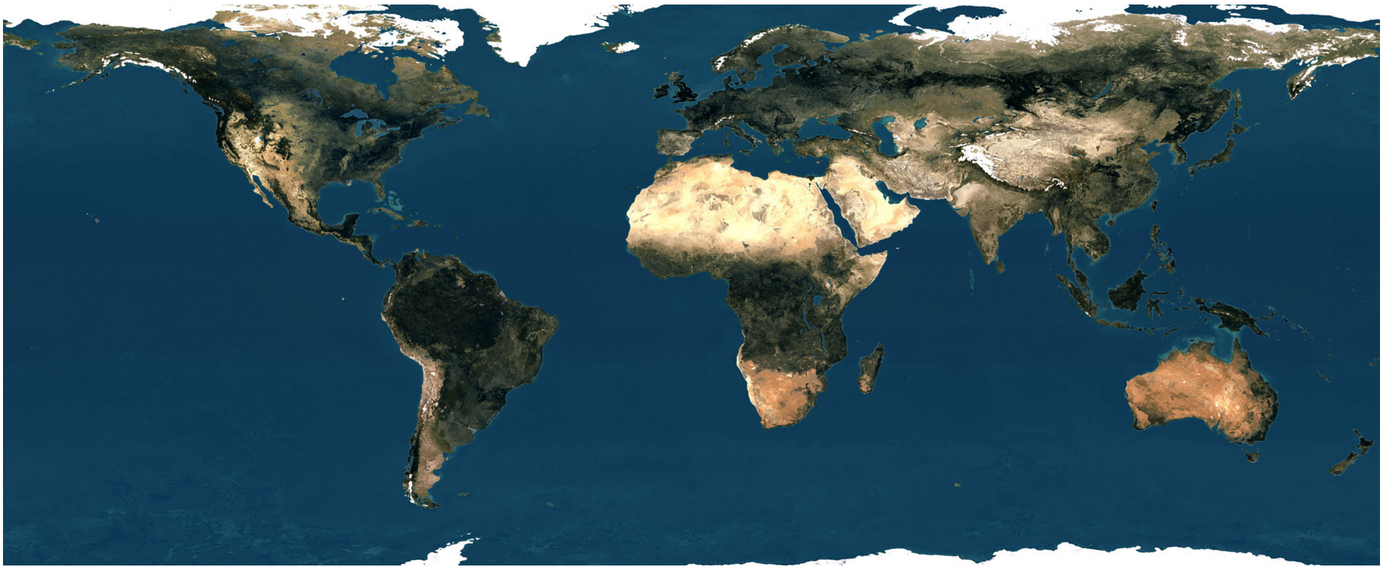

Wageningen University & Research | Research brief

Estimating future economic effects of biodiversity loss and strategies to mitigate it

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December 2024

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Disclaimer: The estimates presented in this note are preliminary and should be used cautiously in decision-making processes. Complete and more precise estimates will be presented in a comprehensive report in the next six months. The findings, interpretations, and conclusions expressed in this note are entirely those of the authors. They do not necessarily represent the institutional views of Allianz, APG, Commerzbank, Deloitte, ING, and Ortec Finance.

Acknowledgements: The authors would like to thank our financial sector partners for their valuable comments and input in co-creating this project and our advisory board, Caroline van Leenders, Roel Nozeman, Wijnand Broer, Romie Goedicke, and Christine Wortmann, for their invaluable guidance and insightful feedback. This project receives financial support from the Top Sector Agri & Food, specifically from the Knowledge and Innovation Agenda for Agriculture, Water, and Food 2024-2027 (KIA), mission Nature, and six financial sector partners. Within the Top Sector, businesses, knowledge institutions, and the government work together on innovations for safe and healthy food for 9 billion people in a resilient world.

Preliminary Key Insights

- Macroeconomic analysis should be enhanced with ecosystem research. To better understand environmental risks, scenario analysis should extend beyond direct ecosystem service losses to consider the role of biodiversity in supporting ecosystem resilience, especially during extreme climate events. We employ a novel approach that connects biodiversity loss to economic activity, considering that biodiversity loss reduces ecosystem resilience to extreme climate events such as the number of days with maximum temperature exceeding 35°C. We aim to quantify the impact of both natural factors and climate events on these dynamics. Combined with a macroeconomic model, we can estimate the impact of impact estimates for ecosystem services loss, enabling us to look at the effect of ecosystem services on the country’s and region’s economy.

- Climate change severely impacts biodiversity, a key factor in agricultural productivity and economic stability. Biodiversity loss undermines ecosystem service quality, such as soil quality and pollination services, and, consequently, the resilience of economies to extreme climate events. Preliminary findings suggest that biodiversity loss can reduce soil productivity losses, reducing overall agricultural production and the production in sectors such as manufacturing food products and food services dependent on agriculture. All this will lead to an overall economic loss.

- There is significant variation at the regional level in the economic impacts of biodiversity loss, particularly regarding the decline of pollination services. For instance, preliminary analysis shows that pollination services decline due to overall biodiversity loss, adversely affecting the economic output of many countries and regions worldwide. Its adverse effect is highest in African countries such as Cameroon, Ghana, Ivory Coast, and Nigeria, followed by Turkey and China and the region of Central Asia. The impact is lowest in Northern European countries. This redistribution of economic activity between countries will likely result in unforeseen macroeconomic effects of biodiversity loss through trade.

- An enhanced abatement strategy can be selected through cost-benefit data for twelve abatement measures. Financial institutions can identify the most effective abatement measures by quantifying risks associated with ecosystem service degradation and comparing the costs and benefits of different measures. Our study identifies twelve measures to improve soil quality and reduce the decline in pollination caused by biodiversity loss, which cost-benefit data should support. This aligns with supporting biodiversity-positive outcomes as demanded by the global biodiversity framework targets while enhancing portfolio resilience and guiding institutions towards abatement investments that contribute to reducing biodiversity-related macroeconomic risks.

1. Introduction

The 'Biodiversity-Related Risks and Opportunities for the Financial Sector' (BiROFin) project is a step towards bridging the knowledge gap in understanding the macroeconomic implications of biodiversity loss. The global natural system is under significant pressure from societal and economic demands. Air, water, soil, and biodiversity are experiencing heightened harm and risk irreversible depletion. In response, governments are investigating ways to measure and reduce the impact on these essential resources and exploring options to incorporate nature into financial decision-making processes.[1] While recent developments in the financial sector have made strides in recognising biodiversity-related risks and opportunities, a critical knowledge gap remains around understanding the macroeconomic impacts of biodiversity loss and the resulting loss of the many ecosystem services that biodiversity provides to society. Current frameworks do not simultaneously capture those macroeconomic effects in various sectors and countries. Without knowing about those effects, financial institutions cannot fully integrate biodiversity considerations into risk assessment and strategic planning. BiROFin, launched in 2024, is an ambitious initiative designed to address this gap by quantifying the macroeconomic effects of biodiversity loss.

BiROFin is a public-private partnership (PPP) project between Wageningen University and Research (WUR), the Foundation for Sustainable Development (FSD), and six prominent private-sector partners—Allianz Group, APG, Commerzbank, ING, Ortec Finance, and Deloitte (both Deloitte Consultative Services B.V. in the Netherlands and Deloitte Sustainability & Climate GmbH Germany as lead private partners)—to develop a state-of-the-art methodology that aligns biodiversity impact assessment data with advanced economic modelling techniques. This approach provides a comprehensive view of how a change in the provision of ecosystem services due to a (projected) change in biodiversity can impact economies at both country/regional and sectoral levels, thus filling a critical gap in current risk assessment frameworks.

The application of the MAGNET[2] (Modular Applied General Equilibrium Tool) model offers critical insights into the economic impacts of biodiversity loss. At the core of the project's methodology is the MAGNET general equilibrium model, a multi-regional, multi-sectoral applied computable general equilibrium model that builds on GTAP[3] (Global Trade Analysis Project) datasets (Woltjer and Kuiper, 2014). BiROFin uses MAGNET to estimate the effects of losses in ecosystem services, such as pollination and soil quality, and quantify the economic ramifications of their potential decline. This is expected to enable financial institutions to assess the implications of biodiversity loss on sectors, regions, countries, and portfolio levels, ultimately informing more robust long-term strategies.

BiROFin's abatement measure dataset can serve as a tool for the financial sector to develop targeted mitigation strategies. BiROFin delivers a dataset with location-specific, intervention-based abatement measures, detailing capital and operational expenditures (CapEx and OpEx) to support the design of effective mitigation strategies. This dataset will be instrumental in enabling the financial sector to pinpoint opportunities for enhancing investment activities and reducing investment risks related to biodiversity. It will support the development of efficient, targeted mitigation strategies that drive fundamental improvements in biodiversity, setting a new standard for incorporating ecosystem service valuation into financial decision-making.

This note aims to clarify our methodology for BiROFin partners and stakeholders, focusing on two specific ecosystem services: soil quality (regulation) and pollination services.[4] The objective of this note is to share our methodology with our public and financial sector partners and a broader community of financial sector practitioners (e.g., central banks, other banks, and insurance companies). We will initially focus on soil quality and pollination services on which we have already begun building capacity.

Soil is crucial in supporting five ecosystem functions, contributing to the well-being of both natural and human systems. For example, (1) soils act as a carbon sink for climate regulation, storing organic carbon and helping regulate atmospheric carbon dioxide levels. Soil can influence microclimate through thermal properties, impacting temperature and humidity. (FAO, 2015a; Berryman et al., 2020); (2) Soils serve as a reservoir and mediator of essential nutrients (nitrogen, phosphorus, potassium, etc.) for plants and microorganisms. Hence, microbial activity in the soil is necessary for decomposing organic matter and releasing nutrients for plant uptake (FAO, 2022); (3) Soil provides habitat and sustenance for diverse organisms, from microscopic bacteria and fungi to larger organisms like earthworms. Therefore, biodiversity

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[1] For instance, see KIA-LVW (2024) on the Dutch government's knowledge and innovation programme including nature.

[2] https://www.magnet-model.eu/

[3] https://www.gtap.agecon.purdue.edu/

[4] Please see the ENCORE database for the definitions of these services.

in the soil contributes to ecosystem stability and resilience (European Commission, 2010); (4) Soils are essential in water filtration and purification, helping maintain water quality. They regulate water flow, reducing the risk of flooding by absorbing and slowly releasing water (FAO, 2015b); (5) Soil structure influences water retention, aeration, and root penetration. Activities such as the decomposition of organic matter and the action of soil organisms contribute to maintaining soil structure (Bronick and Lal, 2005).

The ecosystem service known as soil quality regulation (hereafter referred to as soil quality service), is linked to the second ecosystem function of soil. Soil biodiversity is essential for this function and for ensuring agricultural productivity. Soil biodiversity, the diversity of animal and plant species, bacteria and fungi in the soil, is important in maintaining soil biochemical and physical qualities. It engages in the regulation of nutrient cycling and decomposition of organic matter. It contributes to the formation of soil structure, which is key to plant nutrient uptake, water availability and the regulation and control of pests and diseases, influencing land and productivity.

Pollination significantly contributes to global food crop production, accounting for a substantial portion of yield and market value. For many crops, pollination depends on insects. According to IPBES (2016), more than three-quarters of the leading types of global food crops rely to some extent on animal pollination for yield or quality. Pollinator-dependent crops contribute to 35 per cent of global crop production volume. It is estimated that 5 to 8 per cent of global crop production, with an annual market value ranging from USD 235 billion to USD 577 billion (in 2015 USD) worldwide, is directly attributable to animal pollination (IPBES, 2016).

The current estimates are preliminary and should not be relied upon for decision-making until a comprehensive report is published. We sometimes utilise preliminary estimations from our scenarios and the MAGNET model to clarify our methodology. However, we avoid providing precise estimates of soil and crop productivity or GDP losses, as some assumptions linking these ecosystem services to soil and crop productivity have yet to be sufficiently substantiated through available literature or sensitivity analysis. As a result, any estimates regarding soil or crop productivity or GDP losses mentioned in this note are indicative and should not be used for decision-making. Complete and more precise estimates will be presented in a comprehensive report in the next six months.

The note is organised around BiROFin's three core workstreams: (1) building future scenarios for ecosystem service changes, (2) integrating these scenarios within the MAGNET model, and (3) estimating the costs and benefits of abatement measures.

2. Scenarios for assessing change in the provision of soil quality and pollination services

Our analysis highlights the critical relationship between biodiversity, ecosystem services and agricultural productivity. As a first step, we identify indicators that allow us to determine the state of biodiversity, the diversity of genes, species and ecosystems, on the most spatially detailed scale possible for the world. Since there is no complete overview of the extent and status of biodiversity, we focus on high-resolution geoinformation data that indicate the pressure biodiversity receives. We hypothesise that a higher pressure indicates lower biodiversity compared to a pressure-absent state where biodiversity is optimal. With this approach, we provide a globally comparable index to showcase the extent of biodiversity loss each region experiences. Next, we estimate how a change in this pressure as a proxy for biodiversity level affects the provision of specific ecosystem services and, thus, productivity levels, assuming that this relationship is the same for different locations.[5] We initially focused on biodiversity's contribution to crop pollination and the provision of good soil quality in agricultural land to articulate the impacts of biodiversity loss on agricultural productivity. Finally, we calculated how these indicators will change under different socio-economic scenarios and the resulting environmental changes.

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[5] This is a restrictive assumption. However, for global scenario development, we do not have location specific data to also link the level of productivity loss and ecosystem services loss per biodiversity loss at the regional level.

2.1 Assessing (future) pressure on biodiversity

Two proxy indicators, the Human Modification Index (HMI) and the Pesticide Application Rate Index (PARI), were used to determine the overall pressure on biodiversity. HMI is based on information on 14 different stressors[6] at a resolution of 0.09 km^2 for the globe (Theobald et al., 2020), varying from 0 (no human modification) to 1 (complete human modification). In this study, we assume very high biodiversity in areas without human modification and low biodiversity in areas with complete human modification. HMI accounts for the presence of agricultural areas and the intensity of agricultural activities, such as cropping and the number of rotations, tilling, and cutting operations, all impacting biodiversity.[7] We also introduced the PARI as an indicator for agricultural intensification. In high-intensity agricultural systems, there is likely to be more use of pesticides, fertilisers, heavy machinery that compacts the soil, irrigation water, and modification of the local water flows. Our current study used the total glyphosate application rate, the most widely used herbicide in the world (Giesy et al., 2000), on agricultural land in 2015 to calculate the PARI by scaling the total glyphosate application rates per grid between 0 (no agricultural intensification) and 1 (very high agricultural intensification).[8, 9] For each grid cell of agricultural land, we assessed the pressure on biodiversity by calculating the average of the Human Modification Index and the Pesticide Application Rate. The Biodiversity Index for each grid cell is then one minus the average pressure. (Please see Appendix 1 for further details on methodology and how biodiversity is linked with soil biodiversity loss and pollination loss.)

This study utilises the GLOBIO model and its projections for Mean Species Abundance (MSA) to estimate future changes in the Biodiversity Index. Future projections for HMI and PARI are not available. To assess future changes, we use the output from the GLOBIO model that assesses changes in MSA (Schipper et al., 2020). MSA metric indicates local biodiversity intactness, with values ranging from 0 to 1. A value of 1 means the species assemblage is fully intact, while 0 indicates all original species are locally extinct.[10] MSA is calculated by comparing the abundance of individual species under specific pressures to their abundance in an undisturbed, natural environment. Only species present in the reference situation are included, and any increases in abundance are ignored to prevent inflation from generalist species thriving in disturbed habitats. Although MSA suggests that it includes population data, it is also a pressure indicator. However, it uses less pressure than the HMI, and agricultural intensification is not incorporated. GLOBIO combines the pressure–impact relationships with data on MSA's past, present or future pressure levels to make those projections for MSA levels. For our study, we use those MSA changes from Schipper et al. (2020) and determine the change in MSA from 2015 to 2050 for each grid cell, and then we adjust the Biodiversity Index accordingly.[11]

2.2 Implications of state of biodiversity for providing good soil quality and pollination

The study highlights the critical connection between biodiversity, soil quality and pollination ecosystem services. Biodiversity provides various ecosystem services relevant to agricultural production. In this study, we translate a change in biodiversity to an impact on providing two ecosystem services: good soil quality and pollination. Figures 1a and 1b introduce our scenario framework, considering the impact of biodiversity loss on productivity via a change in soil biodiversity or pollinator presence. In both cases, we determine a situation where we exclude and include climate change impacts on biodiversity.

While the exact impact of soil biodiversity on crop productivity is unclear, we assume a maximum 50% decline under severe pressure. No data on soil biodiversity's role in determining crop productivity are available. In the current assessment, we assumed that the agricultural productivity of all crops would maximally decrease by 50% if biodiversity is under maximum pressure (when both HMI and PARI equal 1).[12] In our existing scenario work, following the standard approach in the literature, the technology for production stays the same, and farmers can only try to compensate for the loss by adding more inputs (e.g., nutrients, applying

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[6] The stressors considered in HMI are the presence of built-up area, croplands and pasture lands, grazing, oil and gas production, mining and quarrying, renewable and non-renewable power generation, roads, railways, power lines, electrical infrastructure, logging and wood harvesting, human intrusions, reservoirs, and air pollution.

[7] We will test the robustness of using alternative pesticides instead of glyphosate application rates in the final report.

[8] Pesticide application rates are available for agricultural areas with ten dominant crops grown from the Global Pesticide Grids (PEST-CHEMGRIDS) data set (Version 1.01). It contains 20 of the most-used pesticide active ingredients at five arc-minute resolution (about 10 km at the equator) in kilograms per hectare per year.

[9] The highest application rates are on genetically modified herbicide-tolerant crops and annual crops (especially for desiccant purposes), but not on perennial crops. Therefore, our biodiversity index might be upward biased for the areas where more perennial crops are grown.

[10] Please see GLOBIO website for more detailed information on MSA metric and note that MSA does not count for new species in an area, as MSA is calculated for the abundance of species in the reference situation.

[11] For these calculations only data from SSP3 with RCP 6.0 moderate level climate change were available. In the future we also plan to assess changes in pressure factors under different SSP scenarios.

[12] Please note that this assumption will be substantiated by future literature studies and robustness checks.

pesticides, irrigating crops, etc.).[13] So, the impact will only sometimes be tangible for the farmers. In locations without pressure on biodiversity, we assume no additional productivity loss caused by biodiversity loss.

Our analysis assumes that the decline in biodiversity indicates the loss of insect populations and, thus, pollinators affecting agricultural production. Similar to soil biodiversity, there are no global, regional, or even local data available on the number of insect species or their population sizes. Recent studies do suggest significant declines. Hallmann et al. (2017) found that the total biomass of flying insects in protected areas in Germany declined by more than 75% from 1989 to 2016. In our analysis, we assume that the calculated biodiversity loss and its impact on productivity via the loss of soil quality also indicates the loss of insects and, thus, pollinators. Unlike soil quality impact calculation, we assess the impact by applying information on each crop's pollination dependence and introduce the productivity loss at the crop level, which cannot be compensated by adding more inputs, as in the case of soil productivity loss.

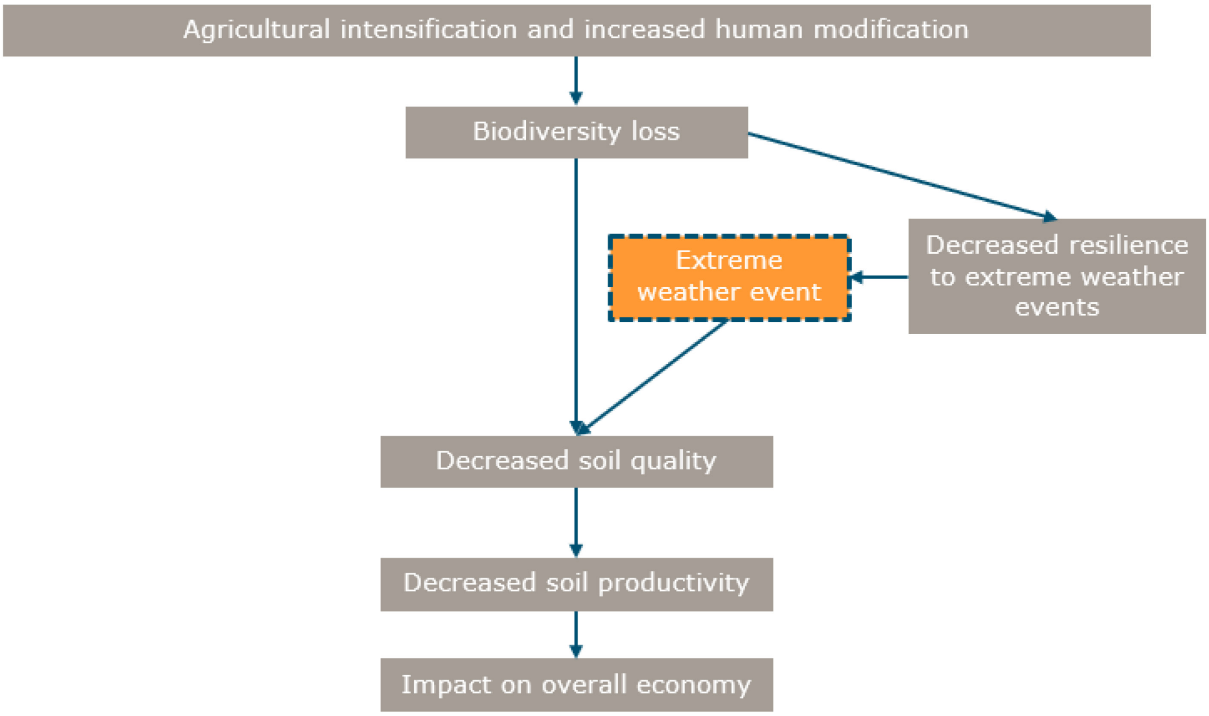

Figure 1a *Soil quality loss scenario framework*
The figure shows that agricultural intensification and increased human modification of nature decrease the (soil) biodiversity level in nature. Decreased biodiversity influences the soil quality by negatively affecting soil organic matter content, soil structure, and nutrient cycling. A reduction in soil quality impacts the productivity of the crops that grow on these soils. We also consider the joint impact of biodiversity loss and climate change, where biodiversity loss decreases soil resilience and the ability to withstand extreme climate change. In the case of extreme weather events, this is translated into additional loss of productivity. The soil productivity uniformly affects all crops depending on their land use. Consequently, no crop level dependence rate for soil productivity is introduced, whereas crop insect pollination dependency rates are incorporated into the framework for pollination services scenarios.
Source: BiROFin project.

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[13] This assumption will be relaxed in future scenario work, and farmers can choose profitable practices that are natural and resilient.

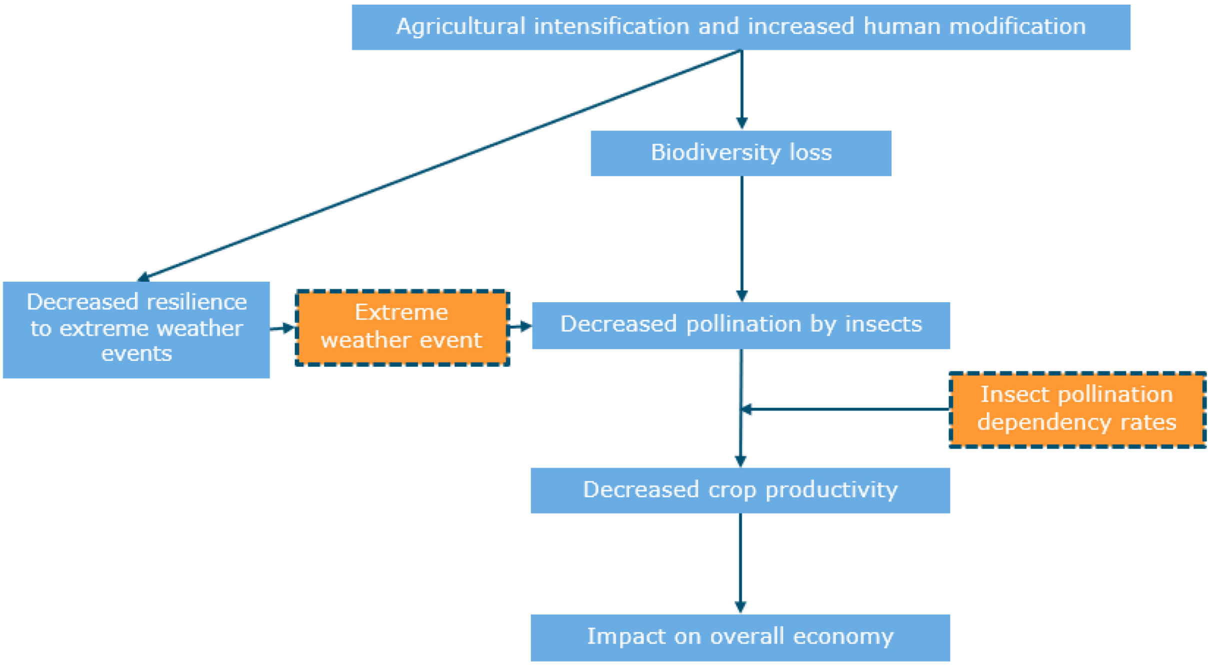

Figure 1b *Pollination services scenario framework*
The figure shows that agricultural intensification and increased human modification of nature decrease the biodiversity level in nature. Decreased biodiversity decreases pollination by insects through two mechanisms. The first is a direct impact, in which decreased biodiversity loss reduces insect pollination. Additionally, we consider the joint impact of biodiversity loss and climate change. More insects die, further decreasing pollination by insects. Agricultural intensification and human modifications can directly decrease pollination services. For instance, the increased use of pesticides can kill wild pollinators. In the resilience to extreme climate events pathway, these changes also weaken the ecosystem's resilience, making pollinator population more vulnerable; for instance, an adverse weather event can be fatal to insect pollinators and their population growth, further decreasing pollination services. Different crops depend on insect pollinators to varying degrees. As a result of reduced pollination services, the productivity levels of crops decline in proportion to their dependency on pollination.
Source: BiROFin project.

The survival of species is very much determined by extreme climate events. Rapid climate change is expected to have severe consequences for species' survival. Extreme weather events can have a significant impact on biodiversity. Müller et al. (2023) found that changes in weather conditions mainly explain the insect decline observed by Hallmann et al. (2017). Our scenario framework considers extreme weather events to better account for climate change's impact through extreme weather events on biodiversity and, thus, the provision of ecosystem services. Following those academic studies, we assume crops and insect populations are more resilient to extreme weather events under higher biodiversity conditions. Biodiversity loss diminishes soil's resilience and, thus, its ability to support plants against extreme weather. For pollinators, especially insect pollinators, we consider the sensitivity of insects towards weather conditions and assume that when the climate risk of a region is high, the additional risk of pollinator loss is also high (Müller et al., 2024; Outhwaite et al., 2022). In our scenario work, we use changes in annual mean temperature per decade, changes in the number of days per year with a maximum temperature above 35°C and changes in the standard precipitation index to gauge the intensity of extreme weather, determining the likelihood of this extreme climate event in that region (please see Appendix 1 for details of the extreme weather event indicator and data source). For this purpose, we use data from the IPCC interactive Atlas for the SSP2-RCP 4.5 pathway.[14]

2.3 Summary of the scenario setup

Four future scenarios are used for assessing crop productivity loss in 2050 compared to 2019 via the impact of a change in biodiversity on the provision of soil quality and pollination, both with and without considering the impact of extreme climate events. Table 1 shows the list of scenarios varying in terms of soil quality and productivity, pollination services, crop productivity, and

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[14] SSP2 is the middle of the road scenario socio-economic pathway (SSP) scenario social, economic, and technological trends do not shift markedly from historical patterns with RCP4.5 intermediate climate change scenario with 4.5 4.5 W m-2 radiative forcing in 2100.

extreme climate events in the future. Crop productivity changes between 2019 and 2050 are estimated for 56 distinct regions and countries.[15] (For further information on countries and regions, see Appendix 2, including the list of countries and regions for which BiROFIN data generates data.)

Table 1 *Scenario setup*

Scenario	Soil quality and productivity change	Pollination services and crop productivity change	Extreme climate events
1. *Soil quality scenario without extreme climate event*	Yes	No	No
2. *Soil quality scenario with extreme climate events*	Yes	No	Yes
3. *Pollination scenario without extreme climate events*	No	Yes	No
4. *Pollination scenario with extreme climate events*	No	Yes	Yes
5. *Reference scenario*	No	No	No

Those scenario outcomes are compared with a reference scenario to estimate the economic impact of a loss in agricultural productivity via the reduction in the provision of good soil quality and pollination services. The reference scenario does not account for a change in the provision of good soil quality and pollination by biodiversity, and the world economy follows a path as depicted in socioeconomic pathways-middle of the road (SSP2) where social, economic, and technological trends do not shift markedly from historical patterns towards 2050.[16] The scenario component used in the benchmark MAGNET model equivalent includes the commonly used characteristics of the SSP2-RCP45 scenario, excluding the climate change-related characteristics.[17]

2.4 Example preliminary outcomes from soil quality scenario

This section presents preliminary soil productivity changes at the country level, as anticipated by our soil quality scenarios, as an example. Pollination scenario outcomes on crop productivity levels are not presented as they are crop-country-specific, need more detailed elaboration and are left for the full report, which will be published next year.

Preliminary analysis highlights that European countries faced the most significant agricultural productivity losses via a loss in providing good soil quality due to pressures on biodiversity in 2019 (see Figure 2). The estimates for this period indicate that European countries experienced the highest levels of productivity loss. In contrast, lower loss levels are estimated for African nations and countries like Russia, Australia, and Canada. Our study uses these estimates for soil productivity and pollination loss from the 2010s as benchmark levels for comparison with future losses.

The expected change in productivity by 2050 in the soil quality scenario with climate change-induced changes in extreme climate events varies significantly among countries (see Figure 3). So, it shows the productivity that is projected to be lost in addition to what has been lost until 2019 (please refer to Figure 2 for the changes that occurred up to 2019) and highlights the varying degrees of productivity decline caused by biodiversity loss-induced soil quality loss with an elevated effect due to climate change. For instance, the productivity decline in Nigeria is projected to be 4 times the productivity decline in Ireland by 2050 compared to 2019. Specifically, productivity is expected to decrease most in cocoa-producing African countries, including Cameroon, Ghana, Ivory Coast, and Nigeria, followed closely by Brazil, North Africa and the Middle East. In contrast, countries like the United Kingdom, Ireland, the Philippines, Taiwan, and the Netherlands are projected to experience the lowest decreases due to the same factors. Countries projected to face more significant productivity loss between 2019 and 2050, like Nigeria, cocoa-producing African countries, are expected to experience more human modification, agricultural intensification, and, more importantly, more extreme climate events than those with less severe productivity declines.

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[15] The list of countries and regions for our estimations are determined by their importance to the portfolios of our financial sector partners.

[16] For more details on SSP scenarios please see Fricko et al. (2017) and Riahi et al. (2017).

[17] Excluding climate change related characteristics does not have an important implication in our estimations, as this scenario serves as a counterfactual for estimating the effect of soil quality and pollination loss on the economy under other scenarios which are generated by taking into account SSP3 (high challenges to climate mitigation and adaptation) with RCP 6.0 (moderate level climate change) scenario.

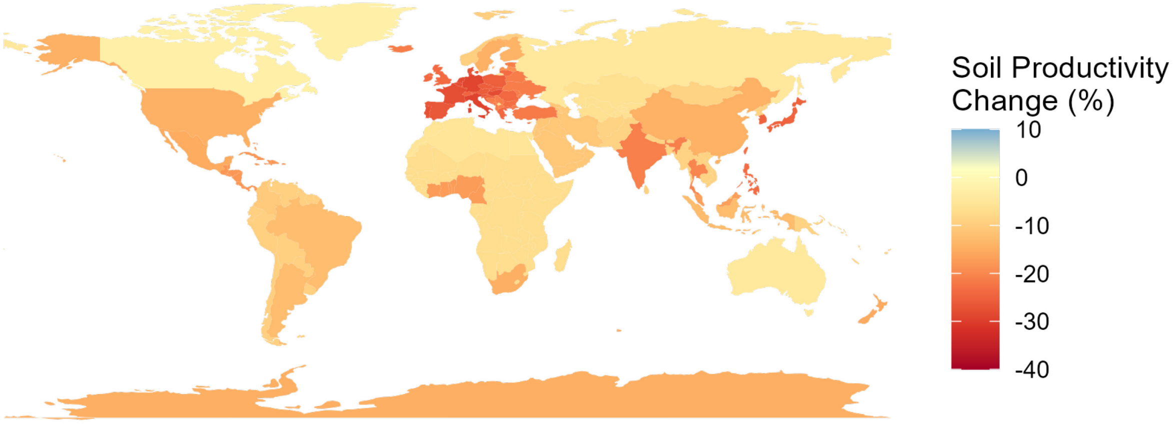


Figure 2 *Estimated average change in soil productivity level at the regional level that has happened in 2019 due to the loss of soil quality due to the loss of biodiversity*
Source: BiROFin project.

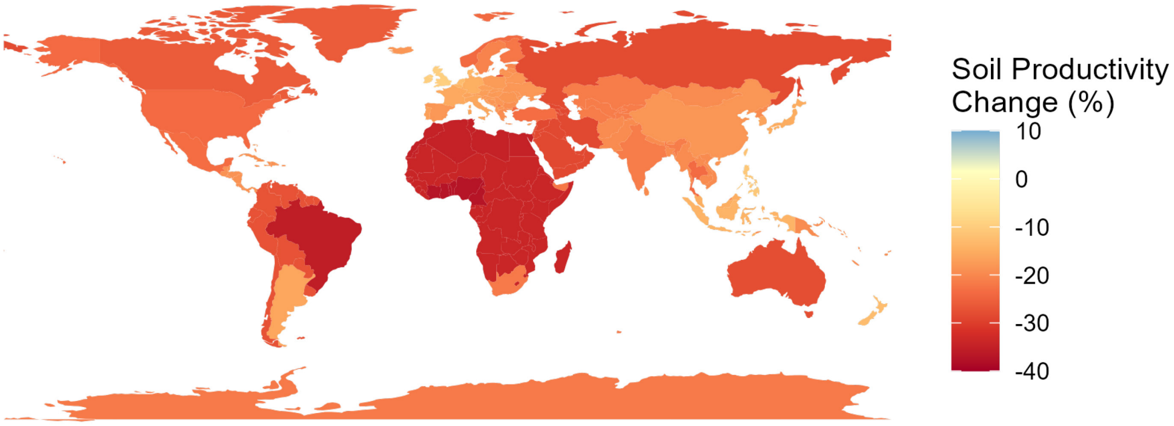


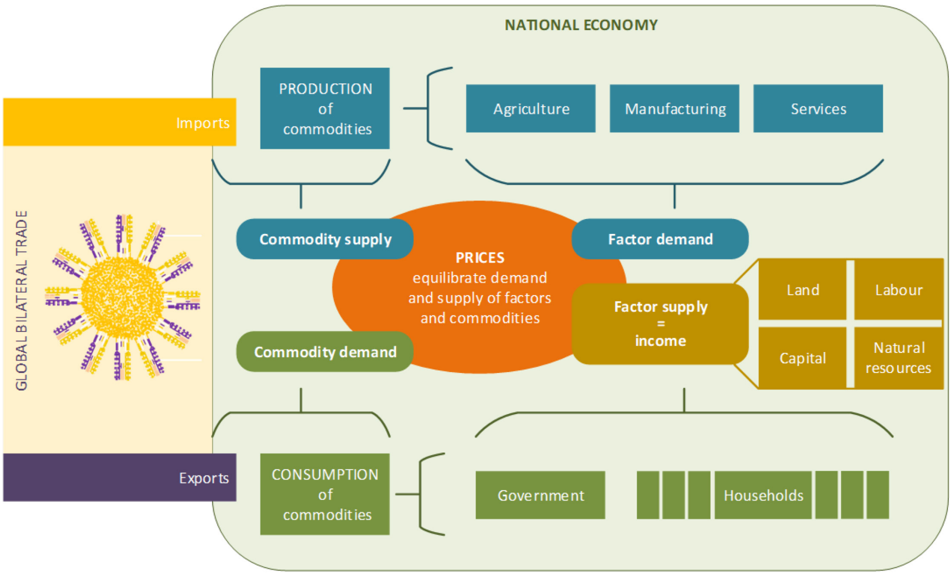
Figure 3 *Projected average change in soil productivity level between 2019-2050 by the loss of soil quality due to the loss of biodiversity, country regional level results*
The above map shows the total soil productivity loss in 2050 due to soil quality loss compared to current (2019) soil quality levels from the soil quality loss scenario with an extreme climate event.
Source: BiROFin project.

3. Integrating future scenarios into economic models

The MAGNET model estimates the outcomes of ecosystem service scenarios at the sector-country level (refer to the MAGNET model description in Box 1). The productivity shocks or other impacts estimated for ecosystem scenarios serve as input for the MAGNET global general equilibrium model, which generates production effects across different economic sectors in multiple countries and regions engaged in trade with one another.

Box 1: Magnet model

MAGNET (Modular Applied GeNeral Equilibrium Tool) is a multi-regional, multi-sectoral applied computable general equilibrium (CGE) model which builds on GTAP datasets (Woltjer and Kuiper, 2014). CGE models combine economic theory with data to derive the effects of economic shocks or policy change. In MAGNET, perfect competition is assumed, and actors choose the cheapest combination of production factors: labour, land, capital and natural resources. Contrary to partial agri-food models, MAGNET includes income feedback loops between primary and industrial sectors to cover the entire (bio)economy (MAGNEt-model.eu, n.d.). MAGNET will be linked to land use models related to ecological data – such as IMAGE and GLOBIO – to include ecological details.[18]



The model can simultaneously provide a monetary estimate of the impact of an economic shock on several sectors. When a shock, such as an agricultural productivity decline, is introduced, different commodities are exchanged at new prices. This change affects factor demand, production levels across various sectors, trade between regions, and consumption of different commodities. As a result, the effects of the shock spread through multiple and interlinked channels (please see Appendix 3 for how pollination loss can affect the macroeconomy in the MAGNET model). A concrete example would be that the food processing industry is negatively affected by higher agricultural prices, increasing the cost of intermediate inputs with cascading effects on their supply and demand. When a production shock is introduced into the model, production factors—such as land, labour, and capital—can be reallocated from sectors directly affected by the loss of ecosystem services to less-impacted industries like manufacturing or services. Furthermore, shocks are typically not uniform across countries, and sectors in those countries with comparatively low shocks may see relative benefits. Due to this resource reallocation, the model may estimate that some sectors not directly affected by the shock may also increase their production.

The model is estimated to have specifications that meet the needs of the financial sector. Those specifications include:

- Estimation for 56 distinct country regions (for a detailed list, please refer to Appendix 2), including key markets for the financial sector, such as the 21 countries with the largest economies.
- Covers 93 MAGNET-specific sectors, which can be mapped to 37 ISIC codes (see Appendix 3 for the sectoral classification used by BiROFIN).

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[18] The MAGNET model was recently reviewed for recommendations by the NGFS on how to apply these kind of models for assessing nature related economic and financial risks, see https://www.ngfs.net/en/ngfs-recommendations-toward-development-scenarios-december-2023

- General equilibrium effects of various ecosystem service scenarios on several outcome variables, including land demand, emissions, total employment, GDP volume, population, production, value-added, consumer prices, producer prices, and agricultural yield. The outcome variables are determined jointly by financial sector partners, and the financial sector is expected to utilise these outcomes for risk analysis, among other purposes.[19]
- Economic modelling years covering 2025, 2030, 2035, 2040, 2045, and 2050 are relevant for the financial stress testing that may be conducted in the sector.

Modifying the model's initial soil and crop productivity levels based on future scenario results under some assumptions. Based on the soil scenario assessment results, the model adjusts each country's soil productivity levels. In contrast, crop productivity levels are modified according to the outcomes of pollination service scenarios (refer to assumptions outlined in Appendix 5). This means a decline in soil quality leads to reduced productivity across all agricultural lands and the crops produced on those lands. A loss of pollination services due to decreased insect pollinators results in decreased crop productivity, particularly for those crops that rely heavily on insect pollination.

3.1 Preliminary estimates from the macroeconomic model

Preliminary estimates show that biodiversity loss-induced soil quality and pollination loss can reduce global economic activity by 2050, especially in the face of extreme climate events. Figure 4 shows the projected decline in annual global GDP in 2040 and 2050 due to the biodiversity loss-induced loss of pollination and soil quality services compared to the reference scenario. As assumed, in both soil quality and pollination scenarios, the negative impact of biodiversity loss-induced soil quality and pollination services on economic activity increases with each modelling year, as the extent of biodiversity loss is assumed to increase throughout 2019-2050.[20] In scenarios with extreme climate events, the loss of pollination and soil quality services due to biodiversity loss reduces global economic output more than in scenarios that do not consider climate events. This is because the projected soil productivity loss due to soil quality loss and crop productivity loss due to pollination loss are elevated when the effect of climate events is considered.

The model predicts that soil quality scenarios create a more severe decline in the world economy than pollination scenarios. In 2050, the negative impacts of soil scenarios on annual global GDP are about 2.5 times the impacts of pollination scenarios. Our observations indicate that this difference arises primarily because soil scenarios negatively affect land productivity, impacting all crops, whereas pollination scenarios generate productivity shocks at the crop level. The severity of these shocks at the crop level depends on the degree to which crops rely on insect pollinators. For example, fruits and nuts are highly dependent on insect pollinators. At the same time, crops such as wheat and rice are primarily wind-pollinated, so our pollination scenario results do not influence their productivity.

According to our preliminary model results, the impact of biodiversity loss on pollination services at the country level varies significantly. Figure 5 illustrates the preliminary estimates of how the loss of insect pollinators' pollination services affect annual GDP levels in different countries in 2050 compared to the reference scenario when extreme climate events are considered. Pollination loss most severely affects African countries (excluding South Africa), followed by countries like Turkey and China and the region of Central Asia. For instance, Northern European countries are less severely affected by pollination loss than these countries.

Some countries, especially in Northern Europe, can sustain better crop productivity and economic output. The final macroeconomic effects of our model depend on the share of pollination-dependent economic sectors and foreign trade. According to our scenario results, some countries, such as the United Kingdom, Ireland, the Philippines, Taiwan, and the Netherlands, are expected to experience relatively low crop productivity losses from 2019-2050 due to biodiversity-induced pollination losses. This is the result of the combination of two factors. First, they are projected to have less additional agricultural intensification and human modification. Second, extreme weather events are less likely in those countries. This may place them in a more advantageous position in the international trade of agricultural products. Please note that our pollination loss scenarios affect several regions simultaneously; therefore, imports can substitute for reducing domestic production, creating export opportunities for other countries. The final macroeconomic effects depend on the share of pollination-dependent economic sectors and foreign trade. For some cash crops that play an essential role in the economy, the GDP impacts can be more severe because of the deterioration in the trade balance than others.

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[19] Indicators such as government bond credit spreads, corporate credit spreads, interest rates, equity prices, FX rates, and inflation rates are also used for risk analysis in the financial sector. However, global macroeconomic models producing sector country-level results do not predict those, yet our outcome variables are good predictors for those indicators as well as the value of assets for different sectors and credit default rates.

[20] In the years leading up to 2040, the influence of soil and pollination ecosystem services remains minimal, exerting little to no effect on economic activity. For this reason, they are not included in the figure.

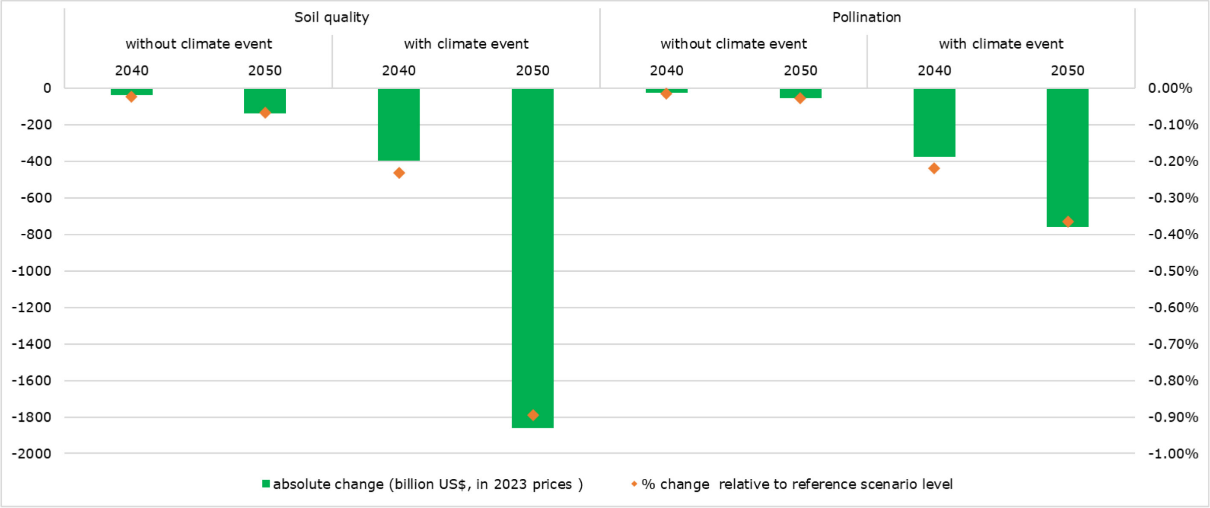

Figure 4 *The estimated economic impact of biodiversity loss-induced soil quality and pollination loss on global annual real GDP in 2040 and 2050 relative to the reference scenario with or without an extreme climate event.*
The figure illustrates the changes in annual World GDP due to the loss of pollination and ecosystem services compared to the reference scenario by different modelling years. The bars represent the absolute differences, while the markers show the relative percentage changes. To calculate the percentage change in GDP levels, we compared the GDP estimates of the pollination and services loss scenario for a given year (in constant prices) with the estimates from the reference scenario for the same year. To convert the percentage change into a dollar amount in 2023 prices, we have multiplied absolute changes in constant prices (2017 USD prices) with the change in GDP price deflator from 2017 to 2023 for the US (equivalent to 1.22) from BEA.
Source: BiROFin project.

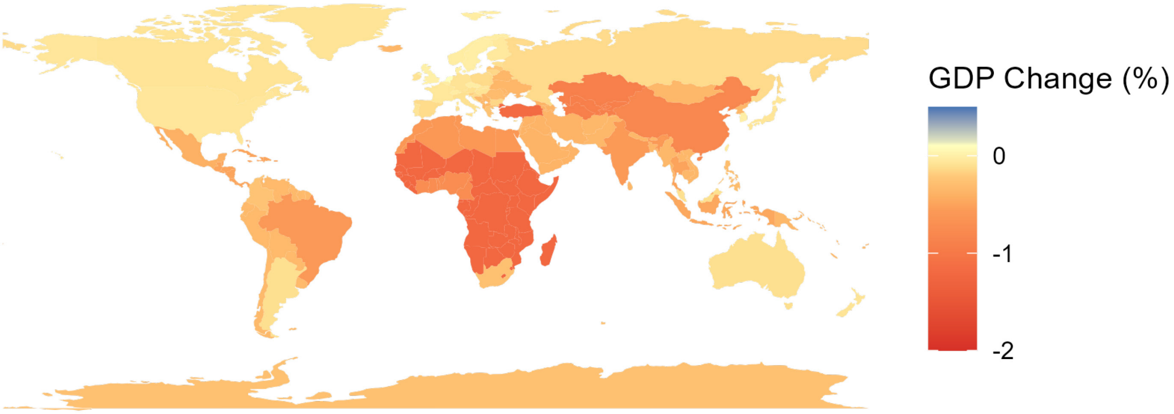

Figure 5 *The impact of biodiversity loss-induced pollination services loss on economic output at the country level under an extreme global climate event, % change in annual real GDP, relative to the reference scenario, 2050*
The map shows the effect on annual county-level GDPs due to the loss of pollination services loss with extreme climate event scenario compared to the reference scenario in 2050. The lighter green, yellow, and red negatively affect GDP.
Source: BiROFin project.

4. Estimating abatement measures’ costs and benefits

Estimation of net benefits for measures to abate biodiversity loss to guide the financial sector in prioritising the right measures. The project assesses the costs and benefits of abatement measures to reduce the decline of key ecosystem services across six countries. These abatement measures include practices and strategies that mitigate ecosystem service loss per spatial unit. They are identified through a comprehensive scientific and grey literature review and consultations with ecosystem experts. The selected measures have either a strong, empirically supported link to improving specific ecosystem services or their components. For example, pollinator populations are a component of pollination services; thus, a measure that contributes to the recovery of insect (pollinator) populations contributes to the recovery of pollination services. Cost and benefits data for these measures are collected for France, Germany, the United Kingdom, the Netherlands, and the United States. The financial sector can use the cost and benefit estimates when financing decisions and guide their clients to invest in measures that can minimise or even restore biodiversity loss.

We estimate each measure’s country-specific capital and operational costs (Figure 6). Specifically, we estimate capital expenditures (CAPEX) per hectare at the country level, including equipment, infrastructure, and other fixed expenses that should be made when implementing the measure for the first time. We also assess annual operational expenses (OPEX) per hectare, such as labour, materials, and maintenance costs, to determine the operational expenses.

Benefits are calculated at the hectare and country levels linked with MAGNET model estimates. To estimate the direct benefits of implementing abatement measures, we collected data on productivity gains and potential cost reductions arising from these measures. To capture indirect benefits, we also gather data on the anticipated impact of abatement measures on key ecosystem services, including pollination and soil quality. Many of these assessments are qualitative and were integrated with the quantitative estimates of direct benefits. At the country level, we aggregate the productivity gains and cost reductions at the hectare level to the country level, taking into account adoption rates. We also use MAGNET scenario results to establish the link between the benefits of measures to abate pollination and soil quality losses and global GDP. We aggregate these costs and benefits for implementation periods of 5 and 25 years, as applicable. The net benefits per hectare and at the country level are estimated by subtracting the cost from the total benefits (direct and indirect).

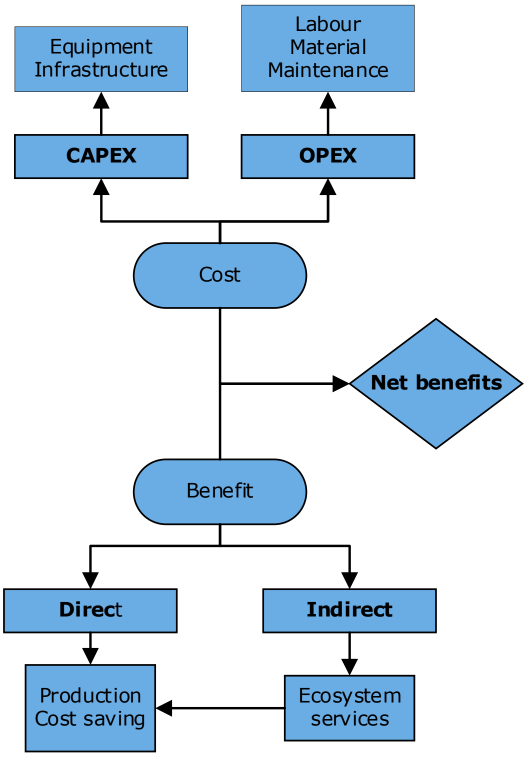

Figure 6 *Our cost and benefit analysis approach. Cost components categories are illustrative examples The figure illustrates the costs and benefit components to estimate the profitability of abatement measures. Source: BiROFin project.*

The existing literature, expert opinions, and estimates from the Magnet model are utilised to evaluate costs and benefits. Data are collected from peer-reviewed studies and reports from reputable organisations (e.g., Wageningen University & Research and the European Parliamentary Research Service’s Scientific Foresight Unit) to estimate direct costs and benefits—such as the value of productivity gains from adopting these measures. These data is calibrated for different countries through structured interviews with experts from various regions. A detailed expert survey has been developed for this purpose. To assess indirect benefits, we first identify the ecosystem services each measure recovers annually (for example, the percentage of pollination services recovered compared to the previous year) by consulting the scientific literature. To determine the value of the recovered ecosystem services, we use the global annual macroeconomic value corresponding to the percentage of ecosystem service change projected for 2050, as the Magnet model estimates.

4.1 Application of the approach to abatement measures

In the project's first year, cost and benefit data for measures to recover soil quality and pollination services are collected. This data will be disseminated by the first half of 2025.

Twelve measure types have been identified for the data collection that can prevent soil quality and pollination services from declining due to biodiversity loss (please see Appendix 5 for the full list of selected measures). The measures are selected among those that can prevent soil quality loss and enhance soil biodiversity and organic matter, thereby enhancing soil organic carbon. Measures are backed by evidence demonstrating their effectiveness in improving one or more of these components. Likewise, to address the decline in pollination services, we selected measures that help protect at least one type of pollinator. For example, measures that create habitats for wild pollinators can support the growth of pollinator populations.

Visual analyses will be used to demonstrate the economic benefits and cost measures. We are currently collecting data to estimate the costs and benefits of these measures. The cost-benefit analysis results will be summarised in a marginal biodiversity loss abatement opportunity curve that focuses on improvements in soil quality and pollination (see Figure 3 in Zimmer et al., 2024). Additionally, we will create a comparison plot illustrating the investment needed versus the indirect economic value of soil quality and pollination service measures (see Figure 4.10 in Pamuk et al., 2023). These graphs will show the measures that are interesting to invest in from an economic perspective and those which are less viable.

5. Concluding remarks

Working with researchers and financial sector practitioners is vital to make scientific knowledge usable for transitioning to a nature-inclusive financial sector. The model outcomes are challenging to interpret as they consider sectoral relationships and international trade. The study projects the effects of varying soil quality levels and pollination loss on countries. According to the modelling results, some countries can experience positive effects from the global losses of those ecosystem services trade. This project aims to build a shared understanding of these outcomes and their implications by bringing together researchers and practitioners.

As the next steps, financial sector partners will evaluate the data for the economic impact of pollination and soil quality services, with findings to be reported soon. The cost and benefit data for abatement measures will be collected and shared with consortium partners in 3 months. Once the economic impact estimates and abatement measures have been checked by the research teams from WUR and FSD, other consortium partners are expected to internally test the sector-country level data sets generated for scenarios related to pollination and soil quality services. They will provide feedback on the usability and credibility of the data. Feedback from these tests will be collected and used to refine the data. The research findings will be compiled into a report and policy brief, released in the coming months. The BiROFIN consortium will also determine which ecosystem services to focus on and announce their decisions by the end of the year.

The soil quality and pollination scenarios, and modelling assumptions necessitate further validation through literature support and sensitivity analysis.

- Several assumptions were made while developing the soil quality and pollination scenarios, particularly in creating a biodiversity index and linking it to soil productivity and pollination loss (see Appendix 1 for these assumptions). We will support these assumptions with findings from the literature and conduct a sensitivity analysis to relax some of them.
- In scenarios involving extreme climate events, we assumed that all countries experience the event in the same year. However, we will revise this assumption by considering the likelihood of the event occurring in different countries at varying times.
- The MAGNET model does not consider that the effects of biodiversity loss and productivity losses can be persistent. For example, the loss of financial capital due to decreased soil productivity can impact economic activity for several years and persistent, meaning the consequences of such shocks could be significantly greater.
- Our estimations also do not account for the fact that changes in economic activity, as predicted by the MAGNET model, may alter the level of human modification and agricultural intensification in the future.

- We introduced changes in soil and crop productivity as estimated by the scenarios at five equal time intervals. In the final estimation, we will relax this assumption by considering past trends in human modification and agricultural intensification.
- The preliminary analysis does not address the impacts of joint pollination and soil quality loss scenarios. Since the combined loss of these ecosystem services could substantially affect the economy, we will estimate these standard shocks in the coming months and incorporate the findings into the full report.
- Sectoral classifications we use in the macroeconomic modelling may hide the effects of soil quality and pollination services loss when looking at specific crops such as cocoa or flowers. For instance, the model shows that countries like the Netherlands would often gain in case of a worldwide reduction in agricultural productivity. Still, those effects result from different types of crops (in the Netherlands, other crops are flowers and not cocoa).
- Our macroeconomic effect estimates do not account for changes in dietary outcomes and their associated health effects. For example, while the economic loss from pollination decline is less severe than the loss from soil quality deterioration, it still results in reduced production and consumption of fruits and nuts, classified as healthy food options.

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Appendix 1 Linking Agricultural Intensification and human modification with Soil Quality, pollination, and Crop Productivity Losses

For the first pathway, to evaluate the direct (future) impact of agricultural intensification and human modifications on soil productivity and pollination services, we utilise the Human Modification Index (HMI) and the Pesticides Application Rate Index (PARI) to create a pressure index equals to an average of those, $PI = \frac{HMI+PARI}{2}$. However, to our knowledge, no academic studies explicitly link soil productivity and pollination services with agricultural intensification and human modification.

Then, we can devise a soil biodiversity index. $SBI = 1 - 0.5\mathrm{PI}$ As a result, we make a preliminary assumption: At maximum, 50% of productivity loss can be attributed to the soil quality change due to the loss of biodiversity, and a maximum of 50% of loss in pollination service levels can be explained by the pressure on biodiversity. $0.5 \times (1 - \mathrm{SBI})$. When $\mathrm{SBI} = 1$ There is full biodiversity and no soil productivity or loss of pollination services. When $\mathrm{SBI} = 0$ there is a 50% loss in soil productivity or pollination services loss. To refine this preliminary assumption, the project will explore various valuations that connect agricultural intensification and human modifications with soil productivity and pollination services in the upcoming years.

To link extreme weather events with soil services, we develop an extreme Weather Index (EWI), which takes the maximum value from the rate of changes in mean temperature (T_m), precipitation (SPI) and the rate of changes in the number of days when maximum temperatures exceed 35°C ($TX35$). $EWI = \max(T_m, TX35, SPI)$. Each of those indicators was scaled from 0 to 1. Data were obtained from the IPCC-WGI interactive atlas (Gutiérrez, 2021). We assumed that the less pressure the surrounding biodiversity received from external stressors, the higher the resilience of soil and its ability to support plants against climate risks. For pollination services, considering the susceptibility of insect pollinators to weather conditions (Müller et al., 2024; Outhwaite et al., 2022), we assume that when the climate risk is high in a region, the risk of pollination services loss is also high. This is especially the case where biodiversity is under greater pressure. Based on this, with the additional productivity loss due to extreme climate events, equals $[1 - 0.5 \times (1 - SBI)] \times [(-0.4 \times SBI) + 0.8] \times EWI$. Here $[(-0.4 \times SBI) + 0.8]$ is the maximum additional soil productivity or pollination services loss that can be experienced due to climate factors (EWI). We assume that when biodiversity is under high pressure ($PI = 1, SBI = 0$) and the county or region is under high climate disastrous risks ($EWI = 1$) the maximum productivity loss will be 80%. When PI is 0, this loss can be a maximum of 40%. These assumptions will be further validated with precise data from the literature, and their sensitivity will be assessed.

The total soil productivity loss or pollination loss in the case of extreme climate events then equals $\left(0.5 \times (1 - PI)\right) + \left(\left(1 - 0.5 \times (1 - PI)\right) \times \left((0.8 - 0.4 \times \mathrm{PI}) \times \mathrm{EWI}\right)\right)$. The first term shows the direct impact pathway's effect, and the second term indicates the resilience to extreme climate events pathway's effect on soil productivity or pollination services loss.

In relation to the decline of pollination services, we assess the ultimate effect on productivity by examining the reliance on insect pollinators for each crop type. To accomplish this, we apply ratios of insect pollinator dependency from Aizen et al. (2016) and Klein et al. (2007). Using methods similar to those for calculating economic losses by Bauer and Wing (2016) and La Notte et al. (2020), we posit that reductions in pollination services by insects, as outlined in the scenario, result in diminished crop yields according to their specific insect pollinator dependence ratios (PDRs). We compile these ratios from the aforementioned studies and utilise FAOSTAT data on past agricultural output to estimate the decrease in crop production that aligns with the reductions in pollination services projected by our scenario. For instance, a complete loss of 100% in pollination services would lead to a crop production reduction equivalent to the crop's PDR. Conversely, a 50% decline in pollination services would correspond to a production reduction equal to the crop's PDR multiplied by 0.5. As different countries grow varying amounts of pollinator-dependent crops, this methodology results in differences in the effects of lost pollination services across countries. For more information, please consult the prior research conducted by Pamuk et al. (2023).

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Appendix 2 List of countries and regions BiROFin generates data for

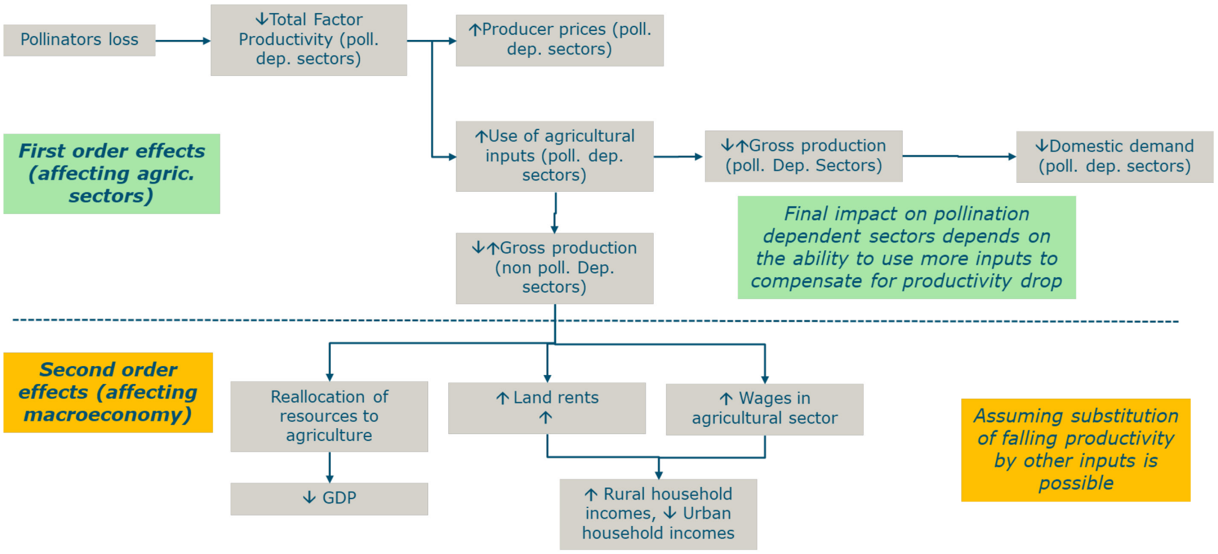
Africa, Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Central America, China, Cocoa producers Africa, Cocoa producing countries in Africa, Colombia, Czech Republic, Denmark, East Asia, Estonia, EU 27, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Republic of, Latvia, Lithuania, Malaysia, Mexico, Middle East, Netherlands, New Zealand, North Africa, Norway, Philippines, Poland, Portugal, Rest Latin America, Rest of EU, Rest of Europe, Romania, Russian Federation, Slovakia, Slovenia, South Africa, Spain, Stans, Sweden, Switzerland, Taiwan, Thailand, Turkey, United Kingdom, United States, World.

Appendix 3 Sectoral classification used in the study

This study utilises the ISIC sectoral classification. Below is the complete list of sectors included in the ISIC classification. Please note that the details of the sectors have been determined based on their relevance to the financial sector, and some sectors have been aggregated accordingly. If you need a sectoral match with the Magnet modelling sectors, it is available upon request.

Full list of sectors is as follows: Growing of non-perennial crops; growing of perennial crops; animal production; forestry and logging; fishing; aquaculture; mining and quarrying; manufacture of food products; manufacture of beverages, manufacture of tobacco products; manufacture of wood and of products of wood and cork, except furniture, manufacture of articles of straw and plaiting materials; manufacture of paper and paper products, printing and reproduction of recorded media; manufacture of coke and refined petroleum products; manufacture of chemicals and chemical products; manufacture of basic pharmaceutical products and pharmaceutical preparations; manufacture of rubber and plastics products; manufacture of basic metals, manufacture of fabricated metal products, except machinery and equipment; construction; manufacture of machinery and equipment n.e.c., manufacture of motor vehicles, trailers and semi-trailers, manufacture of other transport equipment; manufacture of computer, electronic and optical products, manufacture of electrical equipment; manufacture of other non-metallic mineral products; manufacture of furniture, other manufacturing, repair and installation of machinery and equipment; electric power generation, transmission and distribution; steam and air conditioning supply; manufacture of gas, distribution of gaseous fuels through mains; financial and insurance activities; wholesale and retail trade, repair of motor vehicles and motorcycles, real estate activities, professional, scientific and technical activities, administrative and support service activities; water supply, sewerage, waste management and remediation activities; information and communication; education; arts, entertainment and recreation, other service activities, activities of households as employers, undifferentiated goods- and services-producing activities of households for own use; public administration and defense, compulsory social security, activities of extraterritorial organizations and bodies; human health and social work activities; accommodation and food service activities; transportation and storage; manufacture of textiles; manufacture of wearing apparel; manufacture of leather and related products.

Appendix 4 Pollinator loss channels through the economy – case of systematic shocks



Appendix 5 Assumption on integrating soil quality and pollination services loss to the MAGNET model

When integrating the future scenarios for soil quality and pollination loss, we had to make some critical assumptions. Those assumptions and implications are as follows:

- Loss of soil quality leads to decreased productivity on land. This can be compensated for with increased fertiliser, capital, and labour. Crop productivity shocks due to pollination services loss are implemented under the assumption that they are factor-neutral (also referred to as Hicks-neutral) productivity shocks (Johnson et al., 2023). This implies that using specific increased inputs (e.g., fertilisers) will not compensate for the crop productivity loss induced by the loss of insect pollinators. The only way of compensation is to increase the usage of all inputs, which is more costly for the economy.
- Productivity estimates for pollination and soil quality changes are available for 2019 (the current modelling year) and 2050 (the future). We assume a constant rate of change in pollination and soil quality services between 2025 and 2050, applied in five-year increments (i.e., 2025-2030, 2030-2035, etc.). For example, suppose a scenario predicts a 60% decrease in pollination services or soil productivity. In that case, we assume a 10% decrease from 2019 to 2025, a 20% decrease from 2019 to 2030, and so forth. Additional sensitivity analyses will be conducted to consider different rate changes in ecosystem services and strengthen this strong assumption.

Appendix 6 List of abatement measures

- **Decision support systems** are computer-assisted systems that allow, for example, the control of diseases by facilitating optimal timing of fungicide and insecticide use in field crops.
- **Precision pesticide application**: Part of precision spraying is that these technologies allow targeted spraying, obtaining the target (e.g., shape, size, structure, and canopy density) of the tree or plant and then applying pesticides as needed.
- **Sensor-based pesticide application**: This method allows for identifying and quantifying diseases and weeds, in addition to high-resolution spraying, using an exact dosage for each nozzle on the spraying equipment.
- **Controlled traffic farming (CTF):** CTF minimises soil compaction in the crop zone by restricting traffic to permanent tracks. In a strict sense, CTF requires all machinery operations to be on permanent tracks.
- **Nematode application for biological control:** Nematodes are a type of biocontrol, i.e., tools or methods of plant protection that rely on beneficial organisms and their natural mechanisms and interactions. Nematodes are used as natural enemies for some pests.
- **Organic fungicide application:** Similar to nematode application, organic fungicides are a type of biocontrol used to control soil diseases.
- **Diversified crop rotations**: This practice refers to implementing an additional crop.
- **Conservation or no-tillage**: A soil cultivation technique where a significant portion of the previous crop's residues are left on the soil surface after seeding**.**
- **Organic manure application**: The application of animal waste, vegetable compost, or agricultural residues to help maintain and improve soil structure and organic matter content.
- **Cover cropping**: The use of any plants explicitly sown to reduce the loss of soil, nutrients, and plant protection products during the winter or other periods when the land would otherwise be susceptible to losses.
- **Agroforestry**: The combination of agriculture and forestry on the same plot of land. There are different restoration approaches to degraded forests and agricultural land or food production systems, such as combining trees and shrubs with crops such as wheat, corn, and soybeans. Silvopasture, soarable, and forest farming are among the agroforestry systems for food production.
- **Sustainable forest management:** This includes various measures, such as thinning forests, herbivory regulation, litter removal, and improved fire management.
- **Hedgerows or flower margins**: These are permanent areas of diverse flowers and grass.

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