Climate-nature scenario development for financial risk assessment

Presentation of Final Results

November 2024

NATURE FINANCE
EUROPEAN CENTRAL BANK
EUROSYSTEM
PIK
UNIVERSITY OF MINNESOTA

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

Stevanović M.[1], Ceglar A.[2*], von Jeetze P.[1], Costermani Visconti A.[3], Krisht S.[3], Johnson J.A.[4], Borrelli P.[5], Heemskerk I.[2*], Popp A.[1,6], Zadek S.[3]

[1] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

[2] European Central Bank, Frankfurt am Main, Germany

[3] NatureFinance

[4] University of Minnesota, Department of Applied Economics, St. Paul, United States

[5] Department of Environmental Sciences, Environmental Geosciences, University of Basel, Basel, Switzerland

[6] University of Kassel, Faculty of Organic Agricultural Sciences, Witzenhausen, Germany

[*] The views expressed are those of the authors and do not necessarily reflect those of the ECB.

Acknowledgments

This report was undertaken with the generous financial support of the Children's Investment Fund Foundation (CIFF). NatureFinance extends its sincere thanks to CIFF for their invaluable contribution to this work. We are also deeply grateful to the following experts who provided guidance and insights as part of the advisory group of this project: Alexander Barkawi (Council on Economic Policies), Tom Crowther (ETH Zurich), Katie Kedward (University College London), HyeJin Kim (UK Centre for Ecology & Hydrology), Emily McKenzie (Taskforce on Nature-related Financial Disclosures), Alessandra Melis (Taskforce on Nature-related Financial Disclosures), Robert McElderry (ETH Zurich), and Romain Svartzman (Bocconi University). Their expertise greatly enhanced the depth and rigor of this report.

Table of contents

List of abbreviations

AOH: Area of Habitat
BH: Biodiversity Hotspots
BII: Biodiversity Intactness Index
CBD: Convention on Biological Diversity
CCA: Critical Connectivity Areas
CH4: Methane
CO_2: Carbon dioxide
DNB: Dutch National Bank
EBD: Ecoregions of High Beta Diversity
ECB: European Central Bank
EEA: European Economic Area
EU: European Union
GBF: Global Biodiversity Framework
GCM: Global Circulation Models
GDP: Gross Domestic Product
GHG: Greenhouse Gas
GIS: Geographical Information System
GloSEM: Global Soil Erosion Modelling
IFL: Intact Forest Landscapes
IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC: Intergovernmental Panel on Climate Change
IUCN: International Union for the Conservation of Nature
KBAs: Key Biodiversity Areas
LPJmL: Lund-Potsdam-Jena managed Land (Dynamic Global Vegetation Model)
MAgPIE: Model of Agricultural Production and its Impact on the Environment
NCP: Nature's Contributions to People
NDC: Nationally Determined Contributions
NFC: Non-financial Corporation
NGFS: Network for Greening theFinancial System
NIGEM: National Institute Global Econometric Model
PA: Protected areas
PIK: Potsdam Institute for Climate Impact Research
RCP: Representative Concentration Pathways
REMIND: REgional Model of Investment and Development
RUSLE: Revised Universal Soil Loss Equation
SEALS: Spatial Economic Allocation Landscape Simulator
SSP: Shared Socioeconomic Pathways
TC: Technological change
TNFD: Taskforce on Nature-related Financial Disclosures
UNCCD: United Nations Convention to Combat Desertification
UNFCCC: UN Framework Convention on Climate Change

Executive summary

The degradation of nature, including biodiversity loss, is a substantial threat to humanity, the economy and financial stability. Growing evidence shows that nature degradation poses a significant material risk to the real economy and financial institutions. The work of financial institutions to date has largely focused on climate, firmly establishing the relevance of climate-related risks for central banks and financial supervisors. It is imperative, however, that forward-looking risk assessments adopt an integrated approach, encompassing both climate and nature-related aspects, in order not to underestimate financial stability risk. A crucial step for financial stakeholders is to gain a comprehensive understanding of these integrated climate- and nature-related economic and financial risks through scenario development.

In response, the Potsdam Institute for Climate Impact Research (PIK), European Central Bank (ECB) and NatureFinance, have partnered to explore the feasibility of an integrated climate-nature scenario framework. The project marks evolving efforts to develop integrated scenario narratives and showcase their implications through a sophisticated modelling infrastructure that combines macroeconomic and biophysical models. The central question the partners sought to answer was whether integrating climate and nature-related risks into scenario analysis would yield a materially different assessment of these risks. The preliminary answer is a resounding yes. The findings confirm that an integrated approach to climate-nature scenarios provides a more nuanced and comprehensive understanding of biophysical and economic risks compared to analysing these factors separately. The integrated approach reveals material differences in estimated risks under varying climate and nature policy scenarios. In particular, the project shows that while integrated climate-nature policies still present risks, these risks are less pronounced than in scenarios where climate and nature are subject to siloed policies. These findings suggest that integrating nature and climate risks is not only an urgent priority for the risk assessment scenarios used by central banks and financial supervisors, as recommended by the Network for Greening the Financial System (NGFS), but also for broader policymaking and regulation aimed at guiding financial and economic transitions.

This project makes a signature contribution to the emerging field of advanced scenario development by building integrated climate-nature scenario narratives and a sophisticated modelling infrastructure. It demonstrates that the approach of modelling nature and climate risk together in scenario development is feasible and delivers a more rigorous and comprehensive scope of potential risks than existing approaches. The climate-nature scenario narratives build upon the established NGFS climate scenarios and align closely with its newly established recommendations for nature-related scenario development. By integrating existing climate and nature policies and ambitions in different combinations within scenario narratives, our framework simulates potential transitions to achieve specific environmental targets. This allows us to explore diverse pathways and outcomes that could arise from varying policy ambition, offering a comprehensive assessment of the interconnected risks and opportunities associated with both climate and nature protection.

The climate-nature scenario modelling framework focuses on modelling economic risks for the agriculture and land use sector globally from 2020 to 2050. This sector is chosen due to its direct dependencies on various Nature's Contributions to People (NCP) factors. Consequently, modelled changes in land degradation and NCPs are expected to significantly impact this sector. The developed modelling framework uses a wide range of spatially variable biophysical and socio-economic information to derive various indicators of physical and transition risks. **Within the framework, we assess the degradation of ecosystem services, focusing on two key NCP indicators: pollination insufficiency and soil erosion.** These two NCPs were selected due to robust scientific understanding and the availability of comprehensive, global data that underscore their critical role in agricultural production.

While this project marks significant progress in developing an integrated framework, there are several limitations to the modelling and its underlying assumptions. The model primarily focuses on the agricultural and land use sector, limiting its ability to capture the full propagation of climate and nature-related risks throughout the whole economy. **The exclusion of extreme weather events such as floods and droughts, as well as feedback effects of degraded ecosystem services on climate change and agricultural production, likely result in an underestimation of risks.** Additionally, the model relies on assumptions that may themselves become disrupted due to climate change and biodiversity loss, as well as other unpredictable factors. For example, it treats demand for agricultural commodities as inelastic and uniform across different income groups. This might lead to underestimating the socio-economic impacts of modelled risks on heterogenous households. Moreover, the modelling is constrained by its inability to capture local variations in certain transition risk indicators due to a lack of granular data. This shortfall prevents a full reflection of how transition pathways impact different sub-regions, potentially leading to underestimations of localised risks and impacts. Overall, this means that while modelling and related scenarios from this project help us to better capture and understand the scope of increased risks presented by integrating climate and nature, we are likely underestimating those risks overall due to a number of data and methodological challenges and contextual uncertainties.

Our research marks an important step towards developing a comprehensive quantitative risk assessment framework by illustrating the interconnectedness of nature and climate policies. Crucially, our findings indicate that **the business-as-usual scenario lacking both effective climate and nature protection measures leads to significant biodiversity loss and degradation of ecosystem services.** These insights hold true both globally and in the European Union, particularly in the context of land use. Furthermore, **climate protection alone does not safeguard biodiversity.** The scenario focused purely on climate policies may inadvertently create risks to biodiversity through interventions such as large-scale afforestation and monoculture bioenergy production. This underscores the need for dedicated nature protection measures alongside climate policies. Moreover, our findings reveal that the **climate-only scenario presents significant economic risks to the agricultural sector.** The risks stem from the abrupt and delayed implementation of climate mitigation policies, coupled with the introduction of greenhouse gas emission pricing for agricultural activities, which together result in substantial increases in production costs.

Key findings reveal that an integrated climate-nature equilibrium scenario promotes the strongest long-term agro-economic stability and sustainability by using resources efficiently and minimising environmental degradation. This is achieved through the synergistic effects of climate and nature policies. **These not only reduce greenhouse gas emissions while preventing biodiversity loss, but also enhance ecosystem services such as pollination and soil stability.** Our findings underscore the critical role of timely nature conservation efforts. By establishing biomes that enhance terrestrial carbon storage by 2030, the physical and transition risks associated with delayed climate action can be partly mitigated, paving the way for achieving long-term climate goals. Additionally, despite the need for investments in advanced technologies and infrastructure to increase agricultural productivity, the integrated scenario avoids substantial increases in production costs and prices of agricultural products. The incorporation of nature protection policies acts as a buffer against the cost of climate measures. Therefore, the integration of climate and nature protection measures reveals both trade-offs and synergies.

Financial institutions have made noteworthy progress in quantifying climate risks. Leveraging this knowledge can accelerate the adoption of enhanced climate-nature risk management frameworks. A determined effort is needed to connect this progress with emerging knowledge and data in the nature risk domain. This study offers foundational insights for central banks and financial regulators on the critical importance of understanding the connections between climate and nature policies when assessing future financial risks, and how to begin making those connections in practice. It highlights the critical role of biodiversity, soil health, and pollination in supporting European and global economies. The transition risk indicators in this report provide valuable insights into how policy ambitions affect land use and macroeconomic factors such as food prices. They are essential tools for evaluating the complex interdependencies between these policies and economic stability. By developing a comprehensive understanding of these interdependencies, policymakers can identify areas that require action and then implement suitable environmental and sectoral policies.

For financial policymakers, the report underscores the need for innovative modelling solutions, such as sensitivity analyses of banks' portfolios to biodiversity loss, in order to translate these findings into actionable, policy-relevant information. This is critical for developing robust financial policies that can address the risks posed by biodiversity loss and climate change, thus ensuring stability and resilience in the economy and financial system. Without adopting these integrated scenarios and increasingly deploying them through real time supervision and related requirements from financial institutions, central banks and financial supervisors risk running afoul of their mandates in pro-actively monitoring and addressing financial stability risks.

Creating a comprehensive nature-related stress test in the future will require an economy-wide modelling approach to assess financial risks associated with environmental changes. Further research is needed to develop dedicated financial tools to quantify physical and transition risks, contagion within the financial system, and the impact of the financial system on nature. The research should focus on improving modelling approaches to integrate diverse ecosystem services, addressing uncertainties in climate-nature dynamics and tipping points, and assessing the impact of degraded ecosystem services and natural capital on crop yields. Furthermore, expanding the modelling of the effects of climate and nature-related risks beyond agriculture is crucial to understanding economy-wide risks across sectors. This important step will enable models to quantify and assess the risks for the financial sector and develop resilient financial policies.

It is important, however, to recognise that waiting for exhaustive modelling is not necessary. Urgent action is needed by central banks and financial supervisors as delays could lead to further irreversible environmental damage. It is crucial for these actors to adopt heuristic approaches using existing knowledge, allowing them to act now, despite ongoing uncertainties and modelling challenges. This approach facilitates improvement and integration of new insights over time, rather than waiting for an all-encompassing model. The insights from this report provide a vital foundation for both immediate action as well as the continuous development of modelling frameworks, enabling financial supervisors and policy-makers to better address the deeply intertwined threats posed by global warming and ecosystems collapse.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

1

Introduction

This final report presents the outcomes of a collaboration project between the Potsdam Institute for Climate Impact Research (PIK), the European Central Bank (ECB) and NatureFinance. The project explores the practical development of an integrated climate-nature scenario framework to underscore the critical significance of a nexus approach to climate and nature considerations. The developed scenario narratives and modelling framework aim to capture the interconnected and mutually reinforcing impacts of climate change and nature loss on physical and transition risks. Through advanced modelling techniques, the project seeks to provide a comprehensive analysis at both global and EU levels, highlighting future research needs and paving the way for more robust quantitative risk frameworks for central banks.

1.1 The importance of thriving nature for the resilience of society and economy

The essence of our well-being is intricately linked to a thriving natural environment. 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 global Gross Domestic Product (GDP) - a staggering EUR €40 trillion - depends on a healthy environment (World Economic Forum, 2020). Indirectly, the importance of a thriving natural environment extends to all aspects of our economy, because we fundamentally depend on nature's ecosystems for our survival. Approximately 70% of the world's poor and vulnerable depend on biodiversity for their livelihoods and well-being. Yet, amidst the scientifically established advantages we reap from nature, we observe an alarming trend. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) says a worldwide decline in nature has caused the extinction rate of species to 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. The consequences of inaction are dire. Should we falter in our commitments to curb the primary culprits behind rapid nature loss – unsustainable land use, greenhouse gas emissions, overexploitation of natural resources, pollution, and invasive species – we risk the catastrophic breakdown of critical natural systems. This ominous scenario could become reality as early as the mid-21st century, coinciding with the expected peak of world human population growth. The urgency is clear. It is not just a matter of preserving nature, it's about securing our very existence. Timely action is of the essence. Our actions today will shape the fate of our planet and the generations that follow.

[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).

Nature loss is not the only crisis we are facing. Our current climate trajectory indicates a global warming level well beyond 2°C by the end of this century, as highlighted in the Intergovernmental Panel on Climate Change (IPCC) AR6 synthesis report (IPCC, 2022a). Alarming forecasts suggest that globally, 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). Biodiversity would face significant threats, including increased rates of species extinction, habitat loss, and ecosystem disruption (Nunez et al., 2019). Many species, particularly those in sensitive environments such as coral reefs, polar regions, and tropical forests, would be at high risk of extinction. The collapse of some ecosystems and the loss of biodiversity hotspots would impact ecosystem services that societies rely on, such as pollination, water purification, and carbon sequestration.

The degradation of nature and loss of biodiversity is a substantial threat to ecosystems and humanity and thus also to the economy and financial stability. Financial institutions as facilitators of economic activities are therefore heavily reliant on a thriving natural environment. 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 soil erosion control, surface and groundwater provision, and flood and storm protection. If environmental degradation persists at current rates 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.

A growing number of central banks recognise the indispensable value of healthy and resilient ecosystems for economic functionality and financial system stability (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, Martinez-Jaramillo et al., 2023). Additionally, the Network for Greening the Financial System (NGFS) has recognised the need for central banks and supervisors to incorporate nature-related financial risks into their mandates. Acknowledging nature-related impact and dependencies 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, the NGFS has launched a dedicated taskforce for biodiversity loss and nature-related risks. It has also unveiled a beta version of a conceptual framework for nature-related financial risks. This serves as a pivotal guide for central banks and financial supervisors (NGFS, 2024; NGFS, 2023; OECD, 2023).

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

Addressing the interconnected challenges of climate change and nature loss in the financial sector requires a holistic approach. Historically, financial institutions, including central banks and supervisors, have focused on climate-related risks. However, this narrow focus can lead to blind spots in risk assessment and management, neglecting the broader environmental context (Kedward et al., 2022; Ranger et al., 2023; Ceglar et al., 2023; Boldrini et al., 2023). The intricate relationship between climate and nature means that changes in one invariably influence the other. For example, companies contribute to both climate change and nature loss through various drivers, such as GHG emissions, land use changes, pollution, and resource overexploitation, which, in turn, can also disrupt their supply chains. Ignoring these linkages leads to incomplete risk assessments and suboptimal decisions, undermining financial institutions' ability to effectively manage risks and carry out long-term strategic planning. Ultimately, it threatens broader financial stability.

A siloed approach to nature and climate issues can also be detrimental to the identification of investment opportunities, as it fails to account for the interconnectedness of environmental factors and their combined impact on financial performance. For instance, some climate investment opportunities, like nature-based solutions, offer dual benefits by supporting climate adaptation and delivering important ecosystem services, resulting in compounded positive impacts. Conversely, others, such as bioenergy production, have the potential to inadvertently damage the natural environment if not implemented with sufficient safeguards. Therefore, the actual materialisation of business and investment opportunities may vary depending on whether the climate and nature transition are considered individually or together. Additionally, a fragmented approach hampers the development of comprehensive disclosure and reporting standards, making it difficult for investors to accurately evaluate environmental risks and opportunities across different sectors. This lack of integration can undermine the ability of investors to conduct accurate asset and risk valuation and secure sustainable returns (Finance for Biodiversity Initiative & Vivid Economics, 2021).

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, 2024). Similarly, one of the general requirements of the Taskforce on Nature-related Financial Disclosures (TNFD), applicable across all recommended disclosure pillars (Governance, Strategy, Risk and Impact Management, and Metrics and Targets), is its integration with other sustainability-related disclosures (TNFD, 2023a). Addressing climate and nature-related risks in an integrated manner acknowledges their mutual reinforcement and enables consideration of the potential trade-offs and synergies, ultimately highlighting the significant compound effect on the economy and financial system.

Adopting an integrated approach to climate and nature-related risks for both the real economy and financial system involves four key dimensions (NGFS, 2024). Firstly, climate change is 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 flows, nutrient cycling, and water cycling, accelerating climate change through diminished carbon sequestration 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 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 by combating deforestation and protecting wetlands, including 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 (CISL, 2022). 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 play a pivotal role in financial risk assessment for corporations, financial institutions and the broader financial system and economy. They are also crucial for policymakers, enabling them to evaluate the adverse impacts of the financial system on climate and nature, and helping them work towards mitigation and reversing of nature degradation and biodiversity loss. This integrated approach is essential to facilitate faster and more efficient investments in environmentally sustainable initiatives, ultimately minimising future nature- and climate-related hazards, and reducing credit risks for banks.

Significant developments are being made in line with the NGFS and TNFD Recommendations for the development of integrated nature-climate scenarios and risk assessments. The nature-related scenarios analysis work by the NGFS has made recommendations that aim for synergy with climate scenarios while also addressing nature loss and strategies that can support their reversal (NGFS, 2023). The TNFD recommends integrating climate and nature-related risks via holistic risk assessments, standardised frameworks, scenario analysis, cross-sector collaboration, stakeholder engagement and continuous improvement to support sustainable and resilient financial decision-making (TNFD, 2023 a,b; TNFD, 2024). Ranger et al. (2023) underscores the critical importance of integrating such mutual considerations to combat the potential catastrophic impacts of climate change on the economy and financial system. Deriving concrete estimates of economic and financial stability impacts 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, leading central banks, governments, and financial institutions to further assess risks as well as identify mitigative actions.

Therefore, integrated scenarios can be an invaluable tool for financial institutions, as they can support strategic planning for various possible futures and inform decisions around investments and capital allocation. The TNFD recognised the use of scenarios as a key tool for the assessment and disclosure of nature-related issues. Scenarios are already used in climate investment strategies and transition plans as a mechanism to deal with the uncertainties linked to the climate crisis. They can also 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 for business strategy and financial planning (TNFD, 2023b; TNFD, 2024). An integrated approach to scenario analysis can therefore help financial institutions navigate uncertainty across both crises.

Developing integrated climate-nature scenarios poses a challenge given the intricate nature of ecosystem functions and non-linear dynamics. Constructing meaningful scenario narratives requires an inherent trade-off between capturing locally, specific environmental changes and global relevance (NGFS, 2023). In response to the mounting evidence for an integrated approach, our objective is to contribute to the initial efforts in this scenario development efforts. Therefore, we seek to identify key research gaps aiming to guide discourse and research toward building quantitative risk frameworks and stress tests that can be applied by central banks, financial supervisors and regulators.

1.3 The integrated climate-nature scenario development project

The Potsdam Institute for Climate Impact Research, European Central Bank and NatureFinance have partnered to explore a range of ecosystem services that can provide a holistic view of how an integrated climate-nature scenario framework could work. PIK is a leading research institute dedicated to advancing our understanding of climate change and its impacts. Established in 1992 and located in Potsdam, Germany, PIK conducts interdisciplinary research on climate dynamics, risks, adaptation, and mitigation strategies. It contributes to major international assessments and policy advice to address global climate challenges. The ECB is the central bank for the eurozone, responsible for managing the euro and formulating monetary policy to maintain price stability. One of the key research areas in the ECB's climate and nature plan, 2024-2025, focuses on assessing the economic risks posed by biodiversity loss and climate change.[2] NatureFinance is dedicated to aligning financial flows with nature-positive outcomes, ensuring that investments contribute to the preservation and restoration of ecosystems. By developing innovative financial instruments and strategies, NatureFinance aims to drive capital towards sustainable projects that protect biodiversity and mitigate climate change.

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 measures that are already in place or that could be applied in the future. 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 comprehensive and globally applicable framework.

Our objective is to contribute to the initial efforts in scenario development. We seek to provide a holistic view of how an integrated climate-nature scenario framework could work, leveraging the existing NGFS scenarios. We also seek to demonstrate the importance of integrating climate and nature in a nexus approach to capture their amplifying effects on physical and transition risks. We aim to do so by providing a practical example and exploring a set of ecosystem services. The aim is to conduct the analysis both at a global and European Union level (EU) by applying a top-down approach, in order to display the potential materialisation of physical and transition risks that might affect the EU banking and financial sectors. Finally, we aim to expose research needs and knowledge gaps to build more complete, global modelling frameworks that allow us to build quantitative risk frameworks and stress tests applicable to central banks.

[2] https://www.ecb.europa.eu/ecb/climate/our-climate-and-nature-plan/html/index.en.html

To achieve these objectives, the project team conducted the following activities. We developed scenario narratives, and their subsequent implementation projections, into a global, multi-regional, partial equilibrium model for the agricultural sector. Using this, we conducted global-level scenario runs that quantified physical and transition risk indicators. Finally, we evaluated these physical and transition risks both at a global and EU level. The physical and transition risk indicators, as well as biodiversity and ecosystem indicators, provided essential elements for the development of quantitative financial risk assessment frameworks.

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

This report provides a comprehensive set of physical and transition risk results and evaluates their potential materialisation for each scenario. It builds on the initial report by the project team, published in February 2024, which had the main goal of gathering feedback. The document is structured as follows: **Chapter 2** presents integrated climate-nature scenario narratives. **Chapter 3** explains the integrated modelling framework. **Chapter 4** outlines the key innovations and limitations of our approach. **Chapter 5** presents the modelling results. **Chapter 6** evaluates these results for each scenario and its implications for the biophysical system and the agricultural sector. **Chapter 7** provides conclusions and recommendations for future research.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

2

Integrated Climate-nature Scenario Narratives

NATURE FINANCE

EUROPEAN CENTRAL BANK
EUROSYSTEM

PIK

UNIVERSITY OF MINNESOTA

To gain a better understanding of the integrated risk associated with climate and nature, qualitative scenario narratives are first developed as a climate-nature risk scenario framework. These explanatory narratives provide detailed descriptions of potential futures across two dimensions with different levels of ambition for the protection of nature or climate (Figure 1). They are contingent on policy decisions and 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. These scenarios also have a normative aspect, meaning that existing policies and conservation aspirations are integrated to simulate transitions towards specific targets such as the Nationally Determined Contributions (NDCs) on CO_2 reductions. The complexities and nuances of each potential world outcome are articulated by considering the combined impacts of both physical and transition risks, with the focus on indicators from future projections in the agricultural and land use sector. 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 the sector. The evaluation of risk within this sector therefore helps in describing how different levels of policy ambition might affect climate, nature, and the economy.

The climate-nature risk scenario framework is aligned with the established NGFS climate scenarios.[3] This enables a more coherent, comparative assessment of climate-nature risk scenarios with transitional risks in the broader economy. Since the risk indicators are evaluated only for the agricultural and land use sector, connecting each climate-nature risk narrative to the corresponding NGFS scenario offers a chance to understand the possible amplifying impacts on an economy from nature-related risks. The linkage between these two frameworks is established through quantitative instruments (e.g. GHG emission tax) 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, 2023), related especially to overcoming the trade-offs between capturing locally specific environmental changes and maintaining global relevance (c.f. Table 4 and Annex Table S2).

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

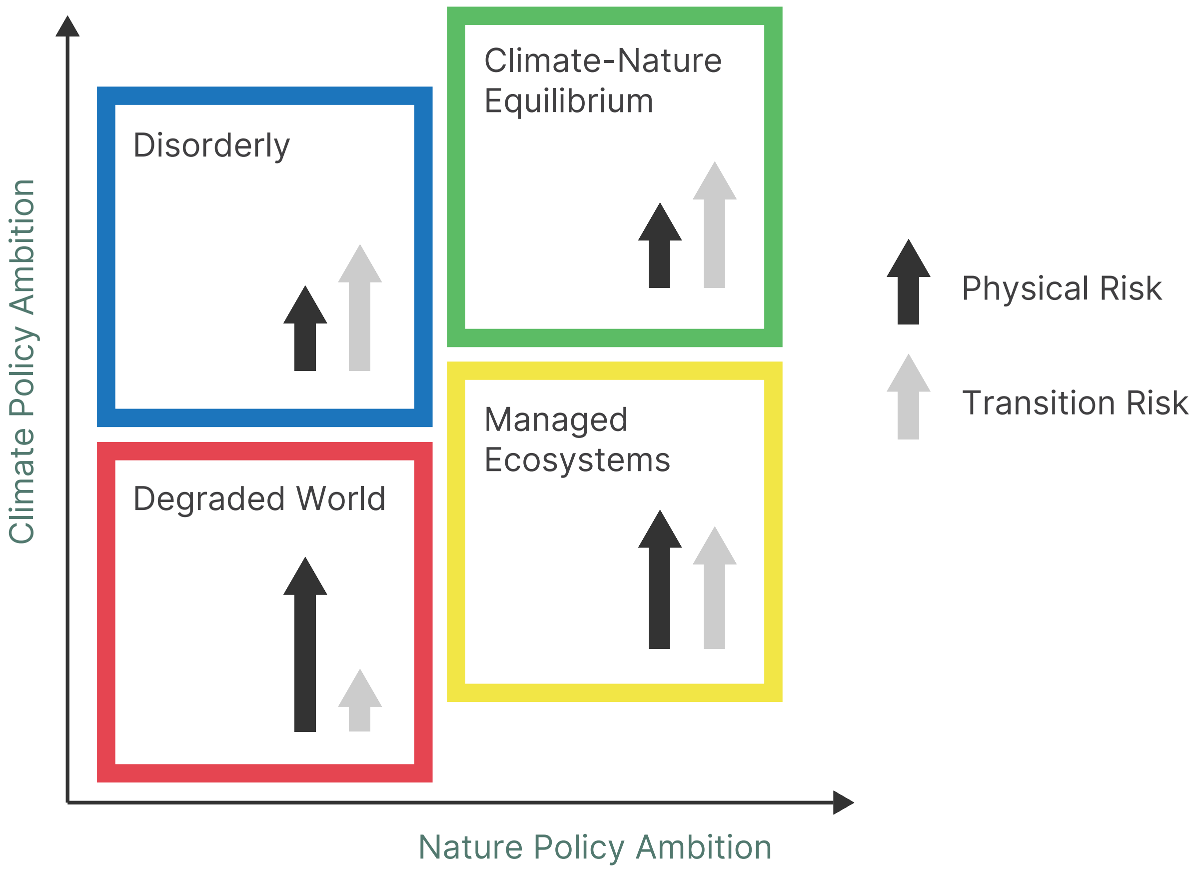


Figure 1. Climate-Nature Risk Scenario Matrix. The primary scenarios are spread along narratives with varying ambition and integration of nature and climate protection targets in the land use sector. Each scenario accordingly shows a certain level of transition and physical risk related to climate change 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 incorporates only three specific targets for nature protection. There could be many additional policies needed to achieve wider safeguarding of nature. Consequently, hypothetical levels of transition risks could potentially be much higher for ambitious nature protection goals.

The framework for climate-nature risk scenarios comprises four primary narratives, which stem from variations in climate and nature protection ambition. Each narrative describes a hypothetical, expected level of physical and transition risk based on assumed regulatory environments, with or without protection policies, and considering the impacts of climate change, nature degradation, and sectoral economic transformation:

1. **Business-as-usual - Degraded World scenario:** There is a notable absence of effective policies aimed at mitigating climate change and preventing the degradation of natural ecosystems globally. This deficiency in proactive measures exacerbates adverse consequences on both climate and environment. The lack of intervention results in increasingly severe impacts from climate change, reaching an increase in global mean temperature of 3.5°C to 4°C by the end of the century (according to the representative concentration pathway RCP7.0). Additionally, it leads to a significant loss of critical ecosystem services, including a decline in pollinators and increased soil erosion. This scenario is marked by elevated levels of physical risks. However, transition risks, reflecting challenges in moving towards transitions to mitigate climate change and protect nature, remain relatively low.

2. **Climate protection only - Disorderly scenario:** The focus of this scenario is on implementing climate mitigation policies. It aligns with the *Disorderly NGFS scenario*, which revolves around divergent policies across countries and sectors which are delayed until 2030 and then abruptly implemented, leading to a sudden and strong transition to target a global mean temperature increase of 1.6°C in 2100 (RCP2.6). The mitigation focus in the land use sector relies on large-scale, land-based carbon uptake measures such as afforestation or large deployment of second-generation bioenergy. A critical challenge arises, however, from the lack of integration with broader sustainability goals, notably maintaining biosphere integrity. This leads to potentially higher physical risk from degraded ecosystem services. There is also a significant increase in transition risks, driven by ambitious yet narrowly targeted climate mitigation policies.

3. **Nature protection only - Managed Ecosystems scenario:** This scenario describes a moderate commitment to climate change mitigation, as outlined in the Paris Agreement and in NDCs, with targets in 2030. The emphasis is on land protection and restoration, aligned with the CBD Global Biodiversity Framework (GBF), extending protected status to approximately 30% of the Earth's land surface by 2030 ("30×30" target[4]). 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 risk remains as the global mean temperature increases to 2.6°C by the end of the century (RCP4.5). Additionally, there are locally significant transition risks from

[4] Marine environments are not considered here due to the project's focus on the agricultural sectors. GFB 30×30 target, however, comprehensively applies to the entire biosphere.

reactive protection and adaptation measures to evolving physical hazards. The emphasis is on the interconnectedness of insufficient climate mitigation and nature protection, and the importance of proactive adaptation strategies within managed ecosystems.

4 **Integrated approach - Climate-Nature Equilibrium scenario:** This scenario describes a co-ordinated effort to integrate climate and nature considerations through ambitious and timely policies. These include net-zero climate targets for around mid-century in order to stay below a 2°C global temperature increase in 2100 (1.6°C following RCP2.6) and the implementation of biosphere integrity policies 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 in all sectors, including the introduction of GHG emissions pricing for agriculture and land use in 2030. The focus extends beyond mitigation alone, recognising the crucial role of enhanced ecosystem functioning in adapting to remaining physical risk. There are moderate to high transition risks associated with the implementation of these integrated policies. However, physical risks 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 mid- and long-term objectives (in the years 2030 and 2050), with a focus on policies and measures relevant to climate and nature protection, including those that are already in place or that could be applied in the future.

Existing policies and policy aspirations are integrated into the climate-nature risk scenarios narratives by simulating the transition to the achievements of proposed targets (Table 1). On the climate change mitigation side, this includes the consideration of NDCs, in particular for the reduction or stopping of deforestation as well as national goals for reforestation and additional afforestation, which is included in all scenarios except for the *Degraded World scenario* baseline. GHG pricing instruments for land-based CO_2 emissions and non-CO_2 emissions from agricultural practice (e.g. CH4 from animal production systems, or N-related emissions from fertiliser application) are included in ambitious climate protection, 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 World scenario* 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.

	Policies measures and conservation targets	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	30×30 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 targets are considered. First, the 30×30 land conservation interventions aim to expand protected areas (PAs) to 30% of global land surface in line with target 3 of the GBF. The enlargement of PAs considers Key Biodiversity Areas (KBAs), pristine habitats in Biodiversity Hotspots (BHs), Ecoregions of High Beta Diversity (EBDs) and Critical Connectivity Areas (CCAs). Secondly, a biodiversity compensation scheme is implemented that closely reflects targets 4 and 14 of the GBF, and ensures no net biodiversity loss after 2030. This compensation scheme makes sure that any reduction in biodiversity intactness at the biome level is offset via designated areas with higher Biodiversity Intactness Index (BII) values, and in which habitat quality increases with maturation over time. Lastly, the measures include the conservation of at least 20% of semi-natural habitats within managed landscapes in line with targets 10 and 11 of the GBF, which research has shown to be critical to sustain key ecosystem functions (Mohamed et al. 2024; Garibaldi et al. 2020). These measures 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 response strategies.

2.1 Placing the scenario narratives in the European Union context

In addition to the global-scale analysis of biophysical and transition risks emerging from the climate-nature risk scenario framework, a special focus is placed on the results at the European Union regional level. Although the EU as a region is relatively less exposed to the direct risk of losing important ecosystem services compared to other biodiversity-rich and nature-dependent world regions, albeit at more indirect risk when considering trade routes between the EU and other highly impacted regions. The aim, therefore, is to collect and assess indicators of ecosystem changes and agro-economic trends to enable further analysis of the exposure of EU banking and financial sectors to the emerging risks in different climate-nature scenario narratives.

To contextualise these climate-nature scenario narratives in the EU, it is important to have a closer look at its current policies and future targets for climate and nature protection. In the ***Degraded World scenario,*** the EU lacks additional policies to protect nature and maintain climate protection ambitions at pre-Paris Agreement levels. This is comparable to the lack of commitments on the global level in the degraded world narrative. Despite this, existing policies still address environmental and natural health, either directly or indirectly. Many EU countries have national regulations that protect forests or manage deforestation rates, ensuring no net deforestation, or minimal deforestation, occurs. However, there is a risk of overexploitation of natural resources such as land and water due to increasing agricultural production, leading to further environmental degradation. In contrast, the ***Managed Ecosystems scenario*** represents a modest step towards climate protection, aligning with the EU's NDCs under the UN Framework Convention on Climate Change (UNFCCC). This scenario aims for no net forest loss in the EU, although specific afforestation and forest restoration targets for 2030 remain undefined. It envisions an increase of 17.5 million hectares (17% more) of protected land by 2030 compared to the *degraded world scenario*. The new EU Nature Restoration law is indirectly captured in this scenario through the global 30×30 land conservation target. The ***Disorderly scenario*** focuses on climate protection, maintaining current levels of first-generation bioenergy demand while gradually increasing second-generation bioenergy demand to 780 PJ/year by 2050. Greenhouse gas (GHG) prices are projected to start at $5 per ton of CO_2 in 2030, assuming a gradual inclusion of the agricultural and land use sector in the direct GHG emission pricing scheme policy after 2030. Finally, the ***Climate-Nature Equilibrium scenario*** combines nature and climate protection measures, aiming for a balanced approach to environmental sustainability and climate mitigation. This integrated strategy reflects the EU's broader climate policy goals, which include reducing net greenhouse gas emissions by at least 55% by 2030 and achieving net zero by 2050.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

3

Methodology

NATURE FINANCE

EUROPEAN CENTRAL BANK
EUROSYSTEM

PIK

UNIVERSITY OF MINNESOTA

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

The policy aspiration for climate and nature protection is modelled through the innovative coupling of various climate, nature, land use and economic models. The scenario building blocks in Table 1 are individually modelled in the land and water use model, MAgPIE (Model of Agricultural Production and its Impact on the Environment), as policies, policy instruments or outcomes (Dietrich et al., 2019). These connect climate-nature risk narratives with 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 2).

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 the production of agricultural and forestry products, as well as nature-based climate mitigation options, such as carbon sequestration by reforestation/afforestation, bioenergy production (Humpenöder et al., 2014; Kreidenweis et al., 2016), and 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).

MAgPIE is a partial economic equilibrium model focusing on the agricultural and land use sector with an objective function of minimising global agricultural production costs. This type of model assesses agricultural supply and demand equilibrium conditions while holding other sectors in the economy constant. MAgPIE is coupled with the REMIND (REgional Model of Investment and Development, Baumstark et al., 2021) economic growth model with a special focus on the energy sector. REMIND-MAgPIE coupling aims to achieve partial integration of macroeconomic and climate policy feedback channels in the land use sector. The macroeconomic linkages however do not account for a multisectoral reallocation of production factors and therefore limit feedback effects throughout the entire economy. The REMIND-MAgPIE coupling operates through an iterative exchange of information between the two models to achieve scenarios with balanced bioenergy and emissions markets. REMIND provides emissions prices and bioenergy demand to MAgPIE, which then returns land use emissions and bioenergy prices. While REMIND endogenously calculates GDP, it also incorporates household expenditure on agricultural products calculated by MAgPIE. A caveat exists regarding nature-related risks and the impacts of climate change on the agricultural sector: Nature is not accounted for in REMIND's production function, and thus the direct propagation of ecosystem service loss through natural capital is not currently modelled (Figure 3). Within the scope of this project, MAgPIE is applied on a standalone basis with climate policy inputs from the coupled REMIND-MAgPIE runs from the NGFS climate scenarios.

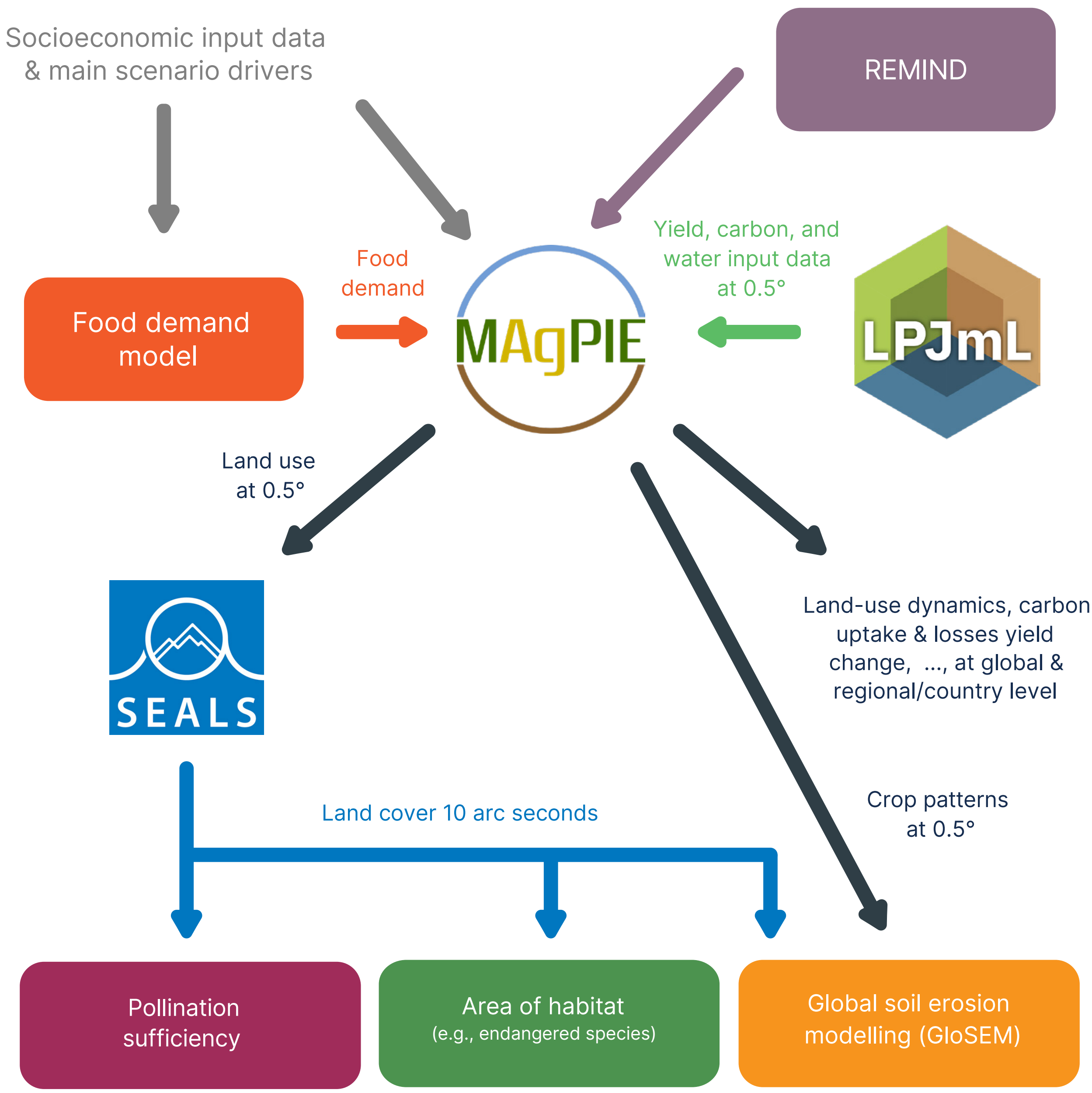


Figure 2. Modelling Framework. The climate impacts modelling chain starts with general circulation models GCMs (Climate models) which are driving the simulations of future crop yields, water availability and terrestrial carbon content in LPJmL, the global dynamic vegetation, crop and hydrology model. 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 (300×300m at the equator).

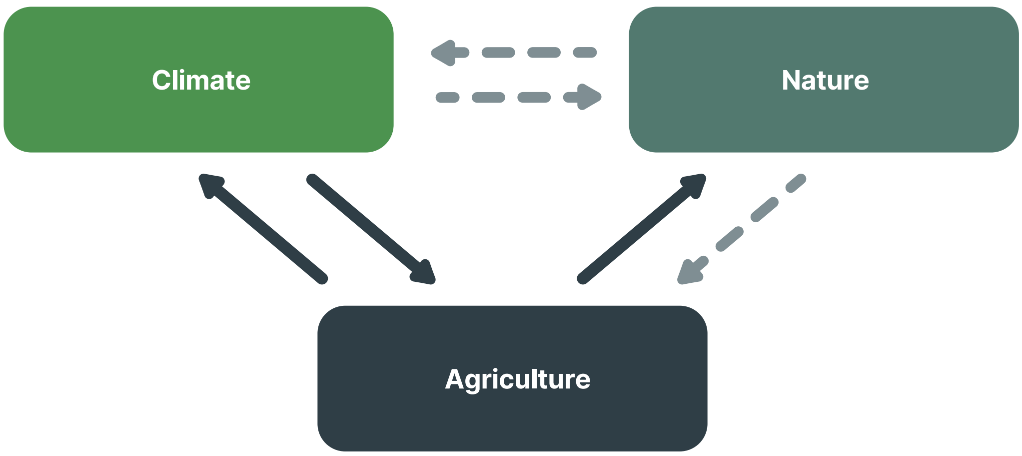
MAgPIE uses inelastic and exogenous demand projections for all scenarios. This means that the model takes regional dynamic food demand as given inputs that remain unchanged across different scenarios. This demand is calculated based on exogenous data about national population and GDP development, taking into account the preferences of a representative consumer (Bodirsky et al. 2020). The agricultural cost structure remains invariant across scenarios, with the model aiming to minimise the total costs of agricultural production for a given amount of regional food and bioenergy demand. The main differences between scenarios in MAgPIE concern the policies applied. These could include various environmental and agricultural policies such as emissions pricing, land protection measures, or trade policies. The specific policies and their implementation would vary depending on the scenario being modelled. More detailed information on the MAgPIE model is provided in the annex's extended methodological description.

Alongside MAgPIE, our modelling framework also 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) in order to capture the future impacts of climate change and environmental degradation (Figure 2). 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 simulates 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 as represented by RCPs in the modelling framework (Figure 2) (Jägermeyr et al. 2021, Stevanović et al., 2016). MAgPIE builds upon these biophysical simulations of LPJmL for selected climate change scenarios (RCPs). It 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 MAgPIE, LPJmL and REMIND models are developed and maintained at PIK.

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 therefore been coupled with the SEALS (Suh et al., 2020; Johnson et al., 2021) model, which allocates coarse-scale MAgPIE projected land use changes on a 0.5°x0.5° grid to a spatial resolution (300×300m) 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).[5]

[5] Additional information about the MAgPIE modelling 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

The interplay between climate change and agriculture is partially addressed, incorporating the impacts of climate change on agricultural sectors (e.g. change in crop yields) and the sector's GHG contribution. However, the framework does not capture the dynamic feedback loop of this relationship. The framework also considers the effects of land use practices on a selected set of ecosystem services, but does not account for how potential losses in these services might affect agricultural production. This means that the potential economic risks to the agricultural sector generated by the model should be taken as conservative estimates. Additionally, the model does not encompass the complex feedback effects between climate and nature disturbances (Figure 3).



——— **Feedback channels that are included in the modelling framework as transmitting effects between the agricultural and land use sectors, climate system and NCPs.**

- - - - **Feedback channels that are present in the real world but are not included in this modelling framework.**

Climate - - - → Nature

Example: Climate change leads to increased temperatures, altered precipitation patterns, and more frequent extreme weather events. These changes can disrupt terrestrial landscapes by degrading habitats and altering ecosystems. For example, it can shift vegetation zones, reducing the area of habitat available for native species.

Nature - - - → Climate

Example: The destruction of natural habitats, such as wetlands and forests, decreases the Earth's capacity to store carbon. When these ecosystems are degraded, the stored carbon is released into the atmosphere contributing to GHG emissions.

Agriculture ——→ Climate

Example: Agriculture contributes to GHG emissions through land use change, agricultural practices like livestock farming and fertiliser use, enhancing so greenhouse effects.

Climate ——→ Agriculture

Example: Changes in climate, such as rising temperatures and changes in precipitation patterns, affect crop yields and productivity, increasing the need for agricultural adaptation strategies.

Agriculture ——→ Nature

Example: Intensive farming and deforestation for agricultural expansion lead to natural habitat loss and soil degradation, impacting pollination supply and biodiversity intactness.

Nature - - - → Agriculture

Example: Loss of pollinators affects crop pollination, reducing agricultural yields and potentially leading to increased agricultural costs and food prices. Soil loss can also have detrimental effects on crop yields.

Figure 3. Feedback channels in the MAgPIE modelling framework.

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 by deriving two NCP indicators: soil loss by water erosion and landscape pollination insufficiency. These two NCPs were selected based on the availability of global data and the relatively good scientific understanding of how they affect agricultural production. Landscape pollination supply 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 landscape heterogeneity. The latter 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).

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 semi-natural land cover in agricultural landscapes such as forest, non-forest and grassland (Chaplin-Kramer et al., 2019). Pollination supply 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 supply scores we rank 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, 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).

Land cover and management factors are determined separately for cropland and non-cropland areas. For cropland, spatial cropping patterns of 20 crop functional types at the 0.5-degree level are taken from MAgPIE. Land cover factors are assigned to each crop functional type based on global reference values from the literature. An area-weighted average between all crop groups in each 0.5-degree grid cell is calculated and aligned with 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 Indicators for transition and physical risk

When assessing the outcomes in the land use sector, our primary emphasis is categorising both indicators for physical and transition risks. A physical risk is defined in this report in terms of physical damages to the environment and to other nature's contribution to people including changes in biodiversity. A transition risk is in turn defined as a potential economic risk that stems from sectoral alignments to climate mitigation and/or nature protection and restoration policies.[6] Physical risk indicators are reflected in the fine-scale, spatial NCP indicators, along with consideration of the status of biodiversity, 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 economic and environmental aspects. To understand the related transition risk, we consider the costs of input factors, investment decisions, and the values of agricultural production output (Table 2).

These definitions are rather different to that of the TNFD and the NGFS. The NGFS and the TNFD define nature-related physical risks as risks to organisations resulting from the degradation of nature and consequential loss of ecosystem services that economic activity depends upon. The TNFD defines nature-related transition risks as risks to an organisation that stem from a misalignment of economic actors with actions aimed at protecting, restoring, and/or reducing negative impacts on nature. These risks can be prompted by changes in regulation and policy, legal precedent, technology, or investor sentiment and consumer preferences.

Physical risk	
Indicator	**Description**
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). For the cropland landscape BII, only cells which contain at least 100 ha of cropland are considered. **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.

Physical risk	
Indicator	**Description**
Land use change	Dynamics in usage of land (cropland, pastures, primary forests, secondary forests, other natural vegetation, urban areas).
Landscape pollination sufficiency	Amount of semi-natural 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 according to IPCC (IPBES, 2018).

Transition risk	
Indicator	**Description**
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.
Investment flows in technology	Total costs of investments in yield-increasing agricultural technological change (e.g. research and development investments in new cultivars, improved agricultural management, infrastructure).
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[7] per capita per year for agricultural commodities dedicated for food use, excluding the value-added in the supply chain.

Table 2. Evaluation indicators for transition and physical risks in the agriculture and land use sector.

[7] International dollars at market exchange rate of 2005 reference year.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

4

Innovative methodological elements and limitations

NATURE FINANCE

EUROPEAN CENTRAL BANK
EUROSYSTEM

PIK

UNIVERSITY OF MINNESOTA

4.1 Innovations and limitations

The climate-nature risk scenarios framework marks the first instance of an innovative approach to integrate modelling of the agricultural and land use sectors with ecosystem services models, all within a comprehensive narrative framework. The aim is to explore integrated actions to protect nature and climate. Previous studies have addressed the economic impact of NCP losses (Johnson et al., 2021) and the economy-wide costs associated with the implementation of biodiversity conservation policies (Waldron et al., 2020), along with extensive literature on transition risks and the cost of mitigating climate change (IPCC, 2022a). However, a unified assessment of both dynamic physical and transition risks tied to action 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 nature degradation and its economic implications within an integrated nature and climate-related risk framework. Specifically, we apply the climate-nature risk scenario framework to examine the future impacts of the land use sector on fine-scale ecosystem indicators, including pollination supply, soil erosion and areas of habitat for endangered vertebrate species. This establishes a direct feedback channel between agriculture and nature (Figure 3).

Perspectives on biodiversity change are provided by assessing changes in Biodiversity Intactness (BII) and in the area of habitat (AOH) of vertebrate species. The 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 that emphasises rare and small-ranged species. 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 need for more sophisticated measures of functional biodiversity across managed and unmanaged systems. Incorporating the area of habitat for endangered species adds a spatial layer that explicitly shows how land use practices contribute to species losses in detail based on specific habitat and species type. AOH for vertebrate species is 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 modelling approach has several limitations in capturing the severity of physical climate change impacts on agriculture yields and agricultural transition risks. While modelled future crop yields consider changing weather conditions, the effects of extreme events such as floods, droughts, pests and diseases, and crop failures are not considered. This is because 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 crop yield is considered as a positive impact of higher CO_2 concentrations. Additionally, though climate change impacts on the agricultural sector are incorporated into scenario narratives at varying degrees of global warming, the impacts on crop yields are often less pronounced in near- and medium-term outputs. This is because a lower degree of global warming is projected around 2050 compared to the end of the century due to the lag in the climate system's response to GHG emissions. This discrepancy suggests that the transition risks derived from the modelling frameworks may be considerably higher than the potentially detrimental effects of climate change on crop yields and water availability. However, while global impacts may appear modest, regional variations can be significant. This discrepancy highlights the need for more integrated approaches that better capture both transition risks and physical climate impacts, to provide a more comprehensive assessment of future agricultural challenges and opportunities.

The model currently cannot account for feedback effects related to changes in NCP on climate change and agricultural production (Figure 3). Climate impacts and ecosystem service losses are examined in isolation, without accounting for potential feedback mechanisms within functioning ecosystems, or impacts of climate change on further deterioration of ecosystem services (e.g. soil erosion can be additionally driven by future climate change), which likely underestimates physical risks. Additionally, the impacts of changes in biodiversity and NCP supply, such as the impact of mismatches between pollination demand and supply or soil loss on agricultural practices and yields, are not modelled. This, again, could result in the underestimation of agricultural physical and transition risks. Incorporating these feedback effects in dynamic, decision-making modelling remains challenging but offers opportunities for future research.

Regarding NCP supply estimation, habitat restoration in agricultural landscapes is driven by current land use patterns and not optimised for NCP supply. Therefore, our pollination supply estimates are conservative, especially in the scenarios that include habitat restoration at the landscape level. An improved spatial allocation of restored habitats through targeted ecosystem management and integrated spatial planning would lead to stronger increases in NCP supply at the landscape level (Garibaldi et al. 2020). An important limitation in this model is that 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 (Drexler et al. 2021). 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. In addition, this study only provides qualitative inferences of how NCP supply and biodiversity changes are associated, since modelling approaches that directly link biodiversity changes to NCP supply could not be applied.

The principles that drive our results for NCP supply are more focused on ecosystem condition (i.e. the presence of pollinator habitats or land cover condition) rather than the direct impacts of biodiversity change. The assumption is that if ecosystems are in a good state they supply NCPs. This implicitly assumes that they harbour the species that provide NCPs.

The MAgPIE model, as a partial equilibrium model of the land use and agricultural sector, has intrinsic limitations in capturing the full-economy scope of climate and nature-related risks. While it provides valuable insights into agricultural sector dynamics, it does not account for risk propagation to other sectors or economy-wide implications. Particularly, those sectors that are downstream to agriculture are not considered. This likely underestimates the impacts of climate change and nature degradation on the economy via the agricultural sector. This limitation prevents comprehensive analyses such as financial stability testing or climate stress tests that require an understanding of impacts on overall GDP. Furthermore, the modelling of natural capital in sectoral production functions would be a crucial element to accurately capture economy-wide, nature-related risk propagation effects. The gap in economic modelling reflects a broader challenge in quantifying the financial impact of changes in ecosystem services and biodiversity. To effectively preserve nature and biodiversity, there is a pressing need to develop more integrated modelling approaches that can assign tangible financial values to changes in various ecosystem services. The model's focus on the agricultural sector limits its ability to capture the broader socioeconomic transformations necessary for a low-carbon transition and move to biodiversity conservation, including shifts in international capital and financial flows.

While the model provides insights into agricultural policies for protecting nature and climate, there is a need for greater granularity in modelling impactful policies for mitigation, conservation, and adaptation. While the current approach provides results for physical and transition risk at the EU level, it still requires a more nuanced application to capture national variations of policies and specific national impacts, given local conditions. To address these limitations, future modelling efforts should aim to integrate agricultural sector dynamics with more detailed local characteristics such as values of local ecosystems, adaptive capacities, and economic development. Additionally, there is a need to provide more detailed national policy scenario analyses that can inform targeted interventions across different regions and sectors. A summary of the limitations within the project's modelling framework can be found in Table 3.

The key data limitations within the project's modelling framework

- **Exclusion of extreme Events:** Floods, droughts, and similar events are excluded due to data and modelling challenges at local frequency levels.
- **Natural capital data gaps:** Insufficient data for modelling natural capital in sectoral production functions limits the ability to capture economy-wide nature-related risks.
- **Shortages of correlation evidence:** Limited available evidence on correlations between climate change and ecosystem service losses, as well as between different ecosystem services.
- **Need for localised data:** Local-level data is needed to model more granular impacts on the agricultural sector.

The key modelling assumptions within the project's modelling framework

- **Partial equilibrium approach:** The model is limited in capturing full-economy scope of risks due to its partial equilibrium approach.
- **Partial feedback channels:** Soil erosion and pollinator loss are not linked to agricultural production as the calibration to historical land degradation is challenging.
- **Partial investment flows:** The focus on agriculture limits the model's ability to capture broader investment flows needed for low-carbon transition and biodiversity conservation.
- **NCP assumptions:** NCP supply estimates are based solely on observed land use patterns.
- **Homogenous household:** The model assumes inelastic demand for a representative consumer, with no distributional effects on heterogenous households considered.

The key assumptions related to time horizons within the project's modelling framework

- **Climate impacts on crops:** Climate impacts on crop yields are less pronounced in the near to medium-term due to lower expected climate change effects by 2050.
- **Long-term increase of risks:** Transition and physical risks modelled could become significantly higher in the second half of the century.

Table 3. Limitation of the modelling framework. Sources contributing to the underestimation of nature-related risk highlight the difficulties in data availability, method underdevelopment and scope of the assessment.

4.2 Comparison of approach with emerging research

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. It is important to note that the work to develop the climate-nature scenario framework presented in this report started before the publication of the NGFS recommendations for scenarios assessing nature-related economic and financial risks (NGFS, 2023). Nevertheless, we found that the framework is, to a considerable extent, aligned with its recommended options for central banks and supervisors for assessing these risks (NGFS, 2023, p. 86). Table 4 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.

The LPJmL-MAgPIE-SEALS modelling framework demonstrates significant potential for addressing the majority of recommended modelling strategies for nature-related risk as outlined by the NGFS Nature Taskforce. Compared to the NGFS (2023b) review of the MAgPIE modelling framework, the modelling framework has improved its environmental scope. Its strength lies in its detailed biophysical modelling, particularly in simulating crop yields and resulting land use patterns. The new integration of MAgPIE with SEALS is especially valuable, enabling future projections of changes in crucial ecosystem services at a highly granular scale of 300×300m. It can now report fine-scale, NCP projected indicators such as pollination supply and soil erosion, as well as a refined index for biodiversity, represented by areas of habitat for vertebrate species. Nevertheless, the NGFS' overall critique remains valid that available modelling frameworks may underestimate or misrepresent the risks associated with nature loss. This is apparent from the limitations outlined above. To address this fully, further research will be required from the scientific community.

Short term Program: Building on available dynamic scenario modelling frameworks with longer-term horizons	
Options for central banks recommended by the NGFS	**Aligned within the scope of the project**
Using a carefully chosen nature-economy modelling framework while acknowledging its assumptions and limitations	[green]
Better transparency of underlying assumptions and communication of implications on results	[green]
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	[green]
Designing ad-hoc shocks in multiple sectors	[light green]
Long term Program: Improvement of dynamic scenarios by improving the interlinkages of nature-economy models	
Options for central banks recommended by the NGFS	**Aligned within the scope of the project**
Representing more numerous ecosystem services and economic dependencies to those services within the nature	[green] [light green]
Representing more policies, technological options, and socioeconomic developments	[green] [light green]
Representing some missing economic transmission channels, such as food security and productivity losses	[green] [red]
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

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

[red] Out of scope of modelling framework

Table 4. Alignment of project scope with NGFS recommendations. Alignment of project scope and modelling framework with NGFS recommended options for central banks and supervisors to assess nature-related economic and financial risks (NGFS, 2023, p. 86).

Our approach to integrated scenario narrative development presents an important building block in addressing a larger and more complex problem. Emerging studies increasingly focus on integrated scenario development (e.g., Prodani et al., 2023; Alvarez et al., 2024). A common thread across these approaches is the importance of scoping in the integrated climate and nature-related financial risk analysis. The Dutch National Bank (DNB) modelling framework (Prodani et al., 2023) differs from PIK's framework primarily in its focus on economic and financial impacts, rather than biophysical ones. DNB emphasises the transition channels from nature protection policies to the economy and financial sector by using a variety of models tailored to different scenarios, scales, and sectors. It assesses sectoral heterogeneity and macroeconomic spillover effects but does not extensively incorporate biophysical models, or directly address physical risks to biodiversity or ecosystem services. The DNB's outputs include quantitative assessments of macroeconomic impacts, evaluations of financial sector exposure to economic sectors, and stress testing for financial institutions. The DNB report suggests that transition measures may not substantially impact the Dutch economy or financial stability. In its conclusion, it acknowledges the need for more integrated modelling of nature and climate change policies, confirming the relevance of the focus area of the framework of this report. Similarly, Ranger et al. (2024) analysed the UK financial system and determined that the impacts of nature loss are highly material for UK GDP; equivalent to several years of lost growth. Their scenarios development approach builds on storyline narratives, focusing on the most material chronic and acute risks for the UK. Economic modelling is conducted using the National Institute Global Econometric Model (NIGEM) (Hantzsche et al., 2018), which provides insights into the compound climate and nature impact on GDP. While the focus of the study has been on nature-related risks, the findings reveal that incorporating nature-related risk amplifications in climate scenarios would double the estimated impact of climate change on the UK economy, compared to those currently predicted by the NGFS. Their findings confirm that considering nature and climate in isolation significantly underestimates the risks.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

5

Results

NATURE FINANCE

EUROPEAN CENTRAL BANK
EUROSYSTEM

PIK

UNIVERSITY OF MINNESOTA

This chapter presents our findings on physical risks and transition risk indicators at global and EU levels. In the context of this report, physical risk indicators measure quantifiable changes in environmental conditions and ecosystem services, including both negative and positive effects on biodiversity, ecosystem health, and NCPs. Transition risks refer to the economic risks within the agricultural sector arising from the shift towards practices and policies for climate and nature protection. The results correspond to the indicators outlined and defined in Table 2. This chapter is supported by further discussion of the results for each scenario in Chapter 6, and by additional complementary results for other indicators in the Annex.

5.1 Physical risks results

The scenario 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). Climate protection policies (*Disorderly scenario*) incentivise the conservation of intact forest landscapes and areas with high carbon uptake potential for atmospheric carbon dioxide sequestration. Thereby, they also provide important synergies with conserving biodiversity in global biodiversity hotspots, of which many are located in the tropics. However, our results also indicate that land-based, climate change mitigation measures could adversely affect biodiversity in managed landscapes. This comes through increased pressures on the intensification and specialisation of agricultural systems, as shown, for example, in the crop diversity and cropland landscapes BII indices. The continued loss of biodiversity in managed landscapes could further degrade critical ecosystem functions and undermine the long-term sustainability of food production (Rasmussen et al. (2024); Estrada-Carmona et al. (2022); Tscharntke et al. (2021); Dainese et al. (2019)). Furthermore, the degradation of nature in the absence of climate and nature protection policies (*degraded world scenario*) exacerbates the decline in biodiversity both in managed and largely intact landscapes globally. Overall, the impact on biodiversity varies across different dimensions of biodiversity change across the d*isorderly, 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. Similarly, in the EU, dedicated nature protection measures increase biodiversity indices by safeguarding critical habitats and species. These measures are essential, as climate policies promoting afforestation projects could inadvertently threaten biodiversity hotspots by converting them into less diverse plantations (*Disorderly scenario*). However, since the model projects the EU's business-as-usual agricultural practices continuing without significant land use changes (Figures S4, S5 and S6), biodiversity does not decline in the baseline *Degraded World scenario*, a situation that might differ if the feedback effects on biodiversity were fully incorporated into the model.

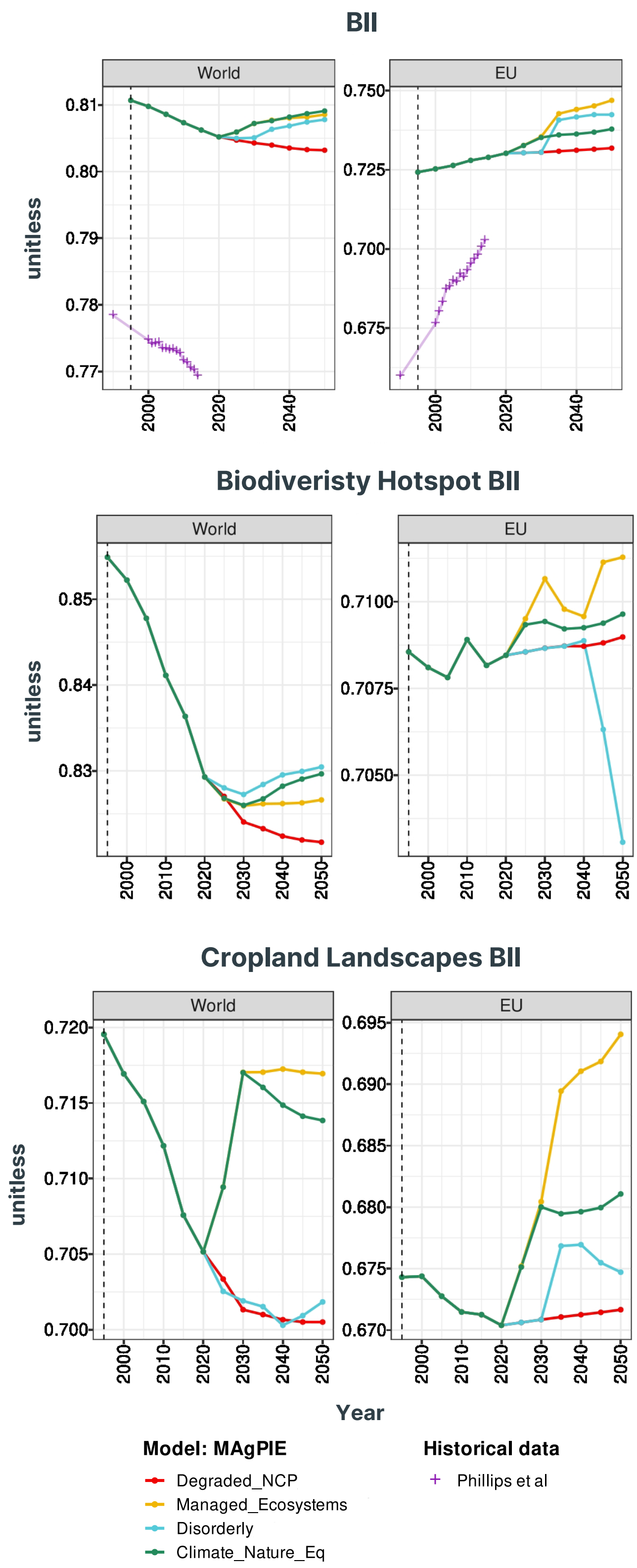


Figure 4. Biodiversity indicators in the climate-nature risk scenario framework, globally and for the EU. The Biodiversity Intactness Index (BII) quantifies net changes in species abundance in response to land use change. Changes are measured relative to a reference land use class (either native forested 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.

The lack of biodiversity protection measures in the *Degraded World scenario*, results in widespread loss of area of habitat across the globe. Habitat loss is particularly pronounced for birds and reptiles, especially in forest habitats, but also significantly affects amphibians and mammals (Figure 5). Conservation action in the *Managed Ecosystems scenario* reduces some of the largest impacts (>40 of habitat loss), but the number of affected species remains considerable. In the *Disorderly scenario*, avoided deforestation as a result of the carbon price incentive leads to slightly lower species impacts, but habitat losses at >40% remain higher than in the *Managed Ecosystem scenario*. In the *Climate-Nature Equilibrium scenario* habitat loss of forest birds, mammals and reptiles is lower. However, there are considerable leakage effects regarding impacts for amphibians and open habitat birds that result from the increased competition for land due to the combined climate and nature policy ambition. The situation underscores the critical importance of conservation efforts that not only include targeted efforts that address these leakage effects (Popp et al., 2014) but also address the underlying drivers of biodiversity loss through additional demand-side actions. Due to the limited land use changes projected in all scenarios for the EU region (Figures S4-S6), limited differences are visible in the AOH at the EU level.

Figure 5. Projected number of species with more than 20 % habitat loss between 2020 and 2050 across different species groups (a) for all assessed species. Results are also presented separately for (b) forests habitat and (c) open habitat species.

In the *Degraded World scenario*, globally the loss of essential NCPs continues over time, with areas experiencing high soil erosion and insufficient pollination supply increasing significantly. By contrast, these issues are considerably reduced in protection scenarios (Figure 6). For the selected 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 and trade-offs. Notably, conservation interventions within the *Managed Ecosystems scenario* show promise in significantly restoring their pollination supply (Figure 6.D). However, these interventions would also lead to cropland relocation to areas with a higher susceptibility to water erosion (Figure 6.B). This underscores the need for a nuanced understanding of the multi-faceted 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. In the EU, synergies between climate protection policies and ecosystem services are evident in increasing cropland areas with high pollination supply, but the *climate-only Disorderly scenario* demonstrates the most positive outcomes for soil erosion and low pollination area reduction by 2050 (Figure S7). This is primarily attributed to the reduced extent of cropland in the *Disorderly scenario* compared to other scenarios in 2050 (Figure S4). However, it's crucial to note the temporal dynamics at play. Before 2050, only scenarios incorporating nature protection measures exhibit lower cropland areas and can consequently indicate better ecosystem service outcomes (Figures S4, S5, S6 on land use dynamics for croplands, forests, and other nature vegetation).

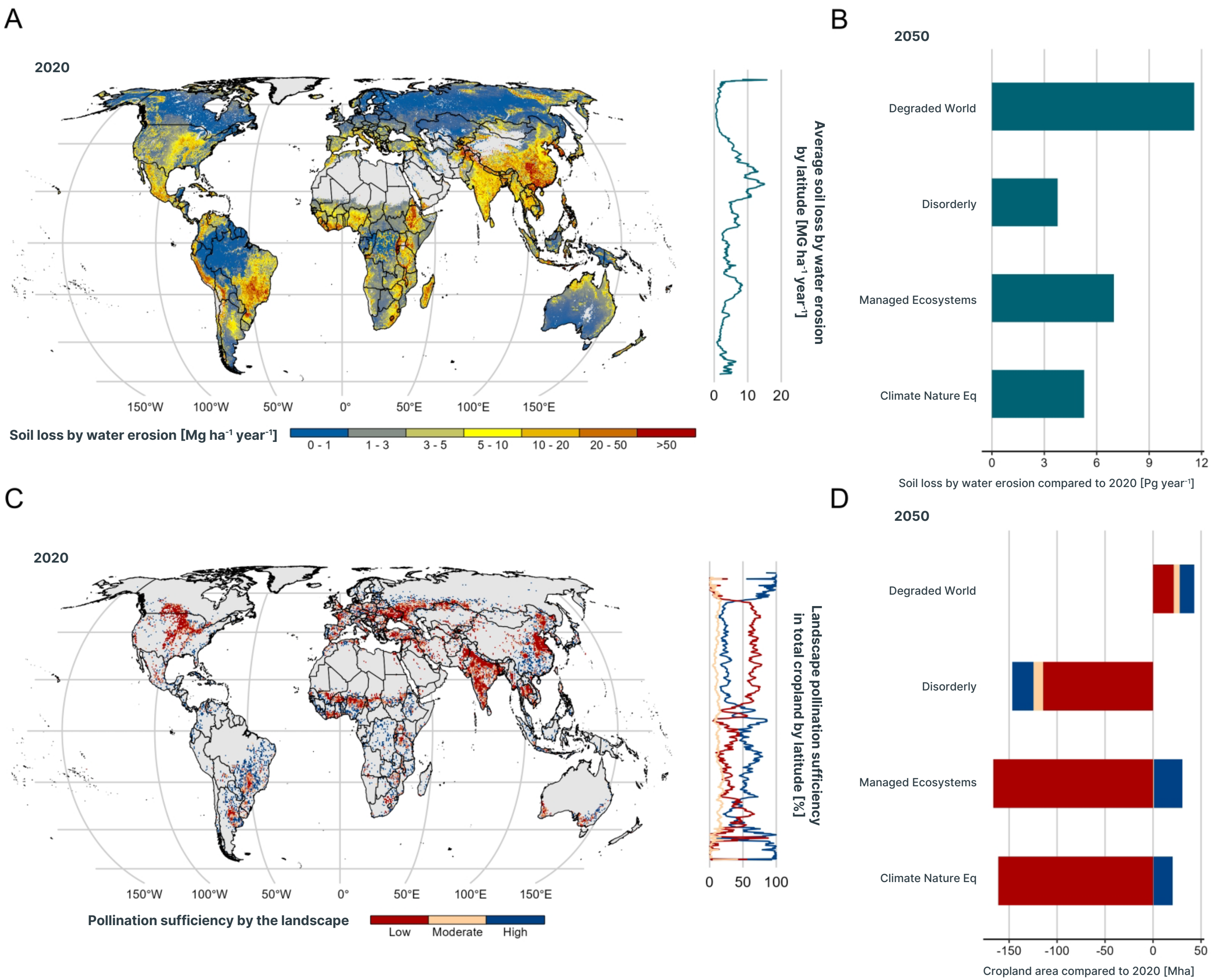


Figure 6. Landscape pollination insufficiency and soil loss by water erosion in 2020 and projected changes by 2050 based on MAgPIE-SEALS. Global maps of pollination insufficiency and soil loss by water erosion for 2020 were directly derived from land cover maps from the European Space Agency's Climate Change Initiative (ESA-CCI). Projected changes (panels B and D) are based on a fine-scale allocation of land use changes in each scenario and show global aggregate values of respective NCPs in terms of cropland affected.

5.2 Transition risks results

The analysis of transition risk indicators highlights a progressive increase linked to the integration of stable climate and nature considerations within the land use system. These indicators are intrinsically linked through economic activities in the agricultural and land use sector, where increased investments lead to higher production costs and rising marginal costs and therefore prices of agricultural commodities. However, this transition also presents potential opportunities for stimulating sectoral economic growth and raising overall agricultural GDP.

Implementation of climate and nature protection measures inherently raises agricultural costs. In the mid term, transition risks in the EU and globally are primarily shaped by nature protection policies, aligning closely with targeted achievements by 2030 (Figure 7). Agricultural production costs associated with these policies are relatively moderate during this period. Beyond 2030, total agricultural production costs increase significantly through 2050, driven largely by intensified climate protection policies aimed at achieving global net-zero targets. This places the *Disorderly scenario* at a higher transition risk level for considerably increased production costs in the agricultural sector.

Integrating nature protection into climate policies plays a crucial role in reducing agricultural costs of production and food prices and thus mitigating associated transition risks. However, projections indicate that increased food demand will continue to drive total and marginal production costs upward across all scenarios (Figure 7). This trend suggests potentially stronger distributional impacts across the population (which are not explicitly considered in the current modelling framework). To address these challenges, additional measures could be incorporated into the nature and climate protection policy package to alleviate impacts on households with different income levels. Notably, liberalising international trade for agricultural commodities could potentially reduce total agricultural production costs, as demonstrated in the sensitivity scenario analysis for trade liberalisation (Figure S2). However, this approach requires careful consideration of trade flow dependencies among global regions, particularly for exporting regions that may experience a loss in market share. Additionally, omitted feedback effects in the model, such as extreme weather events, ecosystem degradation, and interactions between climate and nature could in reality reduce agricultural productivity and diminish the positive impact of trade liberalisation. These findings underscore the complexity of balancing environmental protection, economic considerations, and social equity in agricultural policy design.

Agricultural production costs remain relatively stable and underestimated in the degraded world scenario (Figure 7). This can be attributed to the absence of costly climate and nature protection policies, and because the current modelling framework does not consider transmission channels to agricultural production from nature degradation under business-as-usual. Potential disruptions such as loss of pollinators or extensive soil erosion could significantly impair agricultural production and necessitate costly efforts to reallocate production (Figure 6). The full extent of these impacts warrants further assessment in future modelling exercises.

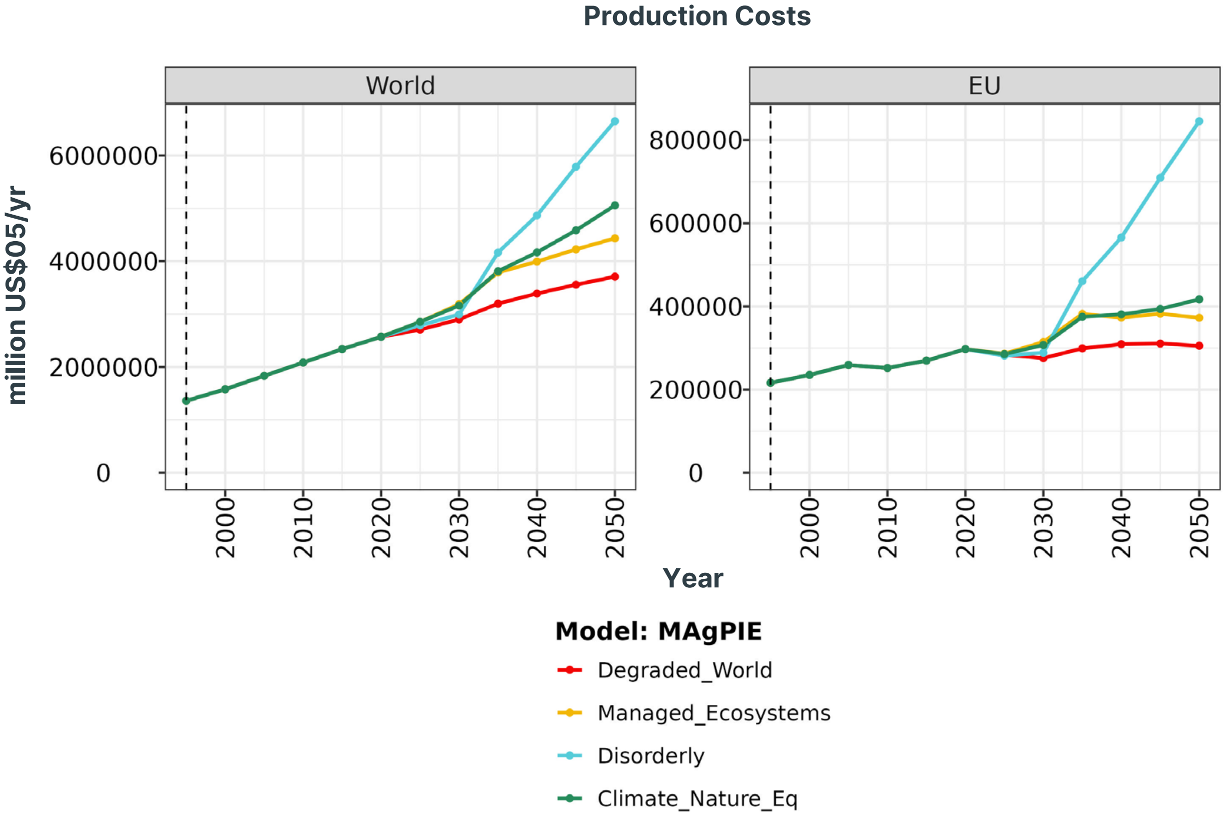


Figure 7. Total agricultural production costs globally and in the EU across scenarios (in million US$2005/yr). These costs include labour, fertiliser, capital, land conversion (non-agricultural to cropland and cropland to rangeland), technological change, irrigation, and costs associated with GHG emissions pricing policy.

While climate and nature protection policies may elevate agricultural costs due to the need for investments in sustainable practices and technologies, they also have the potential to enhance the sector's added value both at the global and EU level (Figure 8). Agricultural products are necessity goods, meaning that demand for them is relatively inelastic to changes in prices. This inelasticity is supported by steadily increasing average income per capita, as assumed in all climate-nature scenario narratives based on the underlying *socio-economic SSP2 scenario*. In the model, agricultural demand is assumed to relate to changes in the residual income of a representative consumer. Consequently, even with rising agricultural costs, the non-declining demand for agricultural commodities ensures that sectoral GDP continues to grow, particularly in scenarios with the highest agricultural prices (Figure 8). While the model results, under the given model assumptions, show that the agricultural sector has the potential for adaptation and can benefit from environmental policies that result in sectoral GDP growth, the effects on the overall economy remain unclear. The effects on inflation could potentially disrupt other sectors and significantly impact overall GDP. This underscores the potentially complex interactions within the economy, where rising agricultural prices can lead to varied outcomes across other sectors and potentially alter consumption patterns.

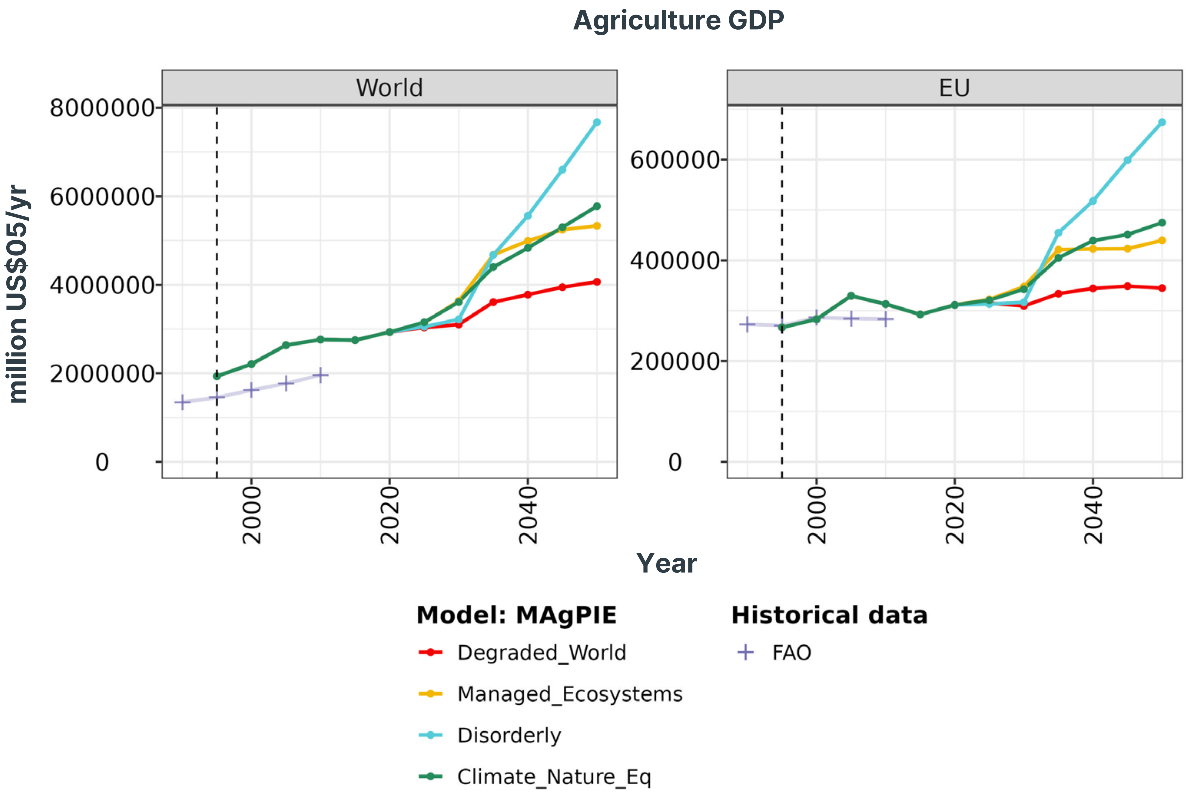


Figure 8. Agricultural GDP globally and in the EU across scenarios in the climate-nature risk scenario framework (in million US$2005/yr). GDP is calculated through cumulative value added as the difference between total agricultural revenue and total production costs. This figure includes only primary and secondary commodities (processed products such as oils, sugar, etc.) for crop and livestock products, excluding the retail sector for agricultural goods.

The climate policy's direct taxation of greenhouse gas emissions from livestock production systems emerges as an important driver influencing the modelled agricultural price index both at the global and EU level (Figure 9). This is primarily due to the substantial increases in the marginal cost of production, which serve as the main drivers for total production costs in the agricultural sector (Figure 7). Interestingly, the *Climate-Nature Equilibrium scenario*, which integrates both nature and climate protection measures, appears to foster greater stability than the *Disorderly scenario* in terms of the transition of food prices (Figure 9) and the added value of agricultural production (Figure 8). This scenario likely achieves this balance by implementing comprehensive policies that both address climate change and preserve biodiversity and ecosystem services while sustainably allocating land for agricultural production before the more ambitious climate mitigation measures are implemented post-2030. Consequently, this scenario potentially offers a more balanced transition for the agricultural sector, maintaining economic viability while still achieving environmental goals in the long term.

Prices Index 2020 Agriculture Food products

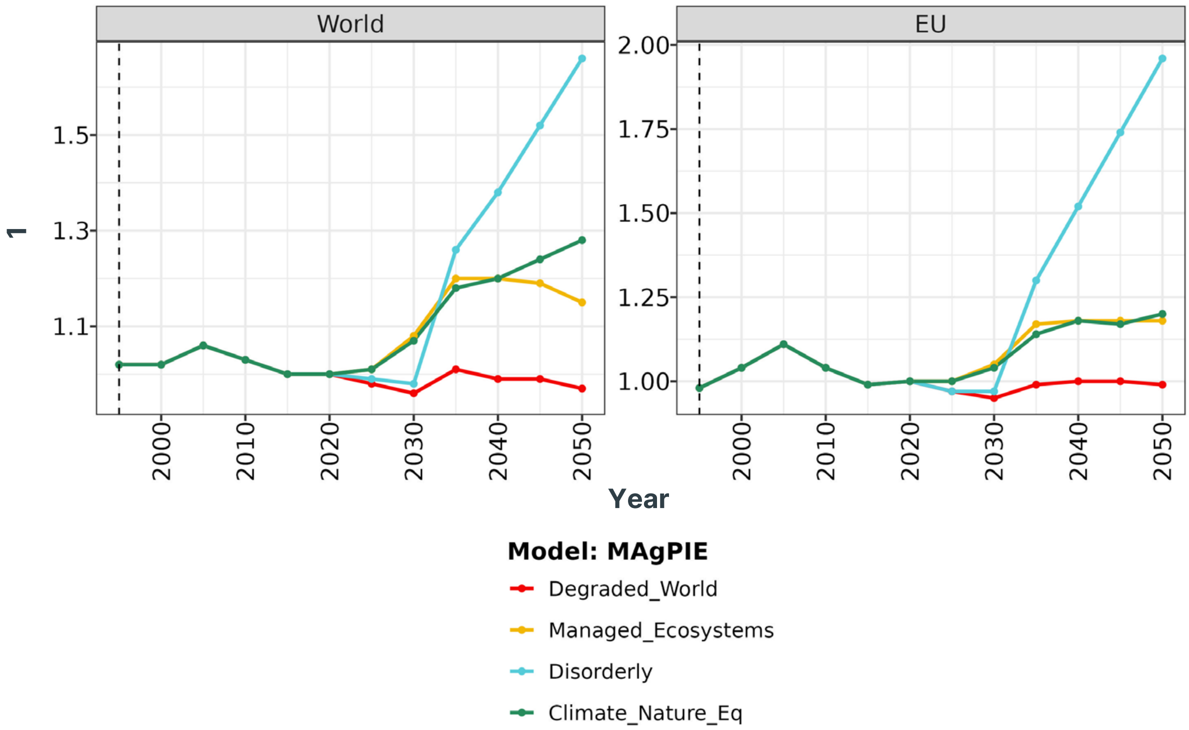


Figure 9. Agricultural commodity price index globally and in the EU across scenarios (index value, normalised to 1 in the year 2020). It is calculated using the Laspeyres price index for crop and livestock products.

Diverse investment strategies reflect the agricultural sector's multifaceted response to climate change mitigation, biodiversity conservation and rising demand for agricultural products (Figure 10). Significant shifts in investment priorities are evident in all protection scenarios (silos and nexus), with a growing emphasis on technological change (TC) advancements (yield-increasing R&D investments, production management efficiencies and infrastructure development). These are particularly high in order to meet nature protection targets in 2030 globally and in the EU. The investments lead to higher crop yields within existing agricultural areas, reducing the need for land conversion, which is highly relevant for supporting biodiversity conservation and land protection measures (*Managed Ecosystems and Climate-nature Equilibrium*). Increasing cropland productivity through investing in TC is also relevant for the *Disorderly climate protection scenario*, albeit to a lesser extent compared to other protection scenarios, as there is more flexibility in investing in land conversion and reallocation. However, the model's assumptions on possible future yield advancements might be optimistic, given that the modelling framework does not account for the feedback between the loss of NCP and agricultural productivity. Investments in new irrigation infrastructure are essential for supporting cropland intensification in all protection scenarios globally. However, it is important to manage water resources in a sustainable manner to ensure long-term environmental and agricultural sustainability. Lastly, capital investments are crucial for supporting various aspects of agricultural practice improvement. These investments primarily involve reallocation of agricultural land and the creation or shift of on-farm capital elsewhere, while supporting increased productivity from advancements in yield-increasing technological investments. Therefore, capital farm investments are increasingly required in climate and nature protection scenarios in regions where more cropland areas reallocation takes place.

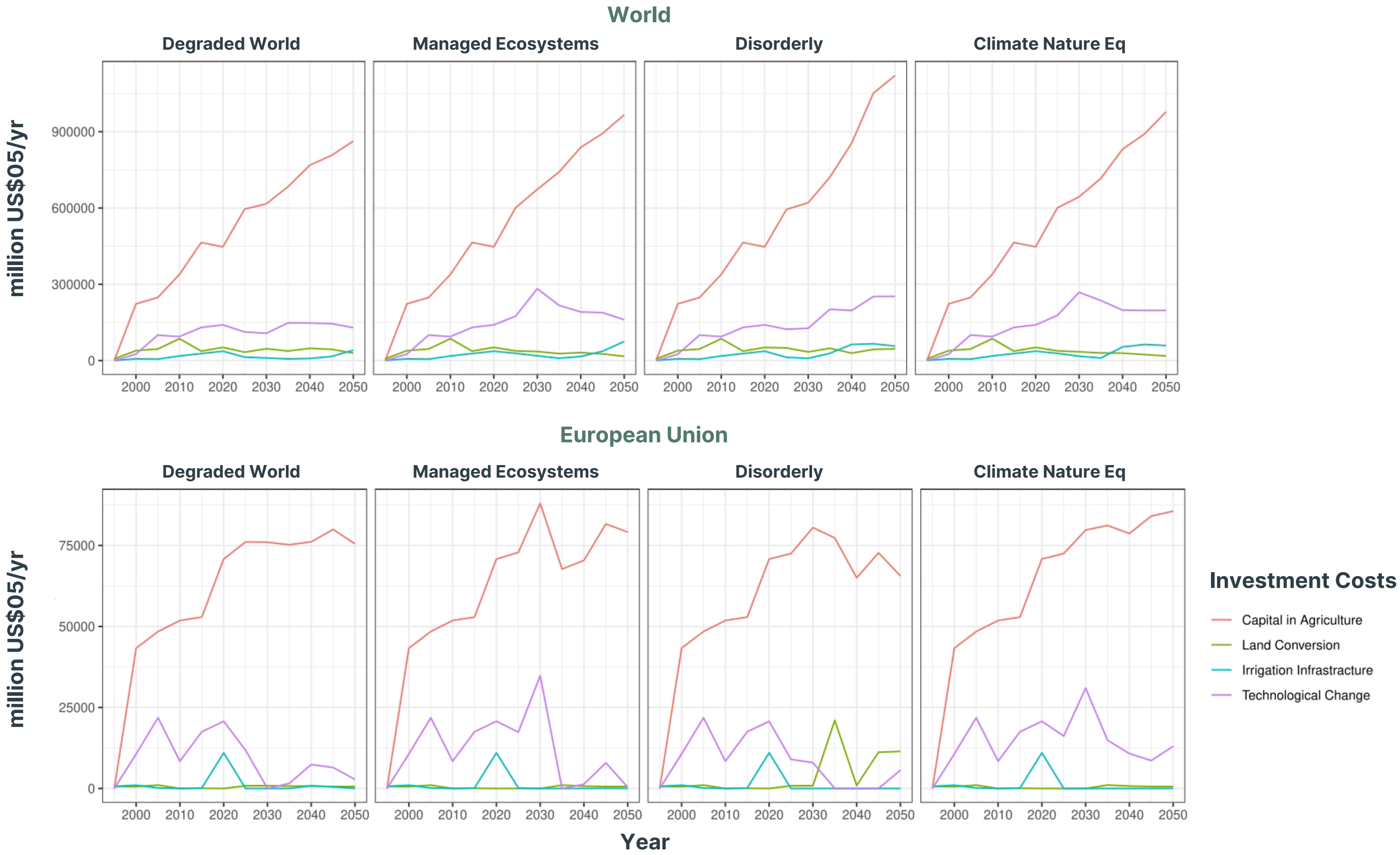


Figure 10. Investment costs in the agricultural production systems globally and in the EU. The model calculates annual (i.e. one modelling period), endogenous levels of different investment types needed to maintain the supply for a given agricultural demand. These include: Investments into on-farm capital needed for establishing, producing, and/or spatial relocation of agricultural land activities; Land conversion costs for converting arable land under forests and other natural vegetation into croplands and pastures; Investments in new irrigation infrastructure; and Yield-increasing technological change investments (including R&D of improved agricultural cultivars, management, and infrastructure)

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

6

Evaluation and implications of results

NATURE FINANCE | EUROPEAN CENTRAL BANK EUROSYSTEM | PIK | UNIVERSITY OF MINNESOTA

This chapter presents our findings on both physical and transition risks in an integrated way by going through each scenario. It is supported by the overview of individual results in Chapter 5 and the additional indicators presented in the Annex.

6.1 Business-as-usual: Degraded world scenario

The *Degraded World scenario* presents a concerning trajectory for land use, ecosystem health and degradation, as evidenced by the physical risk indicators. This is driven by a continuation of business-as-usual practices and a persistent trend of increasing cropland to maintain agricultural production, primarily achieved by converting forests and other areas with rich natural vegetation (Figures S4-S6). The physical risk indicators show the highest rates of biodiversity loss (Figures 4,5), continued decrease in areas with sufficient pollination supply and the greatest soil loss due to water erosion (Figure 6). This scenario underscores the impact of unregulated land use practices on global ecosystems. It highlights the urgent need for comprehensive environmental policies to prevent further degradation. This trend is part of a larger pattern of land degradation, with up to 40% of the planet's land already degraded (UNCCD, 2022).

In the EU, while cropland is expected to remain relatively stable until 2050 due to forest protection measures implemented across member states, the *degraded world scenario* still leads to the highest soil erosion rates. This is attributed to the relocation of arable areas and land swapping, where some agricultural lands are set aside while natural vegetation areas are converted to cropland (Figure S5). Climate change is also driving this shift, making higher latitude areas in the EU more attractive for agriculture. Recent research by Prăvălie et al. (2024) indicates that a significant portion of European agricultural and arable lands are currently threatened: 10–11% of pan-European agricultural landscapes are cumulatively affected by at least four concurrent degradation processes, highlighting the urgent need for sustainable land management practices and policies. Transmission impact channels between climate and ecosystem services and biodiversity, albeit not currently accounted for in the modelling framework, could potentially exacerbate the degradation of land and speed up the manifestation of physical risks.

The *Degraded World scenario*, characterised by no action on climate change and biodiversity conservation, initially presents lower transition risks compared to more ambitious environmental protection scenarios. The assessment suggests that this scenario would result in minimal, mid-term economic disruptions alongside stable costs and prices associated with the projection of agricultural demand (Figures 7-9). However, there are likely long-term consequences due to the time-lagged impact of nature degradation on food production, which could have significant financial implications in the future. These are not captured by the modelling framework given the methodological limitations.

The transition risk associated with the *Degraded World scenario* is significantly underestimated in current assessments, potentially leading to misguided decision-making. While this scenario may appear to offer a more economically stable, near-term future by avoiding immediate economic shocks from nature-related risks, it fails to account for the long-term consequences. The primary reason for this underestimation is the lack of inclusion of feedback channels from ecosystem service losses to agricultural production in the model. Studies have attempted to quantify these impacts, which estimated significant yield reduction coefficients due to pollinator loss for over 40 crops (Klein et al. 2007), and which suggested an 8% crop productivity loss where soil loss exceeds 11 tonnes per hectare (Panagos et al. 2018). However, calibrating these estimates to observed NCP degradation and incorporating them into observed yield patterns remains a significant challenge, leading to an incomplete representation of the true economic costs of ecosystem degradation.

The second major factor contributing to the underestimation of transition risk is the delayed manifestation of climate change impacts on agricultural productivity. The *Degraded World scenario* follows a strong GHG concentration pathway, potentially leading to a temperature increase of up to 4°C by 2100 where agriculture could face severe challenges including widespread crop failures, shifts in growing zones, increased water scarcity, and more frequent extreme weather events, potentially threatening global food security. However, the effects on agriculture of this strong climate change are not easily identifiable in the first half of the century, which is the time horizon for our modelling. Recent studies, such as those by Molina Bacca et al. (2023) and Jägermeyr et al. (2021), indicate that even for strong climate change scenarios, mid-century impacts on crop yields are relatively small, with most significant effects occurring towards the end of the century. This delayed impact creates a false sense of security and resilience in the near term, masking the true extent of the transition risk. As a result, the *Degraded World scenario* may appear less risky in the mid term, but it fails to account for the potentially more dangerous long-term consequences of continued environmental degradation and climate change.

6.2 Climate protection only: Disorderly scenario

Economically, the *Disorderly scenario* has significant implications for the agricultural sector globally and in the EU (Figures 7-9). The most notable impact is on the prices of agricultural products, primarily due to the direct taxing of GHG emissions from agricultural production practices (mainly in the livestock sectors, but also in the use of nitrogen fertiliser on agricultural lands). This policy-driven increase in production costs could potentially have detrimental effects on population cohorts with lower income levels (Soergel et al. 2021). While climate protection efforts may increase agricultural production costs, there is evidence in the scientific literature of several strategies to ease this transition and alleviate the impact on food prices. For instance, shifting diets towards less carbon-intensive products, such as plant-based or artificial meat, not only reduces emissions but also decreases feed demand for the livestock sector, thereby reducing marginal costs of crop production (Springmann et al. 2018, Stevanović et al. 2017). It is important to note, however, that advocating for dietary shifts must be done with care to avoid disproportionately burdening lower-income households. Additionally, trade liberalisation could lead to a more optimal allocation of agricultural production globally, potentially reducing overall production costs (Figure S2). However, careful cross-border agreements need to be established to maintain fair competitiveness for local and regional players in the global market (Stevanović et al. 2016).

The *Disorderly scenario* requires higher investments in technological improvements and more efficient agricultural management, land conversion, reallocation, and infrastructure development in order to maintain the global supply of agricultural products (Figure 10). As climate efforts intensify, albeit belatedly, the need for investment in irrigation infrastructure becomes increasingly crucial. Increased global investment in capital in agriculture, particularly in the context of climate policies, is also needed. If production costs increase while demand and production remain relatively stable, climate mitigation policies may present an opportunity to boost sectoral added value. In fact, if the increase in agricultural commodity prices is moderate enough to keep demand unchanged, the transition risks may even benefit the agricultural sector. However, it remains to be seen how other dependent and downstream sectors are affected by the delayed climate mitigation policy and how this may spill over to consumers and the economy.

From a physical risk perspective, there is a potential danger that climate change mitigation policies could exacerbate, or at least not prevent, further deterioration of some NCPs, in particular biodiversity in different habitats. In the *Disorderly scenario*, policies indirectly reduce natural vegetation areas globally (Figures 5, S5-S6). While forest areas are expanded at the expense of existing croplands and pastures, the reallocation of arable areas potentially leads to significant loss of biodiversity-rich, non-forest biomes. Climate policies might inadvertently jeopardise biodiversity hotspots in pursuit of afforestation projects, which themselves may be poor in species diversity, particularly plant diversity, as they tend to often result in monoculture biomes. In the EU, the *Disorderly scenario* triggers endogenous afforestation as a response to the lack of nature protection elsewhere, although natural vegetation remains largely protected within the EU. Moreover, since the feedback effects of ecosystem service losses on agricultural production are not accounted for in the modelling assessment, neglecting nature protection in the *Disorderly scenario* may result in an additional cost for the sector and the economy.

It is important to note that measures to reduce transition risk in the agricultural sector, such as reallocating production through international trade channels or shifting agricultural demand, might not necessarily improve the prospects for physical risk and nature protection. International trade may lead to leakage effects, where important biomes are disrupted for the sake of lower global production costs (Schmitz et al. 2014). Similarly, diet shifts, particularly in many developing countries, might involve reducing the intake of staple foods in favour of more nutritious plant-based foods, but not replacing resource-intensive livestock products. Even a partial dietary shift though could significantly reduce important barriers to conservation and lower transition risks (von Jeetze et al, 2024, submitted).

6.3 Nature protection only: Managed Ecosystems scenario

The *Managed Ecosystems scenario* presents a comprehensive approach to global conservation efforts, aiming to protect and restore biodiversity while maintaining sustainable agricultural production. This scenario envisions a significant expansion of protected land areas to 30% of the earth's land surface by 2030. This ambitious goal represents a substantial increase from the current 15% of protected land area, adding 1.83 billion hectares globally, with a focus on biodiversity hotspots and intact forest landscapes. The strategy not only aims to preserve existing natural habitats but also emphasises the restoration and retention of at least 20% of (semi-)natural habitats within farmed landscapes. This approach is designed to ensure a stable supply of important regulating ecosystem services, which are crucial for sustainable agricultural production.

Under the *Managed Ecosystem scenario*, the expansion of croplands into natural areas is drastically reduced, with nature protection measures proving most effective in reducing agricultural encroachment (Figures S4-S6). Nature protection measures contribute to the expansion of natural forests globally. In the EU, these conservation efforts are expected to increase biodiversity significantly (Figure 4). Notably, conservation interventions within Managed Ecosystems show promise in significantly restoring pollination services, a critical ecosystem function for agriculture. An important caveat is that these interventions may lead to cropland relocation to areas with higher susceptibility to water erosion, presenting a potential trade-off that needs careful consideration (Figure 6). Even though there are no stringent climate policies in this scenario, the climate effects on crop yields and water availability are expected to be smaller in the medium term, without substantial implications for agricultural production until 2050. However, global warming in this scenario goes beyond 2°C at the end of the century, implying potential damages of much stronger magnitude (IPCC, 2022a). The omission of extreme weather events in the modelling assessment underestimates potential frequent local disruptions of seasonal agricultural outputs, highlighting the need for increased efforts to build more resilient agricultural production options.

From a transition risk perspective, the *Managed Ecosystems scenario* presents a moderate increase in agricultural production costs compared to the higher costs of the *Disorderly scenario* and steady costs of the *Degraded World scenario* (Figure 7). The production costs in the *Managed Ecosystems scenario* arise from the need for additional investments in the sector aimed at increasing productivity (Figures 10, S3). With limited areas available for cropland expansion, there is a shift away from land conversion investments towards greater intensification of crop production. This necessitates larger investments in irrigation infrastructure and, to a greater extent, in yield-increasing technological changes globally. However, this approach in agricultural management could be challenging due to potential future limitations in closing yield gaps and reaching yield saturation levels (Ray et al. 2013). From a modelling perspective, this outcome may be optimistic, as the model does not account for feedback between the loss of NCP and agricultural productivity. The scenario emphasises the importance of mid-term investments until 2030 to meet the targets for global biological diversity protection. In the EU specifically, nature protection measures require larger investments in agricultural research and development. These investments and policy changes aim to balance the needs of biodiversity conservation with sustainable agricultural production, presenting both challenges and opportunities for the agricultural sector as it adapts to new conservation paradigms.

6.4 The integrated approach: Climate-Nature Equilibrium scenario

The *Climate-Nature Equilibrium scenario* presents an integrated approach to addressing both climate change and biodiversity loss, aiming to achieve a balance between the two. This scenario combines climate and nature protection targets, resulting in a maximal reduction of cropland by 2050 worldwide across all of the framework scenarios (Figure S4). It aligns the climate policies crucial for mitigating global warming at 1.5°C and avoiding far-reaching impacts on ecosystems, together with the "30×30" biodiversity protection goal, which aims to protect 30% of land areas globally by 2030 (UNEP-WCMC, 2022). The overall dynamics in agricultural systems focus on reducing croplands, similar to the *Managed Ecosystems scenario*, particularly in the EU, with the potential for further cropland reduction post-2030 in other parts of the world (Leclère et al., 2020). Forest areas increase globally in this integrated scenario to a similar net magnitude as in the climate-only *Disorderly scenario* (Figure S5). However, regional differences may occur. The *Climate-Nature Equilibrium scenario* allows for near-term nature conservation measures to protect or create new forest areas, potentially providing increased storage for carbon dioxide sequestration in these forests for post-2030 mitigation policies (Griscom et al., 2017). In the EU, the integrated scenario does not result in additional forest increase compared to the climate-focused *Disorderly Climate scenario*, suggesting that existing environmental policies in the EU member states may already be optimising forest cover for carbon dioxide removal capacities within this region.

While the integrated approach shows clear positive effects for all physical risk indicators compared to the *Degraded World scenario* (Figures 4-6), these benefits may not be always as pronounced as levels achieved through scenarios with siloed protection approaches. This is primarily due to the interaction between climate and nature protection policies and the subsequent relocation of cropland, given the limited availability of arable areas once certain regions are dedicated to biodiversity protection or atmospheric carbon storage. On a global scale, the *Climate-Nature Equilibrium scenario* does not reduce soil erosion as effectively as the climate-focused *Disorderly scenario* (Figure 6). This outcome highlights the potential trade-offs between the enlargement of protected areas and soil conservation. This is because the relocation of croplands under combined nature and climate policies may inadvertently lead to some increases in soil erosion if cropland is driven into areas that are more susceptible to water erosion. Conversely, for pollination supply in croplands, the integrated approach performs better than the *Disorderly scenario* in restoring areas with pollinators (Figure 6). However, it falls short of the achievements seen in the *Managed Ecosystem scenario*. This difference can be attributed to the additional land requirements for bioenergy monoculture crop production and forest plantations in the *Climate-Nature Equilibrium scenario*, which may limit the available habitat for pollinators. These findings underscore the importance of considering both climate and nature aspects at local scales. The relevance of these NCPs can vary significantly depending on local conditions, making it crucial to tailor protection levels to maximise benefits for both nature and local communities.

In the *Climate-Nature Equilibrium scenario*, the increase in land use productivity is most pronounced, both globally and within the EU, due to the resulting limitations on expansion into forests and other natural vegetation areas (Figure S3). This intensification of agricultural production is a direct response to the dual pressures of climate change mitigation and biodiversity conservation, which restrict the availability of new land for cultivation. To achieve this higher productivity, there is also a greater need for investment in irrigated production systems and the expansion of existing irrigation infrastructure globally and in the EU (Elliott et al., 2014). This shift towards more intensive, irrigated agriculture represents a significant transition risk because it requires substantial capital investment and may lead to increased water stress in some regions (Figure 10).

An integrated approach to environmental protection may lead to more economically sustainable outcomes in the long term. Despite higher requirements for productivity increases, production costs and prices do not increase substantially in the *Climate-Nature Equilibrium scenario* compared to the business-as-usual scenario. When compared to the climate-only *Disorderly scenario*, integrating nature protection policies helps buffer the cost increase from climate protection policies. The transition risks associated with the integrated scenario are thus multifaceted. While the need for increased productivity and irrigation expansion presents challenges, the potential for cost stabilisation through integrated policies offers a pathway to manage these risks.

The complexity of these interactions highlights the need for careful policy design and implementation. While an integrated approach offers substantial benefits, it also requires a delicate balance to avoid unintended consequences (Figures 7, 9). Future research and policy development should focus on optimising the synergies between climate and nature protection while minimising potential conflicts, particularly at local and regional levels.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

7

Conclusions and recommendations for future research

NATURE FINANCE

EUROPEAN CENTRAL BANK
EUROSYSTEM

PIK

UNIVERSITY OF MINNESOTA

7.1 Key findings

Our 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 policies, impacts and risks, as two sides of the same coin. We showcase the results of an integrated climate-nature scenario development and illustrate the relevance of a variety of biophysical and economic indicators globally and in the European Union for the agricultural and land use sector.

Our results show that an integrated approach to environmental protection, as exemplified in the *Climate-Nature Equilibrium scenario*, leads to more economically sustainable outcomes in the long term. Despite the higher technological requirements for increasing agricultural productivity, this scenario does not result in substantial increases in production costs and prices. Notably, the integration of nature protection policies helps buffer the cost increases associated with climate protection measures.

Our results also show the importance of integrating nature-based solutions into climate strategies, revealing that robust nature policies can facilitate more effective and less disruptive climate change mitigation. While climate policies, particularly in the land use and agricultural sector, have been implemented slowly, existing nature protection measures are already contributing significantly to environmental goals. Our findings demonstrate that biomes established through nature protection by 2030 will create expanding terrestrial carbon storage, potentially mitigating transition risks associated with delayed climate action. However, this outcome might be affected by factors omitted from the model, such as impact of climate change on nature, including the resilience of the biome ecosystems and their ability to survive and sequester carbon. The more immediate timelines of nature conservation targets such as the "30×30" initiative from the Kunming-Montreal Global Biodiversity Framework, compared to end-of-the-century temperature targets or mid-century net zero targets, offer opportunities for early, impactful intervention. By prioritising nature conservation, policymakers can address both biodiversity loss and climate change concurrently, potentially easing the path to long-term climate goals.

Protecting the climate does not automatically safeguard nature. The *Disorderly scenario*, which focuses solely on implementing climate policies, demonstrates that such an approach does not consistently yield positive outcomes for biodiversity conservation. In fact, land-based climate mitigation strategies, such as large-scale afforestation and the promotion of monoculture, second-generation bioenergy production, can inadvertently pose threats to biodiversity-rich areas and diverse landscapes. These measures risk converting ecologically valuable habitats into less diverse plantations, potentially undermining biodiversity even as they address climate concerns. This finding highlights the crucial need for dedicated nature protection measures to be implemented alongside climate policies.

The integration of climate and nature protection measures reveals both trade-offs and synergies in addressing global environmental challenges. On the one hand, the integrated approach necessitates increased agricultural productivity and irrigation expansion, which could strain resources and require significant investments in technology and infrastructure, presenting potential challenges and transition risks. On the other hand, important synergies arise from combining climate and biodiversity policies, demonstrating the potential for cost stabilisation and mitigating some economic pressures.

Financial institutions, regulators, and private non-financial corporations (NFCs) have made significant strides in recent years to quantify the implications of climate change on their businesses and risk profiles. This report demonstrates that the knowledge and experience gained in understanding and addressing climate-related risks can be leveraged to develop integrated climate-nature scenarios and risk frameworks. It also provides a building block for central banks and financial supervisors to deepen their understanding of climate- and nature-related risks and to start addressing them effectively.

The results enhance our understanding of the inter-linkages between various policies, which is crucial for assessing changes in financial risks in the future. This integrated assessment evaluates the impact of policy ambitions in climate change mitigation and nature preservation on essential ecosystem services, underpinning the critical role of biodiversity, soil health, pollinators and habitats of species. These are all vital for both European and global economies. Developing a comprehensive understanding of the interdependencies between ecosystem services, climate change and the economy is crucial to correctly identify areas that require the implementation of suitable environmental and sectoral policies. For financial policymakers, the report underscores the need for innovative modelling solutions such as sensitivity analyses of bank portfolios to biodiversity loss in order to translate these findings into policy-relevant information (e.g. Boldrini et al., 2023). This is critical for developing robust financial policies that can address the risks posed by biodiversity loss and climate change, ensuring the stability and resilience of the economy and the financial system.

Furthermore, the report's transition risk indicators, though focused on economic impacts within the agricultural sector, provide valuable insights into how climate and nature policy ambitions have an impact on land use dynamics and macroeconomic indicators such as food prices. These insights can provide valuable tools to better evaluate and address the complex interdependencies between climate policies, biodiversity preservation, and economic stability. The report's results can be applied to assess the spillover effects of shocks in the agricultural sector on other sectors and supply chains, thereby enhancing comprehensive risk management and strategic planning.

Creating a comprehensive nature-related stress test will require an economy-wide modelling approach to further assess financial risks associated with environmental changes. Further research is needed to develop dedicated financial tools that are necessary to assess physical and transition risks, contagion within the financial system, and the impact of the financial system on nature. However, it is important to recognise that waiting for exhaustive modelling is not necessary before taking action. Immediate action is crucial as delays could lead to irreversible environmental damage. Therefore, it is crucial for central banks and supervisors to develop heuristic methods that leverage existing datasets and knowledge by applying approximations, allowing them to take immediate action despite ongoing uncertainties and modelling challenges. A more practical approach may involve using sector-specific modelling frameworks such as the one presented in this report and taking action based on these targeted insights. This allows for continuous improvement and integration over time, rather than waiting for an all-encompassing model. Therefore, the insights from this study provide a vital foundation both for continuous development of modelling frameworks and risk assessment tools as well as heuristic approaches.

7.2 Recommendations for further research

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 through to sustainable wellbeing. This complexity makes it challenging to capture the complete impact cycle in the modelling framework. The integration therefore may result in limitations whereby not all NCP channels are accounted for, crucial land use details are omitted and connections to the broader economy are absent. In future research, PIK aims to combine studies that cover macroeconomic 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. Future work could also seek to explore the feedback between climate, nature, and the economy using complementary modelling approaches, such as system dynamics models (e.g., Distefano et al. 2022). No single model in isolation can build a complete picture of nature-related risks, and a methodologically diversified approach is warranted (NGFS, 2023).

Furthermore, the underestimation of physical risk due to the exclusion of potential disasters from earth systems tipping points is a significant limitation that requires improvement in future assessments. Integrated models typically overlook tipping points and cascading effects. This highlights the necessity for a systematic development to better integrate and rationalise these risks (Franzke et al. 2022, Marsden et al. 2024). To partly address this, the climate-nature scenario framework could be enhanced to incorporate some biophysical and socioeconomic tipping points 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 mostly serve as a narrative for testing high-risk events. This underscores the general need for further research to develop a more comprehensive understanding of the potential impacts of tipping points on the climate and nature system, as well as their implications for human activities and land use.

Further research is needed to better understand and address synergies and trade-offs at the local level, where different ecosystem services and economic conditions might determine varying integrated policy outcomes. For example, it is unclear whether approaches to assess soil degradation impacts are universally applicable. The challenges related to degradation may be more pronounced in developing countries, where adapting to high soil loss could pose greater difficulties for farmers. These uncertainties highlight, once again, the need for further research to develop more extensive, granular and region-specific methodologies particularly in the context of varying regional and agricultural conditions. An increased granularity in the physical and transition risk outputs would also allow the study of varying effects of national environmental, economic and financial policy pathways and commitments.

The importance of modelling natural capital across all economic sectors is crucial for understanding the full scope of nature-related risks and their propagation through the economy. Key focus areas include integrating ecosystem services into agricultural production functions and linking biophysical and economic processes for more precise evaluations. Enhancing spatial and temporal resolution in models is crucial to accurately capture regional variations. Developing robust methodologies to quantify the value of biodiversity in agroecosystems also remains a priority. Furthermore, it is essential to extend the incorporation of natural capital into production functions beyond agriculture into other sectors of the economy. This is necessary for comprehending how nature-related risks propagate throughout the economic system and impact the financial sector.

There is a need for further research to better consider the feedback of degraded NCPs on crop yields (Figure 3). Outside of the scope of this project, PIK is engaged in developing the methodology to address this gap. Uncertainties persist regarding the yield impact resulting from NCP degradation. Moreover, this analysis only considers a subset of ecosystem services. Future work will focus on a more comprehensive approach to assessing the economic impacts of ecosystem services degradation.

To evolve into a more comprehensive tool for assessing nature-related risks, especially in terms of financial implications for central banks, private financial institutions, and other financial supervisors, the assessment framework needs to expand beyond its current focus on the agricultural sector. Recognising this limitation, the teams from PIK and the University of Minnesota are actively seeking collaboration to link their framework with the general equilibrium model GTAP-InVEST (Johnson et al. 2023), which encompasses all other economic sectors. This collaboration aims to incorporate natural capital into economic production functions, thereby enabling a more robust modelling of how nature-related risks propagate across various sectors of the economy. This expansion would significantly enhance the framework's utility for comprehensive nature-related risk assessments in the financial sector.

Integrated climate and biodiversity economic models are crucial for developing robust financial policies and creating strategic plans to mitigate long-term environmental degradation. To be able to fully capture macroeconomic implications, these models should also support cross-sectoral analysis, helping to understand how environmental changes affect different sectors and amplify risks due to spillover effects. Importantly, further research is needed to develop more accurate stress tests and better quantify the complex interdependencies between climate and biodiversity risks.

Effective management of nature-related risks in capital markets requires filling gaps in disclosure and quantitative risk modelling frameworks. The material importance of these risks is increasingly acknowledged by prudential supervisors and central banks. The ECB's ongoing initiatives, including its 2020 guide on climate-related and environmental risk management, emphasise the requirement for banks to assess comprehensive environmental risk information. By implementing these measures, policymakers can enhance their ability to manage the intricate relationships between climate policies, biodiversity conservation, and economic stability.

In summary, the outlined research recommendations provide essential insights for enhancing financial policy by: (i) integrating climate and nature-related risks into monetary policy frameworks and operations, (ii) supporting effective transition plans to preserve nature and align policies with international agreements like the Kunming-Montreal Global Biodiversity Framework, and (iii) improving the implementation of supervisory policies by equipping regulators with tools to assess and mitigate environmental risks faced by financial institutions.

References

Alvarez, J., Ranger, N., Freeman, A., Harwood, T., Obersteiner, M., Paulus, E., and Sabuco, J.: The Green-Scorpion: a preliminary study on the potential amplification of physical climate financial risks by nature-related risks and feedbacks, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-12089, https://doi.org/10.5194/egusphere-egu24-12089, 2024.

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.

Bodirsky BL, Dietrich JP, Martinelli E, et al (2020) The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. Scientific Reports 10:19778. https://doi.org/10.1038/s41598-020-75213-3

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 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.

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.

Distefano T, Isaza AS, Muñoz E, Builes T (2022) Sub-national water–food–labour nexus in Colombia. Journal of Cleaner Production 335:130138. https://doi.org/10.1016/j.jclepro.2021.130138

Drexler, S., Gensior, A., & Don, A. (2021). Carbon sequestration in hedgerow biomass and soil in the temperate climate zone. Regional Environmental Change, 21(3), 74. https://doi.org/10.1007/s10113-021-01798-8

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., & Wisser, D. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences, 111(9), 3239-3244.

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

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

Garibaldi, L. A., Oddi, F. J., Miguez, F. E., Bartomeus, I., Orr, M. C., Jobbágy, E. G., Kremen, C., Schulte, L. A., Hughes, A. C., Bagnato, C., Abramson, G., Bridgewater, P., Carella, D. G., Díaz, S., Dicks, L. V., Ellis, E. C., Goldenberg, M., Huaylla, C. A., Kuperman, M., … Zhu, C.-D. (2020). Working landscapes need at least 20% native habitat. Conservation Letters, 14(3), e12773. https://doi.org/10.1111/conl.12773

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... & Fargione, J. (2017). Natural climate solutions. Proceedings of the National Academy of Sciences, 114(44), 11645-11650.

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

Hantzsche, A., Lopresto, M., & Young, G. (2018). Using NiGEM in uncertain times: Introduction and overview of NiGEM. National Institute Economic Review, 244, R1–R14. https://doi.org/10.1177/002795011824400109

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.

Kedward, K., Ryan-Collins, J., & Chenet, H. (2022). Biodiversity loss and climate change interactions: financial stability implications for central banks and financial supervisors. Climate Policy, 23(6), 763–781.

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.

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H., Chaudhary, A., De Palma, A., ... & Young, L. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature, 585(7826), 551-556.

Nunez, S., Arets, E., Alkemade, R. et al. (2019). Assessing the impacts of climate change on biodiversity: is below 2 °C enough?. Climatic Change 154, 351–365.

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.

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

Jägermeyr J, Müller C, Ruane AC, et al (2021) Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat Food 2:873–885. https://doi.org/10.1038/s43016-021-00400-y
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 .

Johnson JA, Baldos UL, Corong E, et al (2023) Investing in nature can improve equity and economic returns. Proceedings of the National Academy of Sciences 120:e2220401120. https://doi.org/10.1073/pnas.2220401120

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, Vaissière BE, Cane JH, et al (2007) Importance of pollinators in changing landscapes for world crops. Proc Biol Sci 274:303–313. https://doi.org/10.1098/rspb.2006.3721

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.

Marsden, L., Ryan-Collins, J., Abrams, J., and Lenton, T. (2024). Ecosystem tipping points: Understanding risks to the economy and financial system. UCL Institute for Innovation and Public Purpose, Policy Report 2024/03.
Available at: https://www.ucl.ac.uk/bartlett/public-purpose/2024/apr/ecosystem-tipping-points

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

Mohamed, A., DeClerck, F., Verburg, P. H., Obura, D., Abrams, J. F., Zafra-Calvo, N., Rocha, J., Estrada-Carmona, N., Fremier, A., Jones, S. K., Meier, I. C., & Stewart-Koster, B. (2024). Securing Nature's Contributions to People requires at least 20%–25% (semi-)natural habitat in human-modified landscapes. One Earth, 7(1), 59–71. https://doi.org/10.1016/j.oneear.2023.12.008

Molina Bacca EJ, Stevanović M, Bodirsky BL, et al (2023) Uncertainty in land-use adaptation persists despite crop model projections showing lower impacts under high warming. Commun Earth Environ 4:1–13.
https://doi.org/10.1038/s43247-023-00941-z

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

Network for Greening the Financial System. (2024). Nature-related Financial Risks: a Conceptual Framework to guide Action by Central Banks and Supervisors. July 2024.

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.

Panagos P, Standardi G, Borrelli P, et al (2018) Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. Land Degradation & Development 29:471–484. https://doi.org/10.1002/ldr.2879

Prăvălie R, Borrelli P, Panagos P, et al (2024) A unifying modelling of multiple land degradation pathways in Europe. Nat Commun 15:3862. https://doi.org/10.1038/s41467-024-48252-x

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.
Ranger, N., Oliver, T., et al., (2024). Assessing the Materiality of Nature-Related Financial Risks for the UK. Green Finance Institute, University of Oxford.

Rasmussen, L. V., Grass, I., Mehrabi, Z., Smith, O. M., Bezner-Kerr, R., Blesh, J., Garibaldi, L. A., Isaac, M. E., Kennedy, C. M., Wittman, H., Batáry, P., Buchori, D., Cerda, R., Chará, J., Crowder, D. W., Darras, K., DeMaster, K., Garcia, K., Gómez, M., … Kremen, C. (2024). Joint environmental and social benefits from diversified agriculture. Science, 384(6691), 87–93. https://doi.org/10.1126/science.adj1914

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLOS ONE 8:e66428. https://doi.org/10.1371/journal.pone.0066428

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

Martinez-Jaramillo, S., Mora, F., Escobar-Farfán,. L.O.L, Montañez-Enríquez, R., 2023. Dependencies and impacts of the Mexican banking sector on ecosystem services. Banco de Mexico. https://www.banxico.org.mx/sistema-financiero/d/%7BC0066818-3826-DF36-5673-E8009795ACD4%7D.pdf

Schmitz C, Kreidenweis U, Lotze-Campen H, et al (2014) Agricultural trade and tropical deforestation: interactions and related policy options. Reg Environ Change 15:1757–1772. https://doi.org/10.1007/s10113-014-0700-2

Soergel B, Kriegler E, Bodirsky BL, et al (2021) Combining ambitious climate policies with efforts to eradicate poverty. Nat Commun 12:2342. https://doi.org/10.1038/s41467-021-22315-9

Springmann M, Clark M, Mason-D’Croz D, et al (2018) Options for keeping the food system within environmental limits. Nature 562:519. https://doi.org/10.1038/s41586-018-0594-0

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.

Taskforce on Nature-related Financial Disclosures. (2024). Guidance on scenario analysis.
Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C., & Batáry, P. (2021). Beyond organic farming – harnessing biodiversity-friendly landscapes. Trends in Ecology & Evolution, S016953472100183X. https://doi.org/10.1016/j.tree.2021.06.010

United Nations Convention to Combat Desertification (UNCCD). (2022). Global Land Outlook 2nd edition: Land Restoration for Recovery and Resilience. UNCCD.
Retrieved from: https://www.unccd.int/resources/global-land-outlook/global-land-outlook-2nd-edition

UNEP-WCMC (2022). Protected Planet Report 2022. UNEP-WCMC and IUCN: Cambridge UK; Gland, Switzerland.

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.

von Jeetze, Patrick & Weindl, Isabelle & Johnson, Justin & Borrelli, Pasquale & Panagos, Panos & Meyer, Tobias & Florian, & Sauer, Pascal & Dietrich, Jan & Lotze-Campen, Hermann & Popp, Alexander. (2024). Dietary change is not a prerequisite for effective biodiversity conservation but reduces socioeconomic obstacles. 10.21203/rs.3.rs-3914402/v1

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”.

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.

Climate-nature scenario development for financial risk assessment

Presentation of Final Results

8

Annex

NATURE FINANCE

EUROPEAN CENTRAL BANK
EUROSYSTEM

PIK

UNIVERSITY OF MINNESOTA

8.1 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	RCP
Degraded World	Current Policies	RCP 7.0
Managed Ecosystems	NDCs	RCP 4.5
Disorderly	Disorderly	RCP 2.6
Climate-Nature Equilibrium	Orderly	RCP 2.6

Table S1. Mapping between Climate-Nature Risk, NGFS Transition Risks Scenarios, and targeted climate outcomes at the end of the century represented by different RCPs.

The work to develop the climate-nature scenario development framework presented in this project started before the publication of the NGFS recommendations for the development of scenarios for assessing nature-related economic and financial risks (NGFS, 2023). Nevertheless, we found that the framework is well aligned with the recommendations. Specifically, the NGFS 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, 2023, p. 86). Table S2 showcases the alignment of the project and the framework with these options.

Short term program: Building on available dynamic scenario modelling frameworks with longer-term horizons		
NGFS recommendation for options for central banks	**Alignment within the scope of this project**	**Alignment with modelling framework but out of the scope of this project**
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 modelling framework has the capacity to present scenarios on various levels of loss of modelled 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.	

NGFS recommendation for options for central banks	Alignment within the scope of this project	Alignment with modelling framework but out of the scope of this project
Conducting sensitivity analyses, in particular on elasticities of substitution	We conducted variations in scenario assumptions and sensitivities to changes in parameters of modelled international trade. Other modelled processes (e.g. different investment costs in crop yield-increasing technology, different socio-economic scenarios, interest rates, etc.) are possible within the modelling framework.	
Better transparency of underlying assumptions and communication of implications on results	The limitations of the modelling framework are presented in a separate chapter, and clearly communicated in the interpretation of the results. The underlying assumptions are transparently presented in the described methodology and supplementary information, which includes references for further details on related work.	
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	The inclusion in dynamic global scale assessments of important regulating ecosystem services such as pollination insufficiency, 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 (300×300m), 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 of the modelling framework, plans are underway to include the feedback of lost ecosystem services and land degradation on agricultural production.

NGFS recommendation for options for central banks	Alignment within the scope of this project	Alignment with modelling framework but out of the scope of this 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	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.	Feedback effects of food security are not included as economic effects in the model, since the agricultural demand is modelled 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 with NGFS recommendations. Alignment of project scope and modelling framework with NGFS recommended options for central banks and supervisors to assess nature-related economic and financial risks (NGFS, 2023, p. 86).

8.2 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 animal feed, calculated based on feed baskets content, and biomass for biofuel production. The model accounts for the long-term income effect on agricultural consumption but is limited in representing short-term demand adjustments related to changes in prices.

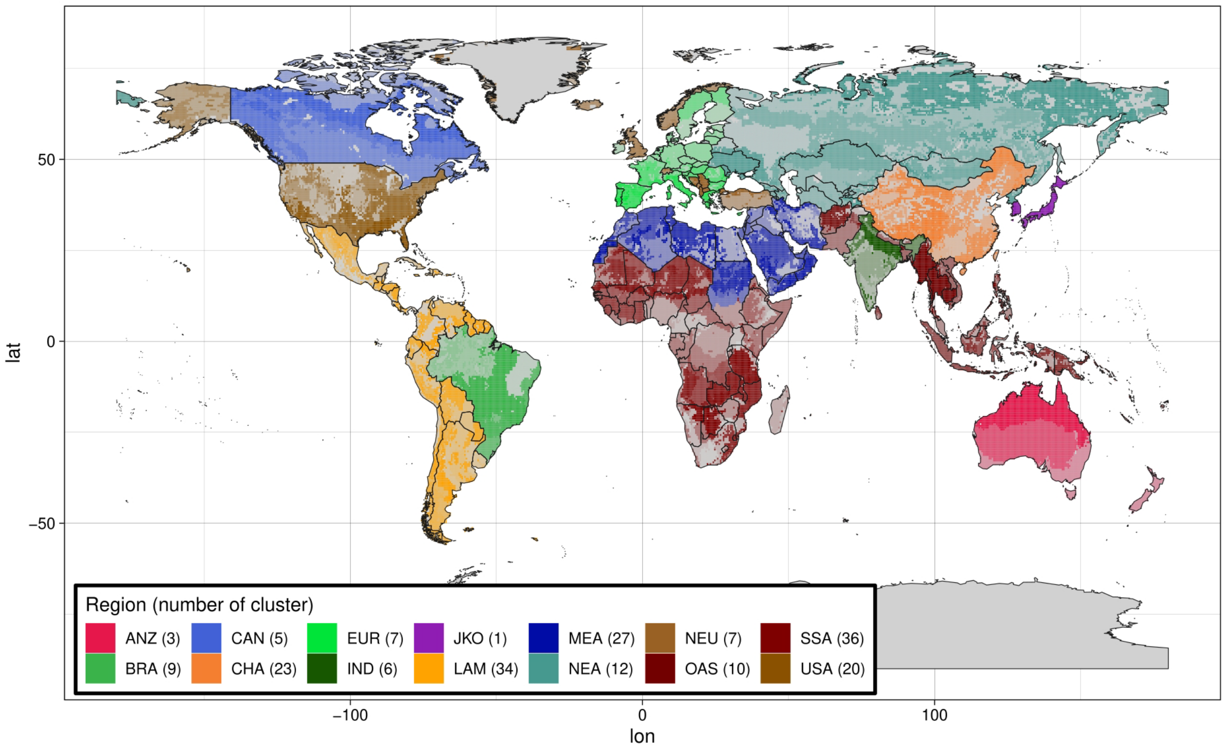


Figure S1. MAgPIE World Regions. ANZ (Australia & New Zealand), BRA (Brazil), CAN (Canada), CHN (China), EUR (European Union), IND (India), JKO (Japan & South Korea), LAM (Latin America excl. Brazil), MEA (Middle East & North Africa), NEA (Northern Eurasia), NEU (Europe Non-EU), OAS (Other Asia), SSA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

Regionally, the supply of agricultural products is 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, the costs 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 a 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.

8.3 Trade liberalisation sensitivity analysis

In all the climate-nature scenario narratives and the modelling framework, we assume trade liberalisation dynamics based on projecting the continuation of current trade trends, aligned with the SSP2 scenario narrative. Specifically, this means maintaining regional historical export shares and self-sufficiency ratios at levels indicative of competitive trade in future time steps. To conduct a sensitivity analysis, a trade barrier parameter is varied to determine the level of trade liberalisation in the model based on the free trade comparative advantages of the modelled regions. This is done without modelling bilateral trade, but by endogenously modelling the supply and demand of a global pool of agricultural products guided by these regional comparative advantages. In this way, the regional trade flows are validated, however without tracking bilateral trade routes. For the default set of scenarios, the level of trade liberalisation is set as 10% for secondary and livestock products in 2030 and 2050 and 20% for crops. In a sensitivity scenario that tests additional policy measures to alleviate transition risk in the climate-nature risk scenario framework, trade is tested with a higher level of trade barrier reduction: 20% liberalisation in 2030 and 30% liberalisation in 2050 for all traded products. Figure S2 presents the results of this sensitivity analysis.

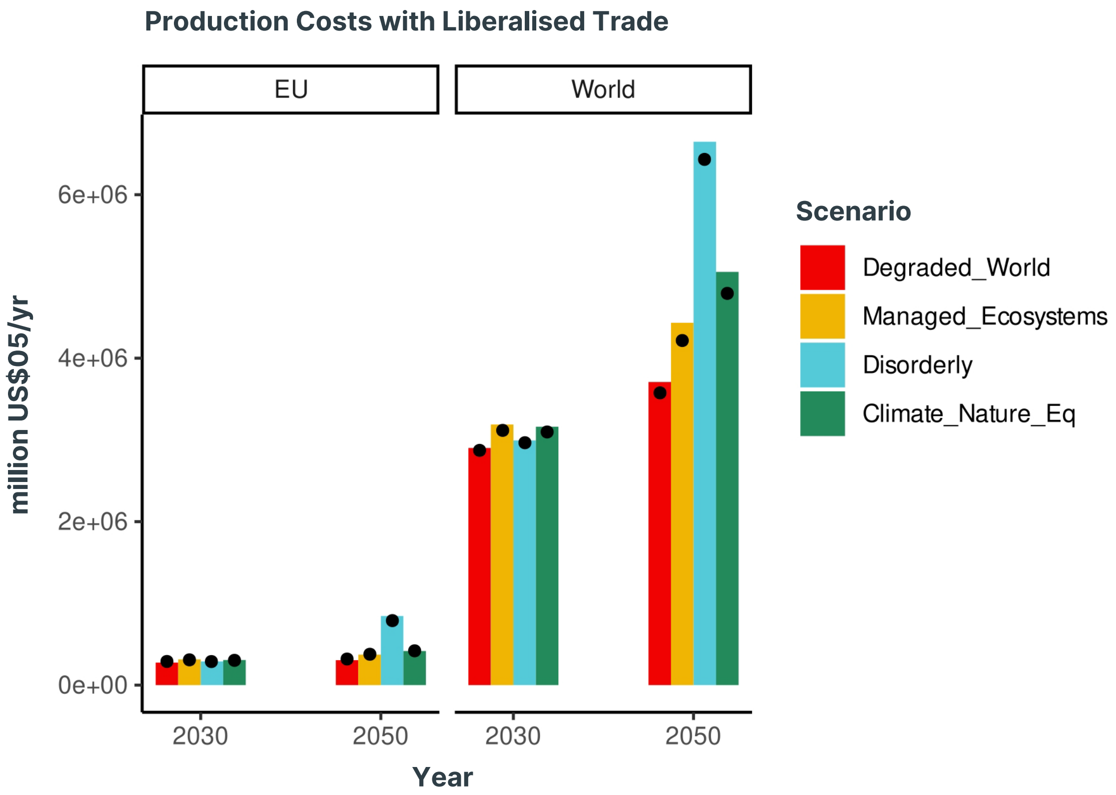


Figure S2. Total agricultural production costs for default and liberalised trade scenario, globally and in the EU. Colours designate the scenarios of the climate-nature risk scenario framework, and dots indicate agricultural cost levels in the sensitivity scenarios with liberalised trade.

8.4 Additional results

The following figures present additional results enhancing the physical and transition risks results presented in Chapter 5 and 6.

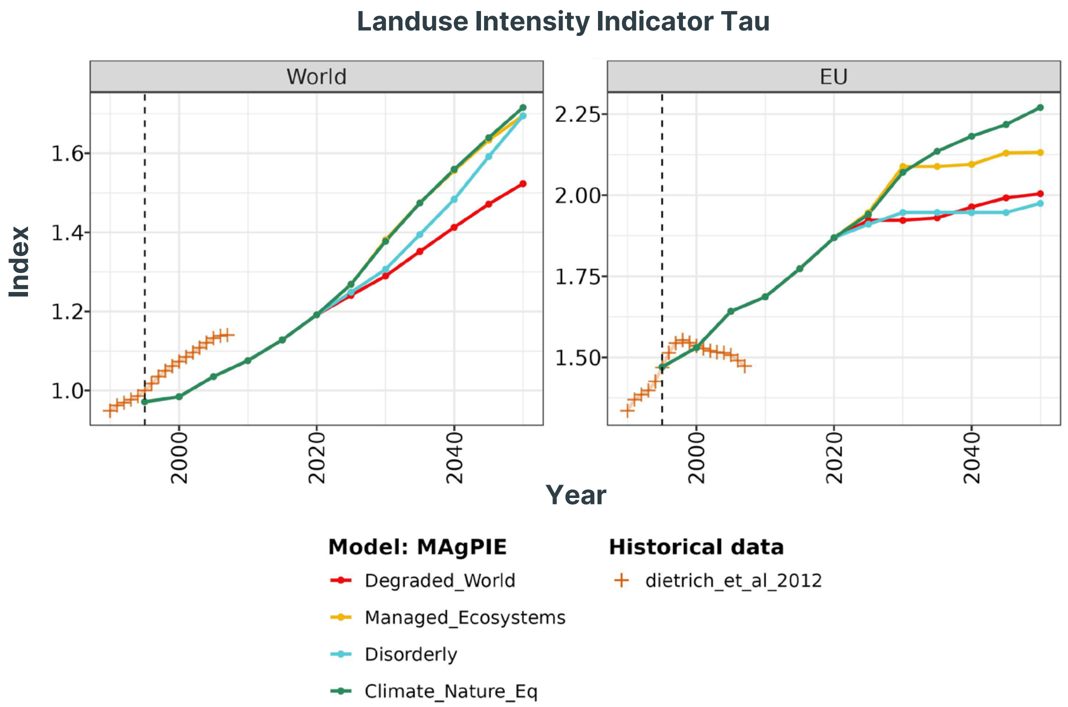


Figure S3. Indicator of land use production intensity (Tau) globally and in the EU. Tau indicates a factor level for increasing agricultural crop yields based on the investments in the model specified technological change. Higher Tau values indicate greater agricultural intensification.

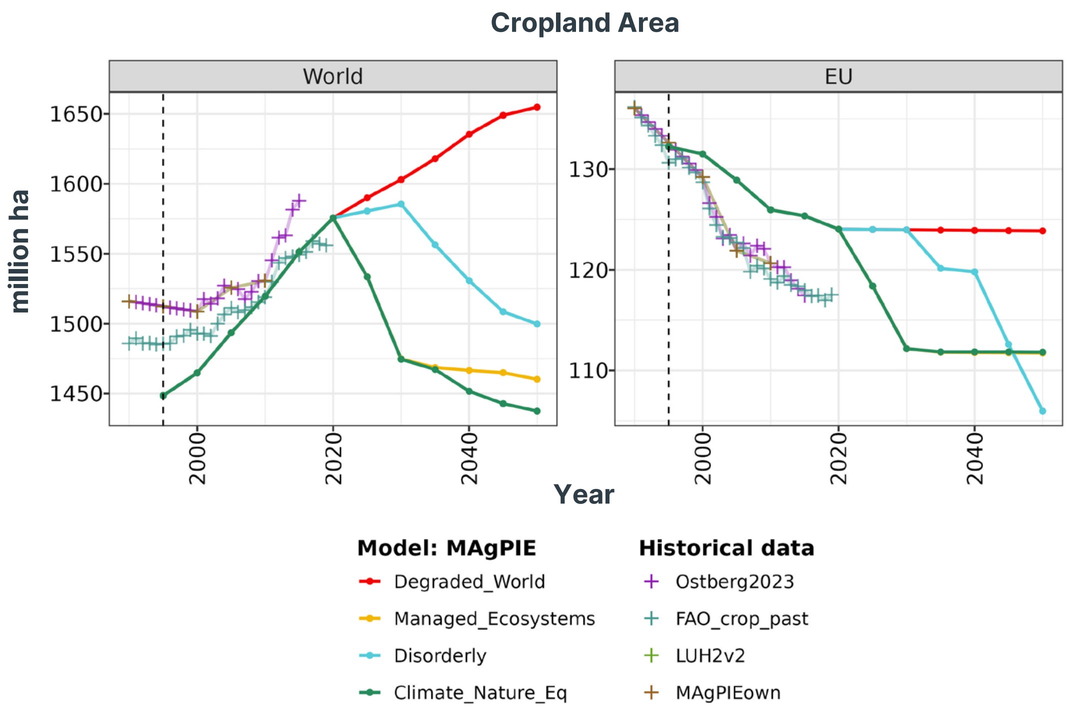


Figure S4. Projected changes in total cropland area globally and in the EU (in million hectares).

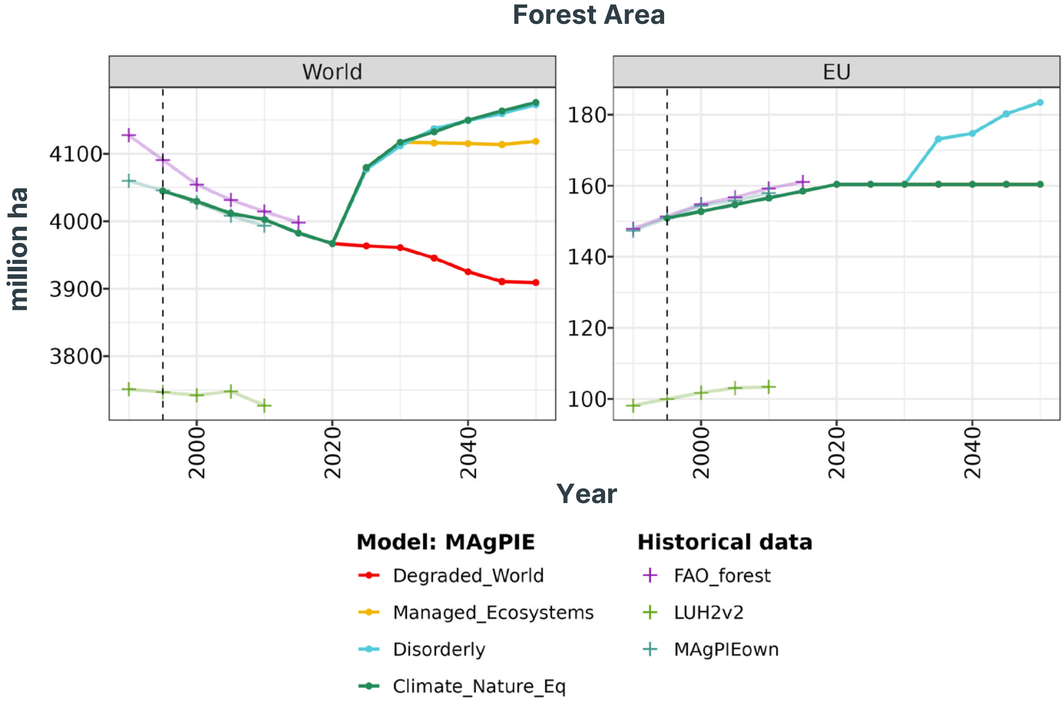


Figure S5. Projected changes in total forest area (managed and intact) globally and in the EU (in million hectares).

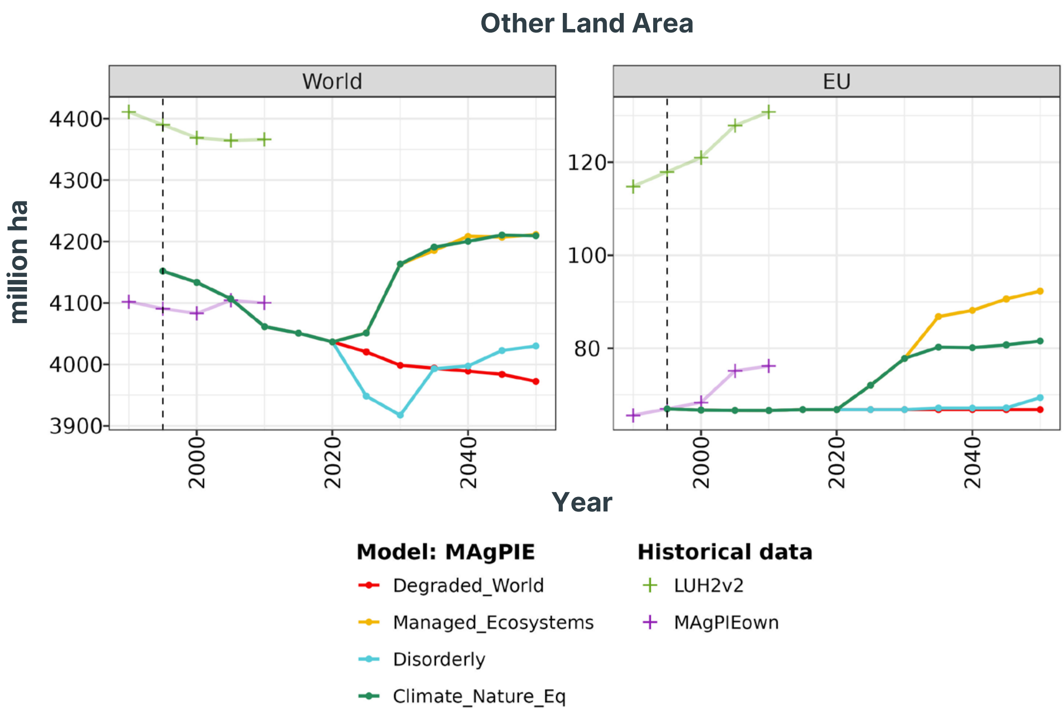


Figure S6. Projected changes in total areas under other natural vegetation globally and in the EU (in million hectares).

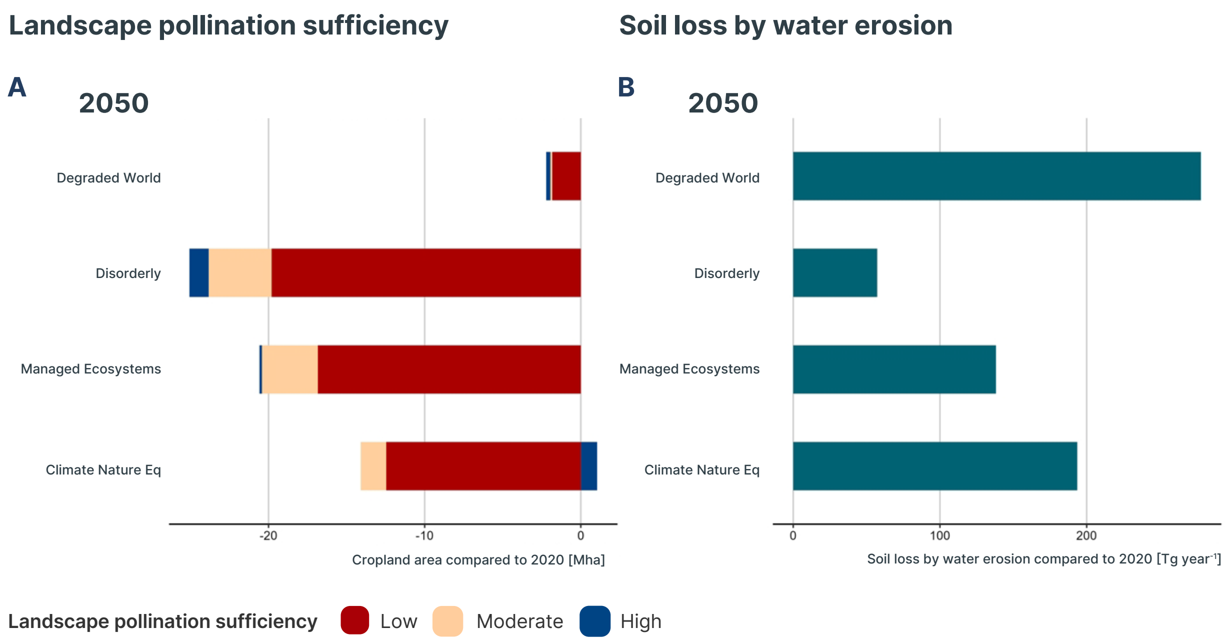


Figure S7. Projected changes in (a) landscape pollination insufficiency and (b) soil loss by water erosion by 2050 in the EU based on MAgPIE-SEALS. EU aggregate values of respective NCPs in terms of cropland affected.

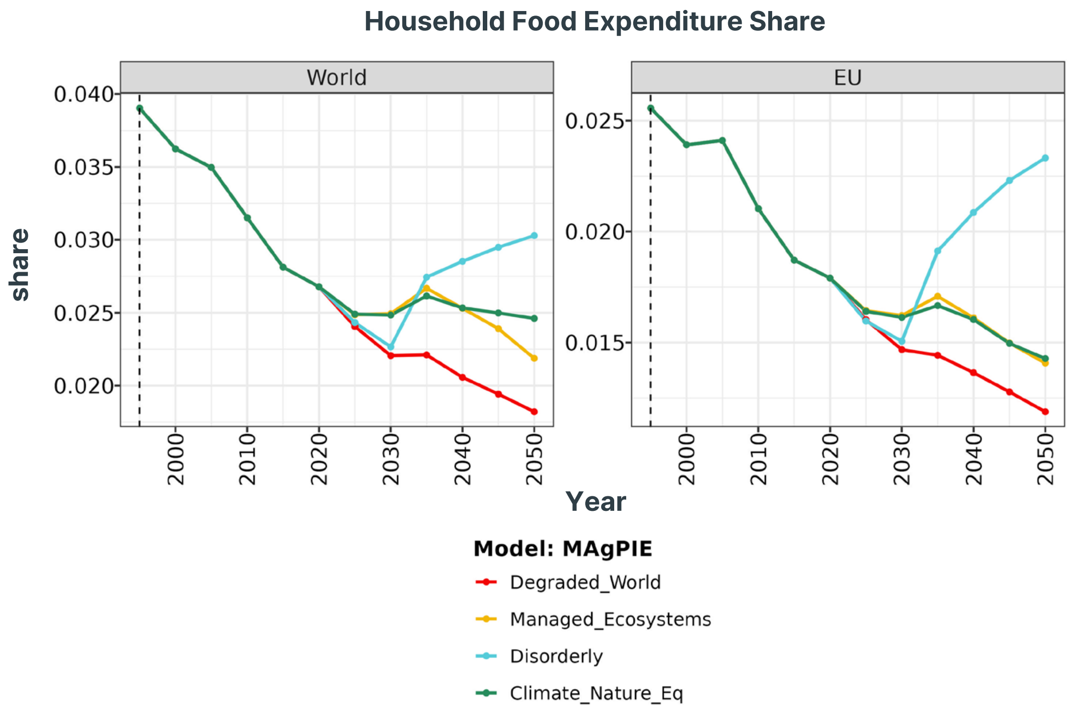


Figure S8. Household food expenditure as a share of income for a representative consumer globally and in the EU. Expenditures in USD05 MER[8] per capita per year for agricultural commodities dedicated for food use, excluding value-added foods in the supply chain. The consumption basket is based on the projected demand for food products. Prices are endogenously and implicitly derived in the MAgPIE model as marginals of the demand constraint. The assumption on income per capita is obtained from the SSP2 scenario GDP and population projection.

[8] International dollars at market exchange rate of 2005 reference year.