Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

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Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

Table of contents

This report represents pioneering efforts in creating a new framework combining climate and nature scenarios. Its sole purpose is to showcase early progress and gather feedback to refine future project outputs.

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Executive summary

The degradation of nature, encompassing the loss of biodiversity, emerges as a substantial threat not only to ecosystems and humanity, but also to the broader economy and financial stability. The work of financial institutions has largely focused on climate, firmly establishing the relevance of climate-related risks for central banks and supervisors. However, it is imperative that forward-looking risk assessments adopt an integrated approach encompassing both climate and nature-related aspects to prevent underestimation of financial stability risks.

One crucial step for financial stakeholders is the formulation of scenarios that provide a comprehensive understanding of integrated climate- and nature-related economic and financial risks. The Potsdam Institute for Climate Impact Research (PIK), European Central Bank (ECB) and NatureFinance have partnered to advance pioneering efforts to develop a novel integrated climate-nature scenario framework. Our project marks initial and evolving efforts to develop integrated climate-nature scenario narratives and showcase their implications through a sophisticated modelling infrastructure combining macroeconomic and biophysical models. It contributes to the nascent and emerging research field of scenario development for assessing climate and nature-related economic and financial risks. The current model focuses on modelling risks for the agriculture and land use sector for a period from 2020 to 2050 at a global spatial scope. The focus on this sector was chosen due to its direct dependence on various Nature's Contributions to People (NCP). Consequently, modelled changes in land degradation and NCPs are expected to significantly impact this sector.

The climate-nature risk scenario framework leverages the established Network for Greening the Financial System (NGFS) climate scenarios and is to a great extent aligned with its nature scenarios development recommendations. This enables a more coherent comparative assessment of climate-nature risk scenarios with transition risks in the broader economy. The existing policies and conservation aspirations are integrated into the climate-nature risk scenarios narratives by simulating transition to the achievements of proposed targets. The developed modelling framework draws on a wide range of spatially variable biophysical and socio-economic information to derive various indicators of both biodiversity and climate risks. Within the climate-nature risk scenario framework, we assess the degradation of ecosystem services, and we derive two indicators of nature's contribution to people (NCP): pollination sufficiency and soil erosion. These two NCPs were selected due to the availability of a relatively good scientific understanding - and global data - regarding their importance for agricultural production.

The interim results indicate diverging biodiversity responses based on varying climate and nature policy ambition, especially in terms of biodiversity in managed landscapes associated with critical ecosystem functions.

The complexity of integrating climate and nature poses challenges in capturing the entire spectrum of dynamics and processes required for modelling and assessing the complete cycle from human impacts through biodiversity, ecosystem functioning, and NCPs to impacting overall human health and economic stability. Our work presents a pivotal initial step towards a more complete quantitative risk assessment framework that could feed into the work of financial institutions and other risk management and modelling experts.

This report thoroughly explores methodological considerations for developing integrated climate-nature scenario narratives and establishing a modelling infrastructure to assess the macroeconomic consequences of diverse scenarios. It also includes initial findings on implications of different scenario narratives for biodiversity, pollination sufficiency and soil erosion. The forthcoming report, planned for mid-2024, will present a more comprehensive array of results and delve into the implications for financial stability arising from the developed scenario narratives. It will specifically underscore potential ramifications for central banks and supervisors.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

1

INTRODUCTION

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1.1 Importance of healthy nature for resilience of society and economy

The very fabric of our wellbeing is intricately linked to the health of nature. Our sustenance, the air we breathe, the water we drink, the energy that powers our lives, and the raw materials for our essentials – all hinge on the vitality of the natural world. Over half of the global Gross Domestic Product (GDP), a staggering EUR €40 trillion, strongly depends on a healthy environment (World Economic Forum, 2020). But indirectly, the importance of healthy nature extends to all aspects of our economy, as we fundamentally depend on these ecosystems for our survival. More than half of the global population depends on biodiversity for their livelihoods, with 70% of the world's poor and vulnerable directly depending on it for their survival and wellbeing. Yet, amidst the undeniable and scientifically established advantages we reap from nature, an alarming trend is being observed. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has provided evidence on the worldwide decline in nature that has seen the extinction rate of species accelerate at a scale unprecedented in human history (IPBES, 2019). Six of the nine planetary boundaries[1] have been transgressed, significantly increasing the risk of generating abrupt large-scale, and potentially irreversible, changes (Richardson et al., 2023).

The clock is ticking, and the consequences of our inaction are dire. Should we falter in our commitments to curb the primary culprits behind this rapid nature loss – unsustainable land use, greenhouse gas emissions, overexploitation of natural resources, pollution, and invasive species – we risk witnessing the catastrophic breakdown of critical natural systems. This ominous scenario could become a reality as early as the mid-21st century, coinciding with the expected peak of the world's human population growth. The urgency is unmistakable. It is not just a matter of preserving nature; it's about securing our very existence. Time is of the essence, and our actions today will shape the fate of our planet and the generations that follow.

The trajectory we are currently on indicates a global warming level well beyond 2 °C by the end of this century, as highlighted in the IPCC AR6 synthesis report (IPCC, 2022a). Alarming forecasts suggest that the 1.5 °C threshold could be breached as early as the 2030s (Jones, 2023). How far beyond that threshold the world goes will make a huge difference. Every fraction of additional global warming will amplify the impacts on humanity and natural ecosystems in a non-linear manner (NatureFinance, 2023). At 2° C of global warming above the pre-industrial average, nearly 37% of the world's population is expected to face increasingly severe heat, with one third of the world's population also experiencing chronic water scarcity (IPCC, Chapter 3, 2022b).

[1] The planetary boundaries framework, rooted in Earth system science, identifies nine crucial processes that maintain the Earth system's stability and resilience, (Richardson et al. 2023).

The degradation of nature, encompassing the loss of biodiversity, emerges as a substantial threat not only to ecosystems but also to the broader economy and financial stability. Our economies, intricately linked to the functionality of financial institutions as facilitators of economic activities, are heavily reliant on the health of nature. A growing number of central banks, recognising the indispensable value of healthy and resilient ecosystems for economic functionality and financial system stability, underscore this imperative (European Central Bank, Boldrini et al., 2023; Banque de France, Svartzman et al., 2021; De Nederlandsche Bank, van Toor et al., 2020; Bank Negara Malaysia, World Bank, 2022; Banco de Mexico, Serafin et al., 2023). Additionally, the Network for Greening the Financial System (NGFS) has formally recognised the criticality for central banks and supervisors to incorporate nature-related financial risks into the fulfilment of their mandates. Acknowledging nature as a potential source of economic and financial risk, these institutions are called upon to meticulously assess the extent to which financial systems are exposed to nature. To address this need, the NGFS has launched a dedicated Taskforce focused on biodiversity loss and nature-related risks. In alignment with this commitment, the NGFS has unveiled a beta version of its conceptual framework for nature-related financial risks. This framework serves as a pivotal guide for central banks and financial supervisors in their collective pursuit of a resilient and sustainable financial landscape (NGFS, 2023a,b; OECD, 2023).

A comprehensive study by the European Central Bank reveals a striking statistic: 75% of corporate loans issued by euro area banks and 31% of investments in corporate bonds and equity by EEA insurers exhibit a high dependency on at least one ecosystem service (Boldrini et al., 2023). Notably, the euro area's economy and financial system are particularly dependent on critical ecosystem services, including mass stabilisation and erosion control, surface and groundwater provision, as well as flood and storm protection. If environmental degradation persists along current trends, the consequences for loan portfolios and economic activities could be significant. Vulnerabilities may intensify, with certain regions and economic sectors facing heightened risks. This underscores the urgency of addressing and reversing the trajectory of environmental degradation (i.e. saving natural ecosystems and improving the sustainability of managed ecosystems) for the resilience and sustainability of our economy and financial system.

1.2 Why should we tackle climate change and nature loss together?

Climate- and nature-related risks are usually treated in siloes. The work of financial institutions has largely focused on climate, firmly establishing the relevance of climate-related risks for central banks and supervisors. Recently, the relevance of broader nature-related issues has led to a positioning of climate- and nature-related risks as two distinct but interrelated issues (NGFS, 2023a). Similarly, a fundamental requirement of the TNFD, applicable across all recommended disclosure pillars (Governance, Strategy, Risk and Impact Management, and Metrics and Targets), is the integration with other sustainability-related disclosures (TNFD, 2023a). It is equally important to consider risks stemming from climate and those from nature, in an integrated manner. Climate-related financial risks are more established and might in many cases be a starting point for broader nature-related risk assessment. However, the physical dynamics driving climate change and nature degradation are mutually reinforcing, while at the same time climate mitigation and restoration efforts present potential trade-offs and synergies. Given the above considerations, the most significant impact on our economy and financial system is likely to materialise as a compound effect of climate change and nature degradation which includes biodiversity loss (Ceglar et al., 2023; Boldrini et al., 2023).

Adopting an integrated approach to climate and nature-related risks for both the real economy and financial system involves four key dimensions (NGFS conceptual framework, 2023a). Firstly, climate change serves as a driver of nature-related risks (IPBES, 2019). The direct impact of climate change on nature results in degradation, leading to biodiversity loss and a decline or complete loss of ecosystem functionality. For example, increased flooding, wildfires, ocean acidification and cyclones can disrupt the water cycle, alter soil temperatures and accelerate habitat and wildlife loss. Secondly, nature degradation contributes to climate risk. A decrease in ecosystem functionality affects carbon, nutrients, and water cycles, accelerating climate change through diminished carbon uptake and the release of long-term stored carbon into the atmosphere. Additionally, the deterioration of vital ecosystems, such as wetlands and mangroves, reduces climate resilience. Thirdly, climate change mitigation and adaptation, if not properly planned, can inadvertently drive nature degradation. For instance, certain strategies aimed at mitigating climate change may unintentionally harm natural ecosystems and biodiversity. Large-scale monoculture reforestation and large-scale bioenergy crop cultivation are examples of such strategies that may have adverse consequences for biodiversity, ecosystem health, and resilience. Lastly, nature plays a crucial role in addressing the climate crisis and mitigating future climate-related risks. Nature conservation significantly contributes to climate change mitigation, preventing the release of stored carbon and facilitating future carbon sequestration through actions like combating deforestation and protecting wetlands and peatlands. Moreover, nature conservation enhances adaptation potential by safeguarding ecosystems essential for protection against climate hazards.

Given the considerations outlined above, it is imperative that forward-looking risk assessments, relevant to central banks, supervisors, financial institutions, corporates and investment opportunities, adopt an integrated approach encompassing both climate and nature. To conduct a comprehensive forward-looking assessment of nature-related financial risks, three key components must be addressed (ESRB/ECB, 2023): (i) performing scenario analysis of potential hazards and shocks that could translate into financial risks; (ii) selecting or developing dedicated metrics to measure financial institutions' exposure to these shocks; and (iii) creating tools to assess the vulnerability of financial institutions by examining their sensitivity and adaptive capacity. These elements not only play a pivotal role in financial risk assessment for financial institutions, corporates, the financial system and the economy, but are also crucial for policymakers. They enable policymakers to evaluate the adverse impacts of the financial system on climate and nature. They work towards mitigating them as well as halting and reversing nature degradation and biodiversity loss. This integrated approach is essential for facilitating faster and more efficient investments in environmentally sustainable initiatives, ultimately minimising the future nature- and climate-related hazards and reducing credit risks for banks.

Developing integrated climate-nature scenarios poses a remarkable challenge given the intricate nature of ecosystem functions and non-linear dynamics. Constructing meaningful scenario narratives necessitates navigating the inherent trade-off between capturing locally specific environmental changes and maintaining global relevance. The nature-related scenarios analysis by the NGFS has yielded a set of recommendations for scenario development, aiming for synergy with climate scenarios while addressing nature loss and strategies for its reversal (NGFS, 2023b).

Significant developments are being made in line with the NGFS and TNFD recommendations for the development of integrated nature-climate scenarios and risk assessment. Ranger et al. (2023) underscores the critical importance of integrating climate and nature considerations in our response to potential catastrophic impacts of climate change on the economy and financial system. Deriving concrete estimates of economic and financial stability impacts arising from such integrated frameworks remains challenging (Prodani et al., 2023). These studies collectively highlight the macro-criticality of risks associated with the degradation of nature, thereby leading central banks, governments, and financial institutions to having to further assess risks as well as identify mitigative actions.

In response to the mounting evidence advocating for an integrated approach, our objective is to contribute to the initial efforts in scenario development. We seek to identify key research gaps, aiming to propel the discourse towards more quantitative risk frameworks and stress tests applicable to central banks.

1.3 The structure of the integrated climate-nature scenario development project

The Potsdam Institute for Climate Impact Research (PIK), European Central Bank (ECB) and NatureFinance have partnered to explore a range of ecosystem services to provide a holistic view of how an integrated climate-nature scenario framework could work. Our project aims to underscore the critical significance of integrating climate and nature within a nexus approach to capture their mutually reinforcing impacts on both physical and transition risks. The scenario framework prioritises mid- and long-term objectives (2030 and 2050), with a focus on policies and measures for climate change mitigation in the land use sector and the protection of nature and ecosystem services, including those measures that are already in place or could be potentially applied. The nature-climate scenario design is based on Shared Socioeconomic Pathways (SSP) storylines as well as measures for climate change mitigation policies and protection of nature and ecosystem services (O'Neill et al., 2017; Popp et al., 2017). Ultimately, our project seeks to exemplify the intricate nature-climate nexus through practical illustrations. In doing so, we aim to identify research needs and knowledge gaps, paving the way for a more comprehensive and globally applicable framework.

One crucial stride for financial stakeholders is the formulation of scenarios that provide a comprehensive understanding of integrated climate- and nature-related economic and financial risks. A recent in-depth assessment by the NGFS on the development of scenarios for evaluating nature-related economic and financial risks (NGFS, 2023b) has duly acknowledged the challenges inherent in crafting narratives for climate and nature-related scenarios. These challenges include the multi-dimensional nature of ecosystems and the non-linear dynamics at play. Despite the intricacies involved, the climate-nature scenarios should be specific enough to capture vital interactions in climate-nature-economy space while remaining sufficiently simple to be actionable for economic and financial stakeholders.

Figure 1 demonstrates the general workflow of the project. The most important steps are aligned with the TNFD recommendations (TNFD, 2023a) and consist of: developing scenario narratives and their implementation in a global multi-regional partial equilibrium model for the agricultural sector, conducting global level scenario runs, quantifying of physical and transition risk indicators, identifying regions vulnerable to ecosystem service loss, and finally, evaluating the materialisation of physical and transition risks. The physical and transition risk indicators as well as biodiversity and ecosystem indicators provide essential elements for development of quantitative financial risk assessment frameworks. We have the first preliminary results of the assessment, and we are currently enhancing the narrative and scenarios that would lead to the final evaluation of financial risk coming from materialisation of physical and transition risks in the land use sector (Figure 1).

Our project marks an initial effort to develop integrated climate-nature scenario narratives and showcase their implications through a sophisticated modelling infrastructure that combines macroeconomic and biophysical models. Due to the complexity of the underlying processes, a meticulous step-by-step development is essential, allowing us to glean valuable insights throughout the process. It is imperative to scrutinise inherent uncertainties and offer recommendations for future research.

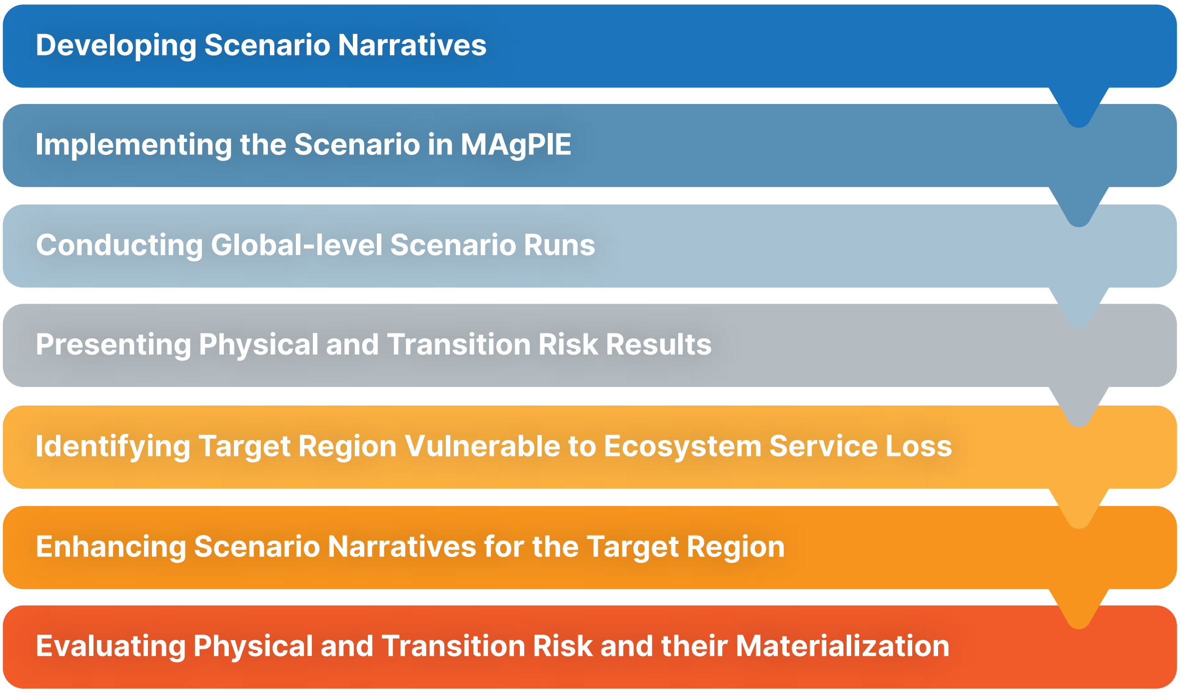

Figure 1: Essential elements of climate-nature risk scenarios project. Orange colour-coding elements denote components of the project that are still work in progress.

In this report, we focus on presenting the first four elements of the project workflow (Figure 1). The document is structured as follows: Chapter 2 presents integrated climate-nature scenario narratives, Chapter 3 explains the integrated modelling framework, Chapter 4 presents selected preliminary results, Chapter 5 discusses implications of using integrated approach for financial institutions and investors, and Chapter 6 provides conclusions with forward-looking next steps. The forthcoming report, planned for mid-2024, will present a more comprehensive array of results and delve into the implications for financial stability arising from the developed scenario narratives. It will specifically underscore potential ramifications for central banks and supervisors.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

2

INTEGRATED CLIMATE-NATURE SCENARIO NARRATIVES

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To gain a better understanding of the integrated risk associated with climate and nature, qualitative scenario narratives are developed as a climate-nature risk scenario framework. This narrative framework provides detailed descriptions of potential futures across two dimensions with different levels of ambition for the protection of nature or climate (Figure 2). These explanatory narratives offer insights into possible future developments, which are contingent on policy decisions and their implementation. The framework also considers the interplay and interconnectedness between climate and nature protection targets, with the aim of rationalising their integrated effects. Subsequently, the narratives are translated into quantitative model scenarios. The scenarios also have a normative aspect, as existing policies and conservation aspirations are integrated to simulate transitions towards achieving specific targets such as the Nationally Determined Contributions (NDCs). The complexities and nuances of each potential world are articulated by considering the combined financial impacts of both physical and transition risks, with the focus on indicators from future projections in the agricultural and land use sector. The focus on this sector was chosen due to its direct dependence on various Nature's Contributions to People (NCP). Consequently, modelled changes in land degradation and NCPs are expected to significantly impact this sector. The evaluation of risk within this sector helps in describing how different levels of policy ambition might unfold and affect climate, nature, and the economy.

The climate-nature risk scenario framework is aligned with the established NGFS climate scenarios[2], enabling a comparative assessment of climate-nature risk scenarios with transitional risks in the broader economy in a more coherent manner. Since the risk indicators are evaluated only for the agricultural and land use sectors here, connecting each climate-nature risk narrative to the corresponding NGFS scenario offers a chance to understand the possible amplifying impacts on an economy arising from nature-related risks. The linkage between these two frameworks is established through the quantitative instruments used for transitioning to climate mitigation targets, and specifically applied in the land use sector (c.f. Annex Table S1). It also integrates several recommendations from the NGFS nature scenario recommendations (NGFS, 2023b), related especially to overcoming the inherent trade-offs between capturing locally specific environmental changes, while maintaining global relevance (c.f. Table 3 and Annex Table S2).

[1] https://www.ngfs.net/ngfs-scenarios-portal/

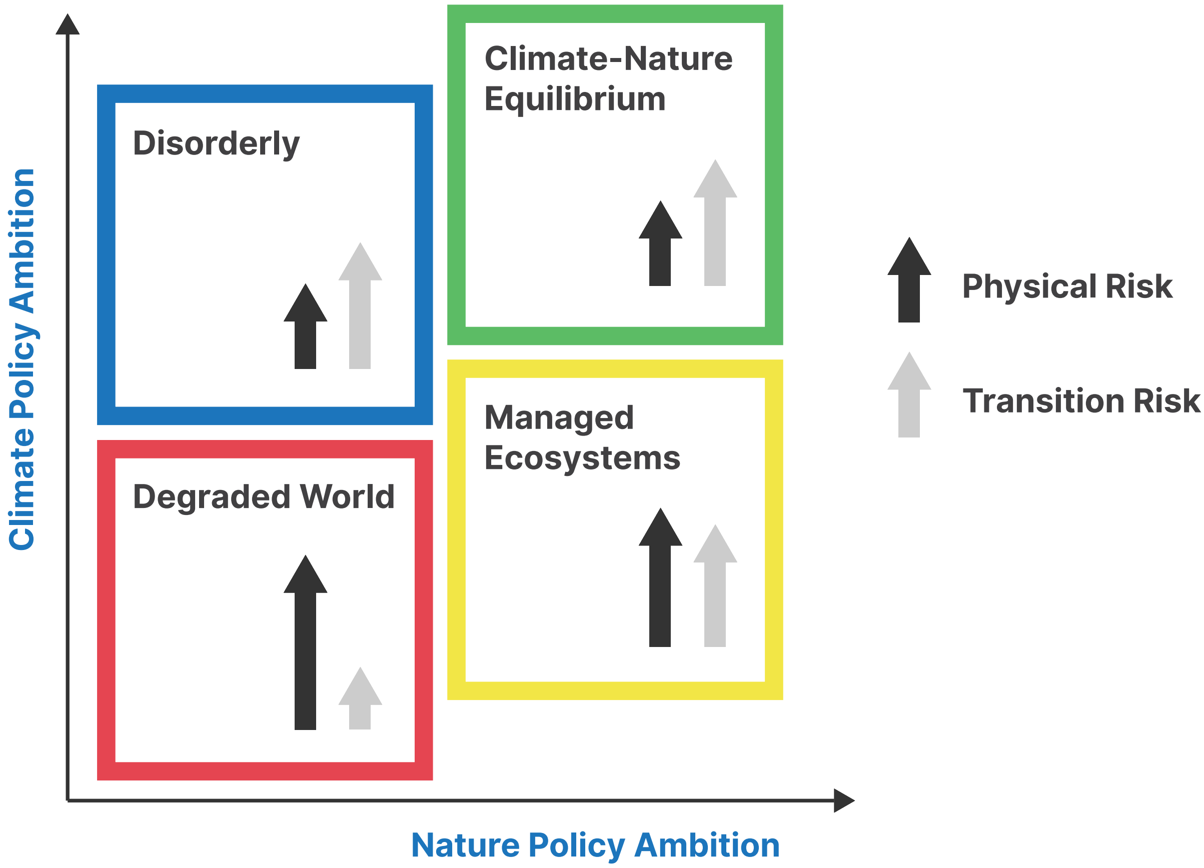

Figure 2. Climate-nature risk scenario matrix: The primary scenarios are spread along narratives with varying ambition and integration of nature and climate protection targets in the land use sector. Each scenario accordingly manifests a certain level of transition and physical risk related to climate change impacts, declining nature contribution to people and related policy and technology trends. While climate protection policies may be deemed adequate for reaching the set targets (as reflected by the choice of optimal GHG emissions pricing path), the scenario framework currently incorporates only three specific targets for nature protection. However, there could be many additional policies needed to achieve wider safeguarding of nature. Consequently, the hypothetical levels of transition risks in the figure could potentially be much higher in the direction of ambitious nature protection goals.

The framework for climate-nature risk scenario comprises four primary narratives, which stem from variations in climate and nature protection ambition. These narratives result in the following set of base scenarios:

1. **Degraded World:** There is a notable absence of effective policies aimed at mitigating climate change and preventing the degradation of natural ecosystems. This deficiency in proactive measures exacerbates the adverse consequences on both climate and the environment. This lack of intervention results in increasingly severe impacts from climate change, exceeding 2°C by the end of the century. Additionally, it leads to a significant loss of critical ecosystem services, including a decline in pollinators and increased soil erosion. From a risk perspective, the situation in this scenario is marked by elevated levels of physical risk, reflecting the threats posed by climate-related events and the deterioration of ecosystems. However, the transition risk, reflecting challenges in moving towards sustainability, remains relatively low in face of lacking necessary transitions to mitigate climate change and protect nature.

2. **Managed Ecosystems:** There is a moderate commitment to climate change mitigation, as outlined in the Paris Agreement and in Nationally Determined Contributions (NDCs). The emphasis is on the protection and restoration of land, aligned with the CBD Global Biodiversity Framework (GBF) to promote holistic nature protection policies. This approach aims to sustain essential ecosystem functions despite the increasing challenges to adapt to climate change. Given the globally insufficient efforts to halt significant global warming a notable level of physical risk remains. Additionally, there is a locally significant transition risk arising from reactive protection and adaptation measures responding to evolving physical hazards. This narrative emphasises the interconnectedness of insufficient climate mitigation, nature protection and the importance of proactive adaptation strategies within managed ecosystems.

3. **Disorderly:** There is a significant increase in transition risk, driven by ambitious yet narrowly targeted climate mitigation policies. The mitigation focus in the land use sector lays on large-scale land-based carbon uptake measures, such as afforestation or large deployment of second-generation bioenergy in energy portfolios. This scenario aligns with the *disorderly NGFS scenario*, which revolves around delayed or divergent policies across countries and sectors. A critical challenge arises, however, from the lack of integration with broader sustainability goals, notably maintaining biosphere integrity, leading to potentially higher physical risk from degraded ecosystem services.

4. **Climate-Nature Equilibrium:** There is a coordinated effort to integrate climate and nature considerations through ambitious and timely policies. These policies include setting net-zero target below a 2°C temperature increase and fostering biosphere integrity in line with the implementation of the GBF. The climate policy ambition assumptions align with the *orderly NGFS scenario*, emphasising the early introduction and gradual strengthening of climate policies. The focus however extends beyond mitigation alone, recognising the crucial role of enhanced ecosystem functioning in adapting to remaining physical risk. Along with the high sustainability ambition, there exist moderate to high transition risks associated with the implementation of these integrated policies. However, the physical risk in this scenario is comparatively low, indicating effective measures to directly address the impacts of climate and nature related hazards.

These scenarios are parameterised according to SSP2 storylines (O'Neill et al., 2017), which represent a steady growth of the current trends in population and income per capita dynamics. The climate-nature risk scenario framework prioritises short- and mid-term objectives (in the year 2030 and 2050), with a focus on policies and measures relevant for climate and nature protection, including those that are already in place or that could be applied.

The existing policies and conservation aspirations are integrated into the climate-nature risk scenarios narratives by simulating transition to the achievements of proposed targets (Table 1). On the climate change mitigation side, this includes the consideration of NDCs, in particular for reduction or stopping of deforestation as well as national goals for reforestation and additional afforestation, which is included in all the scenarios except for the *degraded world* baseline. GHG pricing instruments for land-based CO_2 emissions and the non-CO_2 emissions from agricultural practice (e.g. CH_4 from animal production systems, or N-related emissions from fertiliser application) are included in the ambitious climate protection dimension, with the pricing pathways derived from the *NGFS orderly and disorderly scenarios*. Similarly, second generation bioenergy demand is pulled out from the *NGFS scenarios*, including traditional biomass use in the *NGFS hot house word scenario* which is prescribed in narratives with low climate change mitigation ambition. The number of afforested areas is determined either by NDC national targets or as a response to carbon pricing where carbon premiums are distributed to new stocks of forest.

		Degraded World	Managed Ecosystems	Disorderly	Climate-Nature Equilibrium
Climate Policy	NDCs		Y	Y	Y
	GHG emission pricing			Y	Y
	Afforestation		Y	Y	Y
	Bioenergy	Y	Y	Y	Y
Nature Protection	30by30 land conservation		Y		Y
	No net biodiversity loss after 2030		Y		Y
	Landscape target in line with planetary boundaries		Y		Y

Table 1. Scenario building blocks. Policy outcomes and conservation aspirations as varying blocks for the scenario matrix of climate-nature risk Scenario framework. The intensity of the colour-coding reflects the increasing implementation of policy mechanisms within each scenario.

On the nature conservation side, three main measures aimed at addressing nature-related challenges are considered. Firstly, the 30by30 land conservation interventions aim to expand protected areas to 30% of the global land surface in line with the target set out in the GBF. The enlargement of protected areas (PAs) considers Key Biodiversity Areas (KBAs), pristine habitats in Biodiversity Hotspots (BHs), Ecoregions of High Beta Diversity (EBDs) and Critical Connectivity Areas (CCAs). Secondly, Biodiversity Compensation Schemes are designed to ensure no net loss of biodiversity after 2030 and ensure that any reduction in biodiversity intactness at the biome level is offset by compensation areas. Lastly, the measures include the conservation of at least 20% of semi-natural habitats within managed landscapes to sustain critical ecosystem functions. These conservation measures thereby target different dimensions of biodiversity change across various spatial scales. By integrating these policy outcomes, the scenario narratives provide a coherent assessment of potential future trajectories of climate and nature degradation, enabling stakeholders to develop strategies to address these complex challenges.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

3

METHODOLOGY

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3.1 Modelling of feedbacks between climate, land use and nature contribution to people

Climate and nature protection policy aspiration is modelled in a global land and water use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) (Dietrich et al., 2019). The scenario building blocks in Table 1 are individually modelled in MAgPIE as policies and policy instruments or outcomes, which connect the climate-nature risk narratives with the quantitative outcomes in the scenario analyses. To capture the future impacts of climate change and environmental degradation, our modelling framework expands beyond the MAgPIE global land use model. It includes the dynamic global vegetation, crop and hydrology model LPJmL (Lund-Potsdam-Jena model managed Land, von Bloh et al., 2018) and the Spatial Economic Allocation Landscape Simulator (SEALS, Johnson et al., 2021; Suh et al., 2020) (Figure 3).

LPJmL and MAgPIE are methods with explicit bio-chemo-physical spatial (0.5°x0.5° grid) characteristics and economic premises to properly study past and future dynamics of the land use system. LPJmL provides simulations of crop yields, water availability and terrestrial carbon content based on inputs from global circulation models (GCMs) that project changing climate conditions (temperature, precipitation) under different levels of global warming (Stevanović et al., 2016). MAgPIE builds upon these biophysical simulations of LPJmL, and provides a modelling framework with consistent and linked representations of economic development, regional food and bioenergy demand, as well as spatially explicit patterns of agricultural production, land use change and water withdrawals. The integration of macroeconomic and climate policy feedback in the land use sector is achieved through the coupling between MAgPIE and the REMIND (REgional Model of Investment and Development, Baumstark et al., 2021) economic growth model with a special focus on the energy sector. MAgPIE, LPJmL and REMIND models are developed and maintained at PIK.

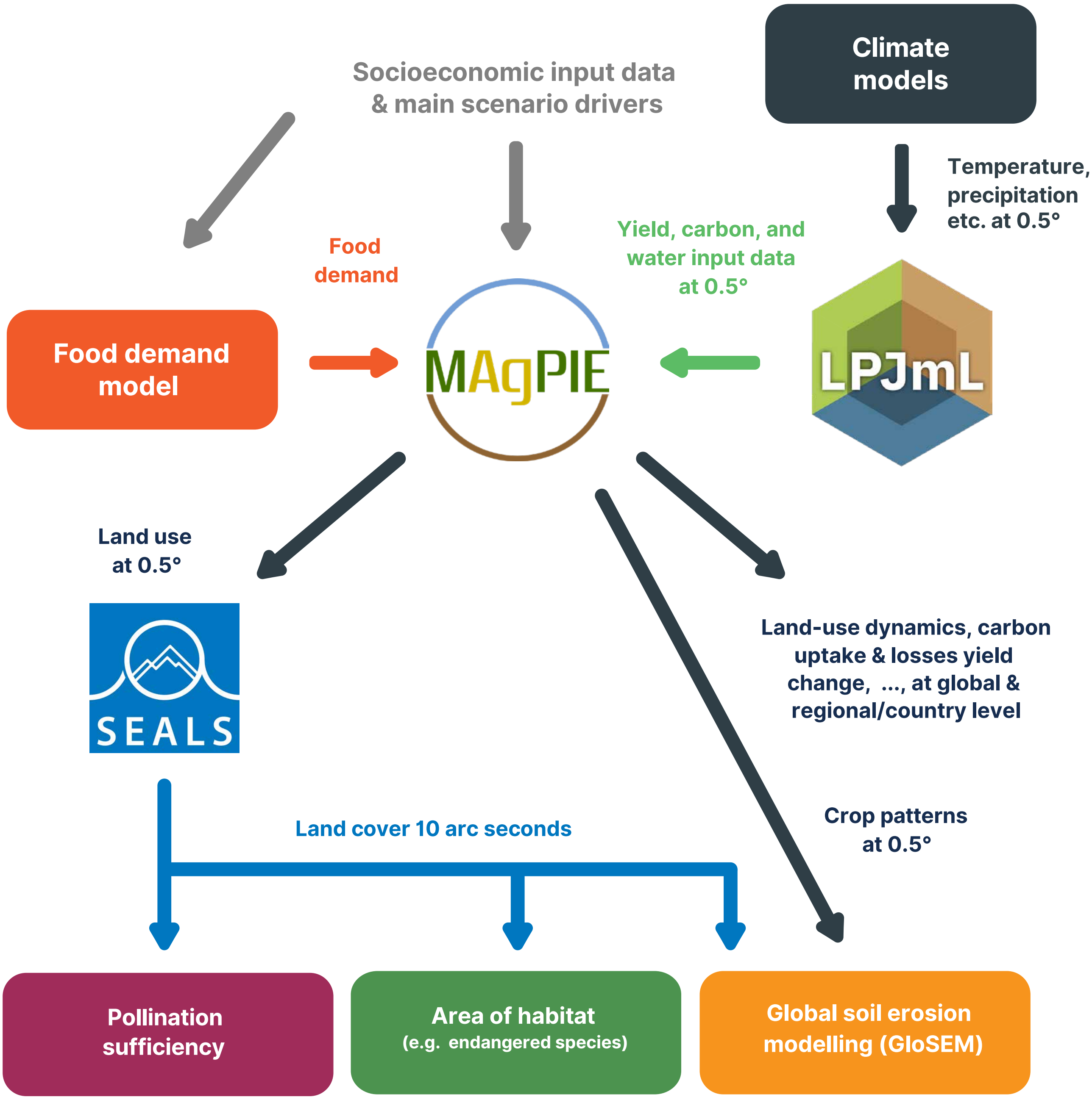

Figure 3. Modelling framework: The climate impacts modelling chain starts with general circulation models GCMs (Climate models) which are driving the simulations of future crop yields, water availability and terrestrial carbon content in the global dynamic vegetation, crop and hydrology model LPJmL. The land use modelling framework MAgPIE is fed by the future biophysical simulations from LPJmL and from socioeconomic future projections of population and GDP (sourced from SSPs) and projections for agricultural demand (food, feed, material). To derive nature's contribution to people indicators, MAgPIE is linked in the post-processing to the SEALS model, which utilises spatially explicit land cover data to allocate projected land cover changes at a resolution of 10 arc seconds (300x300m at the Equator).

As an economic optimisation model of land use, MAgPIE is used to derive economic values of land and water resources used in agricultural production, and to indicate potential risks of natural resource loss and environmental damage (Stevanović et al., 2016). MAgPIE optimises production of agricultural and forestry products, as well as nature-based climate mitigation options, such as carbon sequestration by reforestation/afforestation and bioenergy production (Humpenöder et al., 2014; Kreidenweis et al., 2016), wood storage (Mishra et al., 2022) etc., while exploiting natural resources (land and water) under varying economic and nature conservation constraints. In this analysis framework, different policies, such as economic incentives (e.g., taxes, carbon price, subsidies) or non-economic regulation (e.g. deforestation bans, water quantity limits) are tested with respect to efficacy, possible trade-offs and costs (Stevanović et al., 2017; Humpenöder et al., 2018; Bonsch et al., 2015).

The MAgPIE-LPJmL modelling framework draws on a wide range of spatially variable biophysical and socio-economic information to derive various indicators of biodiversity and climate risks. Recent work has focused on improving MAgPIE's capacity to assess crucial drivers of changes in biodiversity and ecosystem services (Leclère et al., 2020). In most cases, however, these assessments require a higher spatial granularity to capture important drivers of biodiversity and ecosystem service change. MAgPIE has been therefore coupled with the SEALS (Suh et al., 2020; Johnson et al., 2021) model, which allocates coarse-scale MAgPIE projected land use changes on 0.5°x0.5° grid to a spatial resolution (300x300m) that is suitable to estimate impacts of different future scenarios particularly on important regulating ecosystem services, such as pollination supply and soil degradation (von Jeetze et al., 2023).[3]

3.2 Modelling of nature degradation

The unique combination of land use projections from the MAgPIE model and the SEALS downscaling algorithm enables an assessment of fine scale changes in the earth's ecosystems. Within the climate-nature risk scenario framework, we assess the degradation of ecosystem services, and currently derive two nature's contribution to people (NCP) indicators: soil loss by water erosion and landscape pollination sufficiency. These two NCPs were selected based on the availability of global data and the relatively good scientific understanding how they affect agricultural production. Landscape pollination sufficiency is determined by the extent of semi-natural habitat within typical foraging ranges observed in natural pollinator communities. This metric serves as a proxy for both wild pollination supply on cropland and configurational landscape heterogeneity. Configurational landscape heterogeneity also drives several other regulating ecosystem services, including biological pest control, and biodiversity change in cultivated landscapes (Dainese et al., 2019; Estrada-Carmona et al., 2022). Soil loss by water erosion is an important driver of losses in soil-related ecosystem services (IPBES, 2018). Furthermore, in the upcoming stage of the project, we will assess changes in species' area of habitat (AOH).

[3] Additional information about the MAgPIE modeling framework is provided in the Annex Extended Methodological Description and at https://rse.pik-potsdam.de/doc/magpie/4.7.0/. MAgPIE is an open source model: https://github.com/magpiemodel/magpie

To assess wild pollination supply, we use a direct approach based on the presence of pollinator habitat around cropland. Pollinator habitat is defined as all natural or seminatural land cover in agricultural landscapes such as forest, non-forest and grassland (Chaplin-Kramer et al., 2019). Pollination sufficiency is determined by the proportion of pollinator habitat within a 2 km flight radius of each cropland pixel, which is consistent with the typical foraging distance observed in wild pollinator communities. To obtain pollination sufficiency scores we rank all cropland pixels on a scale from 0 to 1, where a value of 1 indicates a proportion of >30% pollinator habitat within a 2km radius of the cropland pixels. Values between 0 and 1 represent proportional areas between 0 and 30%. The threshold of 30% is based on a range of empirical studies that have assessed pollination supply based on the area of (semi-)natural habitat around cropland (Kennedy et al., 2013; Klein et al., 2012; Kremen et al., 2004).

Estimation of soil loss by water erosion is carried out using the Global Soil Erosion Modelling (GloSEM) platform, which uses a global Geographical Information System (GIS) implementation of the Revised Universal Soil Loss Equation (RUSLE) model by Borrelli et al. (2017, 2020). GloSEM provides a simple and robust approach to assessing soil erosion at the field scale, focusing on sheet and drill erosion processes. Like other RUSLE-type models, GloSEM has proven to be suitable for many practical and policy applications. GloSEM includes a driving force (rainfall erosivity), a resistance term (soil erodibility), and fine-scale information on topography and land cover. Global rainfall erosivity maps are derived from the Global Rainfall Erosivity Database (GloREDa, Panagos et al., 2017) using Gaussian process regression with covariates from the WorldClim database (Fick and Hijmans, 2017). Soil erodibility is determined using soil data from the ISRIC SoilGrids database (Hengl et al., 2014) and topographic information is obtained by processing DEM data using a two-dimensional GIS-based approach (Desmet and Govers, 1996).

The land cover and the management factor are determined separately for cropland and non-cropland areas. For cropland, spatial cropping patterns from MAgPIE at the 0.5-degree level are used, with land cover factors assigned to 20 crop functional types based on literature values. An area-weighted average between all crop groups in each 0.5-degree grid cell is calculated and aligned with the fine-scale cropland maps projected by MAgPIE-SEALS. In non-crop areas, land cover factors are estimated by combining literature values for forested and non-forested areas with potential annual vegetation and forest cover maps based on FCOVER data and tree cover data from Hansen et al. (2013) following the methodology detailed in von Jeetze et al. (2023).

3.3 Outputs for transition and physical risk

When assessing the outcomes in the land use sector, our primary emphasis is placed on categorising both physical and transition risks. A transition risk is defined as a potential economic risk which stems from sectoral alignments to a policy regarding climate mitigation and/or nature protection and restoration. In parallel, a physical risk is defined here in terms of physical damages (or gains) to the environment and to other nature's contribution to people (e.g. biodiversity condition). To understand the transition risk related to climate or nature protection measures, we consider the costs of input factors, investment decisions, and the values of agricultural production output (Table 2). On the other hand, the physical risk is reflected in the fine-scale NCP indicators, along with consideration about the status of biodiversity, water, land and terrestrial carbon dynamics. This assessment allows for a comprehensive analysis of the potential challenges and changes in the land use sector, considering both the economic and environmental aspects.

Indicator	Description
Transition risk	
Agricultural Price Index	Laspeyres price index of agricultural commodities with prices weighted based on food (agricultural) baskets in the initial year.
Costs of agricultural production	Overall accounting for the costs required for the total agricultural production of crop, processing and livestock products.
Costs of labour in agriculture	Total costs of labour in production of agricultural outputs.
Investment flows in technology	Total costs of investments in yield-increasing agricultural technological change.
Investment flows in capital	Total costs of capital investments in production of agricultural outputs.
Investment flows in land use	Total costs of investments in land conversion into arable land.
Agricultural GDP	Agricultural value added from production of crop, processing and livestock products.
Household agricultural expenditure	Expenditures in USD05 MER per capita per year for agricultural commodities dedicated for food use, excluding the value-added in the supply chain.

Indicator	Description
Physical risk	
Biodiversity indicators	Biodiversity Intactness Index (BII). The BII accounts for net changes in the abundance of organisms based on the loss of forest and non-forest vegetation cover and age class of natural vegetation, which are expressed relative to a reference land use class (forested or non-forested vegetation) and weighted by a spatially explicit range-rarity layer (unitless). The reference land use (BII = 1) is assumed to have no human land use. For the key conservation landscapes, we considered only cells in biodiversity hotspots (BH) intact forest landscapes (IFL). Area of habitat (AOH). AOH is defined by the habitat available to a species within its geographic range. Changes in AOH are calculated for 6,374 amphibian, 9,124 bird, 5,351 mammal, and 6,877 reptile species based on MAgPIE-SEALS land cover projections.
Water pollution	Polluted water from nitrogen related emissions in surface water.
Land use change	Dynamics in usage of land (cropland, pastures, primary forests, secondary forests, other natural vegetation, urban areas).
Landscape pollination sufficiency	Amount of seminatural habitat within foraging distances typically found in wild pollinator communities around croplands.
Soil erosion	Amount of soil displaced by water erosion and proxy for land degradation (IPBES, 2018).
Carbon sequestration	Land areas under bioenergy crops production or areas under reforestation/afforestation projects.
Environmental flow violation	Water withdrawals exceeding the volume that could be withdrawn when taking minimum environmental flow requirements of aquatic and riverine ecosystems into account, in km^3.

Table 2. Evaluation outputs for transition and physical risk. Set of indicators used for the evaluation of financial impacts from transition and physical risk in the agriculture and land use sector.

3.4 Innovative methodological elements and limitations

The climate-nature risk scenarios framework marks the first instance of an innovative approach, integrating modelling of the agricultural and land use sectors with ecosystem services models within a comprehensive narrative framework. The aim of this approach is to explore integrated efforts for the protection of nature and climate. While previous studies have addressed the economic impact of NCP losses (Johnson et al., 2021) and the costs for an economy associated with the implementation of biodiversity conservation policies (Waldron et al., 2020), along with extensive literature on transition risk and the cost of mitigating climate change (IPCC, 2022a), a unified assessment of both dynamic physical and transition risks tied to actions or inaction for climate and nature protection has been lacking. Building on the original work of von Jeetze et al. 2023, we aim to enhance our understanding of financial risk within an integrated nature and climate-related risk framework in the upcoming stage of the project.

Varied perspectives on biodiversity change are provided by assessing changes in Biodiversity Intactness and in the area of habitat (AOH) of vertebrate species. The Biodiversity Intactness Index (BII) reports biodiversity changes relative to a reference land use class (either native forested or non-forested vegetation). These measurements are further weighted by a spatially explicit range-rarity layer (dimensionless). The reference land use (BII = 1) assumes minimal human land use. Furthermore, we focus on BII changes in Biodiversity Hotspot areas, while the BII for cropland landscapes is computed based on areas containing a minimum of 100 hectares of cropland. It is worth noting that while the BII captures essential aspects of biodiversity in unmanaged ecosystems, there is a recognised need for more sophisticated measures of functional biodiversity across managed and unmanaged systems. In the upcoming stage of the project, changes in the area of habitat (AOH) will be included in the outputs. AOH for vertebrate species are determined by MAgPIE-SEALS land cover projections and associated habitat changes within each species' range. AOH changes provide crucial insights into potential habitat loss and the risk of species extinction. They also serve as useful tools for informing conservation initiatives and have been suggested as an additional indicator for the IUCN Red List (Brooks et al., 2019).

The climate-nature risk scenario framework aligns consistently with the NGFS transition risk scenarios framework and to a great extent with the NGFS nature scenario development recommendations. The connection between the former two frameworks is established through the use of quantitative instruments for transitioning to climate mitigation targets in NGFS transition risk scenarios. They include a tax on GHG emissions and demand for bioenergy, which are both specifically applied in the land use sector in the climate-nature risk scenario framework (c.f. Table S1). This connection offers unique and parallel insights into how a nature-focused approach and land-based nature-related risks can be integrated, aligning them with the transition risks modelled in climate mitigation scenarios for the wider economy. The work to develop the climate-nature scenario framework presented in this report started before the publication of the NGFS recommendations toward the development of scenarios for assessing nature-related economic and financial risks (NGFS, 2023b). Nevertheless, we found that the framework is to a considerable extent aligned with its recommended options for central banks and supervisors aiming to assess these risks (NGFS, 2023b, p. 86). Table 3 showcases the broad alignment of the project and the framework with these options. A more detailed exploration of this alignment can be found in the annex in Table S2.

Options for central banks recommended by the NGFS	Aligned within the scope of the project
Short term Program: Building on available dynamic scenario modeling frameworks with longer-term horizons	
Using a carefully chosen nature-economy modelling framework while acknowledging its assumptions and limitations	[green]
Designing ad hoc shocks in multiple sectors	[blue]
Using assumptions of various SSPs for calibration (not SSP2 only) and co-develop or build on new existing frameworks to go beyond SSP	[green]
Conducting sensitivity analyses, in particular on elasticities of substitution	[yellow]
Better transparency of underlying assumptions and communication of implications on results	[yellow]
Long term Program: Improvement of dynamic scenarios by improving the interlinkages of nature-economy models	
Representing more numerous ecosystem services and economic dependencies to those services within the nature	[green] [yellow] [blue]
Representing more policies, technological options, and socioeconomic developments	[green] [blue]
Representing some missing economic transmission channels, such as food security and productivity losses	[green] [blue]
Better informing the elasticities of substitution, considering making them dynamic	[red]
Developing nature-economy models with alternative macroeconomic modelling assumptions	[red]

[green] Addressed in the current stage of the project and presented in this report

[blue] Outside of the scope of the project but aligned with the modelling framework and potential for future research

[yellow] Within the scope of the project and currently under development to be presented in the forthcoming report final paper

[red] Out of scope of the project

Table 3. Alignment of project scope and nature-risk scenario development framework with NGFS recommended options for central banks and supervisors to assess nature-related economic and financial risks (NGFS, 2023b, p. 86).

The modelling approach has several limitations in capturing the severity of climate change impacts and NCP degradation. While future crop yields consider changing weather conditions, the extreme events such as floods, droughts, pests and diseases, and crop failures are not considered as the scientific methods are nascent for accurately modelling frequencies of such events at a local level. On the other hand, the fertilisation effect from atmospheric CO_2 on enhancing the crop yield is considered as a positive impact of higher CO_2 concentrations. Climate impacts and ecosystem service losses are examined in isolation, without accounting for potential feedback mechanisms within functioning ecosystems, which potentially underestimates risks.

Regarding NCP supply estimation, limitations include the reliance on current land use patterns for land cover allocation, potentially representing a lower bound. Improved land allocation for NCP supply could enhance estimates through targeted ecosystem management and integrated spatial planning. Semi-natural habitats are characterised in a simplified manner, impacting carbon storage estimates. Edge effects on carbon stocks are not considered, although evidence suggests comparable storage with forest vegetation. Second-generation bioenergy crops are only considered in soil loss estimates, neglecting impacts on landscape structure and pollination due to model limitations. Evidence supports potential co-benefits in farmed landscapes.

The model currently cannot account for feedbacks related to changes in NCP supply, such as mismatches between pollination demand and supply or soil loss. Incorporating these feedbacks in dynamic decision-making modelling remains challenging but offers opportunities for future research.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

4

PRELIMINARY RESULTS

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The initial results modelled for a 2020 – 2050 time period indicate diverging biodiversity responses based on varying climate and nature policy ambition, especially with regard to biodiversity in managed landscapes associated with critical ecosystem functions. This emphasises the need to extend biodiversity conservation beyond exclusive reliance on climate mitigation policies (Figure 4). Furthermore, the degradation of nature in absence of climate and nature protection policies (*degraded world scenario*) exacerbates the decline in biodiversity both in managed landscapes and biodiversity hotspots. Overall, the degree of impact on biodiversity varies across different dimensions of biodiversity change across the *disorderly, managed ecosystems and climate-nature equilibrium scenarios*, but consistently declines across all dimensions in the *degraded world scenario*. While nature protection policies in *managed ecosystems and climate-nature equilibrium scenarios* effectively mitigate biodiversity loss, solely implementing climate policy in the *disorderly scenario* does not consistently give positive outcomes for biodiversity sustenance.

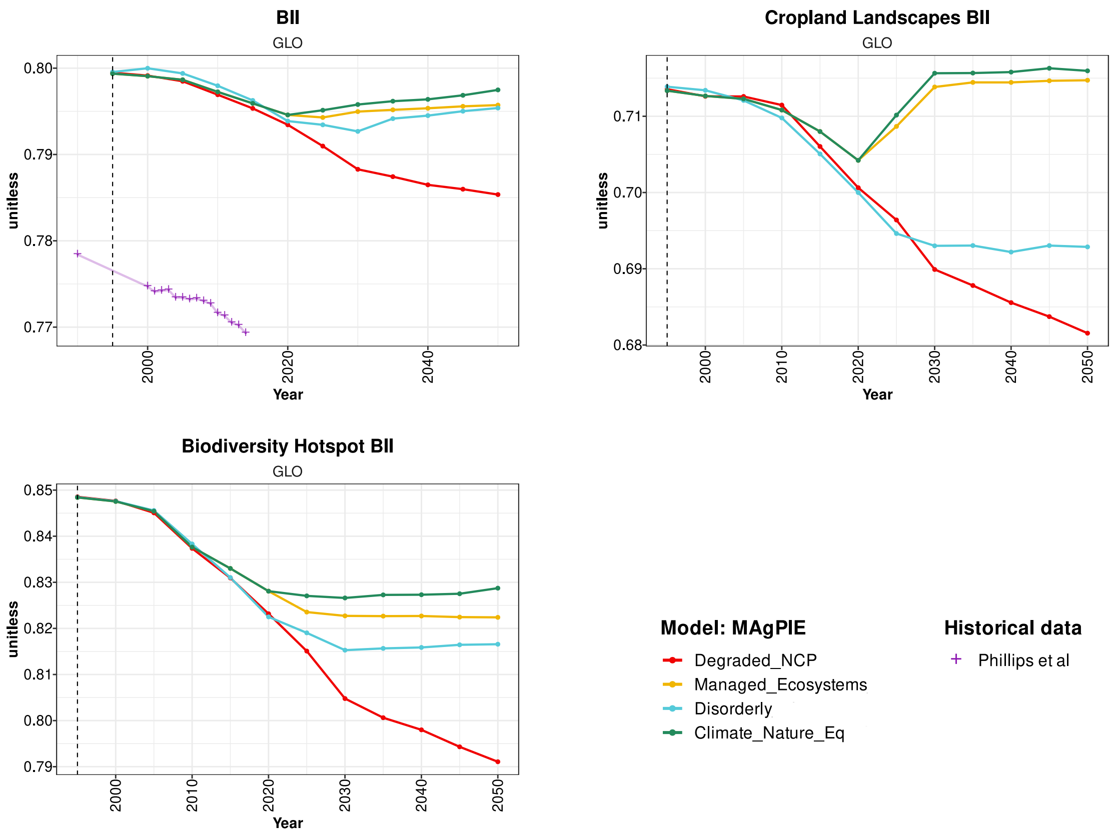

Figure 4. Biodiversity indicators in the climate-nature risk scenario framework. The Biodiversity Intactness Index (BII) quantifies net changes in species abundance in response to land use change. Changes are measured relative to a reference land use class (either native forested or non-forested vegetation) and are weighted by a spatially explicit range-rarity layer (dimensionless). The reference land use (BII = 1) assumes low human land use. We consider BII changes in Biodiversity Hotspot areas, while the cropland landscapes BII is calculated based on cells containing a minimum of 100 hectares of cropland.

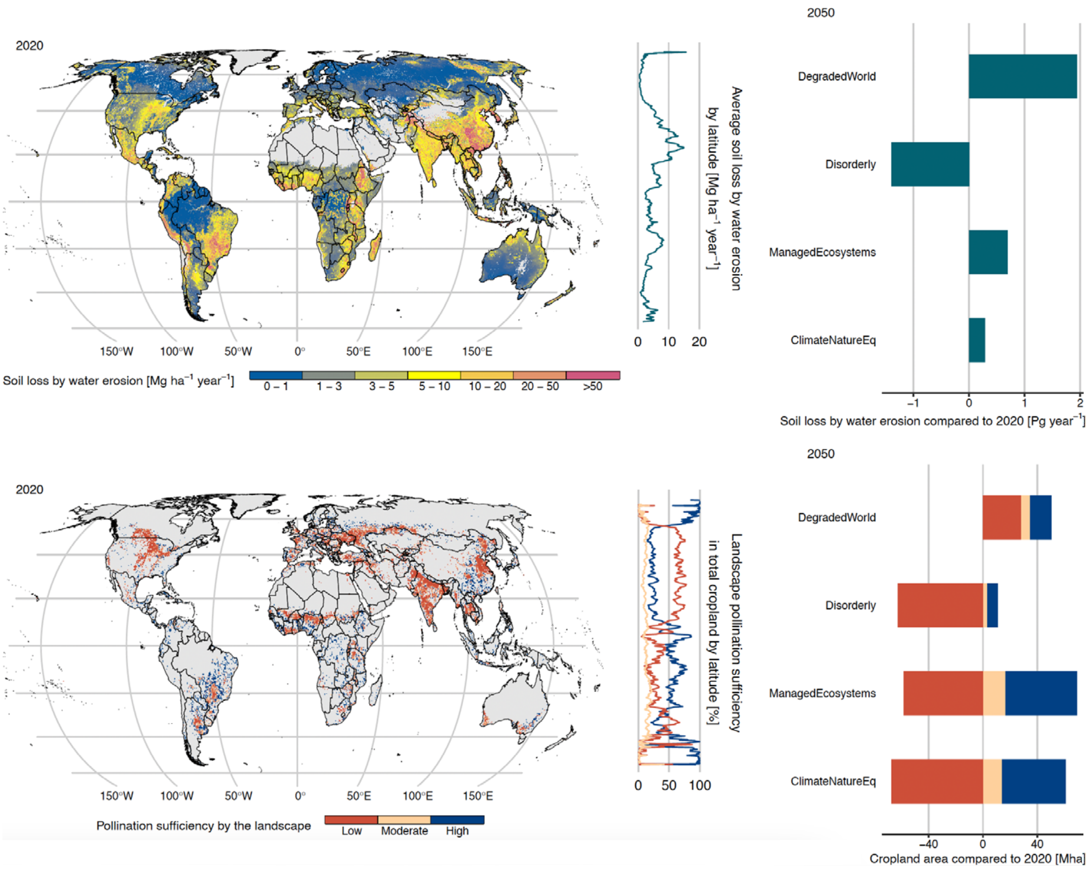

Figure 5. Landscape pollination sufficiency and soil loss by water erosion in 2020 and projected changes by 2050 based on MAgPIE-SEALS. Global maps of pollination sufficiency and soil loss by water erosion for 2020 were directly derived from land cover maps from the European Space Agency's Climate Change Initiative (ESA-CCI). Projected changes (panels B and D) are based on a fine-scale allocation of land use changes in each scenario.

For the NCP indicators, the integration of climate and nature protection measures has different strengths depending on the measured NCP indicator. Beyond the apparent spatial variations that play a significant role in different locations, aggregated results indicate important synergies (Figure 5). Notably, conservation interventions within managed landscapes show promise in significantly restoring their pollination supply. However, we also find that these interventions would also lead to cropland relocation to areas with a higher susceptibility to water erosion. This underscores the need for a nuanced understanding of the multifaceted impact of climate and nature protection policies on different aspects of environmental change, recognising both successes and areas that may require alternative or additional strategies for effective restoration.

Transition risk results are excluded from this report, given their preliminary stage and the likelihood of changes in subsequent stages, which will include additional research and an enhanced methodology. This reflects the ongoing nature of the research and the recognition of potential refinement in the findings. This report aims to provide a transparent overview of the work by presenting the established methodological framework and research aspirations, acknowledging the importance of thorough assessment and the evolving nature of physical and transition risk analysis.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

5

IMPLICATIONS FOR FINANCIAL INSTITUTIONS AND INVESTMENTS

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5.1 Preventing risk underestimation for financial institutions

Presently, within the financial sector, the challenges and financial ramifications associated with climate change and nature loss tend to be addressed separately. A comprehensive assessment that considers both climate and nature is imperative to prevent the underestimation of risks faced by financial institutions (CISL, 2022). In this respect it is crucial to recognise that climate change is just one of the contributors to nature and biodiversity loss and the subsequent decline in ecosystem services (TNFD, 2023b).

Restricting our focus solely to climate-related risks leads to overlooking other crucial aspects. For example, neglecting to extend our view beyond climate-related risks may result in financial portfolios carrying unmanaged nature-related risks (TNFD, 2023a). A myopic emphasis on climate risks alone poses the danger of neglecting sectors that are profoundly affected by the broader issue of nature loss. Therefore, adopting a holistic approach that considers both climate and nature is essential for accurate risk assessment, ensuring that financial portfolios are resilient to the intricate challenges posed by the interplay of climate change and nature degradation. Failure to do so may lead to necessary interventions in certain sectors not being prioritised despite their significant exposure to the ongoing loss of nature.

Exclusively focusing on climate mitigation and adaptation efforts may inadvertently yield unintended consequences for biodiversity and ecosystem health. When decisions regarding investment and lending are solely driven by considerations of climate risks, there is a risk of unintentionally causing harm to nature, as certain activities undertaken for climate mitigation might have adverse effects. It is paramount to recognise and understand these unintended consequences for a comprehensive assessment of risks, uncertainties, and opportunities. This awareness is not only critical for making well-informed decisions but also for effective reputation management and to ensure successful transition.

The forthcoming impact on our economy and financial system is anticipated to be most profound when considering the intertwined dynamics of climate change and the loss of nature (Ceglar et al., 2023). Relying solely on univariate statistics in assessments may significantly underestimate risk, particularly when the impacts hinge on multiple interdependent variables (Zscheischler and Seneviratne, 2017). To accurately gauge these risks, assessments must transcend isolated perspectives and encompass the intricate relationship between climate and nature variables and, ultimately, other variables that are connected such as finance, economic, social and trade (NGFS, 2023a). The interplay of physical risks stemming from climate change and nature loss can result in non-linear risk amplification. For instance, an elevated risk of drought may exacerbate when coupled with the diminished capacity of ecosystems to provide freshwater due to unsustainable land management practices like deforestation (Ceglar et al., 2023). Similarly, land degradation may intensify damages by aligning with extreme rainfall events, while simultaneously reducing the ability of forest ecosystems to shield against flooding. Recognising and comprehensively assessing these complex interactions is imperative for a nuanced understanding of the potential economic and financial implications.

Companies contributing to higher GHG emissions may additionally impact nature and biodiversity by exerting other pressures such as land use changes, pollution and overexploitation of natural resources, whether through their direct activities or within their supply chains. The potential impacts on companies extend beyond climate-related policies; they are also influenced by measures aimed at halting biodiversity loss, such as restrictions on nitrogen use and pesticides. As euro area companies exert substantial pressure on biodiversity and ecosystems crucial to their production processes (Ceglar et al., 2023), an integrated transition risk assessment becomes even more urgent.

Given all the considerations above, the integration of climate-nature assessment is relevant for effective transition planning and the prudent operation of central banks and financial regulators, at both micro-prudential and macro-prudential levels, as well as in the execution of monetary policy. An integrated assessment holds the potential to enhance the evaluation of diverse prudential risk categories overseen by central banks, encompassing business model, credit, market, underwriting, operational, and liquidity risks (NGFS, 2023a). As shown by our preliminary results (Figure 4, Figure 5), neglecting the protection of nature, or solely relying on climate policy, could compromise ecosystem services, leading to biodiversity losses, land degradation through soil erosion and a decline in pollinators. This, as an illustration, could result in diminished agricultural productivity, impacting farmers' income, the collateral value of agricultural land, and the ability of farmers to fulfil their debt obligations, leading to credit risk for banks. The degradation of ecosystems can impair companies' access to essential natural resources required for their production processes. This, in turn, exposes companies to market risk, as a decline in their market value may materialise owing to insufficient availability of natural resources for production processes.

5.2 Avoiding missed investment opportunities

Adopting an integrated climate-nature approach in financial decision-making not only aids companies and financial institutions with risk management but can also play a significant role in identifying potential business and investment opportunities. Using joint climate-nature scenarios could identify a different set of opportunities than when utilizing climate or nature scenarios separately. Combining the TCFD and the TNFD framework, climate and nature-related opportunities for entities in the real economy are activities that aim to mitigate negative impacts on nature and climate or have the goal of generating positive impacts.. Such opportunities can arise when organisations avoid, reduce, mitigate, adapt to or manage climate and nature-related risks. For instance, in agriculture, precision farming utilises technology to minimise the use of harmful chemicals. Opportunities could also aim to create positive impacts on businesses, climate and nature through the strategic transformation of business models, products, services, markets and investments in the climate and nature transition. An example in food and agriculture is the development of products that cater to the rising demand for plant-based foods (Finance for Biodiversity Initiative & Vivid Economics, 2021; TCFD, 2017, TNFD, 2023a).

Organisations that actively work to generate positive outcomes for nature, or to mitigate negative risks and impacts, enhance their business resilience to various climate and nature-related physical, transition and systemic risks. There might be opportunities that arise from capitalising on the climate and/or nature policy and market transition trends. These might include supplying goods and services that will be in higher demand due to policy shifts, changing consumer preferences, and emerging technologies. Some climate opportunities, like nature-based solutions, offer dual benefits by supporting climate adaptation and reinforcing natural ecosystems resulting in compounding positive impacts. Others, however, have the potential to inadvertently damage natural environments if not implemented with sufficient safeguards (Finance for Biodiversity Initiative & Vivid Economics, 2021). Therefore, an integrated climate-nature assessment can help companies to identify synergies and cost efficiencies towards transition to an economy that is consistent with net-zero and positive impacts on nature (CISL, 2022).

The actual materialisation of business opportunities may vary depending on whether the climate or nature transition are considered individually or together. Certain climate mitigation transition opportunities that have unintended negative consequences for nature, such as bioenergy production, may actually see limited market growth if a joint nature-climate transition materialises. Conversely, the nature transition alone could unlock substantial new business opportunities that would not' exist if only climate policy scenarios were taken into account (Food and Land use coalition, 2019). Opportunities that are beneficial to both climate and nature, like nature-based solutions, are likely to see even greater market expansion than when each transition scenario is considered separately. That is why an integrated approach to scenarios and transition planning is of key relevance for identifying potential future market opportunity developments in the real economy.

Investing opportunities could arise for financial institutions when they financially support the real economy to realise these opportunities, such as lending opportunities for banks, underwriting opportunities for insurers and investment opportunities for asset managers. There is a growing body of evidence indicating that financial institutions that integrate Environmental, Social, and Governance (ESG) factors into their decision-making generate significant value in both the short and long term (Alessandrini and Jondeau, 2020; Cornell & Damodaran, 2020; McKinsey, 2020). Conversely, investees with practices harmful to climate and nature may face higher equity and debt costs due to increased exposure, potentially increasing their credit risks and diminishing investment returns if these are not priced in accurately. Financial institutions that consider climate and nature in an integrated manner in their lending and investment strategies can achieve more accurate asset and risk valuation, preventing the materialisation of valuation risks and credit risks for banks. Therefore, this approach is an important element for faster and more efficient investments in environmentally sustainable initiatives which minimise future nature- and climate-related physical impacts.

Therefore, integrated scenarios can be an invaluable tool for financial institutions, as they can provide an aid for their strategic planning for various possible futures and making informed decisions around investments and capital allocation. The use of scenarios is a key tool which is already used in climate investment strategies and transition plans as they are a mechanism to deal with the uncertainties linked to the climate crisis. They can be used in an integrated way to explore the possible consequences of nature loss and climate change, the ways in which governments, markets and society might respond, and the implications of these uncertainties for business strategy and financial planning (TNFD, 2023b). An integrated approach to scenario analysis can help financial institutions navigate uncertainty across both crises. By selecting assumptions about climate and nature that are internally consistent, investment strategies can be developed and refined through iterative stress testing over time. Using integrated scenarios to identify investment opportunities, financial institutions can craft strategic responses to potential market shifts, identify priority areas with integrated impacts and test the resilience of investment strategies against various possible future pathways. This can help institutions to adapt or develop new strategies that are more robust under a variety of future states of the world. Scenarios also provide justifications for investments in risk mitigation by demonstrating potential impacts on portfolios.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

6

TOWARDS QUANTITATIVE RISK ASSESSMENT FRAMEWORK FOR CENTRAL BANKS

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Following this report, the project will further investigate how nature-related risks are spatially manifested and spread, taking into account potential decision-making processes that might impact the outcomes. This assessment will be presented in our forthcoming report which will focus on the EU and another given region highly exposed to physical risk, for which the scenario narratives will be further enhanced. It is important to note that the impact of losing ecosystem services can vary based on socio-political actions, especially those related to trade and cross-border measures, and particularly along trade routes to and from countries most vulnerable to physical risk. Additionally, the project will explore the significance of influence of financial policies on global land use, potentially negatively affecting NCPs. Furthermore, in the next phase, the project will specifically assess the extent of areas designated as species habitats.

The forthcoming report will further incorporate results related to transition risk after consolidating the narrative framework and modelling of scenarios. These will be tailored to facilitate the integration with financial risk assessments. It will also present potential investment portfolios emerging from the integration of nature and climate protection measures within the land use sector. Both approaches demonstrating the practical application of the scenario development framework.

There is a need for further research to better consider the feedback of degraded NCPs on crop yields. Outside of the scope of this project, PIK is engaged in ongoing efforts to develop the methodology to address this gap. Uncertainties persist regarding the yield impact resulting from NCP degradation. For example, it is unclear whether approaches to assess soil degradation impacts are universally applicable across all regions. The challenges related to degradation may be more pronounced in developing countries, where adapting to high soil loss could pose greater difficulties for farmers. Moreover, this analysis only considered a subset of ecosystem services. Future work will focus on a more comprehensive approach to assessing the economic impacts of ecosystem services degradation. These uncertainties highlight once again the need for further research to develop more extensive and region-specific methodologies particularly in the context of varying regional and agricultural conditions.

Furthermore, the underestimation of physical risk due to the exclusion of potential disasters from earth systems tipping points is potentially a significant concern. Integrated assessment models typically overlook tipping elements and cascading effects in their modelling, highlighting the necessity for a systematic development to better integrate and rationalise these risks (Franzke et al. 2022). To address this to a certain extent, the climate-nature scenario framework could be enhanced to incorporate some tipping elements in the narratives, such as the potential dieback of forests. However, it is important to note that these inclusions would not provide absolute certainty regarding the timing of such events and would rather mostly serve as a narrative for testing high-risk events. This underscores the general need for further research in the field to gain a more comprehensive understanding of the potential impacts of tipping elements on the climate and nature system, as well as their implications for human activities and land use.

Integrating climate and nature poses challenges in capturing the entire spectrum of dynamics and processes from human impacts to biodiversity, ecosystem functioning, and NCPs, all the way to sustainable wellbeing. This complexity makes it difficult to capture the complete impact cycle in the models. The integration therefore may result in limitations where not all NCP channels are accounted for, crucial land use details are omitted, or connections to the broader economy are absent. In future research, PIK aims to bridge studies that cover macro-economic aspects with projects that excel in biophysical and economic land modelling. Due to the current and anticipated lack of a comprehensive understanding of the full cycle, assessments based on existing and future literature become essential. These exercises will serve to connect disparate blocks of knowledge, enabling the provision of recommendations grounded in robust scientific insights.

Our initial work presents a pivotal initial step towards the future development of a more complete quantitative risk assessment framework. This initial research outlines the imperative to look at nature and climate as the two sides of the same coin. We show preliminary results of an integrated climate-nature scenario development, illustrating the relevance for a variety of biophysical indicators. During the remaining scope of the project, we plan to produce a more comprehensive presentation of physical and transition risk indicators for the land use sector and delve into the implications for financial stability; provide recommendations to navigate the risk assessment and investment opportunities in the face of inherent uncertainties; and recommendations for the research in the field of integrated scenario development. These sectoral results will pave the way for future research to developing an economy-wide quantitative financial risk frameworks for central banks, such as the one developed for the climate stress test (Alogoskoufis et al., 2021).

Our project will provide one of many building blocks required for central banks and financial supervisors to deepen their understanding of climate and nature-related risks and address them accordingly. Importantly, the project will provide an increased understanding of the interlinkages between different policies and outcomes, and changes in related financial risks. Absolute risk quantification from our analysis will likely lead to an underestimation of the real risk, given that the assessment is only partial, i.e. covering the agricultural sector and limited number of ecosystem services. In the forthcoming report, we will outline the research agenda to progress in the biophysical, micro- and macro-economic modelling on nature degradation. Importantly, in line with the NGFS recommendations (NGFS, 2023a,b), it is essential to recognise that central banks and supervisors should develop heuristics that allow them to benefit from existing datasets and knowledge to act now, notwithstanding remaining uncertainties and modelling challenges that will continue to be addressed in the future.

References

Alessandrini, F. and Jondeau, E. (2020). ESG investing: From sin stocks to smart beta. The Journal of Portfolio Management, 46(3), pp.75-94. URL: https://jpm.pm-research.com/content/46/3/75.abstract

Alogoskoufis, S., Dunz, N., Emambakhsh, T., Hennig, T., Kaijser, M., Kouratzoglou, C., Muñoz, M.A., Parisi, L. and Salleo, C. (2021), "ECB economy-wide climate stress test", Occasional Paper Series, No 281, ECB, Frankfurt am Main, September.

Baumstark, L., et al. (2021). REMIND2.1: Transformation and Innovation Dynamics of the Energy-Economic System within Climate and Sustainability Limits. Geoscientific Model Development, 14, 10.

Boldrini, S., Ceglar, A., Lelli, C., Parisi, L., Heemskerk, I. (2023) Living in a world of disappearing nature: physical risk and the implications for financial stability. ECB Occasional paper series, No 333.

Bonsch, M. et al. (2015). Environmental Flow Provision: Implications for Agricultural Water and Land-Use at the Global Scale. Global Environmental Change 2015, 30, 113–132.

Borrelli, P. et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications, 8(1), Article 1.

Borrelli, P., et al. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). Proceedings of the National Academy of Sciences.

Brooks, T. M. et al. (2019). Measuring Terrestrial Area of Habitat (AOH) and Its Utility for the IUCN Red List. Trends in Ecology & Evolution, 34(11), 977–986.

Ceglar, A., Boldrini, S., Lelli, C., Parisi, L., Heemskerk, I. (2023) The impact of euro area economy and banks on biodiversity. ECB Occasional paper series, No 335.

Chaplin-Kramer, R. et al. (2019). Global modeling of nature's contributions to people. Science, 366(6462), 255–258.

CISL, (2022). "Integrating climate and nature: The rationale for financial institutions", University of Cambridge.

Cornell, B. and Damodaran, A. (2020). Valuing ESG: Doing good or sounding good?. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3557432

Dainese, M., et al. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. Science Advances, 5(10), eaax0121.

Desmet, P. J. J., Govers, G. (1996). A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. Journal of Soil and Water Conservation, 51(5), 427–433.

Dietrich J.P., et al. (2019) MAgPIE 4 – a modular open-source framework for modeling global land systems. Geoscientific Model Development, 12, 1299–1317.

ESRB/ECB (2023). Towards macroprudential frameworks for managing climate risk. December 2023. doi:10.2849/846786

Estrada-Carmona, N., Sánchez, A. C., Remans, R., Jones, S. K. (2022). Complex agricultural landscapes host more biodiversity than simple ones: A global meta-analysis. Proceedings of the National Academy of Sciences, 119(38), e2203385119.

Fick, S. E., Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37(12), 4302–4315.

Finance for Biodiversity Initiative, & Vivid Economics. (2021). The ClimateNature Nexus Implications for the Financial Sector.

The Food and Land Use Coalition. (2019). Growing Better: Ten Critical Transitions to Transform Food and Land Use. https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport-SummaryReport.pdf

Franzke, C.L.E. et al. (2022). Environmental Research Letters, 17, 015004

Hansen, M. C. et al. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. Science, 342, 850-53.

Hengl, T. et al. (2014). SoilGrids1km—Global Soil Information Based on Automated Mapping. PLOS ONE, 9(8), e105992.

Humpenöder, F. et al. (2014). Investigating Afforestation and Bioenergy CCS as Climate Change Mitigation Strategies. Environmental Research Letters, 9 (6), 064029.

Humpenöder, F. et al. (2018). Large-Scale Bioenergy Production: How to Resolve Sustainability Trade-Offs? Environmental Research Letters, 13 (2), 024011

Kreidenweis, U. et al. (2016). Afforestation to Mitigate Climate Change: Impacts on Food Prices under Consideration of Albedo Effects. Environmental Research Letters, 2016, 11 (8), 085001.

IPCC, (2022a). Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC. (2022b). Chapter 3: Impacts of 1.5°C of Global Warming on Natural and Human Systems. In Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (1. Aufl.). Cambridge University Press. https://doi.org/10.1017/9781009157940

IPBES (2018). The IPBES assessment report on land degradation and restoration. Montanarella, L., Scholes, R., and Brainich, A. (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 744 pages.

IPBES (2019). Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Brondízio, E. S., Settele, J., Díaz, S., Ngo, H. T. (eds). IPBES secretariat, Bonn, Germany, ISBN: 978-3-947851-20-1

Johnson, J. A., et al., (2021). The Economic Case for Nature: A Global Earth-Economy Model to Assess Development Policy Pathways; World Bank: Washington, DC, 2021. https://openknowledge.worldbank.org/handle/10986/35882 .

Jones, N. (2023), When will global warming actually hit the landmark 1.5 ºC limit? Nature 618, 20

Kennedy, C. M. et al. (2013). A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. Ecology Letters, 16(5), 584–599.

Klein, A.-M., Brittain, C., Hendrix, S. D., Thorp, R., Williams, N., Kremen, C. (2012). Wild pollination services to California almond rely on semi-natural habitat. Journal of Applied Ecology, 49(3), 723–732.

Kremen, C., Williams, N. M., Bugg, R. L., Fay, J. P., Thorp, R. W. (2004). The area requirements of an ecosystem service: Crop pollination by native bee communities in California. Ecology Letters, 7(11), 1109–1119.

Leclère, D. et al. (2020). Bending the Curve of Terrestrial Biodiversity Needs an Integrated Strategy. Nature 2020, 585 (7826), 551–556.

McKinsey & Company. (2020). The ESG premium: New perspectives on value and performance. URL: https://www.mckinsey.com/business-functions/sustainability/our-insights/the-esg-premium-new-perspectives-on-value-and-performance

Mishra, A. et al., (2022). A. Land Use Change and Carbon Emissions of a Transformation to Timber Cities. Nature Communications, 13 (1), 4889.

NatureFinance (2023). Time to Plan for a Future Beyond 1.5 Degrees. https://www.naturefinance.net/resources-tools/future-beyond-1-5-degrees/

Network for Greening the Financial System. (2023a). Nature-Related Financial Risks: a Conceptual Framework to guide Action by Central Banks and Supervisors. September 2023

Network for Greening the Financial System. (2023b). Recommendations toward the development of scenarios for assessing nature-related economic and financial risks. December 2023

OECD (2023), "A supervisory framework for assessing nature-related financial risks: Identifying and navigating biodiversity risks", OECD Business and Finance Policy Papers, No. 33, OECD Publishing, Paris.

O'Neill, B.C. et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, 42, 169-180.

Panagos, P. et al. (2017). Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Scientific Reports, 7(1), Article 1.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B. L., Dietrich, J. P., Doelmann, J. C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., … Vuuren, D. P. van. (2017). Land-use futures in the shared socio-economic pathways. Global Environmental Change, 42, 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Prodani, J., et al. (2023). The economic and financial stability repercussions of nature degradation for the Netherlands: Exploring scenarios with transition shocks. A first exploration. Occasional Studies, 21-2, De Nederlandsche Bank.

Ranger, N. et al. (2023). 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.

Richardson, K. et al. (2023), "Earth beyond six of nine planetary boundaries", Science Advances, Vol. 9, No 37.

Stevanović, M., et al. (2016). The impact of high-end climate change on agricultural welfare. Science Advances 2:e1501452.

Stevanović, M. et al. (2017). Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. Environmental Science and Technology, 51 (1), 365–374.

Suh, S. et al. (2020). Yield Gap Is Crucial to Avoid Potential Surge in Global Carbon Emissions. Global Environmental Change 2020, 63, 102100.

Svartzman, R., Espagne, E., Gauthey, J., Hadji-Lazaro, P., Salin, M., Allen, T., Berger, J., Calas, J., Godin, A. and Vallier, A. (2021), "A 'Silent Spring' for the Financial System? Exploring Biodiversity-Related Financial Risks in France", Working Paper Series, No 826, Banque de France, August.

Taskforce on Nature-related Financial Disclosures. (2023a) Recommendations of the Taskforce on Nature-related Financial Disclosures.

Taskforce on Nature-related Financial Disclosures. (2023b) Discussion paper on Conducting advanced scenario analysis.

van Toor, J., Piljic, D., Schellekens, G., van Oorschot, M. and Kok, M. (2020), "Indebted to nature: Exploring biodiversity risks for the Dutch financial sector".

von Bloh, W., Schaphoff, S., Müller, C., Rolinski, S., Waha, K., Zaehle, S. (2018). Implementing the Nitrogen Cycle into the Dynamic Global Vegetation, Hydrology, and Crop Growth Model LPJmL (Version 5.0). Geoscientific Model Development 2018, 11 (7), 2789–2812.

von Jeetze, P.J. et al. (2023). Projected landscape-scale repercussions of global action for climate and biodiversity protection. Nature Communications, 14, 2515.

Waldron et al. (2020). Protecting 30% of the planet for nature: costs, benefits and economic implications. https://www.conservation.cam.ac.uk/files/waldron_report_30_by_30_publish.pdf

World Bank and Bank Negara Malaysia (2022), "An Exploration of Nature-Related Financial Risks in Malaysia", March.

World Economic Forum (2020), "Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy", June.

Zscheischler, J. and Seneviratne, S. (2017), "Dependence of drivers affects risks associated with compound events", Science Advances, Vol. 3, No 6.

Annex

Alignment with NGFS Climate Scenarios and NGFS Recommendations on Nature Scenarios Development

This annex presents the approach used to map the project's climate-nature risk scenarios to the climate scenarios set out by the NGFS. The link between these two frameworks is established through the quantitative instruments used for transitioning to climate mitigation targets and specifically applied to the land use sector. Two such instruments are taken from the NGFS transition risk scenarios: a computed tax on GHG emissions which is applied to relevant emissions in the agricultural and land use sectors (including the carbon premium from afforestation projects) and demand for second-generation bioenergy from the energy sector which is supplied from primary energy carrier crops in the land use sector.

Climate-Nature Risk Scenarios	NGFS Transition Risk Scenarios
Degraded World	Current Policies
Managed Ecosystems	NDCs
Disorderly	Disorderly
Climate-Nature Equilibrium	Orderly

Table S1. Mapping between climate-nature risk and NGFS transition risks scenarios.

The work to develop the climate-nature scenario development framework presented in this project started before the publication of the NGFS recommendations towards the development of scenarios for assessing nature-related economic and financial risks (NGFS, 2023b). Nevertheless, we found that the framework is to a great extent aligned with the recommendations. Specifically, they found several synergies with the technical document's suggested short-term and long-term options for central banks and supervisors aiming to assess nature-related economic and financial risks (NGFS, 2023b, p. 86). Table S2 showcases the alignment of the project and the framework with these options. The forthcoming report stemming from this project will address in more detail the compatibility of the framework with the broader set of NGFS recommendations.

Options for central banks recommended by the NGFS	Aligned within the scope of the project	Aligned with modelling framework but out of the scope of the project
Short term: Building on available dynamic scenario modeling frameworks with longer-term horizons		
Using a carefully chosen nature-economy modelling framework while acknowledging its assumptions and limitations	The MAgPIE model has undergone a review in the NGFS nature scenario recommendation technical report. Additionally, MAgPIE is coupled with the SEALS model to map projected land cover changes at a scale relevant for the assessment of biodiversity and ecosystem services change. In the scope of this project, only the agricultural and land use sector is assessed, with no direct links to the broader economy. The project carefully presents the frameworks limitations.	
Designing ad hoc shocks in multiple sectors		Exploration of ad-hoc shocks on agricultural production in terms of developed narratives are listed as potential further research. The modeling framework has the capacity to present scenarios on various levels of loss of modeled ecosystem services. It could also potentially model high-risk events (e.g. forest diebacks) based on constructed narrative analyses.
Using assumptions of various SSPs for calibration (not SSP2 only) and co-develop or build on new existing frameworks to go beyond SSP	The project considers the inclusion of scenarios beyond SSP2 and aligns them with the Nature Future Framework.	

Options for central banks recommended by the NGFS	Aligned within the scope of the project	Aligned with modelling framework but out of the scope of the project
Conducting sensitivity analyses, in particular on elasticities of substitution	The project is in the process of considering variations in scenario assumptions and sensitivities to changes in parameters of certain modeled processes (e.g. different investment costs in crop yield-increasing technology).	
Better transparency of underlying assumptions and communication of implications on results	The underlying assumptions are transparently presented in the described methodology and supplementary information, which includes references for further details on related work. The forthcoming report stemming from this project will incorporate additional information derived from continued analysis of the scenario framework and the implications of the results utility for users.	
Long term: Improvement of dynamic scenarios by improving the interlinkages of nature-economy models		
Representing more numerous ecosystem services and economic dependencies to those services within the nature	The inclusion in dynamic global scale assessments of important regulating ecosystem services such as pollination sufficiency, soil erosion and biodiversity change at a high granularity, are significant advancements by this framework. This is based on a novel modelling approach which allows us to dynamically derive these indicators on a very fine scale (300x300m), where the sensitivity to lost ecosystem services is most pronounced. Changes in other regulating/provisioning ecosystem services (water, climate, etc.) are being assessed.	In a further developing phase, plans are underway to include the feedback of lost ecosystem services and land degradation on agricultural production.

Options for central banks recommended by the NGFS	Aligned within the scope of the project	Aligned with modelling framework but out of the scope of the project
Representing more policies, technological options, and socioeconomic developments	On the climate mitigation side, the effects of an economy-wide transition to achieve climate targets on the land use sector are being considered. Various instruments, such as GHG tax, bioenergy demand for energy portfolios, and demand for negative GHG emissions through afforestation, are being used and implemented in the land-use sector.	Socioeconomic developments, such as a plausible transition to low demand futures including changes in diets, are practicable by the model.
Representing some missing economic transmission channels, such as food security and productivity losses	On the climate impacts side, we include climate change related impacts on agricultural land productivity (i.e. crop yield), water availability and terrestrial carbon dynamics. Dynamic cropland allocation and interplay with intensity of agricultural production is modelled endogenously, as well as production reallocation through trade channels, resulting in different agricultural commodity prices.	Feedbacks of food security are not included as economic effects in the model, since the agricultural demand is modeled exogenously and is rather inelastic due to prevailing assumption of increasing income per capita in SSP2 scenario. We model a representative consumer, i.e. there is no heterogeneity in demand.
Better informing the elasticities of substitution, considering making them dynamic		Not aligned within the scope of the project
Developing nature-economy models with alternative macroeconomic modelling assumptions		Not aligned within the scope of the project

Table S2. Alignment of project scope and nature-risk scenario development framework with NGFS recommended options for central banks and supervisors to assess nature-related economic and financial risks (NGFS, 2023b, p. 86).

Extended Methodological Description

The MAgPIE model is a global partial equilibrium agro-economic model that operates on a spatially explicit scale. It considers local biophysical conditions such as crop yield, water availability, and terrestrial carbon content to influence decision making for optimal agricultural production patterns. The model's objective function is to minimise the costs of global agricultural supply, ensuring that the demand for agricultural products is fulfilled. Agricultural demand is aggregated at the level of a flexible number of MAgPIE defined geo-economic regions (usually 10-15, Figure S1). It consists of demand for food, feed, material, and bioenergy, which comprises 19 primary crops groups, 5 livestock products (ruminant meat, milk, monogastric meat, poultry meat, eggs) and 8 processed agricultural commodities (sugar, oil, alcohol, oilcakes, molasses, ethanol, brans, brewers' and distillers' grains). Food demand is exogenously calculated based on an econometric regression model that projects per capita caloric intake on a national level, considering historical patterns and socio-economic assumptions of future growth in population and income (based on SSP scenarios). Material demand is assumed to be proportional to total food demand. Additionally, agricultural demand includes the demand for animal feed, calculated based on feed baskets content, and biomass demand for biofuel production. The model accounts for the long-term income effect on agricultural consumption but is limited in representing short-term demand adjustments to changes in prices.

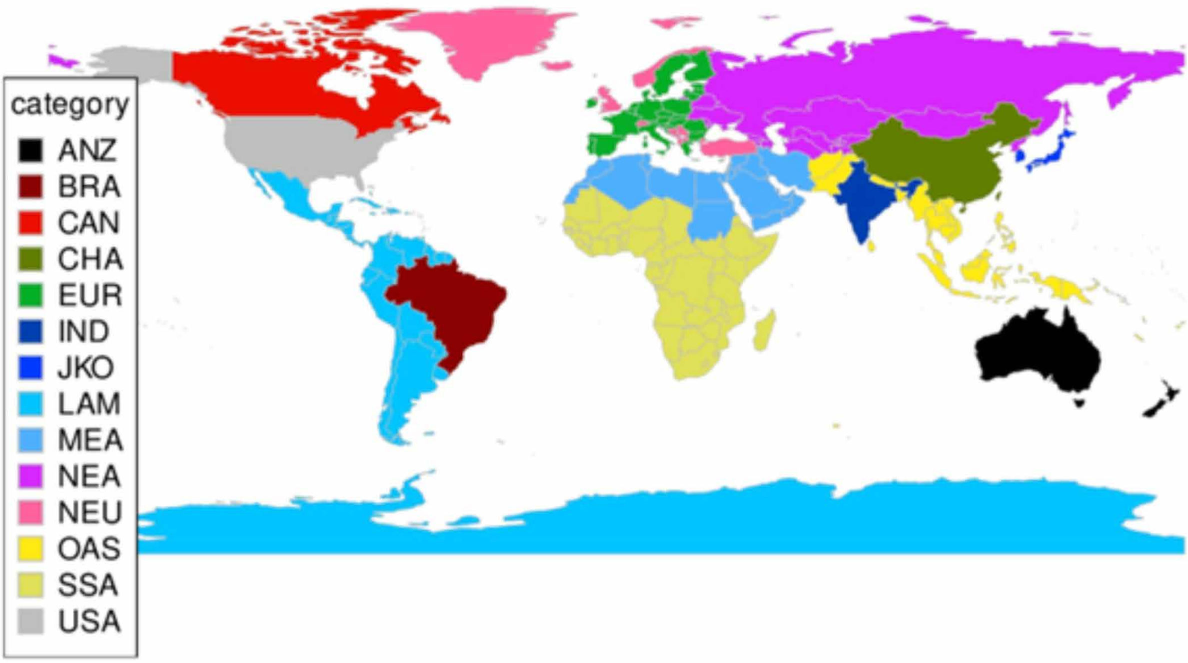

Figure S1 - MAgPIE World Regions.ANZ (Australia & New Zealand), BRA (Brazil), CAN (Canada), CHN (China), EUR (European Union), IND (India), JKO (Japan & South Korea), LAM (Latin America excl. Brazil), MEA (Middle East & North Africa), NEA (Northern Eurasia), NEU (Europe Non-EU), OAS (Other Asia), SSA (Sub-Saharan Africa), USA (United States of America).

Regionally, the supply of agricultural products is internally determined through a combination of production costs and spatially explicit productivity levels. These costs encompass various factors, including input production factors, capital, labour, transport, and the costs associated with converting other land types into arable land. Furthermore, they take into account irrigation infrastructure, yield-increasing technological advancements, and investment expenses. The model integrates information on local biophysical conditions (such as land, water, and terrestrial carbon) and crop yields at a gridded resolution (0.5°×0.5° geographic longitude–latitude) from the LPJmL global crop model. LPJmL dynamically simulates the growth of diverse crop varieties, vegetation types, hydrological conditions, and carbon stocks, incorporating all relevant biogeochemical processes and physical conditions. The data on crop yields, water availability, and carbon content are aggregated from the gridded resolution into 400 regional clusters to facilitate nonlinear optimisation. The reallocation of agricultural production between regions is determined by an exogenously defined rate of international trade liberalisation. This rate implies that a specific portion of agricultural goods is traded endogenously, guided by regional comparative advantages, independent of historical trade patterns. The regional optimisation of agro-economic decisions results in the optimal patterns for land and water use in agricultural production, as well as optimal investments in technology, cropland, capital, and irrigation expansion.

With regard to GHG emissions, MAgPIE estimates CO_2, CH_4, and nitrogen (N) related emissions from land use practices, CO_2 emissions are derived from land use change dynamics, specifically the conversion of various biomes into agricultural land and the subsequent loss of terrestrial carbon stocks. Land conversion, including pasture, forest (pristine and unmanaged), and other natural vegetation (e.g., savannahs, shrublands), contributes to cropland expansion. Additionally, the model dynamically considers two additional pools: forestry (for timber production) and urbanised areas (following demographic changes). The land also serves as a carbon sink, resulting in negative emissions from land use change when cropland is set aside, allowing natural vegetation to regrow or in afforestation projects. Afforestation can be modelled as a prescribed increase in forest area, mimicking NDC afforestation targets, or as a response to a given carbon tax that incentivises afforestation projects. CH_4 emissions in the model originate from agricultural practices related to livestock production (enteric fermentation from ruminant animal husbandry and animal waste management) and paddy rice cultivation, using activity-specific emission factors. N-related emissions are calculated based on the modelled nitrogen cycle, primarily influenced by agricultural management practices, including organic and inorganic fertilisation. Non-CO_2 emissions follow the 2006 IPCC guidelines.

In the context of a climate protection policy, the reduction of GHG emissions is incentivised through an imposed price (tax) per ton of emitted gas. For CO_2 emissions, the price serves as an incentive to curb land use conversion and the subsequent release of carbon. Mitigating CH_4 and N emissions involves employing technical solutions incurring additional costs, also triggered by an emission price. Examples of technical mitigation include using anaerobic digesters for capturing CH_4 from animal waste, altering animal diets, implementing fertiliser spreaders etc. The cost of these technical mitigation options is estimated based on regional marginal abatement cost curves, which assess a broad spectrum of mitigation technologies and practices. Furthermore, negative emissions can be generated by capturing atmospheric carbon through afforestation in suitable areas. As the model operates as a partial-equilibrium model, tax revenues are not recycled.

Climate-nature scenario development for financial risk assessment

Invitation for Feedback on Scenario Development Framework

February 2024

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