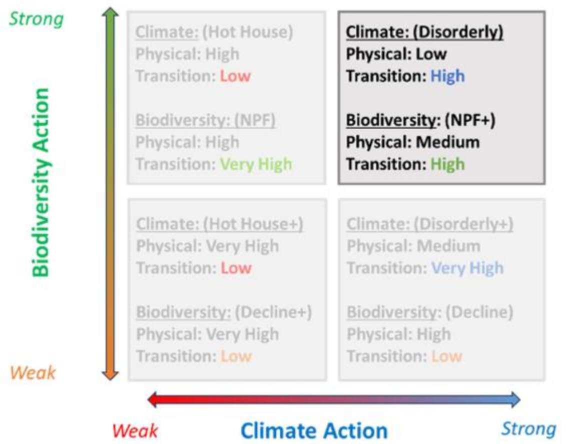


Source: INCAF project, including authors. Note: NPF = Nature Positive Future

[13] Consistent with the NGFS approach for climate change, litigation risk is considered in this Framework as a subset of both physical and transition risks." (NGFS 2023). Litigation risk is not considered in detail in this study.

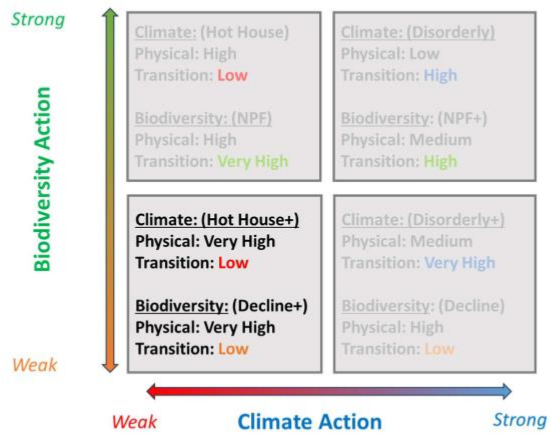
Four different worlds:

Nature positive world scenarios assume both climate and biodiversity policy action are strong. Climate policy compatible with a 1.6 degC world is introduced early and it increases in stringency over time. Biodiversity policy includes wide adherence to the global biodiversity framework and an increase in protection/restoration policies globally. As a result, both transition risks from climate and biodiversity are high, climate physical risk is kept low, and biodiversity physical risk is kept medium*.

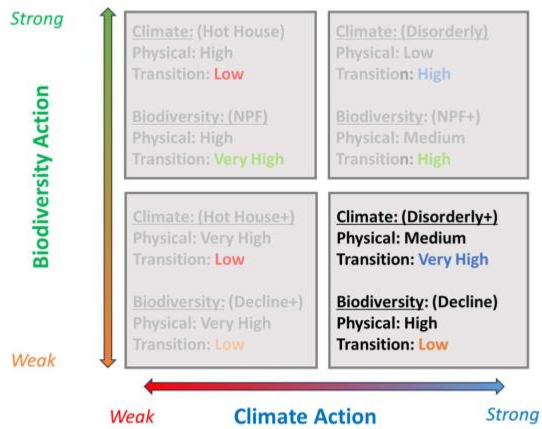


** Given the state of biodiversity degradation (IPBES, 2019) this scenario framework assumes that there is no low biodiversity physical risk.*

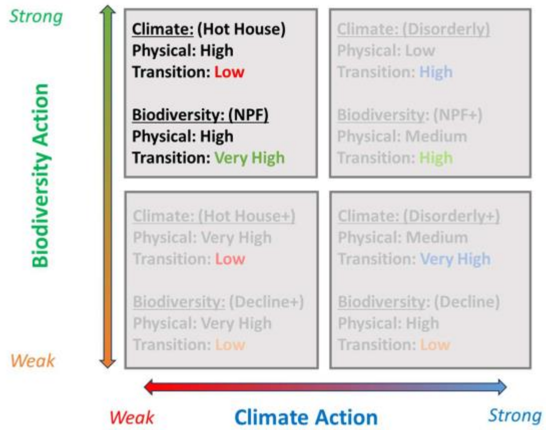
Too little, too late world scenarios assume both climate and biodiversity action are weak. As a result, transition risks for both climate and biodiversity are low. Weak climate and biodiversity policy action fails to avoid very high physical risks from climate change and biodiversity loss and the aftermath (resource scarcity, migration, and conflict).



Biodiversity depletion world scenarios assume climate policy action is strong whilst biodiversity policy action is weak. Climate policy compatible with a 1.6 degC world is introduced early and it increases in stringency over time. Given the misalignment between climate and biodiversity policy action, climate transition risks are very high. Biodiversity policy includes low adherence to the global biodiversity framework and an increase in biodiversity decline globally with an increase in depletion hotspots. As a result, biodiversity physical risks are high.



Hot house world scenarios assume biodiversity policy action is strong whilst climate policy action is weak. Biodiversity policy includes wide adherence to the global biodiversity framework and an increase in protection/restoration policies globally. Given the misalignment between climate and biodiversity policy action, the transition risks from strong biodiversity action are very high. Weak climate policy action fails to avoid high physical risks from climate change and also hinders the strong biodiversity policy action outcomes (misalignment risk) which results in high physical biodiversity risks.



Based on the principles presented in this paper, our recommended solution for an organisation such as the NGFS or for a Central Bank or other, would be to provide, in addition to a set of broad narratives about how the future could unfold in terms of policies and responses, two outputs:

i. A set of defined global shock scenarios. This would allow financial institutions and Central Banks to assess the risks of global nature-climate related shocks in a consistent way, including for example major supply chain interruptions and scenarios such as multiple breadbasket failure (Table 1).

ii. A toolkit of guidance, risk screening tools and scenario building blocks to support financial institutions and Central Banks to construct their own scenarios relevant to their own local context and own portfolios.

Through either in-house analysis, or a participatory scenario design process (as recommended by TNFD 2023), these components could be used to establish a set of location-specific relevant scenarios for financial institutions and Central Banks. The remainder of this report draws upon the evidence to propose an initial set of scenario building blocks and risk screening approach.

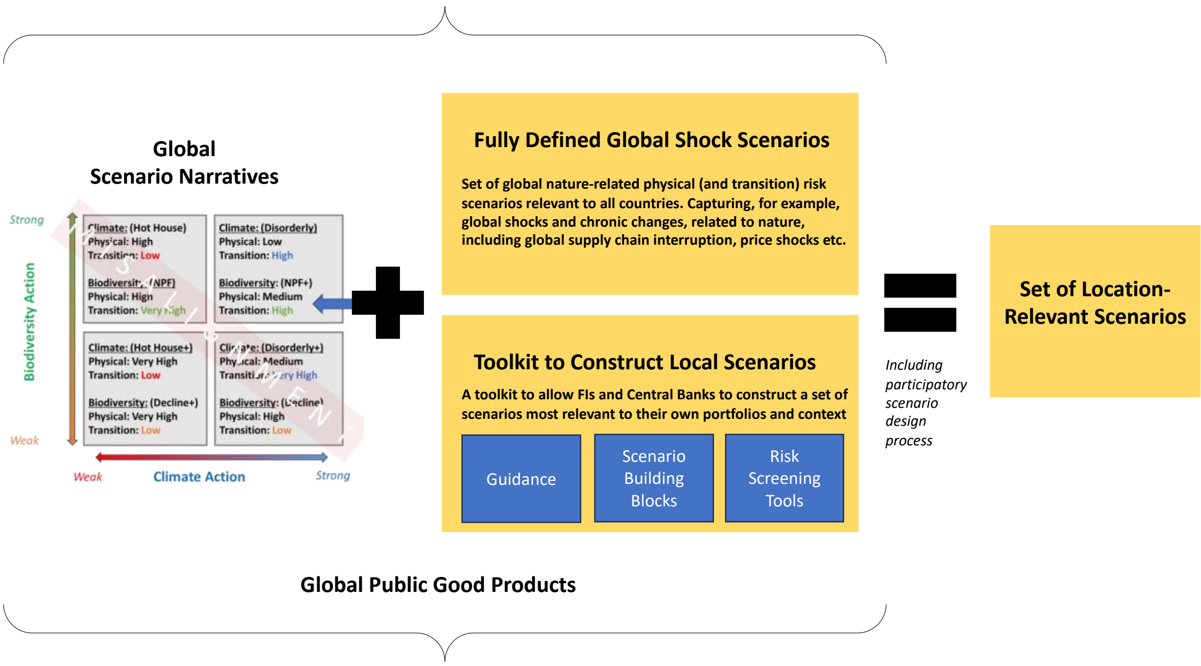


Figure 8: Proposed approach to providing scenarios as a global public good. Source: Authors

3. A Preliminary Set of Physical Nature-Climate Scenarios

The scenarios developed in this report focus primarily on the needs for macro- and micro-prudential risk management and related Central Bank and supervisory policies. This necessitates an approach that builds upon but goes beyond sector-specific risk assessment to capture systems-level cross-sectoral and global risks to identify and quantify the potential for macro-critical risks across an economy. We therefore build our conceptual framework by following the recommendations from the International Monetary Fund (IMF) which states that for stress testing for Central Banks, the priority is to identify and assess macro-financial vulnerabilities that can trigger systemic risk, or, through the operation of the financial system, create downside risks to growth and so signal the need of systemwide mitigating measures (Adrian et al. 2020). Therefore, scenarios for bank stress testing should be *"forward-looking, severe, consistent, and robust trajectories for a comprehensive set of macro-financial variables that react following the materialization of shocks... Scenario design starts with a narrative about how the realization of tail risks could interact with financial vulnerabilities to generate severe but plausible macro-financial impact"* (Adrian et al. 2020). In line with the IMF definition, our focus is primarily on shocks (or tail-risks) as these are the events that are most likely to precipitate crises of most relevance to financial institutions. Chronic changes are important, particularly where they could create pre-conditions that could amplify acute risks.

To build toward a typology of physical shocks, this section first analyses the transmission channels and dimensionality of shocks from the literature and a review of historical nature-related shocks. These two analyses are presented separately but it should be noted they were conducted in parallel and are mutually reinforcing; i.e. the analysis of historical analogues informs the risk transmission channels. These are then used to construct building blocks of scenarios. Note that the full analysis of risk transmission channels will be published soon in a subsequent academic paper.

3.1 Transmission channels for nature-related (physical) financial risks

Previous studies have illustrated the risk transmission channels from nature to finance in qualitative terms, for example, CISL (2021), Kedward et al. (2023) and NGFS (2023). This paper goes a step further to provide an additional level of detail on the physical risk transmission channels necessary to underpin a more complete (quantitative) set of physical risk scenarios. This is based on a detailed review of the literature, both on the science and economics of nature and climate change and their interlinkages with socioeconomic systems, and the literature on transmission channels of sector-level shocks to the macroeconomy and financial system, and the feedbacks therein, as well as the historical analogues analysed in Section 3.2. For simplicity, in this analysis, our focus is on impacts on banks, though we note that other types of financial institutions may experience additional transmission channels and be sensitive to risks on different time horizons, for example for insurance via claims on policy linked to nature-related damages, or for institutional investors via impacts on various fund structures and indices. These are important but will be considered in more detail in later work of the INCAF project.

The IPBES (2019) and IPCC (2022) assessments provide comprehensive evidence on the fundamental drivers of human-induced biodiversity loss and ecosystems degradation (including climate change), the dimensions and potential scale of the impacts on different ecosystem services, as well as evidence on the risks for people (e.g. health, livelihoods), society (culture, settlements) and different industries, in particular agriculture. These reports, which synthesise and assess evidence from thousands of academic papers and experts from across the world, with endorsement from governments, form the basis for our frameworks. From this evidence, it is possible to understand the first steps in risk transmission from nature to finance, from the driver to what we define as the **primary economic receptor** (the sector, asset or people in the case of health). There are particular uncertainties in quantifying these linkages and all their complex feedbacks. The empirical and model simulation-based evidence here is relatively weak, albeit studies exist for particular links (e.g. Table 1).

Figure 9 synthesises this evidence and visualises the main risk transmission channels through which nature (and its interlinkages with climate change) can pose risks to Banks. The final steps of the risk transmission, from the primary economic receptors to the wider real economy, the macroeconomy and financial system, and the feedbacks therein is also well captured in the existing literature for climate-related financial risks, but also wider macroeconomic and financial literature (Adrian et al. 2020). For example, several papers concerning the economic impacts of climate shocks (Botzen et al. 2019), the macroeconomic and financial transmission of shocks (Dunz et al. 2021, BIS 2021, Ranger et al. 2021, Feyen et al. 2020, FSB 2020, Battiston et al. 2017) and the complex feedbacks (e.g. Battiston et al. 2021). There is more (limited) evidence quantifying specific channels of economic impacts, for example, the risks to buildings due to reduced flood protection associated with loss of mangroves (Losanda et al. 2018).

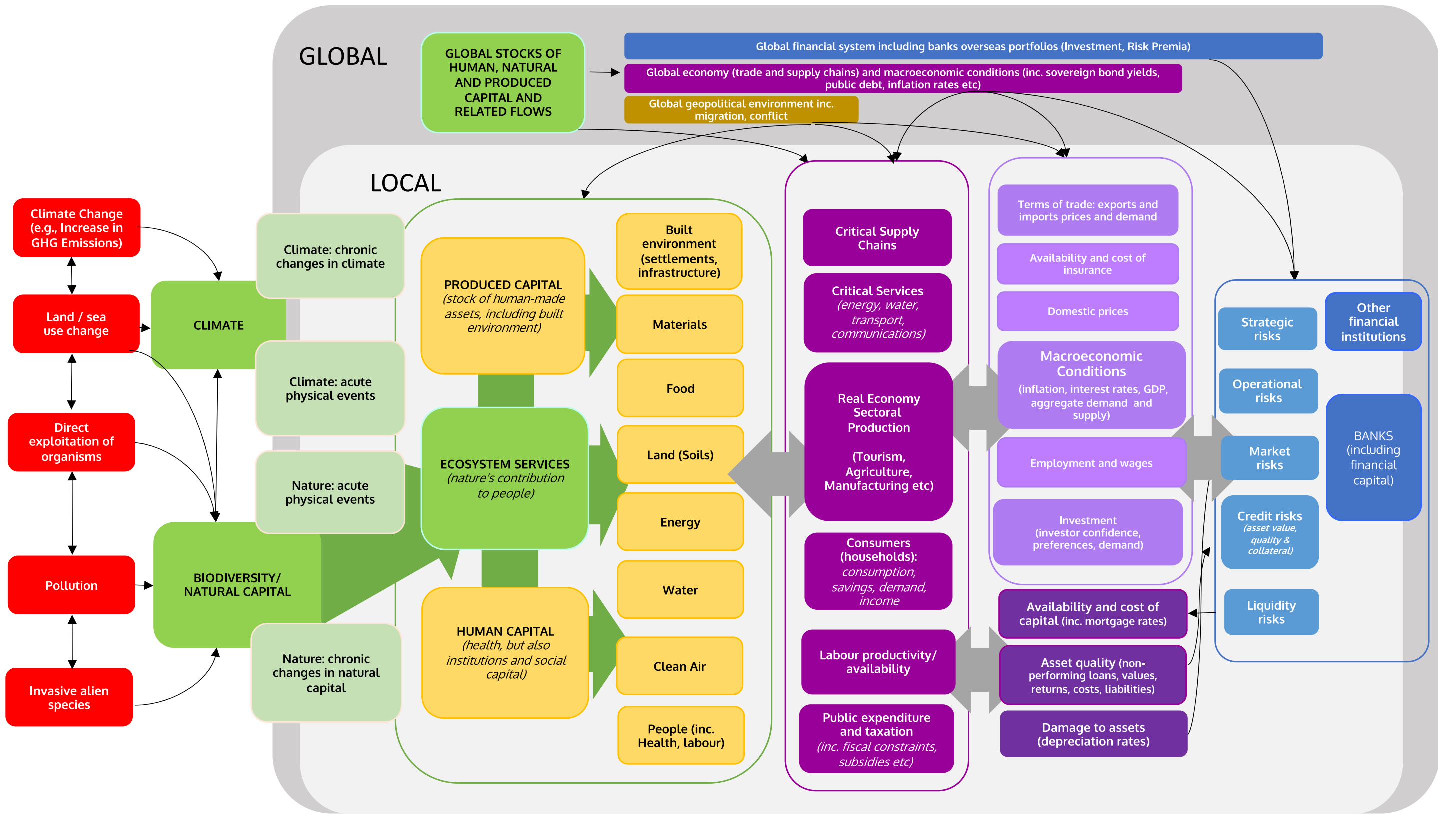


Figure 9: Schematic Risk Transmission Channels. The red boxes on the left-hand side represent different drivers of change (climate change, land and sea use change, direct exploitation of organisms, pollution and invasive alien species) which affect climate and nature and can result in acute and chronic nature and climate changes and shocks (events). These in turn impact on different natural (in green) capital and ecosystem services as then subsequently, human and produced (economic) capital (in yellow, building on the definitions from the Dasgupta Review, including the built environment), with effects on primary economic receptors (in purple, economic sectors, supply chains, critical services such as water and energy, labour, consumers). Impacts on these primary economic receptors can generate direct financial risks (in blue), for example through increases in non-performing loans to specific sectors, as well as second-round (or indirect) economic and global macroeconomic impacts (lilac) that can also directly or indirectly create financial risks. The diagram also represents how local and global processes interact, with global changes impacting locally, though, for example, terms of trade and supply chains, migration and global macroeconomic conditions. Source: Authors, developed as part of the INCAF project

3.2 Typology of Nature-Climate Shocks: Analyses of Historical Analogues

Given that the most likely source of material financial impacts is likely to arise from acute shocks (above), it is instructive to combine the conceptual risk transmission channels in Figure 9 based on literature review and consultations, with an analysis of historical environmental and ecologically-driven crises, both locally and globally. Historical crises bring new insights on transmission channels, including providing additional information on the sources and drivers of shocks and stresses as well as their transmission through the economy. This can be particularly instructive given that model-based simulations of the economic impacts of such crises are narrow, there are significant non-linearities and complexities, and the empirical literature on the impacts of nature-related shocks is much more shallow than, for example, climate change. Like the observational record used in Earth System models to validate model projections, looking into the past can provide valuable insights into unapparent interlinkages between processes and systems.

However, such analyses must also be interpreted with caution. Analysing the past of course cannot tell us everything that might occur in future; historical insights need to be combined with forward-looking models and exploration. Future disasters may be far more severe, due to the increased complexity and interconnectedness of our societies, climate change and the greater strain on natural systems due to human activities; social systems may be pushed to their breaking point. Humankind has essentially never faced some of the upcoming temperature/weather extremes. Backward looking analyses will therefore likely underestimate the size and types of risks that will be faced. Conversely, new technologies, governance and greater wealth reduce vulnerabilities; albeit those systems themselves might be challenged by the stresses and shocks to come.

Looking across both the academic and grey literature, it is possible to identify more than sixty relevant historical shocks acting at either local, national or even global level. The synthesis draws upon a large number of sources not listed here, though we particularly point to the Regime Shifts database (Hakansson et al. 2012). A complication in analysing historical analogues to assess transmission channels is that crises often emerge due to a combination of multiple drivers, for some, the role of human-induced environmental change may be contested. An example of this could be the civil unrest in North Africa related to the Arab Spring, where there is evidence that drought and resulting food price shocks played some amplifying role, but many other (arguably more) important factors were at play (Sternberg 2012, Schilling et al. 2020). There are several similar cases in the record for which there may be complex local political, instability or conflict issues at play and these may be still under debate, making it difficult to attribute losses to other factors. Another example here is the Ethiopian Famine of 1985. In both of these cases, these examples were included (albeit within the 2008-12 food price shocks for the former) as multiple papers provide peer-reviewed evidence on the contributing role of natural capital depletion, e.g. for Ethiopia evidence that agriculture and land use practices played some role in intensifying the impact of the drought that contributed to the severe food insecurity (e.g. Tegegn 2023).

Thirty-two historical analogues were selected to be shown in Table 3, albeit all sixty+ provided contextual information for the analysis. The criteria used to select those for analysis were: (a) magnitude of the shock, for example a significant economic impact at at-least sub-national scale, (b) relevance of shock to current or future conditions (we excluded shocks before the 1900s unless we saw them as adding a particularly important new and relevant dimension to the analysis) and (c) quality of the evidence, including multiple independent peer-reviewed sources. We also sampled the shocks to select those that allowed us to best study the multi-dimensional nature of nature-related risks; for example, we included only one or two examples of impacts of water and air pollution and land-use change to illustrate the risks and transmission channels, even though several more relevant examples were present in the literature. The analysis excluded accidents and focussed on those crises driven by the erosion of natural capital; for example nuclear incidents (e.g. Chernobyl, Three Mile Island, Fukushima), oil spills and industrial accidents were excluded, as were localised disease outbreaks from contaminated water and events related to human introduction of foreign species (rabbit plague in Australia). Shocks driven by natural hazards, such as volcanoes and earthquakes are also excluded. Figure 10 summarises the risks.

From this analysis (and our literature review, e.g. Table 1), it is possible to generate a typology of acute shocks and their characteristics that informs the subsequent section (3.3).

Several points are evident from the historical analogues that are important for the construction of nature-related risk scenarios and support our earlier conclusions from the literature:

- Firstly, just how widespread and frequent crises are: damaging economic and social shocks linked to biodiversity loss and environmental degradation happen across all countries even today;
- The strong linkages between climate and nature (and compounding effects of acute shocks on top of long-term chronic effects): many of the crises have a nature and climate component, for example major agricultural impacts driven by the compounding of a drought with poor agriculture and land-use practices, such as the US Dust Bowl of the 1930s;
- Complex interplay with social and political factors for example the Arab Spring where rising wheat prices contributed to civil unrest in top-importing wheat countries (Sternberg, 2012);
- The second round impacts due to the response to the crisis, for example the foot and mouth disease in the UK in 2001 negatively affected the tourism and supporting industries due to travel restrictions (4-5 Billion GBP, Comptroller and Audit General, 2002).
- The potential for cascading risks, for example, the cascading impacts of droughts that contributed to the global food price shock in 2008-2012, impacting food security across several countries.

Table 3: Historical examples of nature-related risks. Source: Authors based on several sources

Historical example	Date	Geography	Details	Shock and key economic receptors summary	Natural capital being impacted
Aral Sea Crisis	Ongoing from 1960s	Central Asia	Significant decline in water levels starting in the 1960s. Diversion of water for agriculture led to the shrinking of the Aral Sea and increased salinity, devastating local ecosystems. (Micklin, 2007; 2016)	FISHERIES COLLAPSE	WATER
Swine Fever	Ongoing from 2018	Asia-Pacific	Viral disease that effects pigs and boars. A 2019 outbreak in China affected 100 million people and increased food prices. As of 2021, the economic impact in China is estimated at 1.4 to 2% of GDP. (Lloyds of London and CCRS, 2023)	AGRICULTURE (MEAT); DISEASE OUTBREAK	DISEASES/ PESTS
'Bivalves' fisheries collapse (several examples)	Ongoing	Several regions worldwide	Overfishing coupled with disease, habitat loss and an increase in algal blooms from nutrient increase due to agricultural and urban runoff has resulted in bivalves collapse across the world. Negative impacts on ecosystem services include: provisioning (freshwater, fisheries), regulating (water purification) and cultural services which, in turn result in negative economic impacts. In addition, negative health impacts from contamination of seafood and fish. (Hammond et al. 2012 (and references therein); Gobler et al., 2022)	FISHERIES COLLAPSE	BIODIVERSITY
Dust Storms and Desertification	Ongoing	Several (notably Australia, North America and Asia)	Drought and overgrazing contributed to severe dust storms and desertification, impacting agriculture, air quality and -in some cases- visibility. [Several examples, e.g. Ghosh and Pal,2014.]	DUST STORMS, health impacts, property damage, aviation industry.	AIR, LAND
Forest to Savannas	Ongoing	Several regions worldwide	420 Mill. have been deforested between 1990-2020 and recent studies have identified a potential forest to savanna tipping point for the Amazon beyond 40% deforestation. With over 1.6 billion people directly dependent on forests, the extent of this regime shift can have large negative impacts on ecosystem services including: provisioning), regulating and cultural ecosystem services. (Rocha et al., 2017 and references therein; UN-DESA, 2021; Franklin and Pindyck, 2018)	FOREST REGIME SHIFT	LAND
Gulf of Mexico Dead Zone	Ongoing	Gulf of Mexico	Agricultural runoff containing nutrients has led to the formation of a large hypoxic zone, affecting marine life. (Rabalais et al., 2002)	WATER QUALITY, EUTROPHICATION	WATER

Indus River Pollution and Water Scarcity	Ongoing (increasing)	Pakistan	Significant decline in water availability driven by increases in food production to cope with growing population and rise in commodities prices. Negative impacts including crop losses, migration to urban areas and social security. Heavy metal and microplastics pollution negatively impact fish and human health. (Zhang et al., 2020; Janjua et al., 2021; Tsering et al., 2021; Al-Ghanim et al., 2016)	WATER SUPPLY SHOCK; HUMAN HEALTH/RECREATION IMPACT OF WATER	WATER
Lake Chad Shrinking	Ongoing	Sahel	Over-extraction of water for irrigation and climate variability have led to a significant reduction in the size of Lake Chad, impacting water availability and ecosystems. (Gao et al., 2011; Jedwab et al., 2023)	WATER SUPPLY SHOCK; FISHERIES COLLAPSE; migration	WATER
Madagascar chronic loss of arable land	Ongoing	Madagascar	Deforestation and unsustainable agricultural practices have led to extensive soil erosion and loss of arable land. (Scales, 2014; Harvey et al., 2014)	SOIL QUALITY DETERIORATION AFFECTS FOOD PRODUCTION	SOIL
Mangrove transitions	Ongoing	Several (mangrove forests in +100 countries)	Mangrove forests are present in over 100 countries, with almost 75% area in Asia, Africa and South America. Between 20-35% loss in the extent of mangroves globally in the past 50 years. Drivers include: deforestation, aquaculture, shrimp farming, urban development and changes to water salinity (Regime Shifts Database). As a result, there are negative impacts on ecosystem services including: provisioning, regulating and cultural. (Rocha et al., 2017b; Polidoro et al., 2010; FAO, 2020)	MANGROVES COLLAPSE	BIODIVERSITY
Soil Salinisation	Ongoing	Several	Driven by vegetation removal, heavy rainfall and irrigation, soil salinisation affects almost 9% of global land area. There are large negative impacts on ecosystem services including: provisioning (freshwater, crops, livestock, fuel and fiber crops, wild animal and plant foods), regulating (water regulation/ purification, soil erosion) and cultural. Hotspots in China, India, US, Australia, Argentina, Pakistan, Sudan, countries in Central and Western Asia and the Mediterranean coast. (Giusti et al., 2017; Daliakopoulos et al., 2016; FAO, 2021a: 2021b)	SOIL SALINISATION	SOIL

COVID-19	2020-2022	Global	Environmental degradation increases the chance of epidemics and pandemics, with COVID-19 being an example of the significant potential impact on people and economies (Di Marco et al. 2020). The lockdowns in 2020-2021 led to significant labour shortages and major impacts on supply chains as well as disruptions to wider health and social services. Significant impacts on GDP, employment and poverty levels globally.	HEALTH, LABOUR PRODUCTIVITY, BUSINESS INTERRUPTION, SUPPLY CHAINS	DISEASES /PESTS
Ogallala Aquifer Depletion	Since 1950s	US	Overextraction of water for irrigation has resulted in the depletion of the Ogallala aquifer in several regions, negatively impacting water availability for agriculture. (Terrell et al, 2002; Basso et al., 2013; Deines et al., 2020)	WATER SUPPLY SHOCK	WATER
Indonesia Fires	Several	Indonesia	Deforestation has led to growing incidents of fires and associated air pollution impacts. (Frankenberg et al., 2005; Tacconi et al., 2007)	WILDFIRES, AIR POLLUTION (human health); WILDFIRE DIRECT DAMAGE	LAND
River pollution, e.g. Yangtze	Several	Several globally	For example, pollution of the Yangtze River. (Floehr et al., 2013; Yujun et al., 2008)	WATER QUALITY; HUMAN HEALTH/RECREATION IMPACT OF WATER	WATER, BIODIVERSITY
Global coral bleaching	Several including: 1997-98, 2009-10, 2014- 2016	Several regions worldwide (pan-tropical)	Climate change, pollution, diseases, ocean acidification and overfishing have triggered coral regime shifts worldwide. Multiple negative impacts on ecosystem services include: provisioning services (e.g.: fisheries), regulating services (e.g.: natural hazard,), cultural services (e.g.: recreation) as well as negative impacts on livelihoods and the economy (e.g.: tourism sector). (Rocha et al., 2017c and references therein; Hughes et al., 2007)	CORAL REEF COLLAPSE; CORAL REEF COLLAPSE LEADS TO STORM DAMAGE	BIODIVERSITY
Cape Town Water Crisis	2017/18	South Africa	Drought and water mismanagement led to severe water shortages, prompting the city to implement strict water rationing measures. (Millington and Scheba, 2021; Parks et al., 2019)	WATER SUPPLY SHOCK; HUMAN HEALTH/RECREATION WATER. Agriculture, health, tourism.	WATER

Global food price shock	2010/ 2012	Global	Drought in China, Russia and Ukraine combined with excessive rain in Canada and Australia resulted in global wheat supply disruption and doubling of global prices. Top wheat importing countries (many located in Middle East and North Africa) were heavily affected. Impacts on terms of trade, currency and inflation. Knock-on impacts for biofuels production and oil prices. For example, tripling wheat prices in Egypt contributed to civil unrest. Evidence of interlinkages to geopolitical tensions including Arab Spring. (Sternberg, 2012)	MAJOR GLOBAL FOOD SYSTEM SHOCK. Geopolitical impacts. Food prices. Energy.	LAND, WATER
Localised zoonotic disease outbreaks, e.g. Foot & mouth disease outbreaks affecting livestock	Several including UK: 2001, 2007	Several	The 2001 Foot and mouth disease outbreak in the UK resulted in the slaughtering of over 6 million animals, mental health effects in affected communities as well as economic costs. Public economic costs included compensation to farmers, direct costs measures to contain epidemic whilst costs to the private sector included lost revenues to tourism sector and were estimated over 4.6 and 7.7 billion in 2020-21 prices respectively. (Comptroller and Auditor General, 2002; House of Commons Committee of Public Accounts; 2022)	ZOONOTIC DISEASE	DISEASES/ PESTS
Climate shocks of El Niño aggravated by land-use change	1997-98/ 2015-16	SEA, Australia, Indian subcontinent	Prolonged drought in SE Asia, Australia and the Indian subcontinent have higher impacts on agriculture and forestry due to degraded lands, disrupting food and biofuels. Changes in land-use can also increase flood and wildfire risk. Potential disruption to food and biofuels. Drier conditions also affect energy generation in those countries, notably in Latin American countries such as Brazil, Colombia and Venezuela, that tend to rely heavily on hydroelectric power generation. That can lead to power shortages, pushing up prices and stifling activity. (Callahan and Mankin, 2023; Schoeders, 2023; Bloomberg, 2023)	WILDFIRE, FLOOD, ENERGY, WATER, FOOD	LAND, WATER, CLIMATE
Collapse of Newfoundland cod fisheries	early 1990s	Northwest Atlantic	Overfishing coupled with climate change (cooler water temperatures) resulted in the collapse of the Canadian cod fisheries in the region in the early 1990s. Cod abundance decreased by 90% negatively affecting provisioning services (fisheries), livelihoods and cultural identity. (Patel et al., 2017 and reference therein)	FISHERIES COLLAPSE	BIODIVERSITY, WATER
Food security threats: famine in Ethiopia	1983–1985	Ethiopia	Over intensive farming, deforestation, and drought contributed to widespread famine and soil degradation aggravated by local conflict (combination of "war and drought") in Ethiopia. The Ethiopian famine of 1983-1985 affected 7.75 million people,	SOIL QUALITY DETERIORATION AFFECTS EXPOSURE	SOIL

			resulting in an estimated 300,000 to 1.2 million deaths, with 2.5 million internally displaced and 400,000 refugees leaving the country. (De Waal, 1991; Keller, 1992)	TO DROUGHT. Migration, civil unrest.	
Baltic sea eutrophication	1970s	Baltic region (Lithuania, Poland, Latvia, Sweden, Russia, Estonia, Finland, Denmark and Germany)	The Baltic Sea has shifted from oligotrophic to eutrophic as a result of nutrient concentration increase from agricultural, municipal sewage and industry runoff. This has negatively impacted provisioning (fisheries), regulating (water purification) and cultural ecosystem services (e.g.: recreation from beach closures). (Yletyinen et al., 2017)	EUTROPHICATION (SEA, LAKES); WATER QUALITY, EUTROPHICATION	WATER
Lake Erie Pollution (Cuyahoga River Fire) in the United States	1960s and 70s	US	Industrial pollution and oil slicks on the Cuyahoga River caught fire, drawing attention to water pollution issues (Adler, 2002; Stradling and Stradling, 2008)	WATER QUALITY	WATER
Degradation of Maradi Agro-ecosystem	early 1960s	Niger	Government policies on land ownership resulted in land-clearing of trees by farmers in the region driving soil erosion. This resulted in negative impacts on ecosystem services: provisioning, regulating and cultural. This, coupled with population increase and droughts negatively impacted human well-being (e.g.: hunger, poverty increase). (Tshimpanga et al., 2017)	SOIL QUALITY DETERIORATION AFFECTS FOOD PRODUCTION	SOIL
Green Revolution in Agriculture	1950s	Several countries	Intensive use of fertilizers and pesticides during the Green Revolution contributed to soil degradation and water pollution in some areas (Pingali, 2012)	SOIL QUALITY DETERIORATION AFFECTS FOOD PRODUCTION; WATER QUALITY	SOIL; WATER
London Smog	1950s	UK	Air pollution, primarily from coal burning, resulted in a deadly smog that caused respiratory problems and numerous deaths. (Laskin, 2006)	AIR POLLUTION	AIR
American Dust Bowl	1930s	US	Over-intensive agriculture, land-use change and poor land management practices combined with severe drought led to extensive soil erosion, causing dust storms and agricultural collapse. (Hornbeck, 2012)	SOIL QUALITY DETERIORATION	SOIL

				AFFECTS FOOD PRODUCTION	
Forestry disease outbreak (several examples – e.g. US chestnut, maple)	Early 1900s	US	'Chestnut blight', an invasive alien fungus from Asia, spread from New York to other states and resulted in less than 1% of original chestnut trees remaining by the 1950s. Negative impacts on provisioning, regulating and cultural ecosystem services.(Shackleton, 2018)	FORESTRY OUTBREAK (e.g. SILKA SPRUCE PEST; RED MAPLE IN US). Impact on Timber	DISEASES/ PESTS
Indian famine	1896–1897, 1899-1900	India	Drought and its resulting decrease in soil moisture led to famine which affected almost 70 Mill. and 5 Mill. casualties in India in 1896-7. Amidst recovery from the 1896-7 famine, a decrease in monsoon rainfall in 1899-1900 led to famine affecting almost 60 Mill. and 1-4.5 Mill. casualties. (Mishra et al., 2013; 2019 and references therein)	SOIL QUALITY DETERIORATION AFFECTS EXPOSURE TO DROUGHT. Health impacts.	SOIL; CLIMATE
Grande Seca	1877–1879	Brazil	Prolonged drought in Brazil coupled with unsustainable agricultural practices and an inadequate crisis response from government resulted in famine and mass migration from Northeast Brazil to other regions. Mass migration resulted in unsanitary living conditions which led to disease propagation and almost 200k casualties. (Sousa and Pearson, 2009; Aceituno et al., 2009)	SOIL QUALITY DETERIORATION AFFECTS EXPOSURE TO DROUGHT. Mass migration, health impacts.	SOIL; CLIMATE
Northern Chinese Famine	1876–1879	China	Crop failures due to severe drought, aggravated by misguided agricultural policies, including overuse of land and poor irrigation practices, contributed to widespread famine and social upheaval in North China in 1876-9. (Edgerton-Tarpley, 2008; Zhai et al., 2020)	SOIL QUALITY DETERIORATION AFFECTS FOOD PRODUCTION; Civil unrest	SOIL; CLIMATE

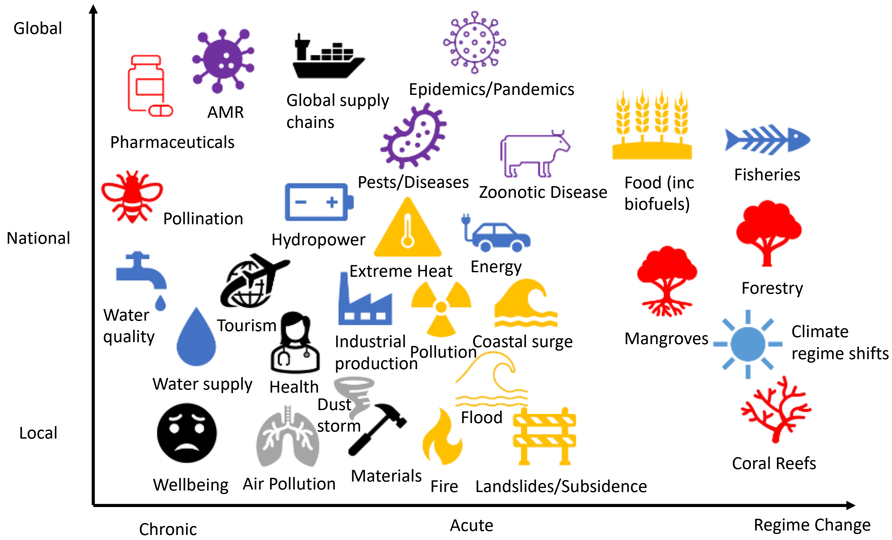


Figure 10: Illustration of the types of nature-related impacts arising and their characteristic geographical scale and temporal distribution (chronic, acute or regime change). See Table 4 for details. Note that some can operate at multiple temporal and spatial scales e.g. food and supply chain interruption, and some are interconnected, for example local climate regime changes can impact flood and heat risk. Primary hazards can also perturbate into important second effects, such as conflict and migration. In addition, while we categorise hazards into chronic, acute and regime change, many can exhibit different characteristics in different contexts, e.g. a regime change can emerge from chronic changes when a threshold is breached. Colours illustrate the main type of natural capital degradation that is linked to the hazard (noting some hazards will have several drivers): red (biodiversity), yellow (land and soils), blue (water), grey (air), purple (disease), black (multiple). Source: Authors

3.3 Scenario Building Blocks

Given the complexities of nature-related risks, and the resulting principles from Section 2, this final part of Section 3 takes the evidence on risk transmission channels and the typology of shocks to create a set of simple building blocks to begin to develop narrative scenarios. The building blocks approach resolves several challenges. It allows the exploration of cascading and compounding impacts through combining different blocks. It also resolves the challenge of providing information globally that can help locally, when the characteristics of nature-related risks are so multi-dimensional and heterogenous across countries. These building blocks allow users to flexibly combine components of risk in order to build narratives relevant to their own country or portfolio. These scenarios can be coupled with the simple risk screening approach, such as that developed in Section 4, to identify which narrative scenarios are most relevant for a particular country.

Our approach to generating narrative scenarios centres on the hazard (or shock) itself, for example, a coastal surge made more impactful by the degradation of mangroves; reduced water quality; increased extreme heat due to removal of vegetation in cities or antimicrobial resistance. This is different to the standard ENCORE-based approach, for example, which starts with the ecosystem service. The focus on the shock first, can help to simplify the analysis, as multiple natural assets and ecosystem services can feed into one shock, and one shock can influence the economy through multiple transmission channels. Each shock can individually become a narrative scenario of its own or can be combined with other shocks to generate more complex narratives, including compounding risks. For example, air pollution due to loss of vegetation in urban areas could be paired with impacts on mental health, fire risk and extreme heat, to build a narrative for a scenario.

Figure 11: Schematic of process to generate narrative scenarios

Building upon the hazards (shocks) identified in Section 3.2, the transmission of the shock was then mapped *forwards* to economic impacts and *backwards* to ecosystem services, natural assets and drivers of degradation along the impact chain, as illustrated in Figure 11, based on the evidence collected from the literature (detailed above), the historical analogues analysis and consultations with experts through the INCAF project. Moving *forward* along the impact chain from the shock, the focus of the analysis is on the *'primary economic receptors'* in the economy, this facilitates the quantification of risk in Section 4. Primary economic receptors, as shown in Figures 9 and 11, include economic sectors but also other components of the economic system that, if shocked or stressed, could generate financial risk. This includes, for example, labour productivity, public expenditure, prices, terms of trade, demand and capital stock (real estate and infrastructure). Importantly, this means that the scope of risk transmission channels, and therefore the assessment of risk, goes beyond what is captured by the ENCORE approach and begins to become compatible with standard financial risk assessment.

Table 4 summarises the initial set of scenario building blocks. This contains around more than seventy unique shock-receptor pairs. The table does capture climate change and acute climate risks as risk amplifiers, but the table does not include 'pure' climate risks (e.g. a flood without any biodiversity loss or environmental degradation). The table focusses on where climate and nature-related drivers, risks and impacts interact. The table contains information on key characteristics of risks and impacts that can be useful in building scenarios. For example, it identifies where an acute climate shock, such as a drought, could compound with the nature-related risk to trigger or heighten further impacts. It characterises the risk in terms of chronic, acute or regime shift, where a regime shift entails an event that could occur rapidly and lead to an irreversible change. Risks are also characterised in terms of their scale.

Importantly, in the context of Figure 8, the following potential global nature-climate related shock scenarios, relevant to all financial institutions emerge:

- Global health-related risk (and opportunities) due to growing risks of epidemics/pandemics and antimicrobial resistance, and knock-on social and economic effects.
- Global food system (water risks, soil erosion and agricultural commodities) shocks
- Global commodities shocks: oil (biofuels), materials (mining products, timber, leather, etc)

The following section introduces the approach to risk screening and assessment that complements this scenario approach, as illustrated in Figure 8. The final section then demonstrates how these can be applied in practice through an application to nature-climate impacts linked to drought in France.

Table 4: Building blocks for narrative scenarios (colours of columns link to Figure 11, with the addition of climate amplifiers in blue). The grey rows are those hazard-primary economic receptor pairs that are explored within the preliminary risk assessment of this study (Section 4). Source: authors

NATURE-RELATED DRIVER	CHRONIC CLIMATE AMPLIFIER	ACUTE CLIMATE AMPLIFIER	NATURAL CAPITAL IMPACTED (PRIMARY)	ECOSYSTEM SERVICE AFFECTED- ENCORE (PRIMARY)	NATURE HAZARD/SHOCK	TIME SCALE	GEO SCALE	ECOSYSTEM DEPENDENCY IMPACTED	PRIMARY ECONOMIC RECEPTOR
Land-use change/ removal vegetation	Climate change	DROUGHT/ HEAT	LAND	Climate regulation; Dilution by atmosphere and ecosystems	WILDFIRES & HEATWAVES, AIR POLLUTION FROM LOSS VEGETATION (including URBAN HIGH RISK)	ACUTE	LOCAL (URBAN)		HUMAN HEALTH
Land-use change/ removal vegetation	Climate change	DROUGHT/ HEAT	LAND	Climate regulation; Dilution by atmosphere and ecosystems	WILDFIRES & HEATWAVES, AIR POLLUTION FROM LOSS VEGETATION (including URBAN HIGH RISK)	ACUTE	LOCAL (URBAN)		BUSINESS INTERRUPTION
Land-use change/ removal vegetation	Climate change	DROUGHT/ HEAT	LAND	Climate regulation; Dilution by atmosphere and ecosystems	WILDFIRES & HEATWAVES, AIR POLLUTION FROM LOSS VEGETATION (including URBAN HIGH RISK)	ACUTE	LOCAL (URBAN)		PUBLIC EXPENDITURE
Land-use change/ removal vegetation	Climate Change	DROUGHT/ HEAT	LAND/AIR	Climate regulation; Dilution by atmosphere and ecosystems	DUST STORMS	ACUTE	LOCAL		HUMAN HEALTH
Land-use change/ removal vegetation	Climate Change	DROUGHT/ HEAT	LAND/AIR	Climate regulation; Dilution by atmosphere and ecosystems	DUST STORMS	ACUTE	LOCAL		BUSINESS INTERRUPTION
Land-use change/ removal vegetation	Climate Change	DROUGHT/ HEAT	LAND/AIR	Climate regulation; Dilution by atmosphere and ecosystems	DUST STORMS	ACUTE	LOCAL		REAL ESTATE
Land-use change/ removal vegetation	Climate Change	DROUGHT/ HEAT	LAND/AIR	Climate regulation; Dilution by atmosphere and ecosystems	DUST STORMS	ACUTE	LOCAL		AGRICULTURE
Pollution	Climate change	DROUGHT/ HEAT	AIR	Dilution by atmosphere and ecosystems	WORSENING AIR POLLUTION IN URBAN AREAS	CHRONIC	LOCAL		BUSINESS INTERRUPTION
Pollution	Climate change	DROUGHT/ HEAT	AIR	Dilution by atmosphere and ecosystems	WORSENING AIR POLLUTION IN URBAN AREAS	CHRONIC	LOCAL		HUMAN HEALTH

Land-use change/ removal vegetation	Climate change	DROUGHT/ HEAT	LAND	Climate Regulation	WILDFIRE DIRECT DAMAGE	ACUTE	LOCAL		REAL-ESTATE
Land-use change/ removal vegetation	Climate change	FLOOD/ STORM	LAND	Flood and Storm Protection	FLOODS DIRECT DAMAGE	ACUTE	LOCAL		REAL-ESTATE
Land-use change/ removal vegetation	Climate change	FLOOD/ STORM	LAND	Flood and Storm Protection	FLOODING OF MINES/QUARRIES	ACUTE	LOCAL	Materials [13]	MINING/METALS
Land-use change/ removal vegetation	Climate change	FLOOD/ STORM	LAND	Flood and Storm Protection	FLOOD INDIRECT DAMAGE	ACUTE	LOCAL		BUSINESS INTERRUPTION
Overexploitation/ Pollution	Climate Change	STORM	BIODIVERS ITY	Flood and Storm Protection	CORAL REEF COLLAPSE – COASTAL FLOOD AND STORM DAMAGE	REGIME	LOCAL	Flood Storms; [9]	REAL-ESTATE & AGRICULTURE
Overexploitation /pollution/removal	Climate Change	HEAT	BIODIVERS ITY	Flood and Storm Protection	SALTMARSH REMOVAL INCREASES FLOOD AND STORM DAMAGE	REGIME	LOCAL	Flood Storms	REAL-ESTATE & AGRICULTURE
Overexploitation/ Pollution/removal	Climate Change	STORM	BIODIVERS ITY	Flood and Storm Protection	MANGROVE COLLAPSE – COASTAL FLOOD AND STORM DAMAGE	REGIME	LOCAL	Flood Storms; [9]	REAL-ESTATE & AGRICULTURE
Land-use change/ removal vegetation	Climate Change	FLOOD/ STORM	LAND	Mass stabilisation and erosion control	LANDSLIDES AFFECTING MINING OPERATIONS	ACUTE/ CHRONIC	LOCAL	Materials [13]	MINING/METALS
Land-use change/ removal vegetation			LAND	Mass stabilisation and erosion control	SUBSIDENCE RISKS TO BUILDINGS	CHRONIC	LOCAL		REAL-ESTATE
Land-use change/removal vegetation			LAND	Mass stabilisation and erosion control	SUBSIDENCE RISKS TO INFRASTRUCTURE	CHRONIC	LOCAL		ENERGY
Pollution	Climate change	All	WATER	Water quality/ Bioremed/Filtration	WATER QUALITY e.g. EUTROPHICATION	CHRONIC	LOCAL		INDUSTRY
Pollution	Climate change	All	WATER	Water quality/ Bioremed/Filtration	WATER QUALITY e.g. EUTROPHICATION	CHRONIC	LOCAL		AGRICULTURE
Pollution	Climate change	All	WATER	Water quality/ Bioremed/Filtration	WATER QUALITY e.g. EUTROPHICATION	CHRONIC	LOCAL		HUMAN HEALTH

Pollution	Climate change	All	WATER	Water quality/ Bioremed/Filtration	WATER QUALITY e.g. EUTROPHICATION	CHRONIC	LOCAL		BUSINESS INTERRUPTION
Overexploitation	Climate change	DROUGHT/ HEAT	WATER	Groundwater/Surfacewater/Water flow maintenance/Water quality	WATER SUPPLY SHOCK	ACUTE/ CHRONIC	NATIONAL		INDUSTRY
Overexploitation	Climate change	DROUGHT/ HEAT	WATER	Surfacewater/Water flow maintenance/Water quality	HUMAN HEALTH/RECREATION	CHRONIC	NATIONAL		HUMAN HEALTH (Also migration)
Overexploitation	Climate change	DROUGHT/ HEAT	WATER	Groundwater/Surfacewater/Water flow maintenance/Water quality	WATER SUPPLY SHOCK	ACUTE/ CHRONIC	NATIONAL		MINING/METALS
Overexploitation	Climate change	DROUGHT/ HEAT	WATER	Groundwater/Surfacewater/Water flow maintenance/Water quality	WATER SUPPLY SHOCK	ACUTE/ CHRONIC	NATIONAL		AGRICULTURE
Overexploitation	Climate change	DROUGHT/ HEAT	WATER	Groundwater/Surfacewater/Water flow maintenance	WATER SUPPLY SHOCK - SOLAR	ACUTE/ CHRONIC	NATIONAL		ENERGY PRICES (SOLAR)
Land conversion	Climate change	DROUGHT/ HEAT	WATER	Water flow maintenance/Mass stabilisation and erosion control	HYDROPOWER WATER SHOCK	ACUTE/CHRONIC	NATIONAL	Energy (11)	ENERGY PRICES (HYDRO)
Land conversion	Climate change	DROUGHT/ HEAT	WATER	Water flow maintenance/Mass stabilisation and erosion control	ENERGY - NUCLEAR/GAS/COAL	ACUTE/CHRONIC	NATIONAL	Energy (11)	ENERGY PRICES
Pollution	Climate change		WATER	Bioremediation/Dilution/Filtration	FISHERIES COLLAPSE	ACUTE	NATIONAL	Food and Feed	FISHERIES
Overexploitation	Climate change		BIODIVERSITY		FISHERIES COLLAPSE	REGIME	NATIONAL	Food and feed (10)	FISHERIES
Overexploitation/ Pollution	Climate change	HEAT/ STORM	BIODIVERSITY		CORAL REEF COLLAPSE	REGIME	NATIONAL	Materials (13)	TOURISM
Overexploitation/ Pollution	Climate change	HEAT/ STORM	BIODIVERSITY		CORAL REEF COLLAPSE	REGIME	NATIONAL	Materials (13)	LIVELIHOODS

Overexploitation/ Pollution	Climate change	HEAT/ STORM	BIODIVERS ITY		MANGROVES COLLAPSE	REGIME	NATIONAL	Materials (13)	FISHERIES
Overexploitation/ Pollution	Climate change	HEAT/ STORM	BIODIVERS ITY		MANGROVES COLLAPSE	REGIME	NATIONAL	Materials (13)	LIVELIHOODS
Pollution	Climate change	DROUGHT/ HEAT	WATER	Bioremediation/Dilution/Filtrati on	EUTROPHICATION (SEA, LAKES)	CHRONIC/ REGIME	NATIONAL	Food and Feed	FISHERIES
Change in use	Climate change	DROUGHT/ HEAT	WATER	Disease Control	PEST OUTBREAK AQUACULTURE IMPACT	ACUTE	NATIONAL	Food and Feed	FISHERIES
Change in use	Climate change	DROUGHT/ HEAT	WATER	Disease Control	PEST OUTBREAK AQUACULTURE IMPACT	ACUTE	NATIONAL	Food and Feed	HUMAN HEALTH
Land-use change	Climate change		DIS/PEST	Disease Control/Genetic Materials	ANTIMICROBIAL RESISTANCE	CHRONIC	NATIONAL/ GLOBAL		HUMAN HEALTH
Land-use change; wildlife trade; agricultural expansion/intensification	Climate change		DISEASE /PESTS	Disease Control	ZOONOTIC DISEASE	ACUTE	NATIONAL	Animal-Based Energy	AGRICULTURE (ANIMAL ENERGY)
Land-use change; wildlife trade; agricultural expansion/intensification	Climate change		DISEASE /PESTS	Disease Control	ZOONOTIC DISEASE	ACUTE	NATIONAL	Food and feed (10)	AGRICULTURE (LIVESTOCK)
Land-use change; wildlife trade; agricultural expansion/intensification	Climate change		DISEASE /PESTS	Disease Control/Genetic Materials	ZOONOTIC DISEASE	ACUTE	NATIONAL		HUMAN HEALTH
Land-use change; wildlife trade; agricultural expansion/intensification	Climate change		DISEASE /PESTS	Disease Control	ZOONOTIC DISEASE	ACUTE	NATIONAL		PUBLIC EXPENDITURE
Land-use change	Climate change		WATER	Disease Control	VECTOR-BORNE DISEASES	CHRONIC	NATIONAL		HUMAN HEALTH
Land-use change	Climate change		WATER	Disease Control	VECTOR-BORNE DISEASES	CHRONIC	NATIONAL		EXPENDITURE

Land-use change	Climate change		BIODIVERSITY	Mediation of Sensory Impacts	MENTAL HEALTH	CHRONIC	NATIONAL		HUMAN HEALTH
Pollution (Pesticides); Diseases	Climate change		BIODIVERSITY	Pollination	LOSS OF POLLINATION SERVICE	CHRONIC	NATIONAL	Food and feed (10)	AGRICULTURE
Land-use change/pollution	Climate change		BIODIVERSITY		TOURISM IMPACT	CHRONIC/ ACUTE	NATIONAL		TOURISM
Overexploitation/Pollution	Climate change		WATER	Surface Water	IMPACT ON RECREATION	ALL	NATIONAL		TOURISM
Land-use change/pollution	Climate change		BIODIVERSITY	Genetic Materials	PHARMACEUTICALS	CHRONIC	GLOBAL	Medicinal, genetic resources [14]	INDUSTRY (PHARMA)
All	Climate change		BIODIVERSITY		RISING DEMAND FOR HEALTH CARE	CHRONIC	NATIONAL		INDUSTRY (HEALTH)
Land-use change/pollution	Climate change		BIODIVERSITY	Genetic Materials	EPIDEMIC/PANDEMIC OUTBREAKS	ACUTE	GLOBAL		HUMAN HEALTH
Land-use change/pollution	Climate change		BIODIVERSITY	Genetic Materials	EPIDEMIC/PANDEMIC OUTBREAKS	ACUTE	GLOBAL		BUSINESS INTERRUPTION
Land-use change/pollution	Climate change		BIODIVERSITY	Genetic Materials	EPIDEMIC/PANDEMIC OUTBREAKS	ACUTE	GLOBAL		PUBLIC EXPENDITURE
Land-conversion/ deforestation/overexploit	Climate change	DROUGHT/ HEAT/FLOOD /STORM	LAND	Climate Regulation	MAJOR GLOBAL FOOD SYSTEM SHOCK (INCLUDING OTHER AGRICULTURAL COMMODITIES)	CHRONIC/ ACUTE	GLOBAL	Food and feed (10)	FOOD PRICES
Land-conversion/ deforestation/overexploit	Climate change	DROUGHT/ HEAT/FLOOD /STORM	LAND	Climate Regulation	MAJOR GLOBAL FOOD SYSTEM SHOCK (INCLUDING OTHER AGRICULTURAL COMMODITIES)	CHRONIC/ ACUTE	GLOBAL	Food and feed (10)	MIGRATION
Land-conversion/ deforestation/overexploit	Climate change	DROUGHT/ HEAT/FLOOD /STORM	LAND	Genetic Diversity	GLOBAL FOOD SYSTEM - UNDERMINED RESILIENCE	CHRONIC	GLOBAL		FOOD PRICES

Land-conversion/ deforestation/overexploit	Climate change	DROUGHT/ HEAT/FLOOD /STORM	LAND	Climate regulation/Flood and storm protecton	INTERRUPTION TO GLOBAL SUPPLY CHAINS FOR KEY COMMODITIES AND GOODS	ACUTE	GLOBAL	Materials and assistance (13)	INPUT PRICES
Land-conversion/ deforestation/overexploit	Climate change	DROUGHT/ HEAT/FLOOD /STORM	LAND	Climate Regulation	ENERGY SYSTEM GLOBAL SHOCK - OIL PRICES, BIOFUELS	CHRONIC/ ACUTE	GLOBAL	Energy (11)	ENERGY PRICES
Overexploitation	Climate change	DROUGHT/ HEAT	SOIL	Bioremediation/Dilution /Soil Quality	SOIL QUALITY DETERIORATION IMPACTING ON AGRICULTURAL PRODUCTION	CHRONIC/ REGIME	NATIONAL	Food and feed (10)	AGRICULTURAL PRODUCTION
Overexploitation	Climate change	DROUGHT/ HEAT	SOIL	Bioremediation/Dilution /Soil Quality	SOIL QUALITY DETERIORATION IMPACTING ON AGRICULTURAL PRODUCTION	ACUTE	NATIONAL	Food and feed (10)	AGRICULTURAL PRODUCTION
Overexploitation	Climate change	DROUGHT/ HEAT	SOIL	Bioremediation/Dilution /Soil Quality	BIOFUEL PRODUCTION AFFECTED (VIA SOILS)	CHRONIC	NATIONAL	Energy (11)	ENERGY
Overexploitation	Climate change	DROUGHT/ HEAT	SOIL	Bioremediation/Dilution/ /Soil Quality	ECOLOGICAL REGIME SHIFT AFFECTING AGRICULTURE	REGIME	NATIONAL	Food and feed (10)	AGRICULTURAL PRODUCTION
Land-conversion/deforestation /overexploitation		DROUGHT/ HEAT	SOIL	Bioremediation/Dilution /Soil Quality	SOIL SALINISATION	REGIME	NATIONAL	Food and feed (10)	AGRICULTURAL PRODUCTION
Land-conversion/deforestation /overexploitation		DROUGHT/ HEAT	LAND	Bioremediation/Dilution /Soil Quality	FOREST REGIME SHIFT AFFECTING FORESTRY PRODUCTS	REGIME	LOCAL	Materials and assistance (13)	FORESTRY
Land conversion, pollution	Climate change		PESTS	Disease Control/Pest Control	GRAIN CROP PEST/PATHOGEN OUTBREAK	ACUTE	NATIONAL	Food and Feed (10)	AGRICULTURAL PRODUCTION
Land conversion, pollution	Climate change		PESTS	Disease Control/Pest Control	FORESTRY OUTBREAK (e.g. SITKA SPRUCE PEST; RED MAPLE IN US)	ACUTE	LOCAL	Materials (13); Energy (11)	FORESTRY
Land conversion, pollution	Climate change		PESTS	Disease Control/Pest Control	AMAZONIAN PARASITES ON HEVEA BRASILIENSIS (i.e. conducive rubber trees)	ACUTE	NATIONAL	Materials (13)	INDUSTRY (AVIATION, RUBBER sectors)

Trade			BIODIVERSITY	Invasive Species (Pest Control)	LIVELIHOODS IMPACT - ANIMAL BREED; TOURISM	ACUTE/ CHRONIC	LOCAL	Food and Feed (10)	HOUSEHOLDS
Trade			BIODIVERSITY	Invasive Species (Pest Control)	CROP FAILURE AND DECLINING AGRICULTURAL PRODUCTIVITY	ACUTE/ CHRONIC	LOCAL	Food and Feed (10)	AGRICULTURE
Trade			BIODIVERSITY	Invasive Species (Pest Control)	DAMAGE TO PROPERTY AND INFRASTRUCTURE	ACUTE/ CHRONIC	LOCAL		REAL-ESTATE
Trade			BIODIVERSITY	Invasive Species (Pest Control)	FISHERIES COLLAPSE	ACUTE/ CHRONIC	LOCAL	Food and Feed (10)	FISHERIES
Land conversion, pollution	Climate change	FLOODS	LAND	Climate Regulation/Flood and Storm Protection	CHANGING INTENSITY OF EXTREMES - FLOODS	ACUTE	NATIONAL		REAL-ESTATE
Land conversion, pollution	Climate change	FLOODS	LAND	Climate Regulation/Flood and Storm Protection	CHANGING INTENSITY OF EXTREMES - FLOODS	ACUTE	NATIONAL		INDUSTRY (BI & DAMAGE)
Land conversion, pollution	Climate change	DROUGHT	LAND	Climate Regulation/Water flow maintenance	CHANGING AG PRODUCTIVITY (INC DROUGHT)	ALL	NATIONAL	Food and feed (10)	AGRICULTURE
Land conversion, pollution	Climate change	DROUGHT/ HEAT/FLOOD /STORM	LAND	Climate Regulation/Water flow maintenance	FORESTRY COLLAPSE	CHRONIC/ REGIME	NATIONAL	Materials and assistance (13)	FORESTRY
Land conversion, pollution	Climate change	DROUGHT/ HEAT	LAND	Climate Regulation/Water flow maintenance	WATER SUPPLY SHOCK	ACUTE	NATIONAL		INDUSTRY
Land conversion, pollution	Climate change	DROUGHT/ HEAT	LAND	Climate Regulation/Water flow maintenance	IMPACTS ON ENERGY PRODUCTION (WIND/ HYDRO/SOLAR/NUCLEAR/GAS/COAL)	CHRONIC/ ACUTE	NATIONAL	Energy (11)	ENERGY

4. Preliminary Risk Screening and Assessment Approach to Identify Key Material Risks to a Country

4.1 Conceptual framing

The scenario methodology (Section 3) is complemented by a preliminary risk screening and assessment approach to identify the key material risks to a country. This screening can guide the next steps in preparation of scenarios (Figure 8) and also give a preliminary 'order-of-scale' quantification of the different dimensions of risk facing a country, sector or globally.

The geographical scale of study for approach developed in this paper is national, albeit it is important to recognise that risks will vary significantly within a country, and importantly that a higher degree of graduality of assessment is needed given that some risks will depend on the co-location of economic (and other) activities with particular degraded ecosystems. We note that the methodology explored in this paper focusses on domestic shocks and their transmission through global supply chains in terms of quantity effects (i.e. effectively assuming static prices). The assumption of static prices is consistent with other risk screening methodologies, including Battiston et al. 2017 and Dietz et al. 2016 initial work on climate-related value at risk. Methods to account for price dynamics and quantify more macro-level sensitivities to global price and macroeconomic effects related to climate-nature shocks is considered in parallel work.

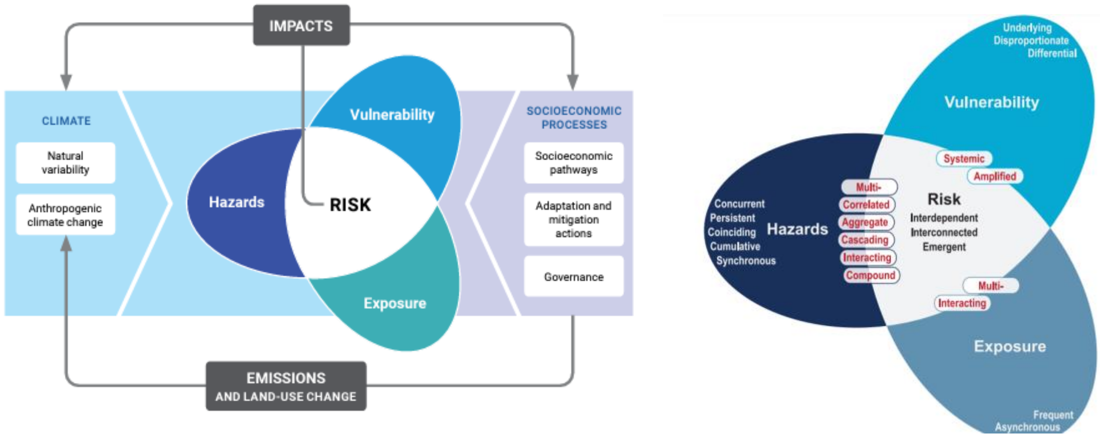


Figure 12: Illustration of the core concepts of weather and climate risk, hazardous events, exposure and vulnerability. Source: Adapted from IPCC 2014 and Simpson et al (2021).

In this report, we draw upon a standard framework for risk assessment, as outlined by the Intergovernmental Panel on Climate Change, to propose an approach to move from dependencies into risk. This standard framework (Figure 12) combines three fundamental components of risk assessment: hazard, exposure and vulnerability. Following the definitions of IPCC (2014), **Hazard** refers to the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. For climate risk assessment, this could be a flood or storm, whereas for nature-related risks it could manifest as degradation of water quality or disease. **Exposure** implies the presence of people, livelihoods, species, or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected. **Vulnerability** is the propensity or predisposition to be adversely affected by the hazard. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. The risk is often presented as a function of the three factors: **Risk = Hazard × Exposure × Vulnerability.** These definitions are subject to interpretation and may be adapted or expanded upon for specific studies or contexts (Simpson et al., 2021). Arguably, the current dependency-based studies capture the exposure and some representation of the vulnerability of sectors. To quantify risk, this needs to be combined with hazard information and some form of damage function that can specify what level of loss would be expected for a particular level of hazard.

This foundational approach is adaptable and well-suited to the complex, interdisciplinary, and global nature of climate/human-induced natural capital erosion, making it a valuable tool for analysis and policymaking. It has been a core underpinning to climate-related financial risk assessment to date both within and outside of the financial community (UNEP FI 2023), particularly for insurance. A common metric in financial risk assessment is 'Value at Risk', which can be defined as *"the level of financial risk within a firm, portfolio, or position over a specific time frame; it estimates how much a set of investments might lose under normal market conditions, over a set time horizon, and at a specified confidence level. Financial institutions widely use this measure to gauge the extent of potential losses in their investment portfolios and to make informed decisions about risk management and investment strategies"* (Schwerdt, 2010). Dietz et al. (2016) define Climate Value at Risk (cVaR) as "the size of loss on a portfolio of assets over a given time horizon".

Risk can be represented probabilistically or deterministically (or a combination of both), linked to a specific scenario or set of scenarios. The latter deterministic approach is consistent with that proposed by the NGFS (e.g. NGFS 2021, 2022), where a financial impact is quantified for a specific scenario contingent on a set of assumptions about how policy, emissions and consequently the climate will change and its impacts. One scenario leads to one outcome. In more advanced applications, consistent with the definition of Value at Risk given above, financial risk is expressed in probabilistic terms but dependent on a deterministic scenario. One scenario leads to different outcomes with specific probabilities. For example, the 1 in 100 year cVaR for typhoon risk under a high emissions scenario and in the 2050s (for example, from Hallegatte et al. 2022 for the Philippines), or the 99th percentile cVaR is USD24.2 trillion over 2015-2100 (Dietz et al. 2016).

An added complexity of nature-related risk, versus approaches to climate-related financial risk assessment to date, is that risks need to be assessed along an impact chain that spans several different forms of capital, from natural capital, to economic or human capital and to financial capital. The risk to one form of capital, generates the hazard to the next capital in the chain (Figure 13). Taking the example of the impacts of soil erosion on the financial system: soil is a form of natural capital; soil quality is at risk from several human drivers including removal of vegetation, pollution or intensive agriculture (soil has a vulnerability and exposure to these hazards); the degradation of soil quality (the ecosystem service) then acts as a hazard to agricultural production (which has its own exposure and vulnerability to that hazard); the resulting risk to agricultural production then impacts the economy overall, dependent on the exposure and vulnerability of the economy to agriculture; and then this in turn can translate into a financial risk both through direct exposures to the agricultural sector or the wider economy. This chain is illustrated within Figure 13. To assess nature-related financial risks, each of these many impact chains, or risk transmission channels, needs to be assessed. One form of natural capital can contribute to multiple ecosystem services and then to risks to many different economic sectors through multiple risk transmission channels. This framework forms the basis of the approach outlined in this report.

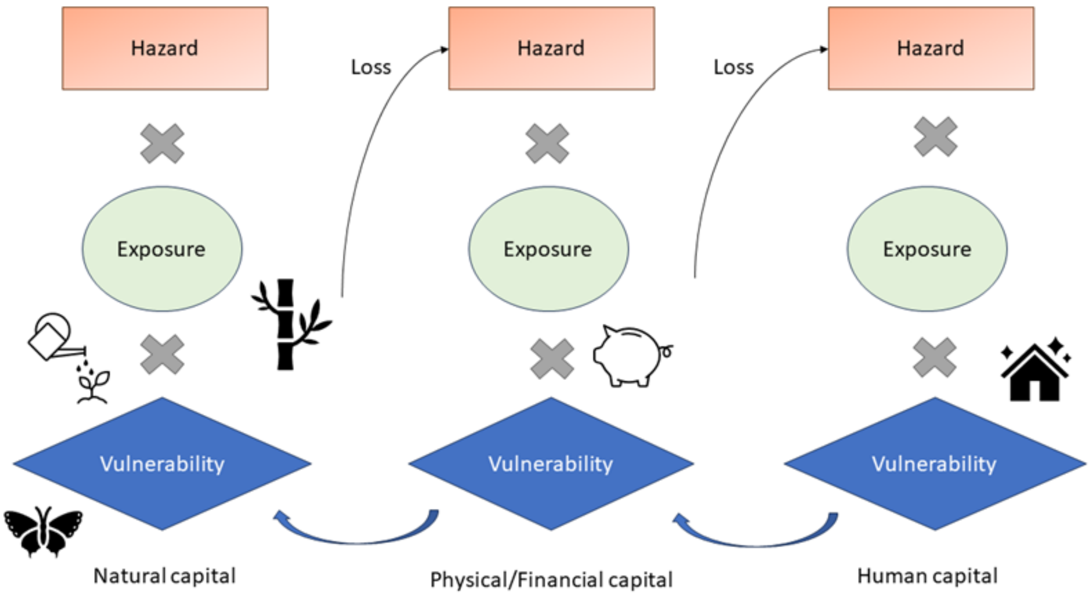


Figure 13: Mapping global risks from natural capital depletion, from natural capital (e.g. biodiversity, soils, water, clean air), to produced (physical and financial capital) to 'socioeconomic' or human capital (sectors, people). Source: Authors

4.2. Risk quantification approach: methods

A full approach to quantify the impact chain outlined in Section 4.1. would require a complex integrated assessment model. However, as discussed in Section 2, there are challenges in the current suite of models and studies to date have captured a relatively narrow range of the risks. Here, we propose an approach that is both simpler and more comprehensive, and so suitable for initial risk screening to understand the key material financial risks to a country, sector or portfolio.

The risk quantification approach proposed in this technical paper has three objectives:

- rapid risk screening to identify the potential key material financial risks at a country-level as a first step in scenario analysis to inform priority focal areas for more in-depth analysis
- a globally consistent approach to categorise countries on the basis of the risks
- to provide preliminary nature-related value at risk (nVaR) scores that can be used within sensitivity analyses as a first step in nature-related financial risk assessments

In this study, we use an indicator-based framework for risk assessment. Indicator-based approaches have been widely used as useful tools for assessing, comparing, and monitoring the complexity of environmental risk from local to global scales. An advantage of such approaches is their replicability across countries, sectors and risks, allowing risks to be assessed with a consistent approach. Box 3 includes a list of prominent indicator-based risk assessments that are commonly used within a range of environmental, economic and financial policy contexts. While such approaches are potentially powerful, particularly in terms of their ability to more comprehensively assess risks versus IAMs, it is also important to recognise their limitations. For example, why an indicator-based approach can represent the relative contributions of different factors to risk, it cannot represent their complex interactions and it is not possible to fully represent the myriad of local factors that drive or mitigate risk. Understanding the role of individual indicators in explaining risk and their spatial and temporal granularity is important to interpretation. However, the suitability of such approaches for risk screening and sensitivity analyses is well accepted.

Box 4: Examples of composite indicators for climate, environmental and nature-related risks

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

Biodiversity Habitat Index (BHI) & **Bioclimatic Ecosystem Resilience Index (BERI).** The BHI measures the impact of land use change and connectedness on the biodiversity of ecological communities at fine resolution over time. BERI synthesises the effects of landscape connectivity and climate change on biodiversity persistence (Harwood et al. 2022).

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

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

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

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

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

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

Resource Efficiency Scoreboard evaluates resource use efficiency by combining indicators related to resource consumption, waste generation, and recycling rates.

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

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

The Notre Dame Global Adaptation Initiative (ND-GAIN) Index is used to assess the vulnerability of countries to climate change and other global challenges, along with their readiness to improve resilience. It aims to help businesses and policymakers understand where and how to best allocate resources for climate adaptation, and to measure progress over time (https://gain.nd.edu/about/)

The ESCAP Composite Environmental Vulnerability Index (EVI) is an indicator developed by the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP). It is designed to assess the environmental vulnerability of countries, particularly in the context of small island developing states (SIDS) and other countries within the Asia-Pacific region (https://rrp.unescap.org/).

Source: Authors' own synthesis

The methodology includes three components:

- **Estimation of probable maximum loss (L) to a sector (s) and country (c) for a specific ecosystem service (*e*) ($L_{s,c,e}$):** ENCORE dependency scores per sector are used to generate estimates of scope 1 and scope 3 nature-related maximum exposures for each country through using the EXIOBASE input-output modelling approach, building upon the approach initially developed by Svartzman et al. (2021)[14] We note that a limitation of using EXIOBASE is the lack of geographical coverage for lower middle and lower income countries, but it is used here in this demonstrator approach given its wide coverage of sectors. Future work will explore opportunities to combine EXIOBASE with other data sources to extend geographical coverage.
- **Country- and ecosystem service-specific risk index ($R_{c,e}$)**: Generating composite hazard-vulnerability indices that represent the likelihood that an ecosystem service is degraded for a specific country and the potential magnitude of loss or damage given the national circumstances in terms of hazard and vulnerability (Methodology outlined in Annex 3).
- **Sector and country-specific loss probability distribution ($L_{c,s}(P)$)**: This distribution is pegged to historical analyses of annual variability in sector output over 30 years (1992-2022) using data from the World Bank's World Development Indicators database. Across all countries, the 95th percentile annual variations in output for agriculture, industry and services respectively are 40%, 30%, 25% (99th percentile: 50%, 55%, 55%). We use the same baseline probability distribution for all countries and split between agricultural and non-agricultural sectors, given that the country specific risk index captures variations in national circumstances and L captures sector specific relative dependencies. Two baseline distributions are used: for

[14] ENCORE provides an aggregate dependency scores for NACE sectors. In our application, to calculate pollination risks, we adjusted dependency scores from ENCORE to represent the differential dependencies across different crop types for agriculture included in EXIOBASE; specifically setting wheat, rice and cereals to low risk and fruits and nuts to medium-high risk in line with the literature. For all other sectors, we use the ENCORE dependency scores.

agriculture this is calibrated on agriculture output variability across all countries, and for non-agriculture, calibrated on the averages of industry and services output variability. In this report, all nVaR are calculated for the 95th percentile (1-in-20 year event or 5% annual probability).

The nature-related Value at Risk, nVaR, is then the product of these three components. Both direct nVaR (referred to as *'scope 1'*) and upstream nVaR are calculated (relating to supply chains, referred to as *'scope 3'*). The total nVaR is the addition of scope 1 and scope 3. This approach allows quantification of risks transmitted through industry sectors, as represented by EXIOBASE and ENCORE, and would require some adaptation to consider risks transmitted through e.g. human health and labour productivity, real-estate damages and public expenditure (from Table 4), as well as macroeconomic vulnerabilities to international shocks, such as volatility in oil and food prices. This is a focus of ongoing research to be presented in subsequent reports. The grey rows in Table 4 illustrate the hazard-economic receptor pairs that are captured in the method here, covering the five ecosystem services studied. This serves to illustrate the risks presented in this report, while covering a broader scope of impacts than many previous studies, still do not capture all the potential risks from nature-climate interactions to the financial system.

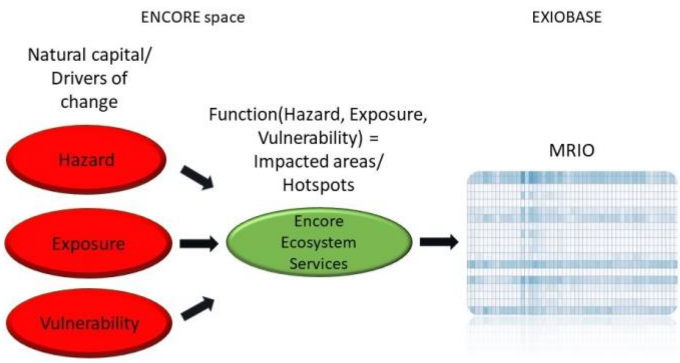


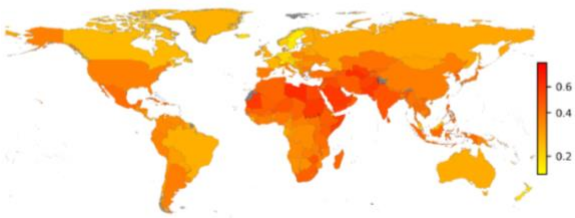
Figure 14: Mapping global risks from natural capital depletion. Source: Authors

This methodology (illustrated in Figure 14) brings a geospatial aspect to the analysis not present in standard dependency tools such as ENCORE or previous studies, as well as a risk perspective. The output is a metric of nature-related Value at Risk (nVaR) that varies by country and sector. As noted above, VaR metrics are defined for a specific timeframe and level of probability. The indices developed in this report represent near-term risk. For example, the influence of longer-term (>5 – 10 year) climate change or socioeconomic change is not explicitly represented.

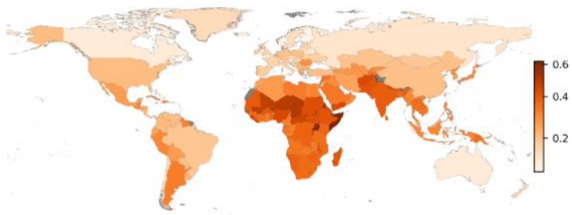
It should be noted that results for individual ecosystem services are not additive; i.e. the risks to a country are not the sum of all five. This is because there are overlaps between services. It should further be noted that these are indicator-based analyses and suitable for risk screening and assessment of key sensitivities at a country-level. The purpose is to identify the key risks as well as visualise relative risks across countries. They alone are not sufficient, for example, for regulatory stress testing exercises. They should be coupled with additional analyses if they are to be used within nature-related financial risk assessments. We suggest, however, that the preliminary step enabled by the analysis described here is helpful to enable financial institutions to identify where key material risks may exist in order to guide the specifications for future work.

4.3. Ecosystem hazard-vulnerability indices

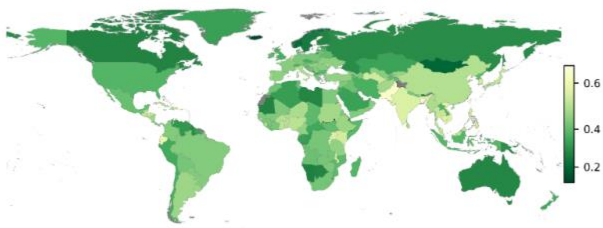
This section presents and describes the composite hazard indices used to create the nVaR scores. The methodologies are given in Annex 3. These indices represent a combination of the hazard (scale and likelihood of hazard) and vulnerability to the hazard. Five demonstration risk assessments are completed for this paper, but the methodology is expandable beyond this and this will be included in future work by the INCAF team. For the five indices created for this paper, the hazard indices vary widely across countries. While generally hazards are higher in lower income countries, this is not always the case. For example, relatively high risks to pollinators across higher income countries due to environmental pollution, and high risks to air pollution (ventilation) across many middle income countries, in particular, India and China.



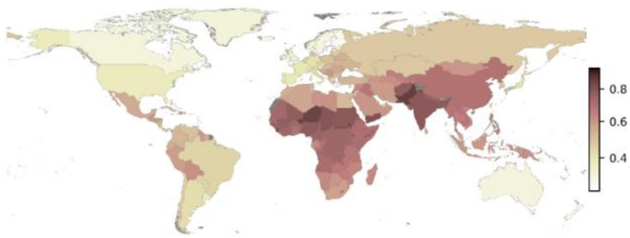
(a)



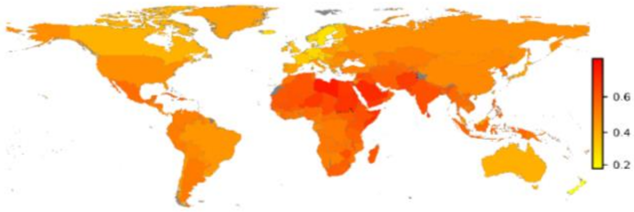
(b)



(c)



(d)



(e)

Figure 15: Global maps of hazard-vulnerability indices: (a) Surface water; (b) Water quality; (c) Pollination; (d) Ventilation (air quality risks); (e) Ground water. Hazard scores (0-1) across the planet. Source: Authors

Many parts of Africa, the Middle East and southern Europe emerge as the regions at higher risk for surface water depletion (Figure 15a). In contrast, regions like Australia, Northern Europe, and North America have relatively lower risk levels.

As shown in Figure 15a and 15e, there is a strong interconnection between surface water risks and groundwater risks globally. In general, surface water (e.g., like rivers, lakes, and streams) and groundwater (e.g., aquifers) are part of the same hydrological system; groundwater feeds into surface water bodies and surface water replenishing groundwater sources.

Figure 15b clearly shows the disparities in water quality risks around the world. It emphasises the importance of sustainable water management to address the diverse challenges across these regions. Parts of central Africa, India, and the Middle East have higher risk scores, reflecting higher mortality rates from water-related issues, significant water stress, and greater general vulnerability. These areas could be affected by poor sanitation infrastructure, high untreated wastewater, and intense water scarcity. Northern Europe, Canada, and Australia, have lower risk scores, reflecting better water management practices, safer water and sanitation facilities, lower water stress, and a lower vulnerability to water quality issues.

Figure 15c demonstrates the variability in risks to pollinators globally. Pollinators are crucial for the reproduction of many crops and wild plants. Areas at higher risk reflect a combination of intensive agricultural practices, high pesticide use and urbanisation. Air quality risks (figure 15d) are more concentrated, particularly in parts of Africa and South and Southeast Asia. Risk factors can include industrial activities, agriculture, urbanization, less stringent environmental regulations as well as natural drivers, e.g. Saharan dust in the Sahel region (HEI, 2022; Bauer et al. 2019).

4.4. Nature-Related Value at Risk

Combining the hazard-vulnerability indices with sector-level outputs and dependencies (Figure 15) enables the calculation of a Nature Value at Risk (nVaR) estimate for both direct (scope 1) and upstream risks (scope 3). This is the first time such an analysis has been completed, bringing the ENCORE analysis from dependency to risk and bringing a geospatial element to estimate both direct and upstream risks. Note all values in this section are expressed as annual output in Euros.

Figure 16 visualises a selection of the results as maps for the total of scope 1 and 3. Each map represents a separate row in Table 4, capturing a specific hazard-economic receptor pair. The greatest risks, in terms of absolute value of nVaR, are found to be to manufacturing, followed by services and agriculture; this largely reflects the relative size of these sectors, but also their high dependence on natural capital. The USA and China immediately stand out as high (absolute) nature-related financial risk largely by virtue of the large size of these economies; in particular, China is the highest risk across all categories with, for example, an nVaR estimated at around €2.0 – 2.7 trillion for water risks (ground water and surface water) to manufacturing and €230 - 300 billion for agriculture, and also relatively high risks related to pollination (€130 billion). The USA is lower with around €600 – 800 billion for water risks (ground water and surface water) to manufacturing and €40 - 60 billion for agriculture. India is prominent as high risk for water-related risks to agriculture (€120 – 150 billion) and also pollination risks to agriculture (€70 billion). The relatively low risk of Nordic countries stands out. China emerges as by far the highest risks related to air pollution, with an estimated €820 billion at risk across all sectors, and water pollution, with an estimated €850 billion at risk. Unfortunately, Brazil is the only South American country covered in EXIOBASE; here risks from water to manufacturing and services are estimated to be greatest at around €65 - 105 billion and €35 - 60 billion, respectively.

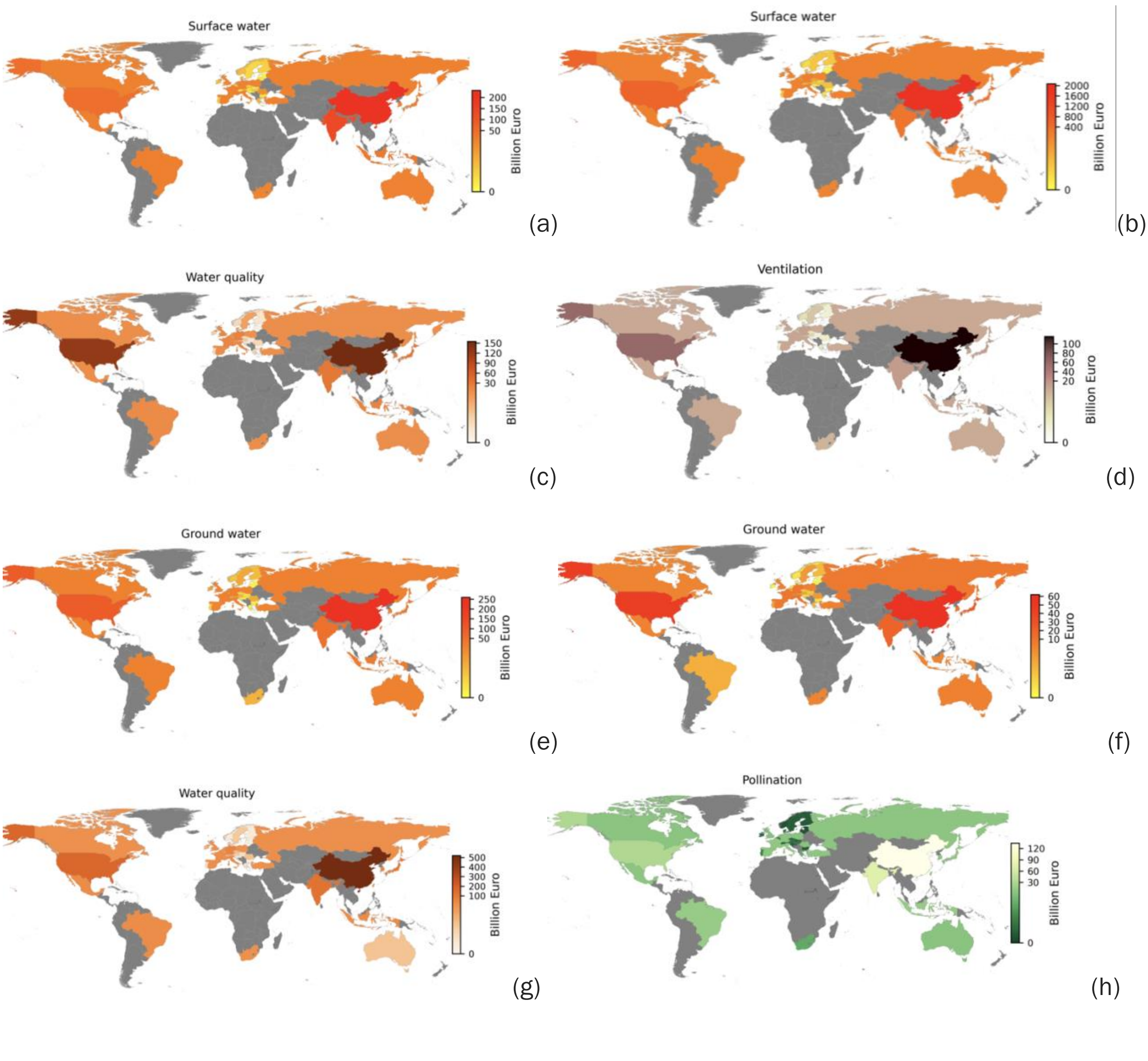


Figure 16: Nature-Related Value at Risk (nVaR) for scope 1 + scope 3 – selected figures: surface water impacts on (a) agriculture and (b) manufacturing; (c) water quality impacts on services; (d) air quality impacts on services; (e) groundwater impacts on construction; (f) groundwater impacts on electricity utilities; (g) water quality impacts on manufacturing; (h) pollination to agriculture. Grey zones are missing data in EXIOBASE. Source: Authors.

Figure 17 shows a selection of nVaR presented in terms of the fractional risk to the sector. From these figures, the strong variation in risk levels between countries is clear. China still features as relatively high risk, while other middle-income countries such as India, Brazil, South Africa and Mexico are also higher risk, due to a combination of their higher nature-related hazard levels (Figure 15), such as high air pollution in India and China, and high vulnerability versus high income countries, as represented by the ND-GAIN index used in the calculations.

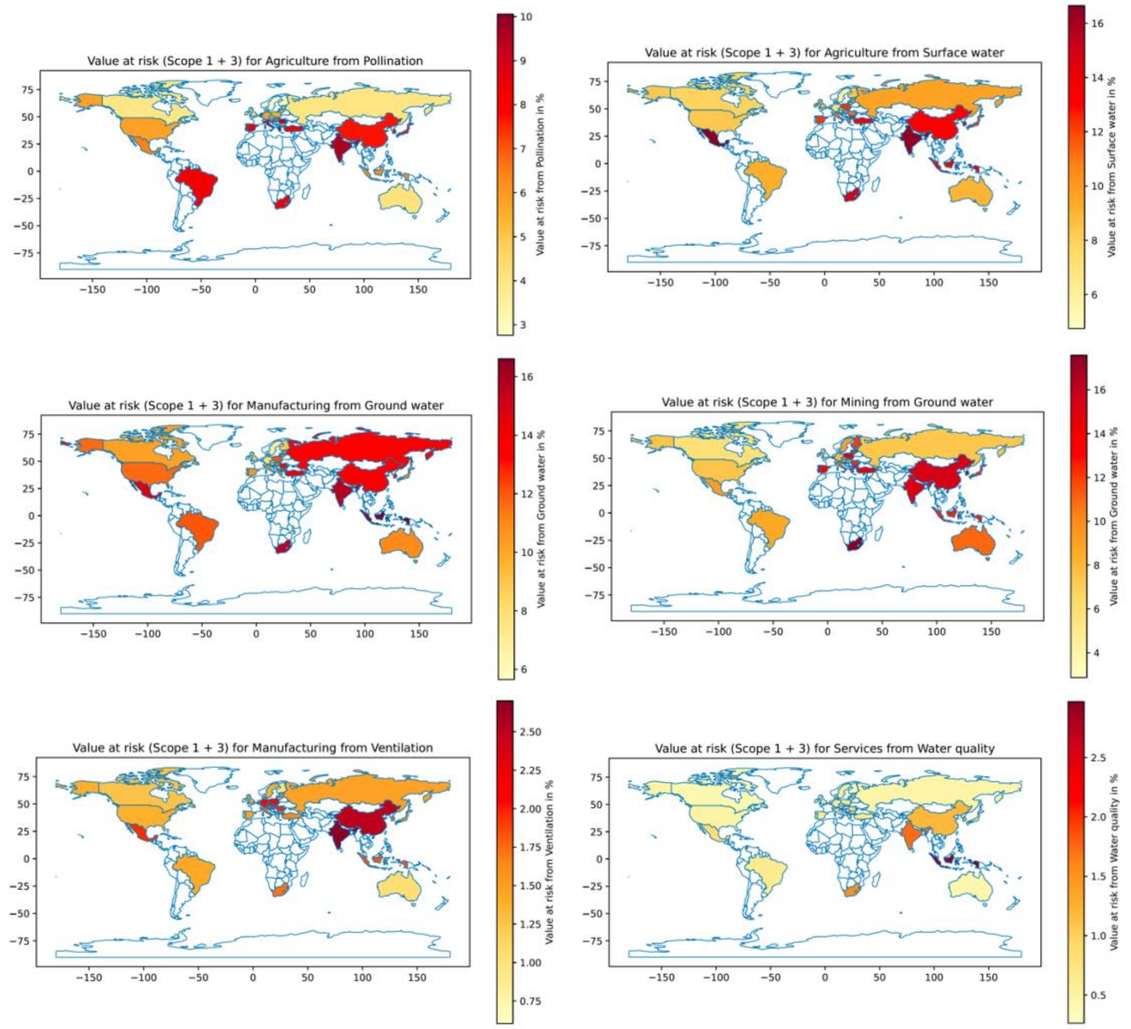


Figure 17: Nature-Related Value at Risk (nVaR) for scope 1 + scope 3 expressed as a fraction of sectoral output – selected figures. Source: Authors.

The main sectoral risks varies by country. For many countries, water risks to manufacturing are clearly dominant. Figure 18 illustrates variations across countries. For example, for India, risks to the agricultural sector are evident (including pollination), whereas for Australia, risks to the service sector and mining are more prominent – water-related risks to services, manufacturing and mining are €50 – 60 billion, €25 – 30 billion and €15 – 25 billion respectively. In terms of %nVaR, Spain stands out as one of the highest risk countries in Europe, with water-related risks to services and manufacturing €55 – 60 billion, €60 – 70 billion, respectively. This illustrates how the combination of the scenario building blocks from Table 4 can be combined with the preliminary risk assessment outlined here to support countries to determine where to focus.

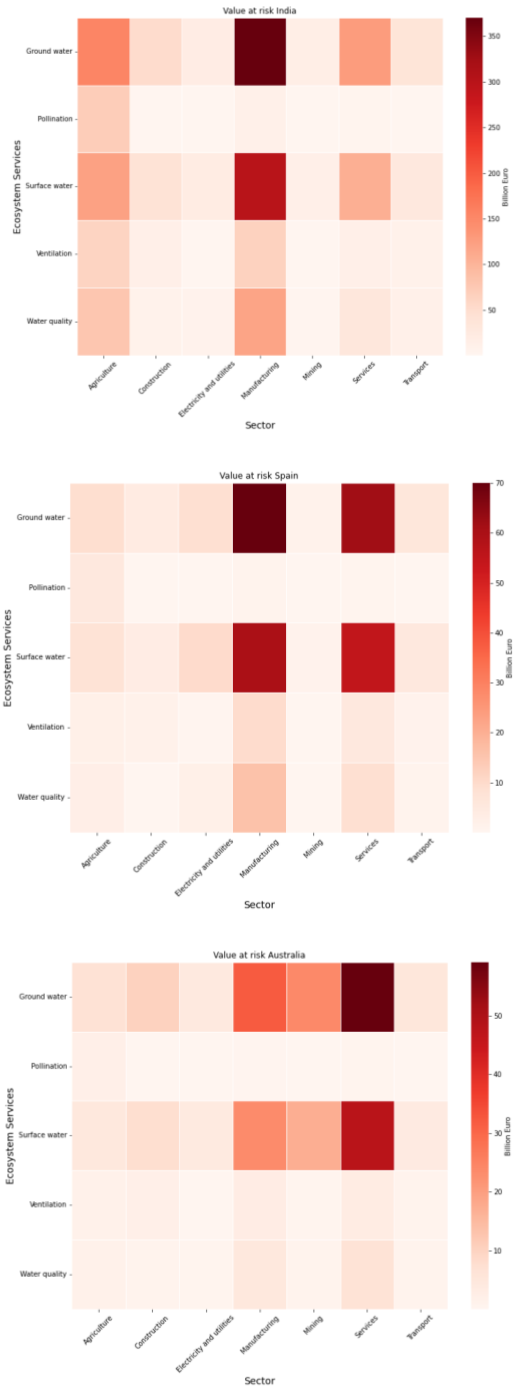


Figure 18: Nature-Related Value at Risk (nVaR) for scope 1 + scope 3 for India (top), Spain (middle) and Australia (bottom) demonstrating the variations across countries. Source: Authors.

Figure 19: Nature-Related Value at Risk (nVaR) comparing scope 1 (blue) and scope 3 (orange) contributions for the six sectors studied. Source: Authors.

The contribution of direct (scope 1) and upstream (scope 3) to the nVaR varies by sector and country. For example, for the services sector around two thirds of the risk is upstream, where upstream includes both domestic and international supply chains (Figure 19). For agriculture, the risks are weighted toward direct risks, particularly for risks associated with pollination, air quality and water quality. Risks to manufacturing are also slightly more weighted toward direct risks.

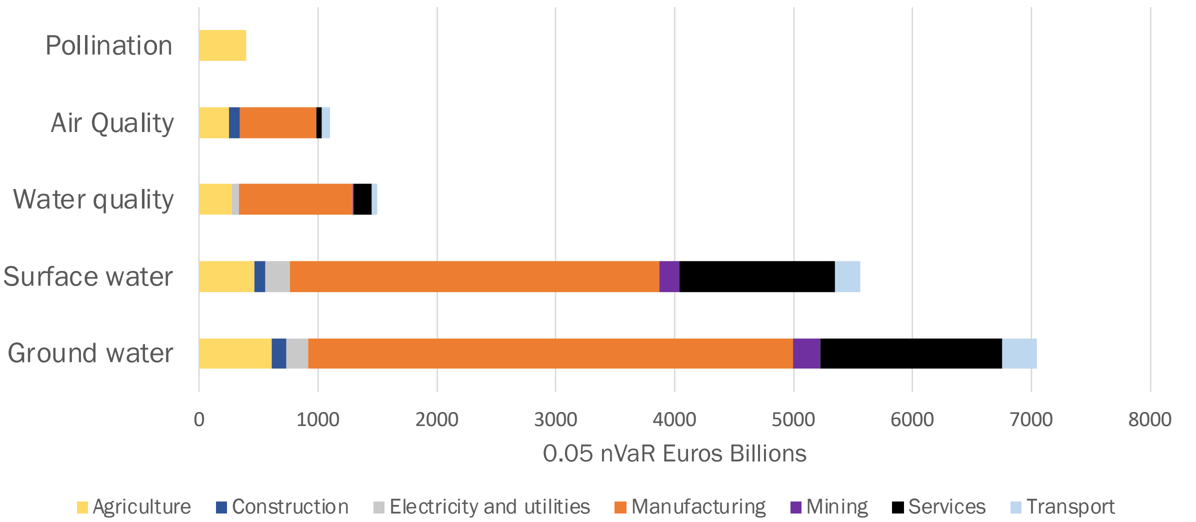


Figure 20: Global Nature-Related Value at Risk (nVaR) for scope 1 expressed as a fraction of sectoral output – selected figures. Note scope 3 is not included to avoid double counting, so these values are likely to be underestimates of the full scale of the risks. Source: Authors.

While the methodology here is designed to compare risks across countries and sectors, rather than to give an accurate estimation of the scale of the risks, Figure 20 gives the total nVaR by ecosystem service globally for both scope 1 (scope 3 not included here to avoid double counting across supply chains) for both the 0.05 nVaR, (a 1-in-20 year event). Table 4 summarises these and includes for comparison, the 0.01 nVaR (a 1-in-100 year event). This is helpful to compare with other studies and also to give a sense of the global macro-criticality of these risks. Water-related risks are dominant, with around 7 – 9%[15] Global GDP potentially at risk (plus additional 2% GDP due to water quality issues) for scope 1 only. Water was not included in the Johnson et al. study. This risk is clearly macro-critical both globally and for many countries, particularly for middle income countries.

Table 4: Total nVaR (0.05 and 0.01) as fraction GDP for six sectors for scope 1 only.

	Ground water	Surface Water	Pollination	Air quality	Water quality
0.05 VaR (1 in 20 year)					
% Global GDP	9%	7%	1%	1%	2%
% Agricultural GDP	18%	14%	12%	7%	8%
0.01 VaR (1 in 100 year)					
% Global GDP	16%	13%	1%	2%	3%
% Agricultural GDP	23%	17%	15%	9%	10%

Risks to the agricultural sector are most severe, with around 14 – 18% at risk due to water-related risks alone and further due to air and water pollution; totalling in excess of €800 billion to €1.2 trillion at risk due to water risks alone. These estimates are of the same order of magnitude as previous studies (Table 1). Pollination risks are the lowest of those studied in financial terms and are estimated at around €400 billion (€480 billion with scope 3 dependencies[16]), but equivalent to a 12% nVAR to the agricultural sector. This is roughly consistent with Johnson et al. (2021).

In this study, we have included five ecosystem services. As noted above, exact numbers should be interpreted with care as the modelling approach does not represent the complex interactions between ecosystem services and the economy, some of which may act to reduce risks and some increases them (including the impacts of the reactions of markets to real and perceived threats). It is important to note that these results do not come from a full macroeconomic model. Nature-related hazards could result in a fall in investment, employment, resource bottlenecks, food shortages, food price hikes, etc. All of these could mean that value at risk could be much larger when accounting for system-wide nVaR. This will be explored further in future studies.

Within this study, while results are presented for five services, analyses were completed for all twenty ENCORE services and this will be presented in subsequent work following additional

[15] Surface water and ground water risks overlap, so we give them as a range in this study. They cannot be combined.

[16] The scope 3 number is given for pollination as the supply chains are more direct, so less double counting.

validation and calibration of the model[17]. The two ecosystem services that stand out most clearly as macro-critical from this subsequent analysis are soil erosion (significant risks to the agricultural sectors) and climate regulation/flood and storm protection, with impacts of similar order of scale.

5. Example application: Step-wise approach to utilising the scenario tool within financial risk assessment

The tools presented in this report represent a starting point to risk assessment and scenario analysis. This final section provides a brief guidance on how the scenario building blocks and preliminary risk screening tool could be used to inform full nature-related scenario development and financial risk assessment by a financial institution, regulatory, supervisor or Central bank. This approach is aligned with that recommended by the TNFD 2023 guidance (TNFD, 2023).

STAGE 1: Initial scoping phase

1. **Initial risk screening:** identify likely critical ecosystem services and hazards relevant to the country or portfolio using the preliminary risk screening tool above (Section 4)
2. **Scenario exploration using the Oxford-INCAF Risk Scenario tool:** utilise the Oxford-INCAF scenario tool (Table 3) to identify relevant scenario building blocks for the country or portfolio based both on the risk screening tool and analyses of key hazards.
3. **Construction of initial narrative scenarios (considering compounding factors):** combine scenario building blocks to develop initial set of scenarios.

STAGE 2 – Scenario verification and development

1. **Developing the evidence base:** using data on historical analogues, empirical evidence and relevant projections from the literature to validate and expand scenarios; including refining the preliminary risk assessment through own analyses.
2. **Participatory scenario development**: working with experts, select scenarios for further development and work collaboratively to develop these over one or more workshops. This should particularly consider the second-round impacts of scenarios and the potential for compounding impacts with other shocks.

STAGE 3 – Scenario quantification and feedback

1. **Model development to quantify and refine scenario parameters.** Select appropriate modelling strategy to the scenario and assess nature value at risk.
2. **Refining scenario.** Based upon initial model simulations, it may be beneficial to gain further feedback from experts before finalising the modelling.

To provide an example, we take the case for drought in France. In this hypothetical case, given recent droughts in the country, decision makers want to explore a scenario of how nature-related

[17] Please contact the Oxford-INCAF team for further information: Nicola.ranger@ouce.ox.ac.uk

risks could intensify the impacts of drought. Based upon Table 4, the following dimensions of risk are identified:

- Water supply shock to industry: leading to both direct and indirect impacts on the economy and implications for exports, as well as increased prices/disruption to energy services
- Agricultural supply shock heightened through soil erosion, with potential impacts on domestic prices (noting substitution effects), exports and employment of casual workers
- Human health impacts through increased pollution risks, particularly in urban areas
- Potential increased wildfire risks due to changes in land-use

The quantitative analysis shown in Section 4 can be used to generate initial shock values to inform nature stress testing. For example, Figure 21 shows values generated for France for ecosystem services related to water and air (e.g. the scope 1 only component of Figure 16) for a roughly 1-in-20 year event. Other return periods could be generated with the same analyses (for example, the 1-in-100 year losses shown in Table 4). It should be noted that this analysis assumes no substitution or demand impacts, and so is arguably an upper bound, but suitable for stress testing. These estimates could form a basis for further co-development of scenarios, including by refining the quantitative estimates with additional lines of evidence from analyses of historical shocks and available climate and nature models for France. See the NGFS Technical Document for more details on the methodology for France (NGFS 2023a).

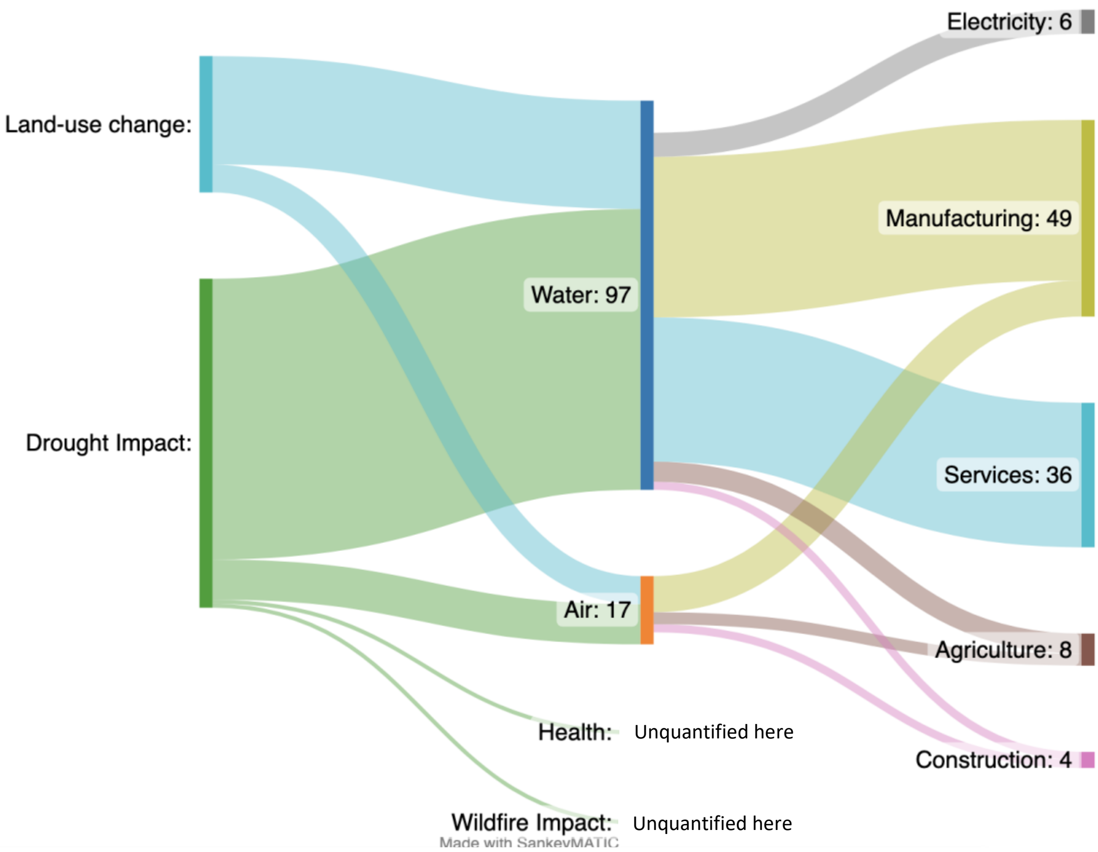


Figure 21: Direct output impact (in billions of Euros) for a hypothetical severe drought impacts aggravated by land-use change in France. Source: Authors

6. Conclusions

This paper has provided an evidence-based set of building blocks for constructing physical nature-climate scenarios for financial risk assessment and a methodology for preliminary risk screening that can work across all countries. We demonstrate the risk screening approach with five ecosystem services, but the approach is expandable to others; the full set of risks for all twenty ENCORE ecosystem services is available from the Oxford INCAF team. Our objective was to demonstrate an approach that is replicable for any country and so could be deployed as a global public good. The next steps are to refine the approach to risk assessment and expand it to additional hazards, such that all the scenario building blocks have some risk quantification.

Our recommendations to the NGFS include:

- Advance the co-development of global nature-climate related risk scenarios, and run the first stress tests based upon these scenarios
- Develop baseline datasets and methodologies, such as those demonstrated in this paper, to enable Central Banks, supervisors and financial institutions to begin to construct their own scenarios relevant to their circumstances and portfolios but in a consistent way
- Work closely with the scientific community to invest in research and development to close the gaps in the evidence base on nature-related financial risks and develop decision-relevant models and approaches as a public good for Central Banks and supervisors.
- Provide a programme of technical assistance to member Central Banks and supervisors to support them to develop appropriate scenarios.

Our preliminary analyses clearly demonstrate the macro-criticality of nature-related risks and motivate further work by Central Banks, as well as governments and financial institutions, to assess risks and identify actions to mitigate them. The approach developed in this report is primarily aimed at comparing risks across sectors and countries, however the values at risk that emerge are substantial. Water-related risks are dominant and could constitute 7 – 9% of global GDP (5% VaR), with significant impacts on the manufacturing sector. Risks to agriculture are also significant, estimated at around 14 – 18% of output at risk from water-related risks and potentially 12% of output at risk related to pollinator decline. These direct impacts could be amplified by cascading feedbacks across markets, and act as a risk multiplier on climate change, leading to significant impacts on people and economies, as well as for the global financial system. It is important to note that in this study, we look at only five ecosystem services and as such, these estimates should be treated very much as a lower bound. However, even on the basis of these five services, and given the uncertainties, there is a clear rationale for precautionary action by Central Banks. This includes identifying and addressing any systemic or structural issues such as regulatory gaps, inadequate oversight or the potential for speculative bubbles that may contribute to financial instability and provide guidance to firms to minimise conditions that could lead to crisis.

7. References

Aceituno, P., Prieto, M.D.R., Solari, M.E., Martínez, A., Poveda, G. and Falvey, M., 2009. The 1877–1878 el Niño episode: associated impacts in south America. Climatic Change, 92, pp.389-416.

Adler, J.H.. 2002. Fables of the Cuyahoga: Reconstructing a history of environmental protection. Fordham Envtl. LJ, 14, p.89.

Adrian, T, Morsink, J. and Schumacher, L. (2020) Stress Testing at the IMF. International Monetary Fund, Monetary and Capital Markets Department. https://www.imf.org/-/media/Files/Publications/DP/2020/English/STIMFEA.ashx

Al-Ghanim, K.A., Mahboob, S., Seemab, S., Sultana, S., Sultana, T., Al-Misned, F. and Ahmed, Z., 2016. Monitoring of trace metals in tissues of Wallago attu (lanchi) from the Indus River as an indicator of environmental pollution. *Saudi Journal of Biological Sciences*, *23*(1), pp.72-78.

Basso, B., Kendall, A.D. and Hyndman, D.W., 2013. The future of agriculture over the Ogallala Aquifer: Solutions to grow crops more efficiently with limited water. Earth's Future, 1(1), pp.39-41.

Battiston S., A. Mandel, I. Monasterolo, F. Schuetze, and G. Visentin. 2017. "A Climate stress test of the EU financial system." Nature Climate Change 7: 283–288. https://doi.org/10.1038/nclimate3255.

Battiston, S., Dafermos, Y. and Monasterolo, I., 2021a. Climate risks and financial stability. Journal of Financial Stability, 54, p.100867. https://www.sciencedirect.com/science/article/pii/S1572308921000267

Battiston, S., Escobar-Farfán, L.O., Martinez-Jaramillo, S. and Roncoroni, A., 2021b. Climate risk and financial stability in the network of banks and investment funds. Journal of Financial Stability, 54, p.100870. https://www.zora.uzh.ch/id/eprint/210391/

Battiston, S., I. Monasterolo, K. Riahi, and B. van Rujiven, 2021c. "Accounting for finance is key for climate mitigation pathways." Science 372 (6545): 918–920.

Bauer, S.E.; Im, U. Mezuman K., Gao, C.Y. (2019) Desert Dust, Industrialisation and Agricultural Fires: Health Impacts of Outdoor Air Pollution in Africa. JGR Atmospheres. https://doi.org/10.1029/2018JD029336

Bayham, J., Yoder, J. K., Champ, P. A., & Calkin, D. E. (2022). The Economics of Wildfire in the United States. Annual Review of Resource Economics, 14(1), 379–401. https://doi.org/10.1146/annurev-resource-111920-014804

Biancalani, R. & Marinelli, M. Assessing SDG indicator 6.4.2 'level of water stress' at major basins level. *UCL Open Environ.* **3**, 1–17 (2021).

BIS (Bank for International Settlements). 2021. Basel Committee on Banking Supervision. "Climate-related financial risks – measurement methodologies."

Bloomberg. 2023. Returns of el Niño threatens new levels of economic disruption. https://www.bloomberg.com/graphics/2023-el-nino-climate-change-extreme-weather/

Boldrini, S. Ceglar, A., Lelli, C., Parisi L., Heemskerk, I. Living in a world of disappearing nature: physical risk and the implications for financial stability. ECB Occasional Paper Series 333. https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op333~1b97e436be.en.pdf?90e7aaae4ef927f887a787587a22adba

Botzen, W.J.W., O. Deschenes, and M. Saunders. 2019. "The Economic Impacts of Natural Disasters: A Review of Models and Empirical Studies." Review of Environmental Economics and Policy 13 (2): 167–188. doi: 10.1093/reep/rez004.

Brauman, K et al. 2020 Global trends in nature's contributions to people, 117, 10.1073/pnas.2010473117 Proceedings of the National Academy of Sciences

Brown, C., Reyers, B., Ingwall-King, L., Mapendembe, A., Nel, J., O'Farrell, P., Bowles-Newark, N., & Dixon, M. (2014). Measuring ecosystem services: Guidance on developing ecosystem service indicators. Cambridge (UK): United Nations Environment Programme World Conservation Monitoring Centre. https://doi.org/10.34892/ZH2N-1J26

Caldecott, B., Howarth, N and McSharry, P. (2013). Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks. Oxford Smith School of Enterprise and the Environment. https://www.smithschool.ox.ac.uk/sites/default/files/2022-03/stranded-assets-agriculture-report-final.pdf

Callahan, C.W. and Mankin, J.S., 2023. Persistent effect of El Niño on global economic growth. Science, 380(6649), pp.1064-1069.

Cambridge Institute for Sustainability Leadership (CISL 2020). Biodiversity Loss and Land Degradation: An Overview of the Financial Materiality. https://www.cisl.cam.ac.uk/system/files/documents/biodiversity-loss-and-land-degradation-overview.pdf

Cambridge Institute for Sustainability Leadership (CISL) and HSBC, 2022. Nature-related financial risk: use case. Impact of water curtailment on credit rating of heavy industry companies in East Asia. https://www.cisl.cam.ac.uk/resources/publications/impact-water-curtailment-credit-rating-heavy-industry-nature-related

Cambridge Institute for Sustainability Leadership (CISL) and NatWest Group, 2022. Nature-related financial risk: use case. Land degradation, UK farmers and indicative financial risk. https://www.cisl.cam.ac.uk/files/cisl_nwg_land_degradation_financial_risk_uk_apr_22final.pdf

Cambridge Institute for Sustainability Leadership (CISL), (2022). Integrating climate and nature: the rationale for financial institutions. https://www.cisl.cam.ac.uk/files/integrating_climate_and_nature_the_rationale_for_financial_institutions.pdf

Cambridge Institute for Sustainability Leadership (CISL), Deutsche Bank and Union Bancaire Privée (UBP), 2022. Nature-related financial risk: use case. The EU Farm to Fork Strategy and Fertiliser Companies. https://www.cisl.cam.ac.uk/files/cisl_db_ubp_farm_to_fork_impact_apr_22.pdf

Cambridge Institute for Sustainability Leadership (CISL, 2021). Handbook for nature-related financial risks: key concepts and a framework for identification. https://www.cisl.cam.ac.uk/system/files/documents/handbook-for-nature-related-financial.pdf

Cambridge Institute for Sustainability Leadership and AON (CISL and AON), 2022. Nature-related financial risk: use case. Mapping exposure to nature-related risks across financial indices.

https://www.cisl.cam.ac.uk/files/cisl_aon_mapping_exposure_to_nature-related_risks_across_financial_indices_apr22.pdf

CDP and Planet Tracker (2022) High And Dry. How Water Issues Are Stranding Assets https://cdn.cdp.net/cdp-production/cms/reports/documents/000/006/321/original/High_and_Dry_Report_Final.pdf?1651652748

Christine Hammond, Juan Carlos Rocha, Reinette (Oonsie) Biggs, Garry Peterson. Bivalves Collapse. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2012-03-22 06:54:22 GMT..

Comptroller and Auditor General (2002). The 2001 Outbreak of Foot and Mouth Disease, Session 2001-02, HC 939, National Audit Office, June 2002.

Comptroller and Auditor General. 2002. The 2001 Outbreak of Foot and Mouth Disease, Session 2001-02, HC 939, National Audit Office, June 2002.

Convention on Biological Diversity (1992) Convention on Biological Diversity, Article 2 Use of Terms

Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P. and Ritsema, C.J., 2016. The threat of soil salinity: A European scale review. Science of the total environment, 573, pp.727-739.

De Waal, A.. 1991. Evil Days: Thirty Years of War and Famine in Ethiopia. United Kingdom: Human Rights Watch.

Deines, J.M., Schipanski, M.E., Golden, B., Zipper, S.C., Nozari, S., Rottler, C., Guerrero, B. and Sharda, V., 2020. Transitions from irrigated to dryland agriculture in the Ogallala Aquifer: Land use suitability and regional economic impacts. Agricultural Water Management, 233, p.106061.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A. and Bartuska, A., 2015. The IPBES Conceptual Framework—connecting nature and people. Current opinion in environmental sustainability, 14, pp.1-16.

Dietz, S., Bowen, A., Dixon, C. and Gradwell, P. (2016) 'Climate value at risk' of global financial assets. Nature Climate Change. Letters. Doi: 10.1038/NCLIMATE2972

Di Marco, M., Baker, M.L., Daszak, P, Ferrier, S. (2020) Sustainable development must account for pandemic risk. PNAS 117 (8) 3888-3892 https://doi.org/10.1073/pnas.2001655117

Dunz, N., A. Essenfelder, A. Mazzocchetti, I. Monasterolo, and M. Raberto. 2021. "Macroeconomic and Financial Impacts of Compounding Pandemics and Climate Risks." Working paper available at SSRN https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3827853.

Edgerton-Tarpley, Kathryn. 2008. Tears from Iron: Cultural Responses to Famine in Nineteenth-Century China. 1st ed., University of California Press. JSTOR, http://www.jstor.org/stable/10.1525/j.ctt1pnzzs. Accessed 2 Nov. 2023.

European Banking Authority (2014) Guidelines on the range of scenarios to be used in recovery plans. EBA/GL/2014/06. 18 July 2014

European Union (2021) Directive 2009/138/EC of the European Parliament and of the Council of 25 November 2009 on the taking-up and pursuit of the business of Insurance and Reinsurance (Solvency II). http://data.europa.eu/eli/dir/2009/138/2021-10-19

Exeter-USS (2023) No Time to Lose: New Scenario Narratives for Action on Climate Change. https://greenfuturessolutions.com/wp-content/uploads/2023/09/No-Time-To-Lose-New-Scenario-Narratives-for-Action-on-Climate-Change-Full-Report.pdf

FAO. 2020. Global Forest Resources Assessment 2020: Main report. Rome. https://doi.org/10.4060/ca9825en

FAO. 2021a. World map of salt-affected soils launched at virtual conference. https://www.fao.org/newsroom/detail/salt-affected-soils-map-symposium/en

FAO. 2021b. World Soil Day: FAO highlights the threat of soil salinization to global food security. https://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/1458974/

Ferrier, S., K. N. Ninan, P. Leadley, R. Alkemade, L.A. Acosta, H. R. Akçakaya, L. Brotons, W. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. Pereira, G. Peterson, R. Pichs-Madruga, N. H. Ravindranath, C. Rondinini, B. Wintle (eds.). (2016): Summary for policymakers of the methodological assessment of scenarios and models of biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

Feyen, E., R. Utz, I. Zuccardi Huertas, O. Bogdan, and J. Moon. 2020. "Macro-Financial Aspects of Climate Change. Policy Research." Working Paper No. 9109. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/33193 License.

Floehr, T., Xiao, H., Scholz-Starke, B., Wu, L., Hou, J., Yin, D., Zhang, X., Ji, R., Yuan, X., Ottermanns, R. and Roß-Nickoll, M., 2013. Solution by dilution?—A review on the pollution status of the Yangtze River. Environmental Science and Pollution Research, 20, pp.6934-6971.

Frankenberg, E., McKee, D. and Thomas, D., 2005. Health consequences of forest fires in Indonesia. Demography, 42, pp.109-129.

Franklin Jr, S.L. and Pindyck, R.S., 2018. Tropical forests, tipping points, and the social cost of deforestation. *Ecological Economics*, *153*, pp.161-171.

FSB (Financial Stability Board). 2020. "The implications of climate change for financial stability." https://www.fsb.org/wp-content/uploads/P231120.pdf.

Gao, H., Bohn, T.J., Podest, E., McDonald, K.C. and Lettenmaier, D.P., 2011. On the causes of the shrinking of Lake Chad. *Environmental Research Letters*, *6*(3), p.034021.

Gaupp, F., Hall, J., Hochrainer-Stigler, S. *et al.* 2020. "Changing risks of simultaneous global breadbasket failure". *Nat. Clim. Chang.* **10**, 54–57. https://doi.org/10.1038/s41558-019-0600-z

Ghosh, T. and Pal, I., 2014. Dust storm and its environmental implications. Journal of Engineering Computers & Applied Sciences (JECAS), 3(4), pp.30-37.

Ghosh, T. and Pal, I., 2014. Dust storm and its environmental implications. *Journal of Engineering Computers & Applied Sciences (JECAS)*, *3*(4), pp.30-37.

Gobler, C.J., Doall, M.H., Peterson, B.J., Young, C.S., DeLaney, F., Wallace, R.B., Tomasetti, S.J., Curtin, T.P., Morrell, B.K., Lamoureux, E.M. and Ueoka, B., 2022. Rebuilding a collapsed bivalve population, restoring seagrass meadows, and eradicating harmful algal blooms in a temperate lagoon using spawner sanctuaries. *Frontiers in Marine Science*, *9*, p.911731.

Gourdel, R., I. Monasterolo, N. Dunz, A. Mazzocchetti, and L. Parisi. 2021. "Assessing the double materiality of climate risks in the EU economy and banking sector." Available at SSRN 3939895, forthcoming as European Central Bank working paper.

Government of Western Australia (2022) Dyland salinity in Western Australia. https://www.agric.wa.gov.au/climate-land-water/soils/managing-soils/soil-salinity (Accessed November 11th 2023)

Hakansson L., Skyllerstedt, S., Selling, N., Reinette (Oonsie) Biggs, Juan Carlos Rocha, Håkan Berg. Lake Victoria. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2012-03-20 14:17:24 GMT.

Hallegatte, S., Lipinsky, F., Morales, P., Oura, H., Ranger, N., Regelink, M.G.J., Reinders, H.J. (2022) Bank Stress Testing of Physical Risks under Climate Change Macro Scenarios: Typhoon Risks to the Philippines. International Monetary Fund, WP/22/163.

Harvey, C.A., Rakotobe, Z.L., Rao, N.S., Dave, R., Razafimahatratra, H., Rabarijohn, R.H., Rajaofara, H. and MacKinnon, J.L., 2014. Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. Philosophical Transactions of the Royal Society B: Biological Sciences, 369(1639), p.20130089.

Harwood, T., C Ware, A Hoskins, S Ferrier, A Bush, M Golebiewski, S Hill, N Ota, J Perry, A Purvis, K Williams (2022): BHI v2: Biodiversity Habitat Index: 30s global time series. v1. CSIRO. Data Collection. https://doi.org/10.25919/3j75-f539. Data: https://bipdashboard.natureserve.org/bip/map.html?ind=BiodiversityHabitatIndex

Harwood, T., C Ware, A Hoskins, S Ferrier, A Bush, M Golebiewski, S Hill, N Ota, J Perry, A Purvis, K Williams (2022): BERI v2: Bioclimatic Ecosystem Resilience Index: 30s global time series. v1. CSIRO. Data Collection. https://doi.org/10.25919/437m-8b91. Data: https://bipdashboard.natureserve.org/bip/map.html?ind=BERI, Metadata:

Hasegawa, T., Wakatsuki, H., Ju, H. *et al.* 2022. "A global dataset for the projected impacts of climate change on four major crops". *Sci Data* **9**, 58. https://doi.org/10.1038/s41597-022-01150-7

Health Effects Institute (2022). The State of Air Quality and Health Impacts in Africa. A Report from the State of Global Air Initiative. Boston, MA: Health Effects Institute.

Hellegers, P. & van Halsema, G. SDG indicator 6.4.1 "change in water use efficiency over time": Methodological flaws and suggestions for improvement. *Sci. Total Environ.* **801**, (2021)) Giupponi, C., Gain, A. K. & Farinosi, F. Spatial assessment of water use efficiency (SDG Indicator 6.4.1) for regional policy support. *Front. Environ. Sci.* **6**, 1–14 (2018).

Hornbeck, R.. 2012. The enduring impact of the American Dust Bowl: Short-and long-run adjustments to environmental catastrophe. American Economic Review, 102(4), pp.1477-1507.

House of Commons Committee of Public Accounts. 2022. Redevelopment of Defra's animal health infrastructure. Twenty-Fourth Report of Session 2022-23.

Hughes, D.J., Alderdice, R., Cooney, C. *et al.* 2020. Coral reef survival under accelerating ocean deoxygenation. *Nat. Clim. Chang.* **10**, 296–307. https://doi.org/10.1038/s41558-020-0737-9

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R. and Bridge, T.C., 2017. Global warming and recurrent mass bleaching of corals. Nature, 543(7645), pp.373-377.

IMF, FSB, and BIS (2009). Guidance to Assess the Systemic Importance of Financial Institutions, Markets and Instruments: Initial Considerations, Report to the G-20 Finance Ministers and Central Bank Governors, available on the internet at: www.bis.org/publ/othp07.pdf, (Washington, DC: International Monetary Fund, Financial Stability Board, and Bank for International Settlements).

INSPIRE & NGFS (2022) NGFS Occasional Paper: Central banking and supervision in the biosphere: An agenda for action on biodiversity loss, financial risk and system stability – Final Report of the NGFS-INSPIRE Study Group on Biodiversity and Financial Stability. https://www.ngfs.net/sites/default/files/medias/documents/central_banking_and_supervision_in_the_biosphere.pdf

International Sustainability Standards Board (ISSB) (2023) IFRS S2: IFRS Sustainability Disclosure Standard – Climate related disclosures. June 2023. https://www.ifrs.org/content/dam/ifrs/publications/pdf-standardsissb/english/2023/issued/part-a/issb-2023-a-ifrs-s2-climate-related-disclosures.pdf

IPBES (2016): The methodological assessment report on scenarios and models of biodiversity and ecosystem services. S. Ferrier, K. N. Ninan, P. Leadley, R. Alkemade, L. A. Acosta, H. R. Akçakaya, L. Brotons, W. W. L. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. M. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini and B. A. Wintle (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 348 pages. https://doi.org/10.5281/zenodo.3235428

IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zenodo.3553579

IPBES (2021) Glossary. https://www.ipbes.net/glossary

IPCC, (2014): Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPR (Inevitable Policy Response) 2023: IPR: Forecast Policy Scenario + Nature (FPS + Nature). https://www.unpri.org/inevitable-policy-response/ipr-forecast-policy-scenario–nature/10966.article (accessed 11th November 2023)

Jack, C.D, R. Jones, L. Burgin, and J. Daron, 2020. "Climate risk narratives: An iterative reflective process for co-producing and integrating climate knowledge." Climate Risk Management 29:100239. https://doi.org/10.1016/j.crm.2020.100239.

Janetos, A., Justice, C., Jahn, M., Obersteiner, M., Glauber, J. and Mulhern, W.. 2017. "The risks of multiple breadbasket failures in the 21st century: a science research agenda." Boston University- The Frederick S. Pardee Center for the Study of the Longer-Range Future. https://www.bu.edu/pardee/files/2017/03/Multiple-Breadbasket-Failures-Pardee-Report.pdf

Janjua, S., Hassan, I., Muhammad, S., Ahmed, S. and Ahmed, A., 2021. Water management in Pakistan's Indus Basin: challenges and opportunities. *Water Policy*, *23*(6), pp.1329-1343.

Jedwab, R., Haslop, F., Zarate, R. and Rodriguez-Castelán, C., 2023. The Effects of Climate Change in the Poorest Countries: Evidence from the Permanent Shrinking of Lake Chad.

Johanna Yletyinen, Thorsten Blenckner, Garry Peterson. Baltic Sea - eutrophication. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017-02-07 11:58:04 GMT.

Johnny Musumbu Tshimpanga, Garry Peterson, Reinette (Oonsie) Biggs, Elin Enfors. Maradi Agro-ecosystem. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017-02-07 12:32:20 GMT.

Johnson, Justin Andrew; Ruta, Giovanni; Baldos, Uris; Cervigni, Raffaello; Chonabayashi, Shun; Corong, Erwin; Gavryliuk, Olga; Gerber, James; Hertel, Thomas; Nootenboom, Christopher; Polasky, Stephen; Gerber, James; Ruta, Giovanni; Polasky, Stephen. 2021. The Economic Case for Nature: A Global Earth-Economy Model to Assess Development Policy Pathways. © World Bank, Washington, DC. http://hdl.handle.net/10986/35882 License: CC BY 3.0 IGO

Juan Carlos Rocha, Garry Peterson, Albert Norström, Reinette (Oonsie) Biggs. Coral Transitions. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017c-01-18 12:43:13 GMT.

Juan Carlos Rocha, Reinette (Oonsie) Biggs, Garry Peterson. Forest to Savannas. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017-08-28 19:48:17 GMT.

Juan Carlos Rocha, Reinette (Oonsie) Biggs. Mangrove transitions. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017b-08-21 12:35:18 GMT.

Kedward, K. Ryan-Collins, J. & Chenet, H. (2023) Biodiversity loss and climate change interactions: financial stability implications for central banks and financial supervisors, Climate Policy, 23:6, 763-781, DOI: 10.1080/14693062.2022.2107475

Keller, E.J., 1992. Drought, war, and the politics of famine in Ethiopia and Eritrea. The Journal of Modern African Studies, 30(4), pp.609-624.

Kim, H., Peterson, G. D., Cheung, W. W. L., Ferrier, S., Alkemade, R., Arneth, A., Kuiper, J. J., Okayasu, S., Pereira, L., Acosta, L. A., Chaplin-Kramer, R., Den Belder, E., Eddy, T. D., Johnson, J. A., Karlsson-Vinkhuyzen, S., Kok, M. T. J., Leadley, P., Leclère, D., Lundquist, C. J., … Pereira, H. M. (2023). Towards a better future for biodiversity and people: Modelling Nature Futures. Global Environmental Change, 82, 102681. https://doi.org/10.1016/j.gloenvcha.2023.102681

Kornhuber et al. 2023 https://www.nature.com/articles/s41467-023-38906-7

Laskin, D.. 2006. The great London smog. Weatherwise, 59(6), pp.42-45.

Leach, K., Grigg, A., O'Connor, B., Brown, C., Vause, J., Gheyssens, J., Weatherdon, L., Halle, M., Burgess, N.D., Fletcher, R. and Bekker, S., 2019. A common framework of natural capital assets for use in public and private sector decision making. Ecosystem Services, 36, p.100899.

Lenton, T., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., Schellnhuber, J.H. (2019) Climate tipping points - too risky to bet against. Nature 575(7784):592-595. doi: 10.1038/d41586-019-03595-0

Lippert, C., Feuerbacher, A., & Narjes, M. (2021). Revisiting the economic valuation of agricultural losses due to large-scale changes in pollinator populations. Ecological Economics, 180, 106860. https://doi.org/10.1016/j.ecolecon.2020.106860

Lloyds of London and Cambridge Centre for Risk Studies (CCRS) (2023) Extreme weather leading to food and water shock. How vulnerable is the global economy to extreme weather and food shocks? https://www.lloyds.com/news-and-insights/futureset/futureset-insights/systemic-risk-scenarios/extreme-weather-leading-to-food-and-water-shortage

Losada, I. J., P. Menéndez, A. Espejo, S. Torres, P. Díaz-Simal, S. Abad, M. W. Beck , S. Narayan, D. Trespalacios, K. Pfiegner, P. Mucke, L. Kirch. 2018. The global value of mangroves for risk reduction. Technical Report. The Nature Conservancy, Berlin.

Lundquist, C.J., Hashimoto, S., Pereira, L., Kim, H., Miller, B.W., Pereira, H.M., Peterson, G., Karlsson-Vinkhuyzen, S.I.S.E., Harrison, P.A., Cheung, W.W. and Kuiper, J.J.. 2023. The Nature Futures Framework, a flexible tool to support the development of scenarios and models of desirable futures for people, nature and Mother Earth, and its methodological guidance.

Mancosu, N.; Snyder, R.L.; Kyriakakis, G.; Spano, D. Water Scarcity and Future Challenges for Food Production. Water 2015, 7, 975-992. https://doi.org/10.3390/w7030975).

Mandel, A., T. Tiggeloven, D. Lincke, E. Koks, P. Ward, and J. Hinkel. 2021. “Risks on global financial stability induced by climate change: the case of flood risks.” Climatic Change 166 (1): 1–24.

Martínez-Jaramillo, S. and Montañez-Enríquez, R. (2021). Dependencies and impact of the Mexican banking sector on ecosystem services. Unpublished NGFS-INSPIRE Study Group Input Paper.

Matteo Giusti, Garry Peterson, Reinette (Oonsie) Biggs, Christine Hammond, Juan Carlos Rocha, Brian Walker. Soil Salinization. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017-08-28 19:59:48 GMT.

Maurin, et al., (2022). Global biodiversity scenarios: what do they tell us for biodiversity-related socio-economic impacts?, Policy Paper, AFD.

Mehrabi, Z., Ramankutty, N. 2019. "Synchronized failure of global crop production". Nat Ecol Evol 3, 780–786. https://doi.org/10.1038/s41559-019-0862-x

Micklin, P., 2007. The Aral sea disaster. *Annu. Rev. Earth Planet. Sci.*, *35*, pp.47-72

Micklin, P., 2016. The future Aral Sea: hope and despair. *Environmental Earth Sciences*, *75*, pp.1-15.

Millington, N. and Scheba, S., 2021. Day zero and the infrastructures of climate change: Water governance, inequality, and infrastructural politics in Cape Town's water crisis. International Journal of Urban and Regional Research, 45(1), pp.116-132.

Mishra, S., 2013. Cattle, dearth, and the colonial state: famines and livestock in Colonial India, 1896–1900. Journal of Social History, 46(4), pp.989-1012.

Mishra, V., Tiwari, A.D., Aadhar, S., Shah, R., Xiao, M., Pai, D.S. and Lettenmaier, D., 2019. Drought and famine in India, 1870–2016. Geophysical Research Letters, 46(4), pp.2075-2083.

Monasterolo, I. 2020. "Embedding finance in the macroeconomics of climate change: researchchallenges and opportunities ahead." CESifo Forum 21 (04): 25–32. München: ifo Institut-Leibniz-Institut für Wirtschaftsforschung an der Universität München.

Natural Capital Finance Alliance (NCFA) and UN Environment World Conservation Monitoring Centre (UNEP WCMC) (2019) Exploring Natural Capital Opportunities, Risks and Exposure: A practical guide for financial institutions, (Geneva, Oxford and Cambridge). https://www.unepfi.org/wordpress/wp-content/uploads/2018/11/NCFA_Exploring-Natural-Capital-Opportunities-Risks-and-Exposure_Nov-2018.pdf

Network of Central Banks and Supervisors for Greening the Financial System (2020) NGFS Guide to climate scenario analysis for central banks and supervisors. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_guide_scenario_analysis_final.pdf

NGFS (2021) NGFS Climate Scenarios for central banks and supervisors. https://www.ngfs.net/sites/default/files/media/2021/08/27/ngfs_climate_scenarios_phase2_june2021.pdf

NGFS (2023) Nature-related Financial Risks: a Conceptual Framework to guide Action by Central Banks and Supervisors. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_conceptual-framework-on-nature-related-risks.pdf

NGFS (2023a). Recommendations toward the development of scenarios for assessing nature-related economic and financial risks. https://www.ngfs.net/en/ngfs-recommendations-toward-development-nature-scenarios-december-2023

NGFS (2023b) Compound Risks: Implications for Physical Climate Scenario Analysis: On the necessity for climate financial risk management to integrate compound events in physical climate risk scenario analyses. https://www.ngfs.net/sites/default/files/media/2023/11/07/ngfs_compound_risks_implications_for_physical_climate_scenario_analysis.pdf

NGFS (2023c). NGFS Scenarios for central banks and supervisors. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_climate_scenarios_for_central_banks_and_supervisors_phase_iv.pdf

OECD (2023), "Assessing biodiversity-related financial risks: Navigating the landscape of existing approaches", OECD Environment Policy Papers, No. 36, OECD Publishing, Paris, https://doi.org/10.1787/d52137a5-en

Ong, L. L. (2014) A Guide to IMF Stress Testing: Methods and Models. International Monetary Fund. https://www.imf.org/en/Publications/Books/Issues/2016/12/31/A-Guide-to-IMF-Stress-Testing-Methods-and-Models-41117

Parks, R., McLaren, M., Toumi, R. and Rivett, U., 2019. Experiences and lessons in managing water from Cape Town. Grantham Institute Briefing Paper, 29, pp.1-20.

Paudel, Y.P., Mackereth, R., Hanley, R. and Qin, W. 2015. Honey bees (Apis mellifera L.) and pollination issues: Current status, impacts, and potential drivers of decline. Journal of Agricultural Science, 7(6), p.93.

Pescaroli, G. and Alexander, D., 2018. Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. Risk analysis, 38(11), pp.2245-2257.

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. Proceedings of the national academy of sciences, 109(31), pp.12302-12308.

Polidoro, B.A., Carpenter, K.E., Collins, L., Duke, N.C., Ellison, A.M., Ellison, J.C., Farnsworth, E.J., Fernando, E.S., Kathiresan, K., Koedam, N.E. and Livingstone, S.R., 2010. The loss of species: mangrove extinction risk and geographic areas of global concern. *PloS one*, *5*(4), p.e10095.

Pörtner, H.-O. et al. (2022): Technical Summary. [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska,K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 37–118, doi:10.1017/9781009325844.002.

Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W.L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., ReyesGarcía, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-

Madruga, R., Roberts, D.C., Rogers, A.D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., Ngo, H.T. (2021). IPBES-IPCC co-sponsored workshop report on biodiversity and climate change; IPBES and IPCC. DOI:10.5281/zenodo.4782538.

Rabalais, N.N., Turner, R.E. and Wiseman Jr, W.J., 2002. Gulf of Mexico hypoxia, aka "The dead zone". *Annual Review of ecology and Systematics*, *33*(1), pp.235-263.

Ranger, N., Clacher, I. and Bloomfield, H. (2023) Learning from the 2021/22 Climate Biennial Exploratory Scenario (CBES) Exercise in the UK: Survey Report. Collaboraton between the UK Centre for Greening Finance and Investment and the Climate Financial Risk Forum. https://www.cgfi.ac.uk/wp-content/uploads/2023/03/CBES-Reports-Survey-Report.pdf

Ranger, N., O. Mahul, and I. Monasterolo. (2021). "Managing the financial risks of climate change and pandemics: What we know (and don't know)." One Earth 4 (10): 1375–1385. https://linkinghub.elsevier.com/retrieve/pii/S259033222100539X

Ranger, N.A., Mahul, O. and Monasterolo, I., (2022). Assessing financial risks from physical climate shocks: a framework for scenario generation. World Bank.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W. and Feulner, G., 2023. Earth beyond six of nine planetary boundaries. Science Advances, 9(37), p.eadh2458.

Ringler, C., Agbonlahor, M., Barron, J., Baye, K., Meenakshi, J. V., Mekonnen, D.K. & Uhlenbrook, S. (2022) The role of water in transforming food systems. Global Food Security. 33 (December 2021), 100639. doi:https://doi.org/10.1016/j.gfs.2022.100639.

Ross Shackleton, Brendon Larson, Reinette (Oonsie) Biggs. American chestnut dominant forests to red maple dominant forests. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2018-01-26 12:03:01 GMT (and reference therein).

Roweena Patel, Kate Williman, Viveca Mellegard, Philipp Siegel, Reinette (Oonsie) Biggs, Juan Carlos Rocha. Collapse of Newfoundland cod fisheries, Northwest Atlantic. In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017-02-07 12:18:06 GMT.

Scales, I.R., 2014. The drivers of deforestation and the complexity of land use in Madagascar. In *Conservation and environmental management in Madagascar* (pp. 105-126). Routledge.Harvey,

Schilling, J. Hertig, E, Tramblay, Y. and Scheffran, J. (2020) Climate change vulnerability, water resources and social implications in North Africa. Regional Environmental Change. 20 (15)

Schroders. 2023. Is El Niño's economic impact being underestimated? https://www.schroders.com/en-us/us/intermediary/insights/is-el-nino-s-economic-impact-being-underestimated-/

Schweizer, P.-J., and Renn, O. (2019). Governance of systemic risks for disaster prevention and mitigation. Disaster Prev. Manag. 28, 862–874.

Schwerdt, W. (2010) Chapter 6 - Introduction to Practical Risk Modelling. in Pricing, Risk, and Performance Measurement in Practice (ed. Schwerdt, W.) 139–164. Academic Press. doi:https://doi.org/10.1016/B978-0-12-374521-7.00009-2.

Sousa, A. Q., & Pearson, R. D.. 2009. Drought, Smallpox, and Emergence of Leishmania braziliensis in Northeastern Brazil. Emerging Infectious Diseases, 15(6), 916-921. https://doi.org/10.3201/eid1506.071331.

Sternberg, T. (2012) Chinese drought, bread and the Arab Spring. Applied Geography. https://doi.org/10.1016/j.apgeog.2012.02.004

Stradling, D. and Stradling, R.. 2008. Perceptions of the burning river: deindustrialization and Cleveland's Cuyahoga River. Environmental History, 13(3), pp.515-535.

Tacconi, L., Moore, P.F. and Kaimowitz, D., 2007. Fires in tropical forests–what is really the problem? Lessons from Indonesia. Mitigation and adaptation strategies for global change, 12, pp.55-66.

Tegegn, D. (2023) The trigger of Ethiopian famine and its impacts from 1950 to 1991, Cogent Arts & Humanities, 10:1, DOI: 10.1080/23311983.2023.2264017

Terrell, B.L., Johnson, P.N. and Segarra, E., 2002. Ogallala aquifer depletion: economic impact on the Texas high plains. Water Policy, 4(1), pp.33-46.Basso, B., Kendall, A.D. and Hyndman, D.W., 2013. The future of agriculture over the Ogallala Aquifer: Solutions to grow crops more efficiently with limited water. Earth's Future, 1(1), pp.39-41.

Trust, S., Joshi. S. Lenton, T., Oliver, J. (2023) The Emperors New Climate Scenarios. https://actuaries.org.uk/media/qeydewmk/the-emperor-s-new-climate-scenarios.pdfUN Climate Change High Level Champions (2022) Assessing the Financial Impact of the Land Use Transition on the Food and Agricultural Sector

Tsering, T., Sillanpää, M., Sillanpää, M., Viitala, M. and Reinikainen, S.P., 2021. Microplastics pollution in the Brahmaputra River and the Indus River of the Indian Himalaya. *Science of the Total Environment*, *789*, p.147968.

United Nations Department of Economic and Social Affairs, United Nations Forum on Forests Secretariat (2021). The Global Forest Goals Report 2021

United Nations Environment Programme Finance Initiative (2023) The 2023 Climate Risk Landscape. https://www.unepfi.org/themes/climate-change/2023-climate-risk-landscape/

Wang et al. (2022) https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021AV000654

WBCSD (2023) Exploring climate transition risks and opportunities: food, agriculture and forests. https://climatescenariocatalogue.org/

Yujun, Y.I., Zhaoyin, W., Zhang, K., Guoan, Y.U. and Xuehua, D., 2008. Sediment pollution and its effect on fish through food chain in the Yangtze River. International Journal of Sediment Research, 23(4), pp.338-347.

Zhai, X., Fang, X. and Su, Y., 2020. Regional interactions in social responses to extreme climate events: A case study of the North China Famine of 1876–1879. Atmosphere, 11(4), p.393.

Zhang, D., Sial, M.S., Ahmad, N., Filipe, A.J., Thu, P.A., Zia-Ud-Din, M. and Caleiro, A.B., 2020. Water scarcity and sustainability in an emerging economy: a management perspective for future. *Sustainability*, *13*(1), p.144.

Zscheischler, J., Westra, S., van den Hurk, B.J.J.M. et al. Future climate risk from compound events. Nature Clim Change 8, 469–477 (2018). https://doi.org/10.1038/s41558-018-0156-3

Annex 1: Summary and descriptions of Nature's Contribution to People, as defined by IPBES and ENCORE Ecosystem Services

	Nature's contribution to people	Brief description
Regulating	Habitat creation and maintenance	The formation and continued production of ecological conditions necessary or favorable for living beings important to people
	Pollination and dispersal of seeds	Animal facilitation of pollen movement and seed dispersal of beneficial organisms
	Regulation of air quality	Filtration, fixation, degradation or storage of pollutants and gasses
	Regulation of climate	Emission and sequestration of greenhouse gases, biogenic volatile organic compounds, and aerosols; biophysical feedbacks (e.g., albedo, evapotranspiration)
	Regulation of ocean acidification	Regulation by photosynthetic organisms on land and sea of atmospheric CO2 concentrations and thus seawater pH
	Regulation of freshwater quantity	Regulation of the quantity, location, and timing of the flow of surface and groundwater
	Regulation of freshwater quality	Ecosystem filtration and addition of particles, pathogens, excess nutrients, and other chemicals
	Formation and protection of soils	Soil formation and long-term maintenance of soil fertility, including sediment retention and degradation or storage of pollutants
	Regulation of hazards and extreme events	Amelioration of the impacts of hazards; reduction of size or frequency of hazards
	Regulation of detrimental organisms	Regulation of pests, pathogens, predators, competitors, parasites, and potentially harmful organisms
Material	Energy	Biomass-based fuels such as biofuel crops, animal waste, and fuelwood
	Food and feed	Food and feed from wild, managed, or domesticated organisms from terrestrial, freshwater, and marine sources
	Materials and assistance	Cultivated or wild materials and direct use of living organisms for industrial, ornamental, company, transport, labor, and other uses
	Medicinal and genetic resources	Naturally derived medicinal materials; genes and genetic information
Nonmaterial	Learning and inspiration	Capabilities developed through education, knowledge acquisition, and inspiration by nature for art and technological design
	Experiences	Physically and psychologically beneficial activities, healing, relaxation, recreation, and aesthetic enjoyment based on contact with nature
	Supporting identities	The basis for religious, spiritual, and social cohesion; sense of place, purpose, belonging, or rootedness associated with the living world; narratives, myths, and rituals; satisfaction from a landscape, seascape, habitat, or species
	Maintenance of options	Capacity of nature to keep options open to support quality of life in the future

Source: IPBES, Brauman 2020

Ecosystem services	Animal-based energy Bio-remediation Buffering and attenuation of mass flows Climate regulation Dilution by atmosphere and ecosystems Disease control Fibres and other materials Filtration Flood and storm protection Genetic materials	Ground water Maintain nursery habitats Mass stabilisation and erosion control Mediation of sensory impacts Pest control Pollination Soil quality Surface water Ventilation Water flow maintenance Water quality
Natural capital assets	Atmosphere Habitats Land geomorphology Minerals	Ocean geomorphology Soils and sediments Species Water

Source: ENCORE[18]

[18] https://www.encorenature.org/en/data-and-methodology/services

Annex 2: Existing Scenario Narratives Relevant to Physical Nature Risks

Food, agriculture and forest scenarios of WBCSD (2023)

Level of action (low to high) → Types of drivers: Policy action, Tech-driven action, Demand-side action

Input assumptions	>3°C Historic Trends	<2°C Forecast Policy (IPR)[2]	<2°C Coordinated Policy	1.5°C Societal Transformation	1.5°C Innovation
GDP & Pop/Trade	**Medium:** IPCC Shared Socioeconomic Pathway 2 (SSP2), a 'middle of the road' scenario: Population grows from 7bn at 0.6% p.a. before slowing, 2070 peak at 9.5 bn. GDP doubles by 2050 **Current patterns:** Maintains current trade policy regime, without systematic liberalisation or de-liberalisation				
GHG Prices $/ton of CO_2e	**Current prices** $4/ton CO_2e by 2050	**Disorderly** ~$115/ton CO_2e by 2050[3]	**Medium** $100/ton CO_2e by 2050	**High** $153/ton CO_2e by 2050	
Bioenergy pathway Exajoules (EJ)	**Current levels** 8.8 EJ/year in 2050 (no 2nd generation bioenergy crops)	**Disorderly** Demand reaches moderate levels only after 2040 (72 EJ/yr 2nd generation)	**Moderate** 90 EJ/year by 2050 (72 EJ/yr 2nd generation)	**Ambitious** 100 EJ/year by 2050 (82 EJ/yr 2nd generation bioenergy crops)	**High** 130 EJ/year by 2050 (112 EJ/yr 2nd generation bioenergy crops)
Diet shifts Caloric Shift between 2020 and 2050	**No diet shift** +18% demand for livestock products between 2020 and 2050	**Medium diet shift** -2% demand for livestock products between 2020 and 2050		**High diet shift** -12% demand for livestock products between 2020 and 2050	**Medium diet shift** -2% demand for livestock products between 2020 and 2050
Protected areas[1]	**WDPA** current protection 13% of terrestrial land surface	**WDPA + Biodiversity hotspots** (After 2025, limited to a subset of countries)	**WDPA + Biodiversity hotspots**	**Meets 50x50 targets** 50% terrestrial area by 2030	**WDPA + Biodiversity hotspots**
Input efficiency Nitrogen Uptake Efficiency (NUE), %	**No change** Global average <60% by 2050	**Medium** Global average ~65% by 2050			**High** NUE global average 70% by 2050
Yield-enhancing tech Per annum growth crop yields	**Low** Crop yields grow < 1%p.a.	**Medium** Crop yields grow at ~1% p.a.			**High** Yields grow >1% p.a.
Food waste reductions % of food wasted	**No reduction** 33% food is wasted by 2050	**Medium reduction** 20% by 2050 (faster reduction from 2030 to 2050)	**Medium reduction** 20% by 2050 (smooth reduction)	**High reduction** 16.5% by 2050 (UN Sustainable Develop Goal 12.3)	**Medium reduction** 20% by 2050
Other climate policies	**Nationally determined policies on reforestation/ avoided deforestation**	**Adjusted land-use Nationally Determined Contributions (NDCs)** Lower forest NDC for China			
Timber demand pathways	**Low demand.** Demand for timber in construction remains low (~0.5%)	**Medium demand.** Demand for timber in construction of new builds grows to 10%.			**High demand.** Demand for timber in construction of new builds grows to 50%.

1. "Protected areas" refers to Cat I, VI World Database for Protected Areas.
2. Action starts between 2025 and 2030.
3. Starting 2025, high-income regions begin to experience higher GHG prices than emerging and developing regions.

IPR (2023): IPR FPS + Nature

Included in FPS				Included in FPS + Nature
Energy-related policy levers			Land-related policy levers	Nature-related policy levers
Carbon pricing	Coal phase-out	100% clean power	Forestry	Land protection and restoration
Carbon taxes and emission trading systems, along with border carbon adjustments	Regulations prohibiting coal, emissions performance standards, and electricity market reforms	Targets for 100% clean power, along with renewables capacity auctions and other support policies	Incentives for reforestation and afforestation, along with penalties for deforestation, supported by consumer pressure	Policies to protect biodiversity hotspots and additional habitats, along with regulation mandating restoration of degraded land
Low-carbon buildings	Clean industry	Zero emission vehicles	Low-emissions agriculture	Nature markets
Emissions performance standards for industrial plant, along with subsidies for new or retrofit clean industrial processes	Laws prohibiting fossil fuel heating, subsidizing low-carbon heating and requiring thermal efficiency; for appliances, minimum energy performance standards	ZEV consumer subsidies along with legislation requiring 100% zero emission vehicle (ZEV) sales and implementing manufacturer ZEV obligations	Subsidies for low-emissions practices and technologies; emissions regulation incl. via tax or cap-and-trade systems; farmer education and technical assistance programmes	Emerging legislation and targets for biodiversity outcomes that support the development of voluntary biodiversity credit markets

FSDA (2022)

Scenario	Description	Transition risk	Physical risk	Natural outcome
Baseline	No accounting of physical or transition risk. All results are measured relative to baseline.			N/A
Current policies	Continuation of accelerating biodiversity loss, widescale depletion of natural capital and fall in the availability and quality of ecosystem services.			Continuation of current nature policies and commitments with no expected increase in ambition for both nature and climate.
Climate only	Ambitious action is taken on climate with limited focus on, or coordination with, nature action. Actions can benefit nature or drive nature loss.			Any nature co-benefits from climate action are largely ineffective at halting the overall decline in nature. Accelerating nature loss continues, but at a slightly reduced pace.
Climate + Protection	Climate action is coupled with substantial expansion and protection of nature but with no further action.			Effective area-based conservation improves nature integrity in key hotspots by 2030, but significant decline continues in other areas of the world.
Climate + Nature Future	Ambitious and coordinated nature action works towards co-benefits for both climate and nature goals. However, transformative change is achieved late.			Trends of nature loss continue to accelerate to 2030 and then decelerate, leading to eventual reversal (i.e., positive nature trend) by 2050.
Climate + Nature Now	Ambitious, holistic, and early nature action is well coordinated with climate, maximising co-benefits and minimising disruption.			Rapid transformation to halt and reverse nature loss by 2030 with significant biodiversity gains achieved by 2050.

Johnson et al. 2021

Overview of the three ecosystem services collapse scenarios

Scenario	Overview of the methods used
Wild pollination collapse	The model looks at the effect of a 90 percent reduction in wild pollination sufficiency on agricultural yields, focusing on crops that are dependent on wild pollination. Crops that are only partially dependent on these services will not see yield reductions as large as the pollinator collapse. The model builds on Bauer and Wing (2016), making the scenarios spatially explicit through the Integrated Valuation of Ecosystem Services and Tradeoffs tool.
Marine fisheries collapse	The model relies on the Fisheries and Marine Ecosystem Model Intercomparison Project data (Lotze et al. 2019). To simulate the regime shift, the model assumes a severe climate change scenario (Representative Concentration Pathway (RCP) 8.5 instead of RCP4.5) and further takes the worst-case outcome in terms of climate change impact reported in the uncertainty bounds and sensitivity analysis. The model simulates severe disruptions of fish migration that lead to a reduced total catch biomass, which in turn impacts the economic model.
Widespread conversion of tropical forests to savannah	The model modifies two elements of the Spatial Economic Allocation Landscape Simulator model to simulate widespread collapse of tropical forests that results in forests converting into grasslands and shrubs: (i) assuming 88 percent less forest cover for all tropical regions; and (ii) lowering expansion suitability for forestry in the Amazon basin. This scenario impacts the economy through reduced provision of timber from native forests in agro-ecological zones 5 and 6 by 90 percent.

Annex 3: Indicators used to construct risk indices

Water stress – Surface water

About

Surface water is provided through freshwater resources from collected precipitation and water flow from natural sources.

Indicators

Dimension	Indicator	Relevance	Unit	Source	Haz/Exp/Vul	Limitation
Overexploitation	Agricultural water withdrawal as % of total renewable water resources	H	%	AQUASTAT	Exp/Vul	Does not differ sustainable/unsustainable water use
	SDG 6.4.1. Irrigated Agriculture Water Use Efficiency	H	1000 m^3/year	AQUASTAT	Exp/Vul	Efficiency alone doesn't indicate the absolute volume of water used or the sustainability of the water source.
	SDG 6.4.2. Water Stress	H	Ratio	AQUASTAT	Haz/Vul	Overlooks local variability and short-term fluctuations (seasonal or event-driven).
	Fresh surface water withdrawal/Surface water produced internally	H	Ratio	AQUASTAT	Haz	
	Vulnerability	H	Score (0-1)	ND-GAIN	Vul	An aggregate measure; does not fully reflect specific vulnerabilities related to surface water or particular sectors.

Note

Agriculture is one of the largest demand sectors for water. Agricultural water withdrawal indicator provides a sense of how much of a country's or region's water resources are being used for agriculture. High percentages may indicate that a country is overly dependent on its water resources for agriculture, potentially leaving less water available for other uses and increasing the vulnerability to water stress (Mancosu et al., 2015). Over-extraction of water for agriculture degrades surface water ecosystems, affecting habitats and decreasing water quality. The higher the withdrawal rate, the higher the risk to ecosystem services.

Irrigated agriculture water use efficiency is crucial for understanding how well water is utilised. Higher efficiency often implies less waste and more sustainable use of surface water (examples: Ringler et al. 2022).

High water stress indicates a high demand for water relative to the available quantity. It reflects the balance (or imbalance) between water availability and demand from all sectors, including domestic, industrial, and environmental needs. There is a strong positive correlation (r≈0.998) between agricultural water withdrawal as a percentage of total renewable water resources and water stress, suggesting that higher agricultural water withdrawals relative to their renewable water resources tend to experience higher water stress. While these indicators are related, they do not measure the same thing. One highlights the impact of a specific sector, and the other provides an overall stress level, offering a more holistic view of water-related risks. Having both metrics allows for identifying targeted interventions. More efficient irrigation practices might be required for high agricultural water withdrawal, while broader water management strategies might be required for high water stress.

The ratio of fresh surface water withdrawal to surface water produced internally indicates the dependency on internally renewable surface water resources. It's important to assess the sustainability of surface water use, but it does not fully account for external water resources (like trans-boundary rivers) or the return flow of water to the system, which can be significant in some regions.

The ND-GAIN vulnerability indicator is highly relevant in assessing a country's overall vulnerability to climate change and its implications for water resources; it broadly reflects a country's ability to cope with water-related challenges, it encompasses governance, economic capacity, and societal resilience.

Water stress – Ground water

About

Groundwater is provided through freshwater resources from collected precipitation and water flow from natural sources.

Indicators

Dimension	Indicator	Relevance	Unit	Source	Haz/Exp/Vul	Limitation
	SDG 6.4.1. Irrigated Agriculture Water Use Efficiency	H	1000 m^3/year	AQUASTAT	Exp/Vul	Does not directly account for the sustainability of groundwater usage
	Fresh groundwater withdrawal/	H	Ratio	AQUASTAT	Haz	Overlooks local

	Groundwater produced internally					variability and short-term fluctuations (seasonal or event-driven).
	Ground water depletion	H	Maximum score (0-4)	Aqueduct	Haz	
	SDG 6.4.2. Water Stress	H	Ratio	AQUASTAT	Haz/Vul	
	Vulnerability	H	Score (0-1)	ND-GAIN	Vul	Does not specifically focus on groundwater issues.

Note

Irrigation efficiency measures can indicate how sustainably water is being used, thus inverse values indicate vulnerability. Low efficiency implies more groundwater is extracted than necessary, potentially depleting aquifers faster than they can recharge. It's crucial to understand how effectively water (including groundwater) is used in agriculture, which directly impacts water availability (Hellegers & van Halsema, 2021).

Water stress assesses the overall demand for water (including groundwater) against its availability. High stress indicates significant use of groundwater, possibly leading to depletion (Biancalani & Marinelli, 2021).

The ratio of fresh groundwater withdrawals and groundwater produced internally helps assess the reliance on local groundwater resources. However, this metric does not account for the quality of groundwater, or external factors like climate change, which can affect recharge rates.

Groundwater depletion rates, on the other hand, indicate the rate at which groundwater levels are falling, which is critical for understanding long-term sustainability and risks of over-extraction, especially in arid regions or areas with high agricultural demand.

The vulnerability indicator broader indicator captures a country's capacity to adapt to various challenges, including those related to groundwater management. Understanding vulnerability helps in assessing how well a country can cope with and adapt to groundwater-related issues.

Pollination

About

Pollination is an important ecosystem service that is primarily provided by bees, butterflies, birds, bats, and other animals, as well as wind and water. It is an essential part of the reproductive cycle for flowering plants, including many fruits, vegetables, and nuts. It is also important for biodiversity because many plants rely on pollinators to produce seeds and thus propagate.

Indicators

Note

Dimension	Indicator	Relevance	Unit	Source	H/E/V	Limitations
Pollution/ Monoculture/ Urban impacts	Pesticides usage	H	kg/ha	FAOSTAT	Haz	Does not provide information on the toxicity of specific pesticides
	Cropland	M	%	FAOSTAT	Exp/Vul	The presence of cropland alone does not indicate whether it is pollinator-friendly or not.
	Artificial Surfaces	M	30-year change %	FAOSTAT	Exp/Vul	Some urban environments can support pollinators with gardens and green spaces, so the mere presence of artificial surfaces doesn't always equate to high risk.
	Vulnerability	H	Score (0-1)	ND-GAIN	Vul	Does not specifically focus on environment/pollination

Pesticides are most relevant indicator as they harmfully impact pollinators like bees, butterflies, and bats. They lead to mortality or sub-lethal effects like disorientation and reduced foraging efficiency in pollinators.

Cropland is a moderately relevant indicator as monocultures or extensive stretches of cropland may lack the floral diversity needed to sustain pollinators. However, cropland can also be managed in a pollinator-friendly manner by incorporating flowering plants, reducing pesticide use, and providing habitats. Therefore, "Cropland" as an indicator is nuanced but important. It could indicate risk if associated with practices harmful to pollinators but could also indicate low risk if managed sustainably.

The extent of land covered by human-made surfaces including urban, suburban, and industrial areas is perhaps least relevant but still significant. Urban and built-up areas typically lack the kind of vegetative diversity that supports pollinators. Moreover, these areas often coincide with increased pesticide use, pollution, habitat fragmentation and other human activities that can disturb natural habitats. However, urban areas may also provide opportunities for creating pollinator-friendly spaces such as urban gardens, parks, and green roofs. Like "Cropland," this indicator can have a nuanced interpretation but is generally relevant for assessing risk to pollination services.

Water quality

About

Water quality as an ecosystem service refers to the natural processes that keep water in natural environments in optimal chemical, physical, and biological conditions. This includes pollutant filtering, harmful compound neutralisation, and biodiversity support, all of which contribute to water purification.

Indicators

Dimension	Indicator	Relevance	Unit	Source	Haz/Exp/Vul	Limitation
Pollution	Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene.	H	per 100000 people	World Bank	Vul	Does not give information on the sources of pollution or specific water quality parameters
	Proportion of river water bodies with good ambient water quality.	H	%	UN SDG 3	Exp	Different standards; does not account for episodic pollution that are not routinely monitored.
	Not treated municipal wastewater/ municipal water withdrawal.	H	Ratio	AQUASTAT	Haz	Does not indicate the concentration or types of pollutants in the wastewater.
	Water stress	M		UNSDG/AQUASTAT/ Aqueduct		Does not directly measure water quality but rather the availability of water.
	Vulnerability	H	Score (0-1)	ND-GAIN	Vul	Does not specifically focus on groundwater issues.

Note

Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (per 100000 people quantifies the direct health impact of poor water quality and sanitation. This is a strong indicator of the failure of water and sanitation systems.

Poor water quality in rivers can affect drinking water supplies, agricultural water sources, and natural habitats. Good for long-term monitoring but may not capture immediate risks like outbreaks of waterborne diseases.

Untreated wastewater is a direct source of pollution and contamination for natural water bodies which is highly relevant for both developed and developing countries for immediate risk assessment.

High water stress can lead to over-exploitation of water resources, affecting water quality as well as quantity.

Ventilation – air

About

Ventilation provided by natural or planted vegetation is vital for good indoor (and outdoor) air quality and without it there are long term health implications for building occupants due to the build-up of volatile organic compounds (VOCs), airborne bacteria and moulds.

Indicators

Dimension	Indicator	Relevance	Unit	Source	Haz/Exp/Vul	Limitations
Reduction of green spaces	Artificial surfaces (including urban and associated areas)	H	%	FAOSTAT	Haz/Exp	Does not directly measure air quality. Some urban areas might have better pollution control policies.
Recovery potential	Tree-covered areas	H	%	FAOSTAT	Haz/Vul	The presence of trees does not necessarily guarantee low pollution levels, especially in areas with high industrial activity.
Pollution	PM2.5 air pollution, mean annual exposure	H	Micrograms per cubic meter	World Bank	Haz	Does not capture seasonal variations or short-term spikes in pollution levels
Pollution	Mortality rate attributed to household and ambient air pollution, age-standardized (per 100,000 population)	H	Per 100,000 population	World Bank	Vul	Mortality rates are also influenced by healthcare access and quality, public health policies, and socio-economic status
	Vulnerability	H	Score (0-1)	ND-GAIN	Vul	Different aspects of vulnerability may have varying impacts on how air pollution affects a population.

Note

Artificial surfaces/Urbanization can significantly air quality and ventilation ecosystem services, particularly by creating heat islands and reducing natural vegetation that contributes to air purification.

Urbanization and industrialization are often associated with higher pollution levels due to increased vehicular traffic, industrial emissions, and other anthropogenic factors. These places can both introduce and trap pollutants due to limited air movement.

Tree-covered areas improve air quality by absorbing pollutants and producing oxygen. A decrease in tree-covered areas can make an environment more vulnerable to air pollution.

PM2.5 particles are harmful to human health and can be an indicator of poor air quality.

Mortality rate attributed to household and ambient air pollution, age-standardized (per 100,000 population) gives a direct measurement of the impact of poor ventilation and air quality on human health.

These indicators encompass hazards, exposures, and vulnerabilities which can provide a comprehensive view of the state and risks related to ventilation and air quality.

Environmental Change Institute

School of Geography and the Environment
University of Oxford
South Parks Road
Oxford, OX1 3QY
United Kingdom

Tel: +44 (0)1865 275848

- Email: enquiries@eci.ox.ac.uk
- Website: www.eci.ox.ac.uk
- Twitter: @ecioxford
- LinkedIn: Environmental Change Institute (ECI), University of Oxford

Corresponding author: Dr Nicola Ranger
Nicola.ranger@ouce.ox.ac.uk