



Global Assessment of Biodiversity-Climate Pathways

Deliverable D3.1

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TRANSPATH

Transformative pathways for synergising just biodiversity and climate actions



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Summary

This report on Deliverable D3.1 of the TRANSPATH project reports on the achievement of Milestone M5: “Synthesis and assessment of global biodiversity-climate pathways”. The present report describes a database and synthesis of global model-based quantitative scenarios for climate change mitigation and/or biodiversity restoration. The interventions implemented in global models and the impacts of scenarios are identified. Synergies and trade-offs of scenarios, scenario types, and archetypes for biodiversity and climate change are investigated.

The **first chapter** describes the methods used to compile the literature and extract information from the studies. Based on an extensive literature review, we compiled a dataset of global policy-screening, target-seeking and policy-oriented exploratory scenarios. These formed the basis for collecting the scenarios' underlying assumptions, such as the qualitative information describing the narratives (i.e. storyline), the interventions applied in these scenarios and their impacts. It is important to note that interventions here include not only policies, but also physical changes (e.g. management changes) or assumptions on future behaviour (e.g. diet changes) that can influence direct or indirect drivers to mitigate climate change or reverse trends in biodiversity loss. Policy instruments aim to shape behaviour, control emissions and encourage the adoption of environmentally sustainable practices through regulation and incentives.

By identifying the scenario type (policy-screening, target-seeking, exploratory), the scenarios were categorized into non-intervention, modest-intervention and intervention scenarios (Van Vuuren et al. 2012, IPBES 2016). In addition, the scenarios were grouped into a predefined set of archetypes based on similar underlying characteristics (IPBES 2019). The interventions implemented in the models for each scenario were extracted and summarized into intervention groups, sectors, types and whether they were policy instruments or physical changes.

Quantitative data on scenario impacts were collected either explicitly from the studies or implicitly from related scenario databases or the supplementary information material of the studies. Several metrics were gathered and harmonized to enable a more detailed comparison across studies and scenarios. For each metric, the percentage change per decade was calculated. To enable consistent impact comparisons, we selected four key metrics – the two most frequently reported climate metrics (Temperature change (since the pre-industrial age (1850-1900)) and total CO₂ emissions) and the two most frequently reported biodiversity metrics (Biodiversity Intactness Index, Mean Species Abundance).

Finally, scenarios that either met the 1.5°C Paris Agreement target or showed a positive decadal percentage change in any of 18 biodiversity metrics were grouped into two target-achieving categories: 1.5°C scenarios and bending the curve scenarios.

In the **second chapter**, we describe the contents of the scenario database. We collected 601 different scenarios, of which 80.2% were intervention scenarios (i.e. policy-screening, target-seeking or exploratory scenarios that apply sustainability-oriented interventions). Most scenarios explicitly quantify climate-related impacts, while fewer than half address impacts on biodiversity or other sustainable development objectives. When it comes to biodiversity, the quantification of impacts is not only less frequent but also more fragmented: we identified 21 different biodiversity metrics used across 23 studies. Similarly, we also found that most of the interventions applied in global models continue to focus on climate change mitigation, with greenhouse gas emission markets (e.g. carbon pricing, carbon taxes) playing a prominent role.

In, the **third chapter** we use the scenario impact information to provide insights into the impacts of different scenarios. The results show that among the intervention scenarios, the most positive outcomes for climate and biodiversity are found in the ambitious target-seeking

scenarios, while the modest-intervention scenarios have a less positive impact. If only single interventions such as plantation forestry, or agricultural trade liberalization, or interventions addressing climate change mitigation are applied, policy-screening scenarios can have more negative consequences for biodiversity.

While climate change mitigation in the models can in principle be achieved through a 'reformed market' archetype, scenarios with a more transformative narrative, aiming at global or regional sustainable development, can lead to synergistic outcomes for both climate and biodiversity.

Moreover, it is not only the socioeconomic conditions or the underlying paradigm of the scenarios that matter. The number of interventions applied within a scenario, as well as the number of sectors targeted by different interventions, has an important impact on the outcome. The more interventions that are applied across sectors, the better the outcome for biodiversity and climate.

While both nature protection and markets for greenhouse gas emissions appear to be essential to reverse biodiversity loss or meet the 1.5°C target, they cannot address either challenge alone. Combining policies can help to minimize trade-offs with other sustainability goals, for example by enabling lower global carbon prices, or by allowing multiple challenges to be addressed simultaneously.

The **three key findings** of this report are:

- (i) Interventions in global models are dominated by climate change mitigation measures and conventional conservation measures to protect and restore terrestrial ecosystems. Furthermore, impacts on climate change are quantified more frequently than impacts on biodiversity or other sustainability objectives.
- (ii) Transformative pathways for biodiversity and climate generally belong to the group of target-seeking scenarios. Scenarios that follow a sustainability paradigm, using multiple interventions at once to transform different sectors simultaneously, have the highest combined positive impacts on climate and biodiversity and offer the greatest potential for transformative change. These scenarios often include measures beyond conventional conservation and climate change mitigation measures such as the sustainable intensification of agriculture, the reduction of food waste, and changes to diets, e.g. a reduced meat consumption.
- (iii) The main pillars for global climate change mitigation and biodiversity restoration in current scenarios are well-known interventions such as carbon markets or nature conservation measures (e.g. protected areas, sparing mechanisms, etc.). However, these do not suffice alone and should be complemented by other measures to create transformative pathways that minimize trade-offs and maximize synergies for biodiversity, climate and society.

List of abbreviations

AFOLU	Agriculture, Forestry, and Other Land Uses
AOH	Area of Habitat
AR6	IPCC Assessment Report Six
BAU	Business-as-usual
BC	Black Carbon
BECCS	Bioenergy with Carbon Capture and Storage
BII	Biodiversity Intactness Index
°C	Degrees Celsius
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CH ₄	Methane
CO ₂	Carbon dioxide
CPI	Consumer price index
DACCS	Direct Air Carbon Capture and Storage
EDGAR	Emissions Database for Global Atmospheric Research
ESH	Extent Suitable Habitat
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicles
FGRS	Fraction Globally Remaining Species
FPI	Food Price Index
FRRS	Fraction Regionally Remaining Species
GDP	Gross domestic product
GHG	Greenhouse gas
GMA	Geometric Mean Abundance
HFCs	Hydrofluorocarbons
IIASA	International Institute for Applied Systems Analysis
K	Kelvin
KMGBF	Kunming-Montreal Global Biodiversity Framework
LPI	Living Planet Index
MIT	Mean Trophic Index
MSA	Mean Species Abundance

MYS	Mean Years of Schooling
N ₂ O	Nitrous Oxide
NO ₂	Nitrogen Dioxide
NO _x	Nitrogen Oxide
NCI_pb	Pressure-based Natural Capital Index
NDCs	Nationally determined contributions
PBL	Planbureau voor de Leefomgeving – Netherlands Environmental Assessment Agency
PDF	Potentially Disappeared Fraction of Species
PFCs	Perfluorocarbons
RCPs	Representative Concentration Pathways
REDD	Reducing Emissions from Deforestation and Forest Degradation
RLI	Red List Index
SDGs	Sustainable Development Goals
SF ₆	Sulphur hexafluoride
SO ₂	Sulphur dioxide
SO _x	Sulphur oxide
SPA	Shared Policy Assumptions
SSPs	Shared Socioeconomic Pathways
TELLUS	The Tellus Institute for a Great Transition

Introduction

Global change impacts on the biophysical conditions of the Earth system are becoming steadily more visible (Steffen et al. 2015). The pressures of global change are exceeding planetary boundaries (Richardson et al. 2023), and increasingly challenge Earth system justice (Rockström et al. 2023, Gupta et al. 2024). Depending on the scenario, temperatures are projected to reach 1.4°C (best case) – 4.4°C (worst case) above pre-industrial levels by the end of the century (IPCC 2023a). Biodiversity is expected to decline, leading to the extinction of many species (IPBES 2019, WWF 2022). Global efforts, such as the Paris Agreement to limit the global temperature increase to 1.5°C above pre-industrial levels (United Nations 2018), the 2030 Agenda for Sustainable Development (UN General Assembly 2015), or the Kunming-Montreal Global Biodiversity Framework (KMGBF) (CBD 2022) should lay the foundation to minimize the impacts of climate change, improve the situation towards a more just and sustainable world, and reverse the trends in biodiversity loss, respectively. In contrast, we are currently far from achieving these goals: global emissions have peaked (UNEP 2024b), global biodiversity is still declining (UNEP 2024a, WWF 2024), and global sustainable development is only 17% on track to meet the Sustainable Development Goals (SDGs) (UNEP 2024a).

The challenges of our time require a portfolio of diverse, scale-independent solutions (Gupta et al. 2024). The importance and need of transformative change towards a more sustainable future is increasing (IPBES 2019, UNEP 2019, IPCC 2023b). Transformative change, “a fundamental system-wide reorganization across technological, economic and social factors, including paradigms, goals and values” (IPBES 2019), offers the capacity to enable a more sustainable system, triggered by various levers (actions, measures to intervene) that directly address leverage points (points to intervene in a system) (Chan et al. 2020), or social tipping points (Otto et al. 2020).

The planning of such levers (here interpreted as **interventions**) must be approached with great care, as addressing individual issues in isolation can lead to unintended trade-offs and undermine progress toward broader sustainability goals (IPBES 2024). In particular global biodiversity loss and climate change are two major environmental challenges that influence one another through a range of ecological and socioeconomic feedbacks. Addressing them in isolation risks overlooking critical interactions and trade-offs (Arneth et al. 2020, Pörtner et al. 2023). Although most climate or biodiversity interventions generally offer more synergies, they need to be carefully planned. For example, climate change mitigation measures may risk further biodiversity loss, for example through the expansion of bioenergy or bioenergy with carbon capture and sequestration (BECCS) (Pörtner et al. 2021, 2023). To minimize such trade-offs, it is therefore essential to develop integrated solutions that address both challenges simultaneously to support the transition to a sustainable and equitable society (Pörtner et al. 2021, 2023, IPBES 2024).

However, assessing whether different solutions work together effectively is often difficult and requires significant time and resources. Hence, **model-based quantitative scenarios** provide a valuable tool for quantifying potential synergies and trade-offs, estimating the impact of specific interventions, and assessing their combined contribution to transformative change (Van Vuuren et al. 2015, IPBES 2016, Rosa et al. 2017). As a result, global scenarios have often been used in the past to quantify the environmental impacts of policies and other underlying assumptions (MEA 2005, UNEP 2007, IPBES 2019, IPCC 2023a). By combining qualitative and quantitative characteristics, scenarios allow the description of potential future conditions and allow the exploration of socioeconomic trends, technological developments, etc. (Van Vuuren et al. 2012).

While some scenarios represent **exploratory futures** of different socioeconomic assumptions, such as the shared socioeconomic pathways (SSPs) (Van Vuuren et al. 2014),

others focus primarily on interventions, such as **policy-screening or target-seeking scenarios** (IPBES 2016). The term pathway is commonly used for scenarios, such as the SSPs and the Representative Concentration Pathways (RCPs) (Van Vuuren et al. 2011a, 2014). In contrast, we consider pathways here as synonym for both policy-screening and target-seeking intervention scenarios (IPBES 2016, Aguiar et al. 2020). These pathways represent different strategies and actions aimed at approaching or achieving specific targets, such as limiting global warming to 1.5°C or halting the ongoing loss of biodiversity (IPBES 2016, Aguiar et al. 2020). However, to avoid further confusion, we will now refer to scenarios rather than pathways, and further distinguish between non-intervention and intervention scenarios based on their scenario type (exploratory, policy-screening, target-seeking).

To better understand the necessary actions and translate **global intervention scenarios** into actionable strategies at the local level, models are needed that integrate not only global climate and biodiversity pathways but also contextual factors that enable transformative change (Pereira et al. 2020). Unfortunately, **transformative scenarios** that address multiple sustainability challenges simultaneously through a combined set of interventions remain underexplored, although there are some notable examples (e.g., Van Vuuren et al. (2015), Kok et al. (2023)). Consequently, this report aims to help fill that gap by providing an overview of such scenarios, including their underlying assumptions and impacts. Furthermore, most scenario analyses tend to assess the impact of interventions on only a narrow set of sustainability issues (Orbons et al. 2024), or focus exclusively on either climate mitigation (e.g., Rogelj et al. (2018)) or biodiversity restoration (e.g., Leclère et al. (2020)), but rarely on both.

To help close this gap and clarify the **current state of knowledge on integrated climate and biodiversity scenarios**, this report provides an evidence-based synthesis of existing global scenarios, highlighting the state of research and what is still needed to support transformative change in global models (Task 3.1, Figure 1). Based on an extensive literature review, we have compiled **a database of target-seeking, policy-screening and policy-oriented exploratory scenarios**, including reference and baseline scenarios (when available) in the relevant studies. For these scenarios, information was collected on their assumptions, on the interventions implemented in the models where possible, and on the quantified impacts of the scenarios. Based on this information, the scenarios were classified as intervention, modest-intervention and non-intervention scenarios.

The literature synthesis will lay the foundation, combined with results from the other work packages, for the second task of our Work Package, a model-based quantification of promising biodiversity-climate pathways (Task 3.2, Figure 1).

The Text is structured into three chapters. The **first chapter (The TRANSPATH scenarios database)** describes the methods used to compile the database and gives an overview of the categorization of scenarios. In the **second chapter (Global scenarios – gaps and state of research)** we present the contents of the database. We describe which scenarios have been found, which interventions have been implemented, and which impacts have been quantified in global scenarios. In the **third chapter (Global scenarios - synergies and trade-offs)**, we analyse the contents of the database, identify synergies and trade-offs for specific scenario types and archetypes, and describe which scenarios have the greatest potential for creating transformative change.

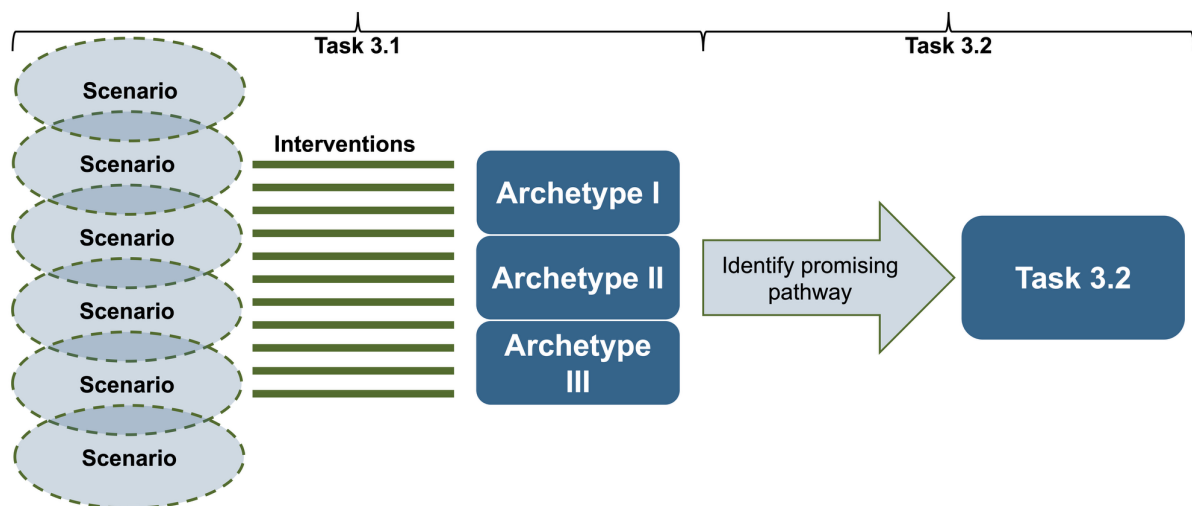


Figure 1: Short schematic overview of the tasks in the work package. Task 3.1 is due in month 32, while the deliverable for task 3.2 is due in month 46.

1 The TRANSPATH scenarios database

The TRANSPATH scenarios database, which forms the basis of this report and for future work in course of the TRANSPATH project, is a database of quantitative policy-oriented exploratory, policy-screening and target-seeking scenarios that quantify impacts on either climate, biodiversity, or both. To compile the database, we reviewed the literature on global scenarios with a focus on climate change mitigation and/or biodiversity restoration. We then collected information on the assumptions underlying the scenarios, the interventions applied and their respective impacts. This provides the basis for a synthesis of current research and the identification of gaps in global model-based biodiversity and climate change scenarios. This chapter describes the methodology we used to conduct the literature review and to extract and categorize relevant data. Figure 2 provides a brief overview of the contents of the database. In general, the database consists of four main parts:

1. **General information:** We first identified which scenarios were included in which studies, along with their associated narratives. Where available, we also recorded the socioeconomic or emissions baselines used (e.g., SSPs or RCPs).
2. **Qualitative assumptions:** Next, we extracted qualitative scenario assumptions using the SSP narrative framework described by O'Neill et al. (2017). In addition, we collected quantitative projections related to population, gross domestic product (GDP), and land cover where these were provided.
3. **Interventions:** Particular attention was given to the interventions applied in the scenarios. When interventions were implemented within the models (i.e., beyond being part of the narrative), we extracted and summarized them. These interventions were then grouped based on similarity, categorized by sector and type, and classified as either physical measures or policy instruments.
4. **Impacts:** Finally, we extracted scenario impacts where possible and assigned each impact metric to a relevant SDG.

Throughout this process, we collected both **explicit information** (from the main text of studies and reports) and **implicit information** (from supplementary materials, referenced sources, or associated databases providing additional quantitative data). This chapter provides a detailed overview of the literature review process and the methods used to categorize, harmonize, and analyse the scenarios.

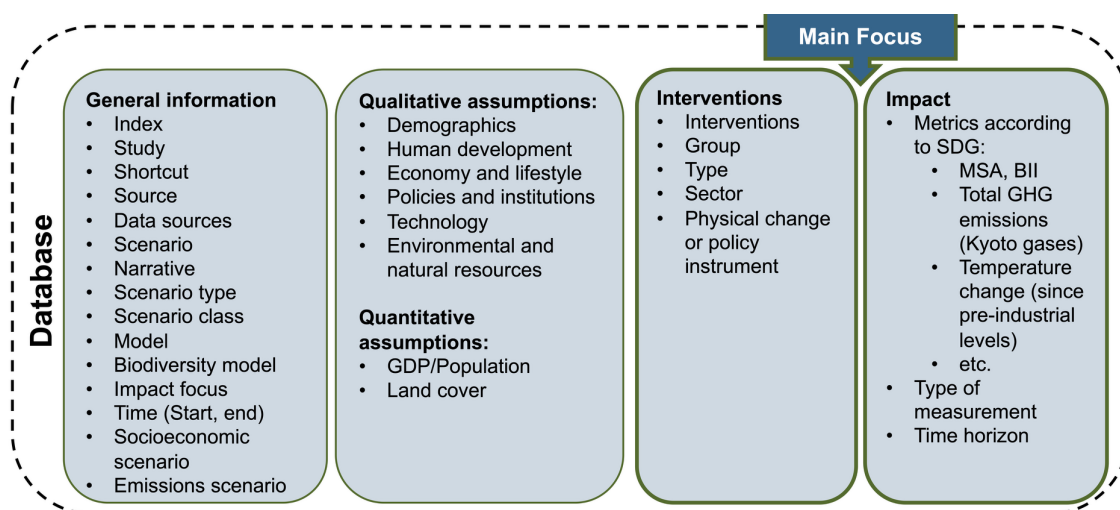


Figure 2: Overview of the contents of the database. The main focus for information extraction was general information, information on the interventions applied and, on the impacts, quantified in the scenario.

1.1 Literature screening

For the literature screening, we followed the PRISMA 2020 guidelines for scoping reviews (Tricco et al. 2018), which aim to map the state of the literature, identify research gaps and provide a comprehensive overview of the evidence already available (Munn et al. 2018, Peters et al. 2020). However, where possible, we also collected quantitative metadata and used these to conduct a quantitative analysis.

To compile our final literature, we reviewed publications from four different sources:

1. The literature list of the IPBES Global Assessment Report, Chapter 5 (Chan et al. 2019 p. 5), as they also included policy-screening/target-seeking scenarios with a similar focus to ours, covering the period 2006-2019.
2. As this did not cover the period 2019-2023, we extended our sources with an additional literature screening using the Web of Science online platform, focusing on biodiversity-related studies.
3. In addition, we added to our database all scenarios from the IPCC Assessment Report Six (AR6) database that were able to achieve a temperature limit of less than or equal to 1.5°C at the end of the century (Byers et al. 2022). These include IPCC scenario categories C1, which 'limit warming to 1.5°C (>50%) with no or limited overshoot', and C2, which 'return warming to 1.5°C (>50%) after a large overshoot' (IPCC 2023a).
4. Finally, we added grey literature, consisting mainly of scenarios from global environmental assessment reports, such as the Second Global Land Outlook (UNCCD 2022) or the Global Biodiversity Outlook (CBD 2006, 2014).

Our final literature consisted of scenarios derived from both studies and environmental assessment reports, but for simplicity we now use the term studies rather than environmental assessment reports. The following search string was used to conduct the biodiversity literature search in the Web of Science database to identify relevant peer-reviewed literature:

((("Global") AND ("Future") AND ("Scenario" OR "Pathway" OR "Model" OR "modelling" OR "Models") AND ("Backcasting" OR "Normative" OR "Target" OR "Target seeking" OR "Policy screening" OR "Ex-ante" OR "Strategies" OR "Interventions" OR "Measures" OR "Actions" OR "Efforts") AND ("Species" OR "Abundance" OR "Richness" OR "Biological" OR "Ecological" OR "Nature" OR "Biodiversity" OR "Organism*" OR "Ecosystem*" OR "Conservation")))*

To ensure the effectiveness of the search term and to cross-validate it, we used three studies that were identified as highly relevant to our objectives and that should appear in the Web of Science search: Leclère et al. 2020, Soergel et al. 2021, Kok et al. 2023. We restricted the search to articles, and searched from 01-01-2019 to 01-01-2024. Finally, of the 3495 studies screened (Including those from the other sources, Figure 3), those that met the following eligibility criteria were selected for further analysis:

- Included scenarios were required to be global in scope, model-based, quantitative, and policy-screening, target-seeking, or policy-oriented exploratory in type.
- Each study had to specify the simulation time frame, with input and output data documented either explicitly in the materials and methods section or implicitly through referenced sources.
- Studies had to assess impacts on either terrestrial biodiversity or climate change. Analyses focusing solely on individual species distribution models were excluded.

Some studies included exploratory scenarios as well as policy-screening or target-seeking scenarios. In these cases, only baseline or reference scenarios, policy-screening and target-seeking scenarios were extracted. As noted in Chapter 5 of the IPBES global assessment

report, there are not many target-seeking scenarios, so we decided to also include policy-oriented exploratory scenarios, which were the subject of Chapter 5 and are also considered by our team to be important intervention scenarios (Chan et al. 2019). Finally, the SSPs have been included in the database as these remark wide-established baseline scenarios for policy-screening or target-seeking scenarios.

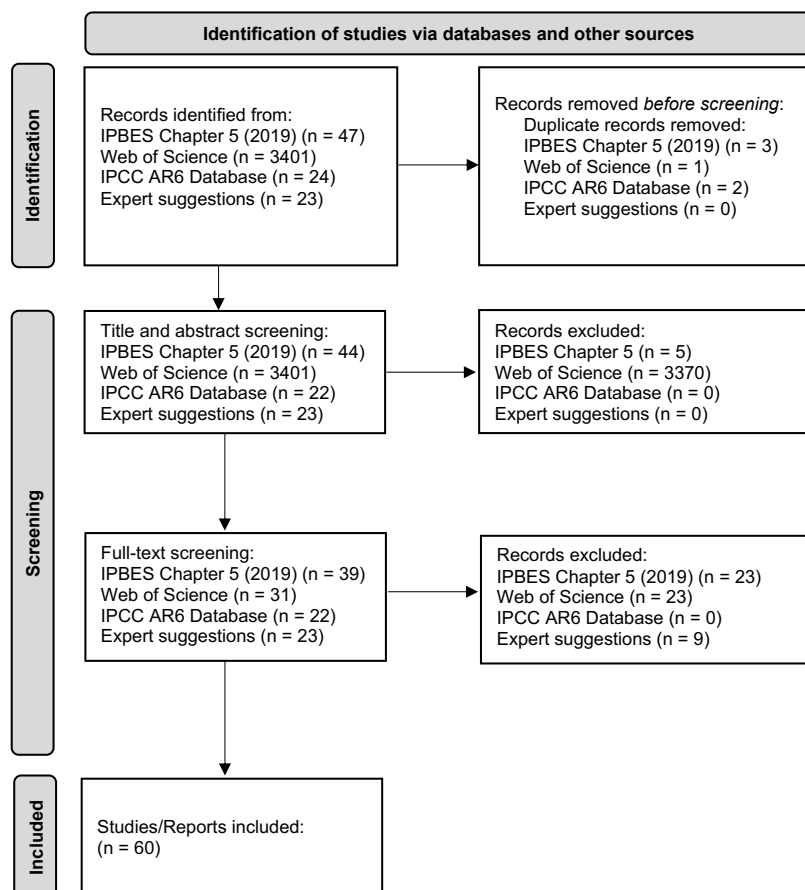


Figure 3: PRISMA 2020 flowchart (Tricco et al. 2018) showing the number of studies included and excluded due to deduplication, title and abstract screening, and full-text screening.

1.2 Data collection

We aimed to gather as much information as possible from the sources on each scenario. This included both explicit and implicit assumptions reported in the studies. It is important to note, however, that implicit quantitative assumptions were only collected if the scenario was not modified from its original formulation by the main source - that is, if no significant changes (e.g. land use changes) were made after the scenario was initially developed and the same model was used. In these cases, quantitative assumptions were only obtained if the scenario was quantified by an external source without changing its original structure (post-processing). For example, Visconti et al. (2016) quantified changes in consumption under the Rio20+ scenarios in relation to biodiversity, while maintaining the original scenario setup of Van Vuuren et al. (2015) and using the same model outputs. Here we have retrieved implicit quantitative assumptions from Van Vuuren et al. (2015). In contrast, when the scenario was modified, such as by Leclère et al. (2020), who adjusted a SSP2 scenario through specific interventions - quantitative outputs of SSP2 scenarios from model-individual studies were not

collected, as they may have changed due to the changes introduced in the new scenario setup.

1.2.1 Qualitative data collection (general information, assumptions)

In addition to general information about the studies, such as study, scenario name, scale, focus, time frame, start and end year, etc. (see Figure 2), qualitative information about the scenarios was collected. For this purpose, the variables used in O'Neill et al. (2017) for the qualitative description (the narrative) of the SSP scenarios have been used as a baseline (Table 1).

Table 1: Short overview of the variables included in the qualitative description of SSP scenarios (adapted and modified from O'Neill et al. (2017)).

Demographics	Human development	Economy and lifestyle	Policies and institutions	Technology	Environment and natural resources
Population (Growth, fertility, mortality, migration), Urbanization (level, type)	Education, Health investment, Access to health facilities, water, sanitation, Gender equality, Equity, Social cohesion, Societal participation	Growth (per capita), Inequality, International trade, Globalization, Consumption and diet	International cooperation, Environmental policy, Policy orientation, Institutions	Development, Transfer, Energy tech change, Carbon intensity, Energy intensity	Fossil constraints, Environment, Land use, Agriculture

Since many scenarios are based on the SSP scenarios, we have adopted all of these assumptions from O'Neill et al. (2017) for the corresponding intervention scenario. If a scenario was not explicitly based on an SSP, we attempted to collect its underlying assumptions using the existing database structure. For SSP-based scenarios, we treated the SSP narratives and assumptions as the baseline. However, when interventions were applied, particularly those influencing key dimensions such as land use, these were considered modifications to the baseline, effectively layered "on top" of the original SSP framework. In such cases, we recorded the baseline assumptions of the relevant SSP under the qualitative assumptions section.

Based on a combination of the socioeconomic assumptions and the interventions applied, we summarized the **narrative** of each scenario. For example, a SSP2 scenario typically follows a "business-as-usual" or "middle of the road" narrative (O'Neill et al. 2017). However, a SSP2-2.6 scenario, such as that presented by Popp et al. (2017), would, based on our logic, follow a narrative such as: "*Middle of the road. Mitigation to achieve 2.6 W/m².*".

1.2.2 Scenario type

Furthermore, we have classified scenarios into their scenario type: **exploratory**, **policy-screening**, and **target-seeking** (IPBES 2016). **Exploratory scenarios** are designed to project alternative futures based on extrapolated past trends and assumptions about forthcoming developments. These are not constrained by specific policy objectives and are particularly useful for illustrating a broad range of plausible outcomes under different socioeconomic and environmental conditions (Van Vuuren et al. 2012, IPBES 2016). In summary, we have interpreted all scenarios as exploratory where the underlying narrative does not allow a specific description of the interventions applied (as these are formulated as qualitative assumptions and do not describe how they are applied within the models).

In contrast, **policy-screening scenarios** evaluate the effectiveness of different policy options by comparing them to a reference, commonly a business-as-usual (BAU) scenario. These scenarios identify the potential impacts of various policy interventions and support the comparison of trade-offs among competing strategies (Van Vuuren et al. 2012, IPBES 2016). Consequently, we have considered all scenarios as policy-screening that applied specific interventions on top of another scenario without any pre-defined targets.

Target-seeking scenarios, on the other hand, are used to investigate pathways necessary to achieve specific environmental or policy goals, such as limiting global temperature rise or stabilizing atmospheric greenhouse gas concentrations. These scenarios provide critical insights into the actions required to reach long-term sustainability targets (Van Vuuren et al. 2012, IPBES 2016). We considered all scenarios as target-seeking, where a specific target was predefined, such as the 1.5°C target of the Paris Agreement (United Nations 2018). Finally, we considered all scenarios that combined a SSP scenario with a RCP targeting a forcing concentration below 6.0 W/m², as these tend to apply strict carbon prices (Thomson et al. 2011, Van Vuuren et al. 2011b).

Scenarios can be further categorized into **intervention scenarios**, **BAU**, and **intermediate scenarios** (Van Vuuren et al. 2012). Based on this terminology, we further characterized scenarios into:

- **Non-intervention scenarios**, which generally align with exploratory or BAU frameworks and assume a continuation of existing trends with minimal or no new policy efforts. These scenarios are important for highlighting the potential consequences of inaction (Van Vuuren et al. 2012, IPBES 2016).
- **Intermediate scenarios**, here referred to as **modest-intervention scenarios** reflect limited intervention and often incorporate currently implemented or near-term policies, such as nationally determined contributions (NDCs) under the Paris Agreement (Van Vuuren et al. 2012). While these scenarios suggest some progress, they generally fall short of the transformative changes needed for significant impact.
- **Intervention scenarios** represent more ambitious policy efforts and may include both policy-screening and target-seeking approaches. These are particularly relevant for exploring how strong, coordinated action could lead to substantial progress toward global environmental goals (Van Vuuren et al. 2012, IPBES 2016). Although SSP1 is formally considered an exploratory scenario, it is treated here as an intervention scenario due to its underlying assumptions of ambitious sustainability policies (Van Vuuren et al. 2017). The interventions under SSP1 vary depending on the model implementation and are therefore collected according to the specific assumptions of each modelling study (Popp et al. 2017). All other SSPs (SSP2-SSP5) are treated as purely exploratory scenarios without coded interventions. Although they may include assumptions such as the expansion of protected areas (e.g. extending protected areas to 17% in line with the Aichi Biodiversity Targets) or improvements in yields and agricultural efficiency, these are interpreted and coded as qualitative assumptions rather than active interventions (Popp et al. 2017).

1.2.3 Exploratory archetypes

To structure the complex information, we grouped scenarios into **archetypes** based on their underlying qualitative storylines, socioeconomic assumptions and scenario logic (Van Vuuren et al. 2012). Archetypes serve to identify salient patterns, highlight key elements, and synthesize recurring assumptions across multiple scenarios (IPBES 2019). While such archetypes are well-established for exploratory scenarios (Hunt et al. 2012, Van Vuuren et al. 2012, IPBES 2019), they often fall short of capturing the processes and dynamics typically associated with policy-screening or target-seeking scenarios (IPBES 2022).

In our approach, we sought to make the **exploratory archetypes** described in IPBES (2019) applicable not only to exploratory scenarios, but also to policy-screening and target-seeking scenarios. In this context, we interpreted the environmental and economic principles outlined in the archetype framework established by IPBES (2019) as a general guideline for distinguishing between archetypes. We combined this interpretation with the underlying socioeconomic assumptions of the scenario, as described in its narrative, and the interventions applied to determine the most appropriate archetype classification (Table 1).

First, the exploratory scenarios were categorized according to the archetypes defined in IPBES (2019). For example, scenarios using SSP1 as a baseline were assigned to **global sustainable development**, those using SSP3 or SSP4 to **regional competition**, and those using SSP5 to **economic optimism**. This classification was made independently of specific interventions, as the underlying socioeconomic assumptions are inextricably linked to the broader scenario narrative and cannot be overridden by the inclusion of a single policy or intervention. For BAU scenarios and SSP-RCP combinations, we developed further guidelines, which are outlined below.

In general we considered scenarios such as SSP2 (O'Neill et al. 2017), NPi (McCollum et al. 2018), OECD baseline (OECD 2012), B2 (IPCC 2000), STEPS and APS (IEA 2022) to be scenarios that fall into the **business-as-usual** archetype (mostly without any intervention, at most with modest interventions (i.e. applying current or near-term policies, including NDCs)). Most scenarios apply interventions on top of such a BAU scenario, so we categorized them based on the interventions applied in the corresponding scenario.

Scenarios that promoted supply-side changes, trade liberalization, economic growth and the deployment of technologies such as carbon capture and storage (CCS), carbon dioxide removal (CDR) were assigned to the **economic optimism archetype** (e.g.: supply side scenario from Leclère et al. (2020)).

Scenarios that introduced greenhouse gas emission markets or focused on demand-side strategies, such as reductions in food waste and loss, dietary shifts, or changes in consumption patterns, were categorized as **reformed markets** (e.g.: demand-side scenario from Leclère et al. (2020)). For the SSP-RCP combinations, all scenarios below SSP2-4.5, SSP3-6.0, SSP4-6.0, SSP5-6.0 were included in the **reformed markets archetype** (this was decided independently of the implemented interventions, as in these scenarios the carbon price is usually used as a controlling element for the emissions trajectory).

Scenarios that emphasized sustainable land use practices, sharing-based principles or regional protected areas were grouped under the **regional sustainability archetype** (e.g.: sharing the planet scenarios from Kok et al. (2023)), while those that implemented global protected area networks or afforestation interventions were classified under the **global sustainable development archetype** (e.g.: conservation scenario from Leclère et al. (2020)). Where scenarios combined elements from several archetypes, they were categorized under

global sustainable development, reflecting the integrative and multilateral nature of this archetype (e.g.: integrated action scenario from Leclère et al. (2020) and Kok et al. (2023)).

Finally, all scenarios assuming SSP3, SSP4 or SSP-RCP combinations greater than or equal to SSP3-6.0/SSP4-6.0 were categorized into the **regional competition archetype**.

Table 2: Guidelines for archetype categorization, adapted and extended from IPBES (2019). The extension includes the socioeconomic context and the interventions commonly used to approach the target.

	Economic optimism	Reformed markets	Global sustainable development	Regional sustainability	Regional competition	Business-as-usual
Principles	Prosperity based on economic growth	Economic efficiency & sustainability	Global sustainability	Equity & local sustainability	Individualism and safety concerns	No change
Environmental principles	More "efficient" use of nature with new technologies, but protection is not prioritised	Use of nature is regulated with reformed policies	Protecting nature and environmental sustainability	Local sustainable use of nature	Lack of concern/low priority of nature	Overexploitation of nature with elements of regulation and protection
Economic principles	Market oriented based on profit maximization	Market regulation based on efficiency & sustainability targets	Market regulation and non-market mechanisms based on global environmental sustainability and equity	Markets oriented to local environmental and quality of life priorities	Market oriented with trade barriers and growing economic asymmetries/polarisation	Market oriented with some barriers and some regulation
Socio-economic baseline	BAU, SSP5, >=SSP5-6.0	BAU, <SSP2-4.5, <SSP3-6.0, <SSP4-6.0, <SSP5-6.0	SSP1, BAU	BAU	SSP3, SSP4, >=SSP3-6.0, >=SSP4-6.0	BAU
Interventions to approach target	Supply-side changes, Technology/Efficiency, Trade liberalization, greenhouse gas emission markets	Demand-side changes, greenhouse gas emission markets	Nature conservation, forestation, combined efforts (e.g. supply-side combined with demand-side changes)	Sustainable land use practices, regional interventions (e.g. biodiversity hotspots protection)		None, modest-intervention (NDCs, current policies, near-term policies)

1.2.4 Intervention data collection (guidelines, categorization)

Unless otherwise specified, interventions were recorded as described in the primary sources. In some cases, it was necessary to translate model adjustments, such as changes to rates, ratios, or other parameters, into qualitative descriptions of interventions. This translation was based on the reported model changes and involved consultation with the authors of this report. Interventions were refined in two stages: first, to consolidate similar model implementations under specific interventions, and second, to standardize terminology across studies. Any exceptions to this procedure are outlined below.

SSP/RCP scenario combinations were assumed to include shared policy assumptions (SPA) and a carbon tax or carbon price. As a result, most SSP/RCP combinations in the database only include a carbon tax or price as an intervention, even if they implicitly direct, for example, decarbonization of the energy sector. This default only applies where explicit interventions are not detailed, such as in well-documented cases. For example, Doelman et al. (2018) describe interventions related to Reducing Emissions from Deforestation and Forest Degradation (REDD) measures and afforestation, or Van Vuuren et al. (2021) describe specific interventions related to lifestyle and renewable energy transition.

For scenarios that used SSP1 as a baseline and extended it with additional interventions, e.g. scenarios in Soergel et al. (2021), the interventions from the model-specific SSP1 implementation were also collected. This was documented based on the documentation available in the main publications and the relevant SSP marker scenario sources (Calvin et al. 2017, Fricko et al. 2017, Fujimori et al. 2017, Kriegler et al. 2017, Van Vuuren et al. 2017). This has been extended to include additional assumptions that explain the implementation of the SSP model for the land use sector in detail by Popp et al. (2017). Only for Obersteiner et al. (2016), SSP1 interventions were not adopted. Although the study used SSP-based socio-economic drivers, only the GLOBIOM model was applied and no direct use of SSP1 interventions from the MESSAGE-GLOBIOM coupling was documented (Obersteiner et al. 2016). Therefore, despite the underlying SSP1-consistent population and GDP assumptions, the scenario was not classified as containing SSP1 interventions. All other scenarios that clearly documented SSP1-based interventions (including correct citation of relevant SSP marker scenario papers) were included in our intervention dataset.

Finally, based on the interventions identified and the intervention overview created, we summarized similar interventions in **intervention groups**. For example, we grouped interventions such as protection, REDD and sparing mechanisms into the final intervention group nature protection. We also grouped carbon budgets, carbon prices, carbon taxes, emission prices, emissions trading schemes and greenhouse gas taxes as greenhouse gas emissions markets.

In addition, the grouped interventions within each scenario have been organized by **sector** (Agriculture, Forestry, and Other Land Uses (AFOLU), Energy, etc.) and categorized by the **intervention type** (land use management, economic instruments, etc.). Furthermore, they were distinguished by how they were applied, whether they involve direct, physical changes or rather interventions of regulatory nature, i.e. such as policy instruments. **Physical interventions** (land use management, technologies, etc.) directly induce changes in the physical environment to mitigate climate change/biodiversity loss. **Policy instruments** (economic instruments, regulatory standards, etc.) are designed to influence behaviour, regulate emissions and provide incentives for sustainable practices. Most, but not all, physical interventions address direct drivers (e.g. lifestyle changes also address indirect drivers), while policy instruments are designed to address both direct and indirect drivers. A full overview of all interventions, the summarizing intervention groups, sectors, types and whether they are physical or policy instruments can be found in the annex of this report (Annex table 1).

1.2.5 Quantitative data collection (assumptions, impacts)

In addition to qualitative assumptions, we also collected quantitative assumptions such as population and GDP projections and land cover changes for the 2030-, 2050- and 2100-time steps. We also collected the impacts of each scenario. To do this, we mapped the collected metrics to the SDG to which they correspond. We collected impact data for the beginning of the simulation, 2030, 2050 and the end of the simulation. To obtain numerical data from figures, we used WebPlotDigitizer, version 4 (Ankit Rohatgi 2024). We also extracted implicit information from the supplementary material and, in some cases, quantitative assumptions and impacts from accessible online scenario databases (Table 2). Quantitative data have been standardized and harmonized as far as possible by converting units, calculating percentage changes per decade and selecting key metrics as described in sections 1.2.6 and 1.2.7.

Table 3: Overview of data sources used to collect quantitative data for the scenarios. Databases were provided by the International Institute for Applied Systems Analysis (IIASA), The Tellus Institute for a Great Transition (TELLUS) and the Netherlands Environmental Assessment Agency (PBL). The content of the licences has been partially summarized to highlight the relevant sections and can be viewed in full on the corresponding database website.

Name	Version	Description	Citation	License	URL
SSP Database	2.0	Quantitative documentation of SSPs	Riahi et al. (2017)	The non-commercial use for scientific publications, education, and figures or tables is allowed, as long as proper citation is provided. Partial data may be archived in online repositories for journal compliance, with a link to the original source and download date. Any full duplication, commercial use, redistribution, etc. without explicit written permission from IIASA is prohibited.	https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10
GEA database	2.0.2	Quantitative documentation of the GEA transformation pathways	Riahi et al. (2012), McCollum et al. (2012)	Content may be freely used for non-commercial and educational purpose, provided conditions. Proper acknowledgement is given as specified. All content is intended for information use only, and individual documents may carry distinct copyright.	https://tntcat.iiasa.ac.at/geadb/dsd?Action=htmlpage&page=welcome
IPCC AR6 database	1.1	Quantitative documentation of climate change mitigation pathways for the sixth assessment report of IPCC Working Group III.	Byers et al. (2022)	EU Sui generis database rights. Adapted from Creative Commons Attribution 4.0 International Public Licence. This modified licence restricts reproduction to only parts of the material, prohibiting sharing of a substantial portion of the licenced material, with an emphasis on linking to the original source instead. Adapted materials can be shared specifically for scientific research, communication, or policy consultancy, such as figures or visual tools, tables and derived analysis.	https://data.ece.iiasa.ac.at/ar6/#/login

RCP database	2.0.5	Quantitative documentation of the RCPs for the fifth assessment report of the IPCC	Hurt et al. (2011), Riahi et al. (2011), Thomson et al. (2011), Van Vuuren et al. (2011)		https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome
GSG scenarios database	2024	Quantitative documentation of the scenarios from the global scenarios group (GSG)	Electric et al. (2009)	CC-BY-NC-ND	https://www.tellus.org/results/results.html
IMAGE scenarios database	2.2, 2.4 - 2.5	Quantitative documentation of the IMAGE scenarios		Version 2.2, 2.4 - 2.5: Modification, translation, decompilation, disassembly or creation of derivative applications based on this software are prohibited, as are rent, lease or any other manner of transferring the rights of this software, or publishing the data and results presented by the software without proper agreement of PBL. The contents of the product and its copyright are the property and are protected by copyright laws and international treaties.	https://models.pbl.nl/image/Download

1.2.6 Harmonizing metrics and units for cross-study comparison

To enable consistent and meaningful comparisons across the wide range of studies and scenario databases, it was necessary to establish a standardized set of quantitative metrics. Different sources often report similar variables using varying definitions, units, or reference baselines, which can hinder direct comparison and synthesis. As such, for some metrics in the database, we identified key metrics that were commonly reported and applied unit conversions or harmonization steps where necessary.

For **temperature and radiative forcing**, we relied on the AR6 scenario database, extracting global mean temperature increases and radiative forcing values based on median projections from the MAGICCv7.5 ensemble. These temperature changes are expressed relative to pre-industrial levels (1850–1900) and reported in Kelvin (K), which are numerically equivalent to degrees Celsius (°C). All temperature values across the other scenarios—including those from the SSPs (Riahi et al. 2017), CD-LINKS project (McCollum et al. 2018), and the AR6 scenario database (Byers et al. 2022), were consistently based on the MAGICC climate model. IMAGE model scenarios similarly use median temperature projections from MAGICC, relative to the same pre-industrial baseline (Stehfest et al. 2014).

Total greenhouse gas (GHG) emissions were collected as aggregated values, covering the full suite of Kyoto gases (carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆) (United Nations 1997)) in megatons of CO₂ equivalent.

Additionally across scenarios in Leclère et al. (2020), we extracted only **Extent of Suitable Habitat** (ESH) projections from the INSIGHTS model, as it was the only model providing consistent ESH values.

To ensure comparability of economic variables such as **GDP and carbon prices** across studies, we standardized all monetary values to constant 2005 US dollars. For this, we used annual percentage changes in the consumer price index (CPI) (inflation rate) obtained from the World Bank Group (International Monetary Fund 2025). Setting 2005 as the base year ($CPI_{2005} = 100$), we recalculated the global CPI values for each year (t) using the following equations:

$$CPI_t = CPI_{t-1} * \left(1 + \frac{Inflation\ rate_t}{100}\right) \text{ for deflation (years larger than 2005), and} \quad \text{Equation 1}$$

$$CPI_t = \frac{CPI_{t+1}}{1 + \left(\frac{Inflation\ rate_t}{100}\right)} \text{ for inflation (years smaller than 2005)} \quad \text{Equation 2}$$

Using these computed CPI values, we converted all nominal values to constant 2005 US dollars. For **deflation**, i.e., converting a value from a later year (e.g., 2010) to 2005 dollars we used:

$$US\$_{2005} = US\$_{2010} * \left(\frac{CPI_{2005}}{CPI_{2010}}\right) \quad \text{Equation 3}$$

For inflation, i.e., converting a value from an earlier year (e.g., 2005) to 2010 dollars we used:

$$US\$_{2010} = US\$_{2005} * \left(\frac{CPI_{2010}}{CPI_{2005}}\right) \text{ for inflation} \quad \text{Equation 4}$$

To convert from petagrams of carbon per year to megatons of CO₂ per year, we used the following equation based on the ratio of the molecular weights of CO₂ and carbon (44/12) (IPCC 2019):

$$Mt_{\frac{CO_2}{Year}} = PG_{\frac{C}{Year}} * 3.67 * 1000 \quad \text{Equation 5}$$

Finally, for certain studies (e.g. CBD (2006), Alkemade et al. (2009)), the percentage change in **mean species abundance (MSA)** relative to the reference or baseline was converted to a percentage change relative to the start of each simulation:

$$\Delta Scenario_{\%change} = \frac{Baseline_{End} - Scenario_{DeviationBaseline} - Baseline_{Start}}{Baseline_{Start}} * 100 \quad \text{Equation 6}$$

1.3 Data analysis

1.3.1 Scenario harmonization:

To ensure comparability across studies, scenario metrics were further harmonized and expressed as percentage change per decade. Some scenarios, such as those in the AR6 database (Byers et al. 2022) were simulated using different models. Additionally, the temporal coverage varied across studies (e.g. some scenarios spanned from 2005 to 2100, while others covered shorter periods such as 2015 to 2075). Consequently, time series were standardized to allow for meaningful comparisons across scenarios and models.

For scenarios simulated by different models, we averaged the quantitative data across the models, i.e. calculated multi-model averages. To allow proper documentation of the models used to calculate these multi-model averages, we documented the models used in the general information of the database. We only did this where interventions in scenarios were implemented independently of the model implementation, i.e. we only explicitly collected interventions documented for these scenarios in the main source.

The scenarios analysed in this report included a variety of metrics measured in different units, making it impractical to harmonize all metrics across the board. We therefore selected the four most commonly used and widely reported metrics to represent climate and biodiversity impacts. This approach ensures consistency and allows direct comparison of impacts between different scenarios in our results. We chose CO₂ emissions and global temperature change as representative climate change metrics, and the Biodiversity Intactness Index (BII) and MSA as representative biodiversity metrics. As the base years of the scenarios often differ, we further harmonized the results where the scenarios had different base years to allow for a direct comparison between scenarios for specific metrics of climate change and biodiversity loss. For the climate change metrics, we calculated the percentage change per decade relative to the average of temperature and CO₂ emissions for the reference period 1991-2020, as proposed by the World Meteorological Organisation for climatological normal (WMO 2017). Thus, the percentage change per decade relative to the reference period 1990-2020 was calculated for all scenarios:

$$\Delta\% \frac{\text{Change}}{\text{Decade}} = \left(\frac{\text{Metric}_{t_2} - \text{Metric}_{t_1}}{\text{Metric}_{\text{Ref}} * \text{Decades}} \right) * 100 \quad \text{Equation 7}$$

$\Delta\% \text{Change/Decade}$ represents the percentage change of a metric per decade. It is calculated as the absolute change in the metric value between two points in time ($\text{Metric}_{t_2} - \text{Metric}_{t_1}$) divided by the reference value of the metric ($\text{Metric}_{\text{Ref}}$), multiplied by the number of decades in the scenario. The reference period average global surface temperature was 14.37°C, based on ERA5 data (Copernicus Climate Change Service 2019). Average CO₂ emissions for 1991-2020 were 30.716 Gt CO₂/year in the 2024 Emissions Database for Global Atmospheric Research (EDGAR) (Crippa, M. et al. 2024). As the BII and MSA already represent changes relative to a pristine ecosystem condition, we have expressed them not as percentage change per decade relative to a reference value (Scholes and Biggs 2005, Schipper et al. 2020), but as percentage change per decade (Pereira et al. 2024).

1.3.2 Descriptive statistics

The descriptive data analysis was conducted using Rstudio version 4.5.0 (R Core Team 2023). See Annex 4.3 for a full list of packages used in the analysis. We calculated the frequency of scenario characteristics and generated descriptive summaries, which were visualized using boxplots. To support this analysis, we manually calculated the number of sectors in which each intervention was applied per scenario, as well as the total number of interventions implemented.

Finally, we classified scenarios into a subset further on referred to as target-achieving scenarios.

- **1.5°C scenarios:** All scenarios that limit global warming to below 1.5°C by the year 2100 (i.e., achieve the Paris Goal (United Nations 2018)).
- **Bending the curve scenarios** (Mace et al. 2018): Here we consider scenarios that had a positive decadal percentage change in any of the biodiversity metrics (ESH, BII, MSA, Extinction per million species years, Fraction globally remaining species, Fraction regionally remaining species, Geometric mean abundance, Habitat range size, INSIGHTS index, Living Planet Index, Suitable habitat loss, Mean species richness, Potentially disappeared fraction of species, Pressure based natural capital index, Red List Index, Reduction vascular plant species, Species affected by 50% range loss, Species range protection level). Ecoregion protection level and biodiversity hotspot loss were excluded from this definition as they represent changes in geographical regions rather than areas directly associated with specific species. It is important to note that this classification represents a highly optimistic interpretation of biodiversity target achievement, and should be understood as such within the broader analytical context.

1.4 Data accessibility

The full-text screened literature overview including all citations and exclusion decisions and the processed database are available on Zenodo (<https://zenodo.org/records/15753209>). All code required to run the analyses, along with a backup of the processed database, is hosted on our GitHub repository (https://github.com/CNeu-hub/Transpath_scenarios_database). A raw data backup is stored internally; we provide only the processed data publicly to comply with licensing restrictions outlined in Table 2. To enable the reproducibility of the analysis presented in Figure 15, only the raw temperature and carbon price data has been uploaded, in line with the licences, as we are not publishing a substantial part of the original data (see Table 2). Permission to upload the derived data was granted by IIASA, TELLUS and PBL to ensure compliance with their licensing restrictions. Nonetheless, the full data processing pipeline, including scripts for calculating percentage change per decade, categorizing interventions, and generating the final dataset, is openly accessible in the GitHub repository.

2 Global intervention scenarios – gaps and state-of-research

2.1 Scenario types

The final literature consisted of 60 studies encompassing 601 different scenarios. When these scenarios were categorized according to their scenario type, **target-seeking scenarios were the most common with 39.8% (n scenarios = 239)** of all scenarios, followed by policy-screening scenarios with 36.1% (n scenarios = 217) and reference scenarios with 12.7% of scenarios (n scenarios = 76) (Figure 4). In contrast, target-seeking scenarios were simulated by 73.3% of the studies (n studies = 44), while reference scenarios were used by 86.7% of the studies (n studies = 52) and policy screening scenarios by only 25% of the studies (n studies = 15).

Furthermore, the database predominantly comprises **intervention scenarios, accounting for 80.2% of the total** (n scenarios = 482). Only a limited number of scenarios (n scenarios = 15) and studies (n studies = 11) were classified as modest-intervention scenarios (Figure 4). While non-intervention scenarios consist only of exploratory and reference scenarios, and modest-intervention scenarios consist of policy-screening and reference scenarios, there is some overlap of scenario types in the intervention scenarios. This is because we categorized certain exploratory scenarios, especially those oriented towards sustainability, such as SSP1 from the SSPs, as intervention scenarios because they incorporate assumptions about sustainable development policies (Van Vuuren et al. 2017). These include scenarios from studies such as UNEP (2002, 2007), MEA (2005), Raskin et al. (2010), Gerst et al. (2013). However, for consistency and due to insufficient documentation of the interventions (except for SSP1), these scenarios were excluded from the intervention, and the impacts analysis in Figures 12 and 13. Finally, most studies did not simulate only one type of scenario, e.g., because they used reference scenarios to compare with the effects of policy-screening or target-seeking intervention scenarios. This is why the percentages of studies in Figure 4 in total do not add up to 100%.

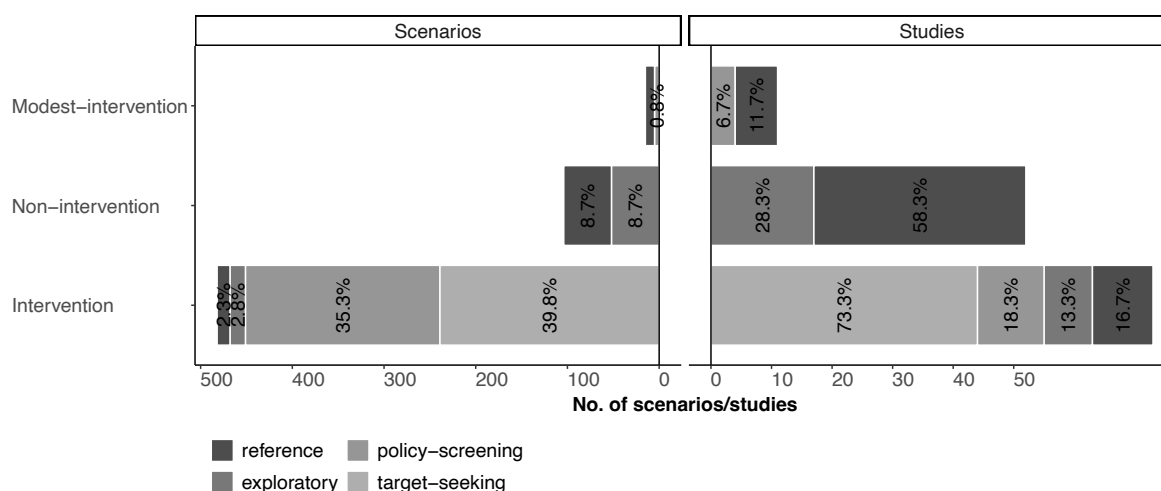
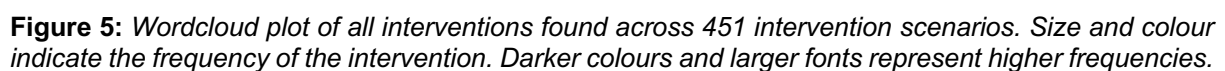


Figure 4: Frequency of scenarios (left) and studies (right), classified by scenario type, presented as stacked bar charts, showing the contributions of reference, policy-screening, exploratory, and target-seeking scenarios.

Across all intervention scenarios we found 101 different interventions (Figure 5). **Carbon pricing mechanisms clearly dominate across all scenarios** (n scenarios = 202). Carbon pricing is often implemented to drive decarbonization in the energy sector. Hence, interventions related to the energy sector, such as energy technology development (n scenarios = 115), improving energy efficiency (n scenarios = 131), and expanding renewable energy use (n scenarios = 150) are also widespread. **Biodiversity-focused interventions mainly focus on nature conservation efforts** (protection is applied in 135 scenarios). Additionally, dietary shifts (n scenarios = 141) and enhancements in agricultural productivity (104 scenarios assume yield improvements) appear frequently. However, many interventions target similar challenges, share common goals, and function in comparable ways, for instance, carbon taxes, carbon pricing, and greenhouse gas taxes.



To provide a clearer and more organized overview, we have grouped such closely related interventions together from 101 different interventions into 32 intervention groups in Figure 6. Annex table 1 gives a full overview of the grouping.

Figure 6a shows a heatmap of all 32 interventions, indicating the number of policy-screening or target-seeking intervention scenarios (n scenarios = 451) in which they were applied. The **most frequent interventions were greenhouse gas emission markets** (n scenarios = 276), renewable energy (n scenarios = 166), energy technology and efficiency improvements (n scenarios = 153), negative emission technologies (n scenarios = 151) primarily addressing climate mitigation and **nature protection interventions** (n scenarios = 138) mainly addressing biodiversity conservation. Additionally, interventions such as **diet changes** (n scenarios = 129), or agricultural technology and efficiency (summarizing yield improvements and increasing fertilizer, livestock, and irrigation efficiency) (n scenarios = 113) have been used often to address both rather than a single environmental issue.

The least common interventions across all scenarios were electrification subsidies (n scenarios = 6), including subsidies that were introduced to stimulate the market for battery electric vehicles (Soergel et al. 2021, Luderer et al. 2021), or subsidies for electrically produced steel (Van Vuuren et al. 2018). This was followed by interventions such as slower infrastructure expansion (n scenarios = 7), lower non-energy demand (n scenarios = 7), energy trade policies (n scenarios = 7), or restrictions on CDR (n scenarios = 7), where CDR was restricted based on limits on biomass production, CCS injection and afforestation, or phasing out first-generation bioenergy (Kriegler et al. 2018, Luderer et al. 2021).

Figures 6b - 6d show the frequency of physical or policy instruments, intervention sectors and intervention types. **Most interventions were physical changes** (n scenarios = 389) rather than policy instruments (n scenarios = 359). **While this indicates that the focus of global scenarios remains on the direct drivers of change, the policy instruments that were most frequently used to address the indirect drivers were economic instruments** (n scenarios = 300) and interventions in the mixed sector (n scenarios = 321), both of which were dominated by greenhouse gas emission markets. The most diverse interventions were found in the energy and mixed sectors, while the transport and industry sectors were the least used for the implementation of interventions. The most diverse interventions affecting direct drivers were introduced through land use management (n scenarios = 253). In contrast, social instruments were hardly used at all (n scenarios = 21). These were dominated by target-based interventions, such as improving access to food, water or basic sanitation (OECD 2012, Van Vuuren et al. 2015, Visconti et al. 2016, Kok et al. 2018), or equal burden sharing (OECD 2012, Soergel et al. 2021, Van Soest et al. 2021), and one study implementing a simplified form of development assistance (CBD and PBL 2007).

As the mixed sector is dominated by greenhouse gas emission markets, most scenarios address climate change mitigation directly, followed by scenarios addressing nature (n scenarios = 227), by applying nature protection (n scenarios = 138), restoration (n scenarios = 39) or forestation (n scenarios = 90) measures for nature conservation and restoration. Thus, the vast majority of scenarios focus primarily on climate change mitigation, either by directly addressing climate change mitigation in the mixed sector, or indirectly by transforming sectors such as energy (n scenarios = 187), building (n scenarios = 114) or transport (n scenarios = 45). The fewest interventions were in the industry sector (n scenarios = 23), with scenarios implementing end-of-pipe measures (Van Vuuren et al. 2015, 2018, Visconti et al. 2016, Kok et al. 2018, Gidden et al. 2019), Industry technology developments/improvements (Ou et al. 2021), reducing emissions from chemical production (Van Soest et al. 2021) or measures such as the replacement of phosphor based detergents (OECD 2012).

Overall, the results show that among the wide range of interventions, those aimed at directly mitigating climate change and conserving or restoring biodiversity were the most prominent. Only a few interventions also have a broader scope, offering important co-benefits for both climate change mitigation and biodiversity conservation, as well as other SDGs.

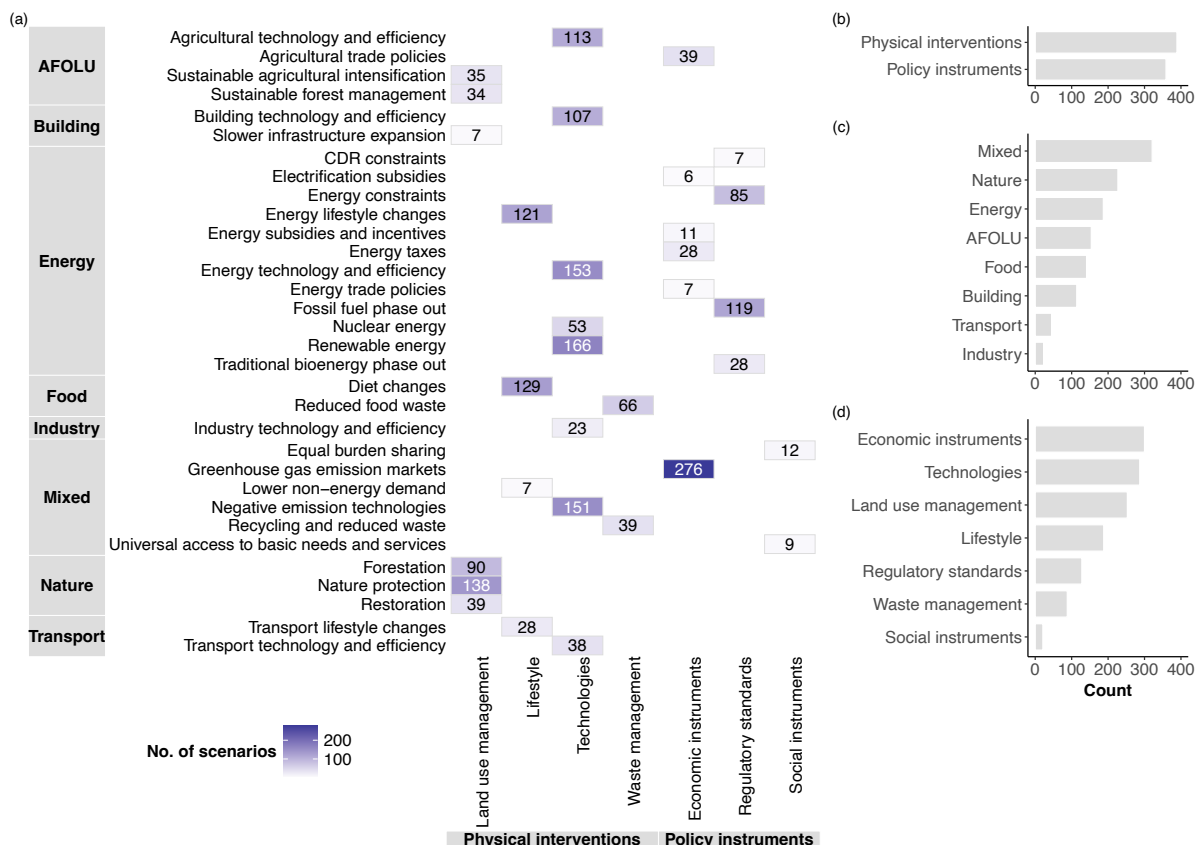


Figure 6: Panel (a) on the left presents a heatmap displaying the 32 intervention groups, showing how frequently they appear across scenarios, organized by intervention type and if they were physical or policy interventions along the x-axis and sector along the y-axis. The numbers represent the count of scenarios for each specific combination. On the right, panels (b), (c), and (d) show the distribution of interventions across sectors, intervention types, and by physical or policy intervention, respectively, summarizing their occurrence across all scenarios and studies (Source: Neumann et al. (2025)).

2.3 Explicit and implicit impacts in global scenarios

Figure 7 shows the number of scenarios and studies that explicitly assessed impacts related to climate change, biodiversity, or the SDGs. The legend indicates the specific focus of each study, distinguishing whether it addressed only one domain, such as climate change, or a combination, like climate change and biodiversity. In total, **485 scenarios and 50 studies quantified climate change impacts**, with 249 scenarios and 31 studies focusing exclusively on climate change. **Biodiversity impacts were quantified in 317 scenarios**, most of which (183) also considered climate change and other SDGs. Notably, 156 of these scenarios came from a single study: Obersteiner et al. (2016). Fewer studies, only 23, examined biodiversity impacts. Since our main focus was on climate change and biodiversity scenarios, the SDGs received the least attention, with just 221 scenarios and 19 studies explicitly investigating their impacts.

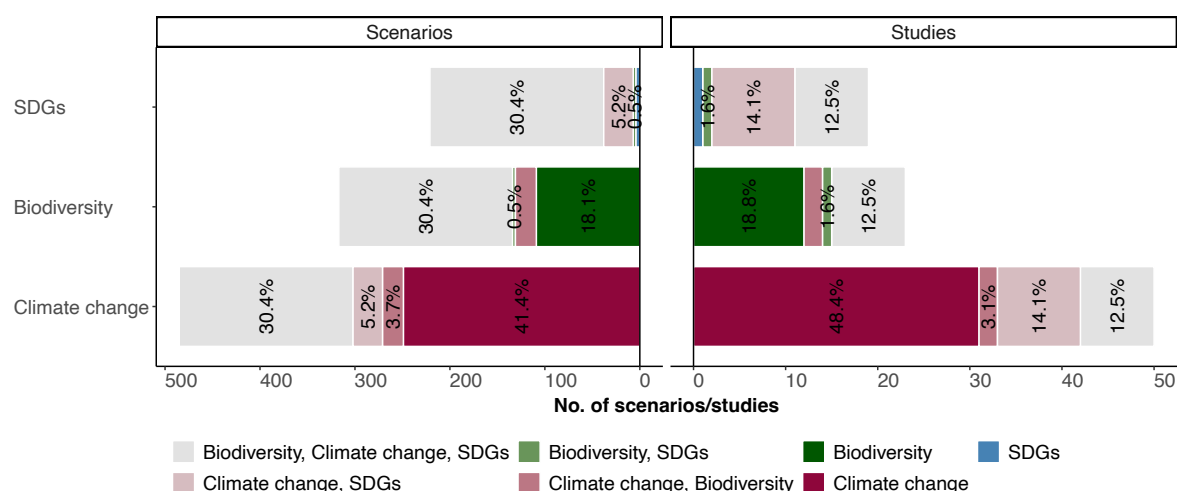


Figure 7: Frequency of scenarios (left) and studies (right) that quantified explicitly an environmental impact related to biodiversity, climate change, or the SDGs either individually or in combination (Source: Neumann et al. (2025)).

Figure 8 shows where we derived also implicit impacts from the studies. Metrics most commonly aligned with SDG13 – Climate Action, appearing in 81.2% of the studies. **The most frequently used metrics overall were total CO₂ emissions (67.2%), radiative forcing (65.6%), and temperature change (65.6%).** SDG3 – Good Health and Well-being was the second most prevalent SDG, represented in 68.8% of the studies, primarily through air pollution-related metrics such as sulphur dioxide emissions (62.5%) and black carbon emissions (60.9%). The third most represented SDG was SDG2 – Zero Hunger (45.3%), featuring metrics like nitrogen fertilizer use (25%) and hunger risk (15.6%).

Other SDGs, such as SDG11 – Sustainable Cities and Communities, SDG9 – Industry, Innovation and Infrastructure, and SDG17 – Partnerships for the Goals, were rarely addressed. Each of these was represented by only a single metric quantified in two separate studies (3.1%). Only 42.2% of the studies assessed a metric related to SDG15 – Life on Land, suggesting biodiversity impacts were less frequently evaluated. However, SDG15 featured the greatest diversity of metrics, with **21 different measures to represent biodiversity**. Notably, 16 of these were reported by just one study each (1.6%). The most common biodiversity metrics were Mean Species Abundance (MSA, 15.6%) and the Biodiversity Intactness Index (BII, 9.4%). Yet, only 6.2% of studies that included the BII presented it in their main results. In two additional cases, BII values were obtained from supplementary modelling outputs (Strefler et al. 2021, Luderer et al. 2021). Although the focus was on terrestrial systems, a small number of studies also quantified impacts related to SDG14 – Life Below Water, using metrics such as aquatic mean species abundance (3.1%) and ocean acidification (4.7%).

As MSA and BII appear to be the most commonly used indicators of biodiversity impact, it seems beneficial to report impacts on both to ensure comparability between studies. **However, biodiversity can be described in multiple ways. Therefore, a variety of metrics covering different aspects of biodiversity are needed** (Butchart et al. 2010, Pereira et al. 2012, IPBES 2016). For example, to provide a representative and comparable set of metrics that track progress of the Aichi 2020 targets (CBD 2010), the Essential Biodiversity Variables (EBVs) have been developed (Pereira et al. 2013). EBVs should describe the different multi-scale aspects of biodiversity (e.g.: genetic composition, species populations, species traits, community composition, etc.), providing input for biodiversity indicators (Pereira et al. 2013, Brummitt et al. 2017). Nevertheless, none of the Aichi targets was met in 2020, which was partly explained by the lack of indicators to monitor progress of target achievement (Affinito et al. 2024). As a consequence, headline indicators for the KMGBF have been developed (CBD

2021, Affinito et al. 2024). However, these indicators typically rely on historical time series data and are not really suitable for future projections of drivers impact on biodiversity using quantitative modelling scenarios (Purvis 2025). Linking model-based indicators to targets (e.g. those of the KMGBF) and increasing efforts for biodiversity monitoring to improve data availability could help create a representative set of model-based indicators that can describe multiple dimensions of biodiversity, enhancing comparability between studies (Gonzalez et al. 2023, Purvis 2025).

Lastly, it is important to note that this overview does not represent a comprehensive list of all metrics calculated across the studies. Instead, it reflects the content captured within our database, based on the metrics explicitly reported and available for comparison. Some studies may have included additional metrics that were either not documented in sufficient detail or not directly aligned with the SDG framework used here.

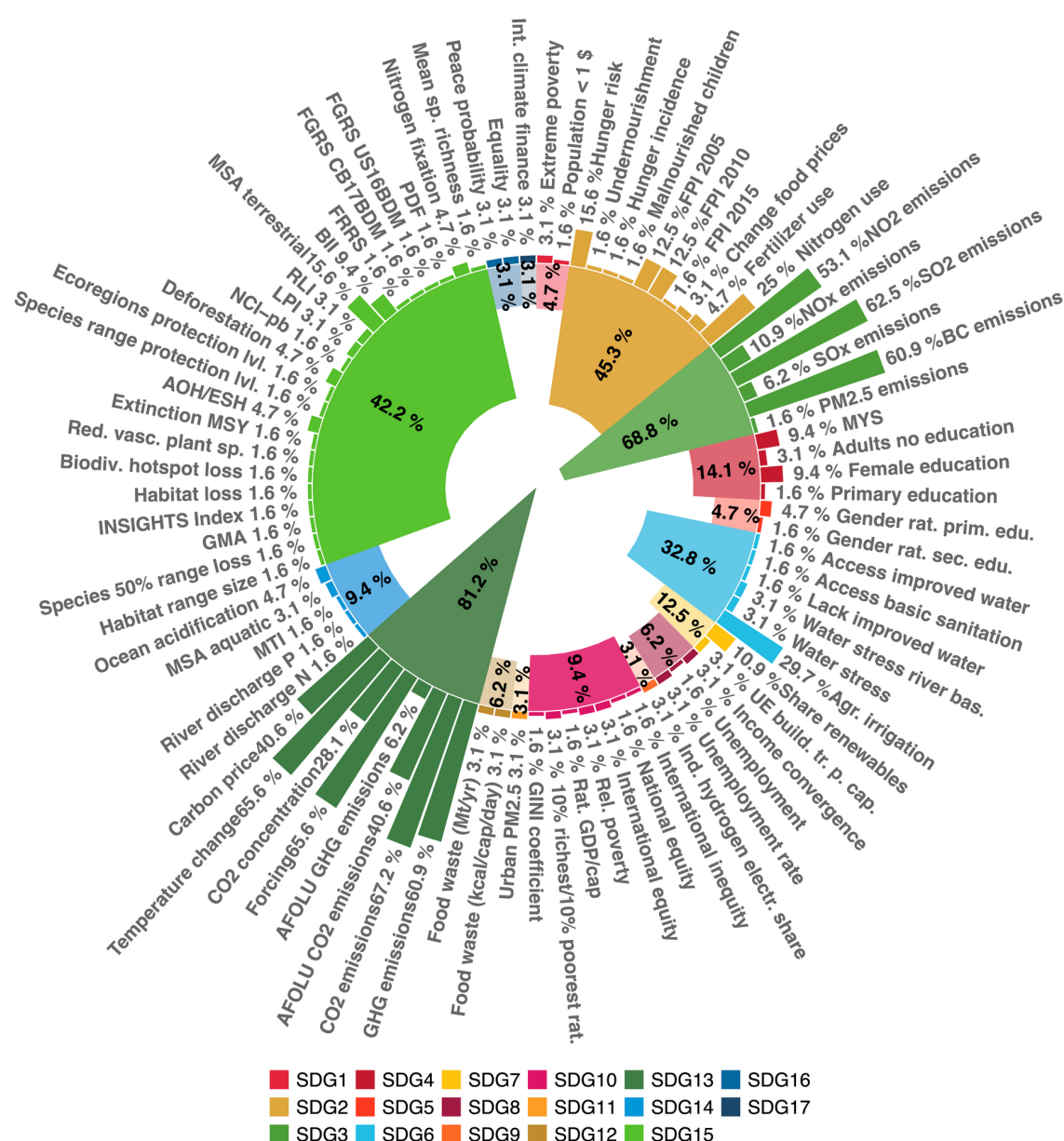


Figure 8: Percentage of studies that explicitly or implicitly quantified a specific metric (outer circle), and percentage of studies that measured a metric related to a specific SDG (inner circle). Explicit impacts were collected directly from the main document of each source, while implicit impacts were collected

based on supplementary material information (see methods). A description of the abbreviations for each metric can be found in Annex table 2 (Source: Neumann et al. (2025)).

3 Global intervention scenarios – synergies and trade-offs

3.1 Modest-intervention is not enough to mitigate climate change, target-seeking scenarios offer greatest potential

Figure 9 shows the impact in percentage change per decade on BII, MSA, temperature change and total CO₂ emissions for each scenario type (intervention, modest-intervention, non-intervention). Not surprisingly, there is a large difference between the intervention and non-intervention scenario types. This difference is most evident in the results for temperature change and total CO₂ emissions. Modest-intervention scenarios appear to have similar impacts on temperature change and CO₂ emissions and are thus less successful in mitigating climate change than intervention scenarios.

This was observed regardless of whether they were reference or policy-screening scenarios, which can be explained by the fact that some studies used reference scenarios that apply NDCs, current policies or near-term policies, such as policy-screening modest-intervention scenarios. In contrast, the range of impacts for intervention scenarios, while generally more positive, is highly dependent on the type of scenario. Comparing the medians, target-seeking scenarios have the greatest potential for positive impacts on biodiversity and climate (+0.0, -1.1, +0.3, -17% decadal percentage change for BII, MSA, temperature change and total CO₂ emissions, respectively) compared to policy-screening scenarios (-0.3, -1.9, +0.4, -18.3% decadal percentage change for BII, MSA, temperature change and total CO₂ emissions, respectively). An exception is the median for total CO₂ emissions, which is lower for the policy-screening scenarios. However, only seven policy-screening intervention scenarios quantified total CO₂ emissions, five of which were from the same study that applied a comprehensive carbon tax while transforming the energy sector, which can be very efficient in reducing final total CO₂ emissions.

Exploratory intervention scenarios behave as expected, since most of them are based on SSP1 without additional interventions, they have the least positive impacts on temperature change and total CO₂ emissions. Only the exploratory non-intervention scenarios (Median: -1.9% decadal percentage change) have a similar negative impact on the MSA as the policy-screening intervention scenarios (Median: -1.9% decadal percentage change). This can be attributed to the fact that 12 of the policy-screening scenarios often used only one intervention such as plantation forestry, simple nature protection, or a liberalization of the agricultural market, or simulated climate change mitigation interventions, such as the impact of bioenergy on MSA (CBD and PBL 2007, Alkemade et al. 2009, OECD 2012). This may have a more negative impact on MSA than exploratory non-intervention scenarios.

In summary, the results clearly indicate that **target-seeking scenarios**, those explicitly designed to achieve specific goals related to climate, biodiversity, or sustainable development, consistently **outperform other types of intervention scenarios**. In contrast, non-intervention scenarios represent the least favourable outcomes across metrics. Moreover, limited interventions that focus solely on mitigating climate change, without addressing other environmental dimensions, may lead to trade-offs on biodiversity (in terms of MSA).

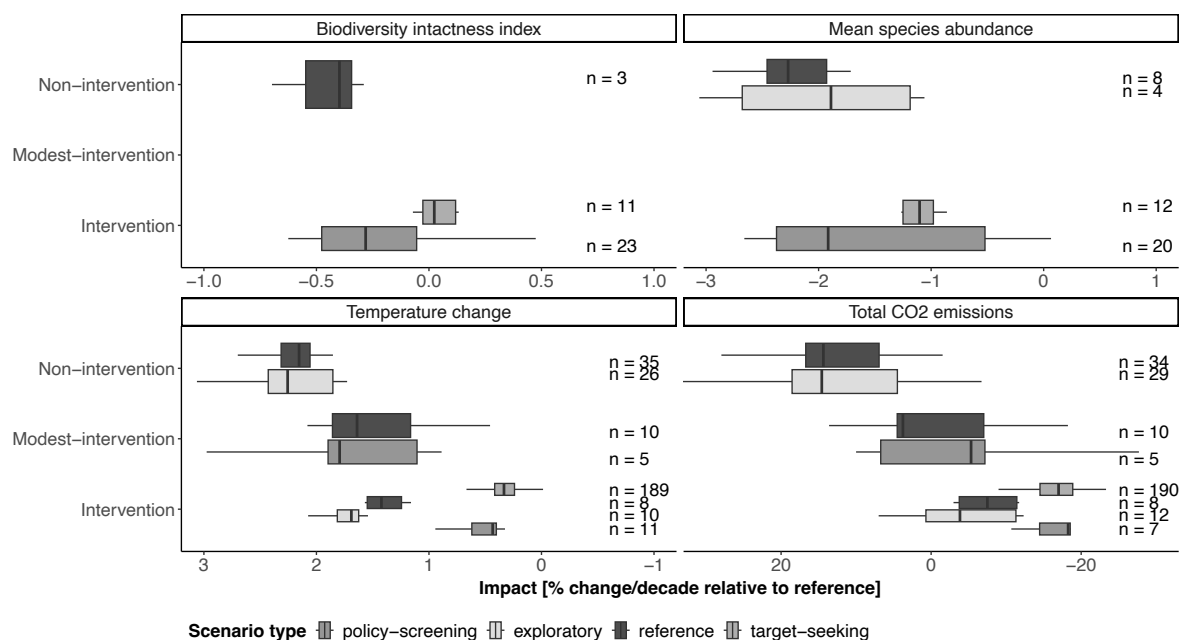


Figure 9: Boxplots show the decadal percentage change for the BII, MSA, temperature change (since the pre-industrial age, 1850-1900), and total CO₂ emissions per scenario type. A positive change indicates a positive impact on biodiversity metrics and a negative change a positive impact on climate metrics. The boxplots show the distribution of each metric over the sample sizes, i.e. scenarios (*n*). The non-intervention scenarios represent the control group. The colour indicates whether the scenario is a policy-screening, target-seeking or reference scenario. Temperature change and CO₂ emissions are expressed relative to the average global temperature and CO₂ emissions for the reference period 1991-2020. Scenario classes with fewer than three scenarios have been excluded.

3.2 Transformative scenarios are the most synergistic

While global sustainable development scenarios and regional sustainability scenarios seem to have the most positive impacts on biodiversity metrics, scenarios that apply reformed markets, have a slightly better impact on climate (Figure 10). Although, in terms of temperature change, global sustainable development scenarios (Median: +0.3 decadal percentage change) achieve a slightly lower temperature increase than reformed market scenarios (Median: +0.4 decadal percentage change). The most severe impacts are clearly associated with the economic optimism and BAU scenarios, which consistently perform worst across both climate and biodiversity metrics.

Interestingly, while the analysis indicates that economic optimism and BAU scenarios tend to rank lowest for biodiversity outcomes, **existing literature suggests that regional competition scenarios may lead to even more severe impacts on biodiversity** (Ohashi et al. 2019, Schipper et al. 2020). For example, regional geopolitical conflicts such as the war between Russia and Ukraine can put a strain on global food systems (Alexander 2024). The resulting increase in energy and fertilizer prices decreases land-use intensity while increasing cropland expansion (Alexander et al. 2022). This, in turn, can have an impact on global biodiversity through cropland expansion (Chai et al. 2024). Nevertheless, the dynamic nature of these impacts still requires further understanding (Alexander 2024). However, due to the limited number of regional competition scenarios in our database that quantified biodiversity indicators such as the BII or MSA, these scenarios were underrepresented in our comparative assessment. Given their underlying socioeconomic characteristics, such as fragmented governance, weak environmental regulation, and heightened resource competition, it is

reasonable to expect that regional competition scenarios could result in even greater biodiversity loss than economic optimism or BAU scenarios (Schipper et al. 2020).

Although policy-screening and target-seeking scenarios were grouped into exploratory archetypes along with exploratory scenarios, the archetypes show broadly consistent and expected patterns of impact. Global sustainable development and regional sustainability scenarios perform very well in terms of both biodiversity and climate, while the reformed markets scenarios tend to underperform in terms of biodiversity. Hence, **scenarios falling into either global sustainable development or regional sustainability offer greater potential for transformative change and synergistic impacts.**

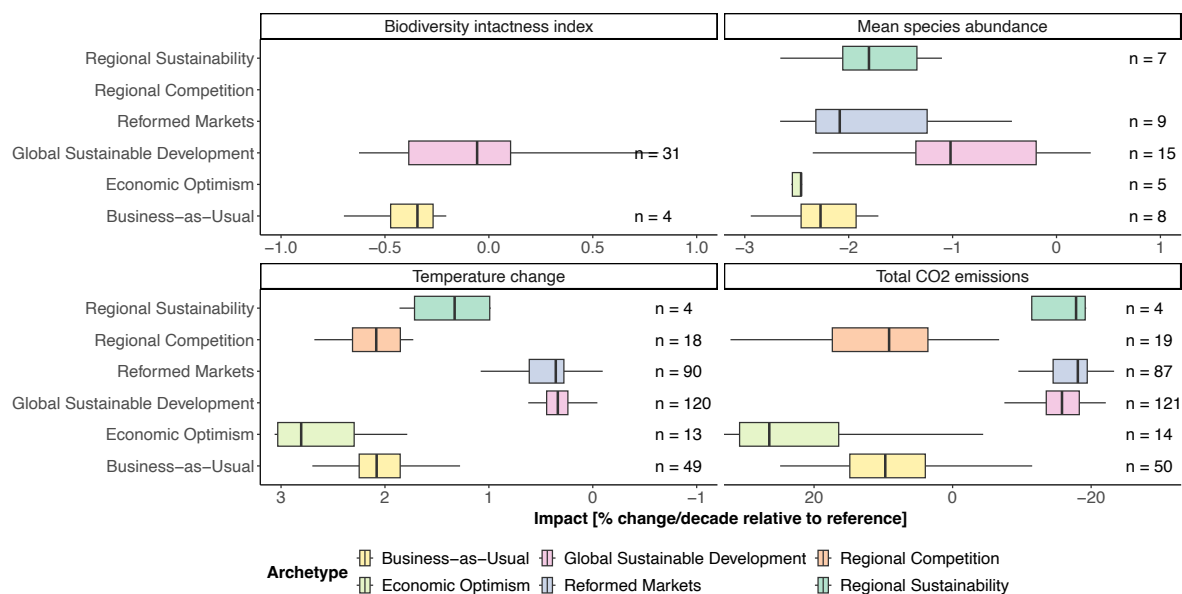


Figure 10: Boxplots show the decadal percentage change for the BII, MSA, temperature change (since the pre-industrial age, 1850-1900), and total CO₂ emissions per exploratory archetype. A positive change indicates a positive impact on biodiversity metrics and a negative change a positive impact on climate metrics. The boxplots show the distribution of each metric over the sample sizes, i.e. scenarios (n). Temperature change and CO₂ emissions are expressed relative to the average global temperature and CO₂ emissions for the reference period 1991-2020. Archetypes with fewer than three scenarios have been excluded.

This is further emphasized by Figure 11, which shows the impacts for the scenarios grouped into the different SSP scenarios used as baseline. First and foremost, the different socioeconomic baseline assumptions also behave as expected, with SSP3 having the worst outcome for climate and SSP1 having a better impact on BII. However, while the impacts on climate metrics of scenarios using SSP1 as a baseline for projections are less positive than those based on SSP2, the impacts on BII are much more positive (median: +0.1%/decade for SSP1-based scenarios compared to -0.2%/decade for SSP2-based scenarios). This suggests **that SSP1-based scenarios are not sufficient to address climate change and biodiversity loss simultaneously**, and that it depends on the interventions that are combined with them. This is consistent with the scenarios that have a positive BII here, as they implement a comprehensive set of different combined interventions, aiming for sustainable development that goes well beyond what is already included in a SSP1 scenario (Strefler et al. 2021, Soergel et al. 2021). However, the number of scenarios also suggests that most studies use SSP2 as a baseline to create an intervention scenario, which may help explain their slightly

more positive impacts, as these outcomes could be partly influenced by the higher frequency of SSP2-based scenarios in the dataset.

The large spread in the results for temperature change and total CO₂ emissions for scenarios based on SSP3, SSP4 and SSP5 can be explained by the wide variety of RCP emission scenarios that have been combined with these socioeconomic assumptions. For example, Popp et al. (2017) or Doelman et al. (2018) have simulated SSP3-4.5, SSP4-2.6, SSP5-2.6, while Rogelj et al. (2018) have even simulated a SSP5-1.9 scenario. Usually, they are combined with much higher RCPs in their baseline assumptions, e.g.: SSP3-7.0 or SSP5-8.5 (O'Neill et al. 2016, Riahi et al. 2017). RCPs that reach concentrations below this usually imply climate mitigation policies, so we have categorized them in Figure 10 according to our guidelines described in Section 1.2.3 in the reformed markets archetype. As a result, we have a smaller interquartile range, and hence spread of data, in Figure 10 compared to Figure 11.

In conclusion, the results in Figure 11 highlight that **not only the choice of baseline, but also the type, combination and number of interventions applied may play a crucial role for achieving positive outcomes for both climate and biodiversity**. If it is not further complemented by effective interventions, a sustainable development paradigm is not sufficient to cope with both crises simultaneously.

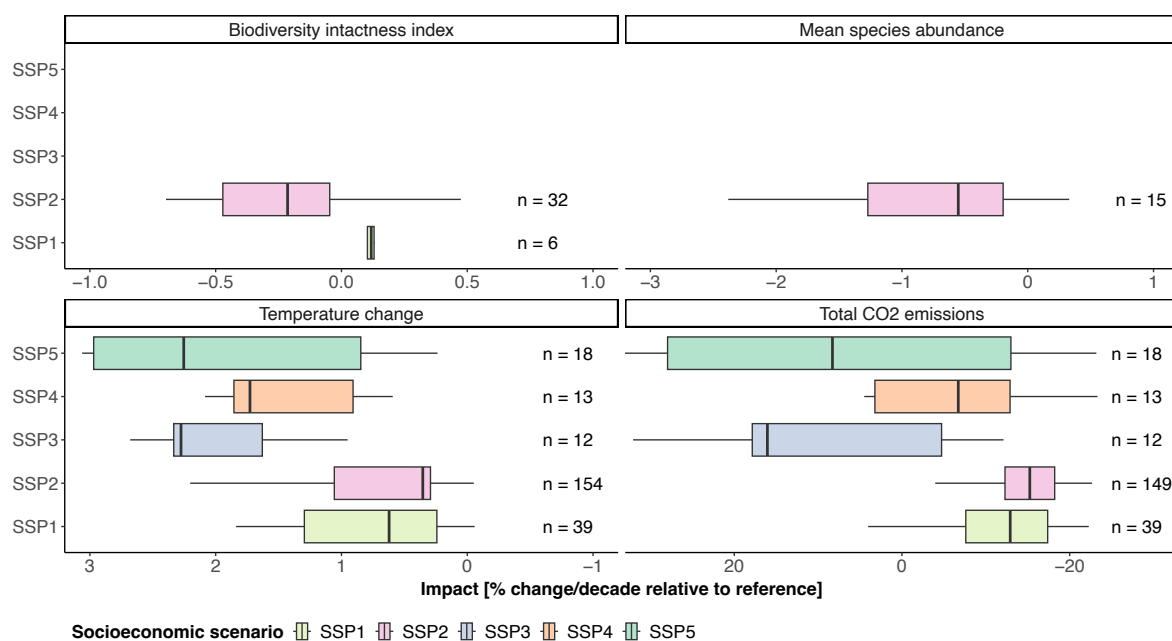


Figure 11: Boxplots show the decadal percentage change for the BII, MSA, temperature change (since the pre-industrial age, 1850-1900), and total CO₂ emissions per socioeconomic scenario (SSPs). A positive change indicates a positive impact on biodiversity metrics and a negative change a positive impact on climate metrics. The boxplots show the distribution of each metric over the sample sizes, i.e. scenarios (n). Temperature change and CO₂ emissions are expressed relative to the average global temperature and CO₂ emissions for the reference period 1991-2020. SSPs with fewer than three scenarios have been excluded.

Consequently, the results suggest that the number of interventions included in a scenario plays a clear role in achieving more positive impacts (Figure 12), as does their combination across different sectors (Figure 13). Looking at the impact on biodiversity indicators, it is clear that **the more interventions were implemented in a scenario, the more positive the impact on biodiversity was**. This is less obvious for climate, where scenarios that apply only

1-5 interventions simultaneously have a slightly more positive impact on total CO₂ emissions than scenarios that apply more than 10 interventions simultaneously (median: -17.2% change/decade for 1-5 interventions compared to -16.9% change/decade for more than 10 interventions).

This difference between biodiversity and climate impacts is similar considering the number of sectors in which an intervention was applied (Figure 13). **With the exception of temperature change, scenarios with interventions in more than six (three for the BII) sectors perform best for each of the other metrics.** For temperature change, studies that applied interventions in one to three different sectors performed better (Median: 0.3%/decade) than scenarios that applied interventions in more than six sectors (Median: 0.9%/decade). This may be related to the fact that most scenarios use GHG emission markets as a single intervention, when in most cases this implies a much deeper decarbonization process, steering several other instruments. This is related to the functioning of models that use very frequently carbon pricing through marginal abatement cost curves as a tool to steer decarbonization and implement climate policy, e.g. in the energy sector (Kriegler et al. 2015, Harmsen et al. 2021, IPCC 2023c, Neumann et al. 2025).

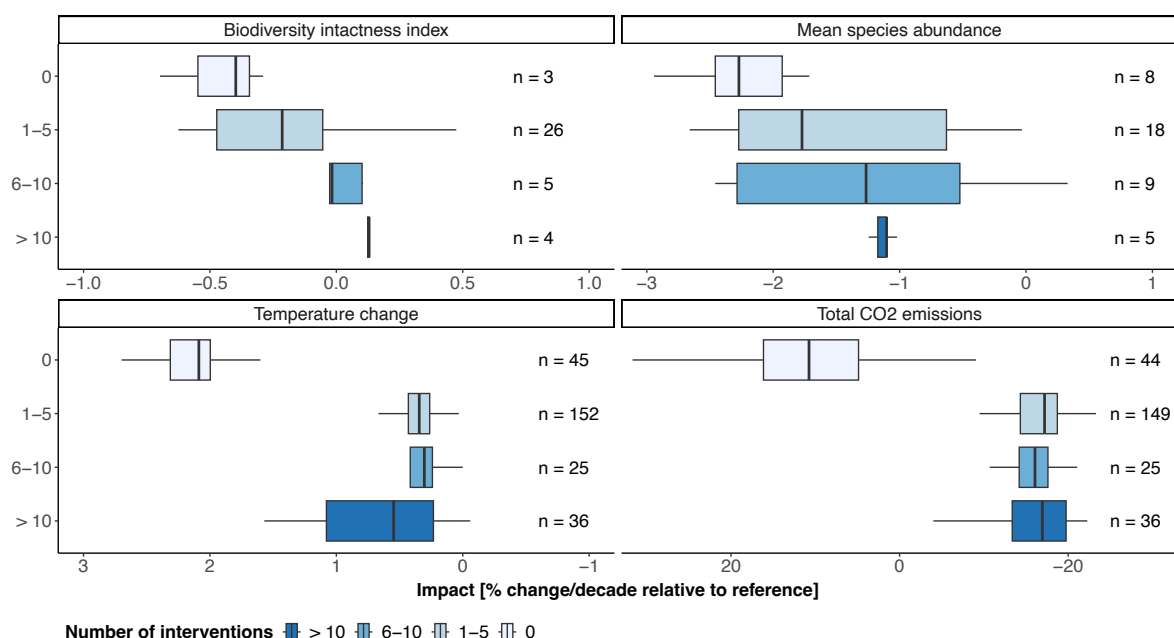


Figure 12: Boxplots illustrating the decadal percentage change for temperature change (since the pre-industrial age, 1850-1900), total CO₂ emissions, the BII and MSA according to the number of interventions that were applied in a scenario. A positive change indicates a positive impact on biodiversity metrics and a negative change a positive impact on climate metrics. The boxplots show the distribution of each metric over the sample sizes, i.e. scenarios (n Temperature change and CO₂ emissions are expressed relative to the average global temperature and CO₂ emissions for the reference period 1991-2020). Classes with fewer than three scenarios as well as exploratory scenarios have been excluded.

Furthermore, the scenarios in Figure 13 suggest that the majority of scenarios incorporating interventions across more than three sectors were capable of reversing the declining trends in BII, with five out of six scenarios achieving this outcome (Strefler et al. 2021, Soergel et al. 2021). In contrast, only one scenario resulted in a positive percentage change per decade in the MSA with more than three sectors targeted by interventions (Kok et al. 2023). However, a

comparison of the median of scenarios with interventions in more than six sectors (Median: -1.1%/decade) with scenarios targeting three to six sectors (Median: -1.2%/decade) or one to three sectors (Median: -1.8%/decade) indicates a smaller reduction in global biodiversity, thus a higher effectiveness for cross-sectoral scenario approaches.

Finally, scenarios that reform markets, e.g. through greenhouse gas emissions markets, may be very efficient in mitigating climate change but have negative impacts on biodiversity. Conversely, scenarios that rely more on global or regional sustainable development may not be the most effective in mitigating climate change, but may have fewer negative impacts on biodiversity. Furthermore, the effectiveness of scenarios depends not only on their socioeconomic baseline, but also on the number of interventions and their combination across sectors. **More transformative scenarios, going beyond current sustainability baselines (SSP1) and using multiple interventions in combination across sectors, are the most promising to avoid trade-offs and allow for synergistic impacts on biodiversity and climate change at the same time.**

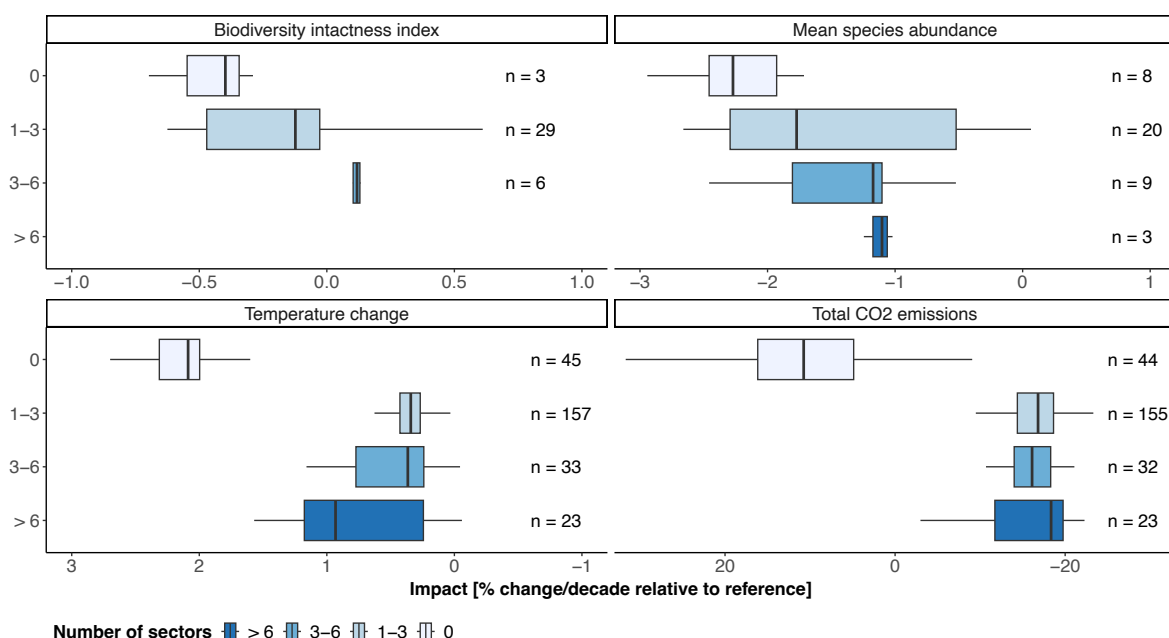


Figure 13: Boxplots illustrating the decadal percentage change for temperature change (since the pre-industrial age, 1850-1900), total CO₂ emissions, the BII and MSA according to the number of sectors in which an intervention was applied. A positive change indicates a positive impact on biodiversity metrics and a negative change a positive impact on climate metrics. The boxplots show the distribution of each metric over the sample sizes, i.e. scenarios (n Temperature change and CO₂ emissions are expressed relative to the average global temperature and CO₂ emissions for the reference period 1991-2020. Classes with fewer than three scenarios as well as exploratory scenarios have been excluded.

3.3 Basic pillars: Carbon pricing and nature conservation – but combination is key

The results show that scenarios that follow a sustainability paradigm and apply multiple interventions simultaneously across different sectors can have high potential for synergistic impacts on climate and biodiversity. Since it has been found that certain scenarios with fewer interventions in fewer sectors can have high potential, at least in terms of climate impacts, the question arises as to which interventions can demonstrate such effectiveness. Another

question is which combination of interventions will achieve the best possible synergistic effects with the fewest trade-offs for climate and biodiversity. However, the studies in the database vary widely in their methods, including the models, indicators and socioeconomic assumptions used. In particular, the fact that each scenario usually includes not just one but several interventions make it very difficult to compare the effects of individual interventions in terms of their effectiveness.

In an attempt to identify the interventions that could have the most positive impacts on climate and biodiversity, we examined in detail all scenarios that meet the 1.5°C Paris target, as well as all scenarios that reverse declining biodiversity trends, and the interventions implemented in them (Figure 14). While we found **150 scenarios able to achieve the 1.5°C target, only 14 scenarios were able to reverse declining biodiversity trends**, i.e. have a positive decadal percentage change in at least one of 18 biodiversity metrics (see section 1.3.2 for the methodological description of the grouping).

While we found a comparable number of different interventions (26 different interventions in 1.5°C scenarios, 26 different interventions in bend the curve scenarios) in both target categories, the interventions applied differed. For example, 1.5°C scenarios applied lower non-energy demand, CDR constraints, building technology and efficiency, recycling and reduced waste, transport technology and efficiency, which were not included in the bending the curve scenarios. In contrast, the bending the curve scenarios applied restoration, slower infrastructure expansion, universal access to basic needs and services, sustainable forest management, which were not included in the 1.5° scenarios.

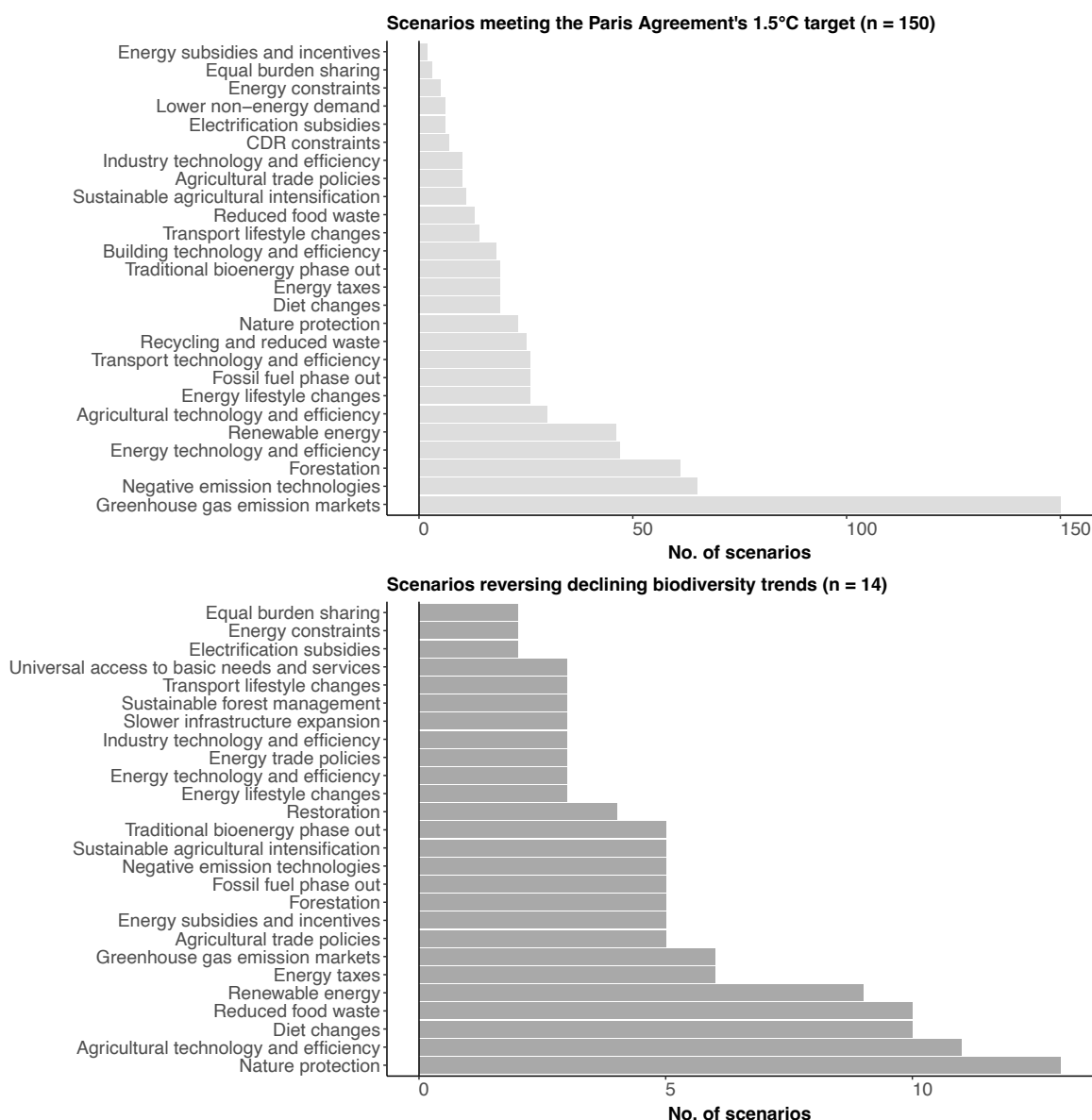


Figure 14: Frequency of scenarios (left) or studies (right) in which a specific intervention is applied (y-axis). Targets are based on either the Paris target of 1.5°C or the bending of the biodiversity loss curve. The definition of 'bending the curve of biodiversity loss' was based on a positive decadal percentage change in any of the biodiversity metrics (ESH, BII, MSA, Extinction per million species years, Fraction globally remaining species, Fraction regionally remaining species, Geometric mean abundance, Habitat range size, INSIGHTS index, Living Planet Index, Suitable habitat loss, Mean species richness, Potentially disappeared fraction of species, Pressure based natural capital index, Red List Index, Reduction vascular plant species, Species affected by 50% range loss, Species range protection level).

Importantly, **all 1.5°C scenarios included greenhouse gas emission markets, while almost all bending the curve scenarios (13 out of 14) included nature protection measures.** In the 1.5°C scenarios the top five interventions were (in descending order): Greenhouse gas emission markets, negative emission technologies, forestation, energy technology and efficiency, renewable energy. In the bending the curve scenarios those were: Nature protection, agricultural technology and efficiency, diet changes, reduced food waste, and renewable energy.

Consequently, greenhouse gas emission markets, as well as nature protection interventions seem to be indispensable to achieve 1.5°C, or reverse declining biodiversity trends, respectively. Additionally, the adoption of both interventions does not automatically rule out the other target; bending the curve scenarios also use greenhouse gas emission markets, and 1.5°C scenarios, in turn, use nature protection interventions. However, although both measures could serve as 'main pillars' for mitigating climate change or restoring biodiversity, they are not sufficient on their own. For example, conservation policies are not sufficient to mitigate biodiversity loss (Leclère et al. 2020, Kok et al. 2023), while biodiversity-focused interventions alone are not sufficient to cope with climate change (Kok et al. 2023). More integrative scenarios and combinations of multiple interventions are needed to trigger transformative change (IPBES 2019, Díaz et al. 2019, Leclère et al. 2020). Consequently, the effectiveness of nature conservation, or climate mitigation, depends significantly on the measures with which they are combined, in order to achieve synergies not only between biodiversity and climate goals, but also across a broader range of sustainability objectives.

This point is further illustrated in Figure 15, which shows that global carbon prices are projected to rise substantially by the end of the century. The figure also suggests that **scenarios implementing a broader range of interventions, across multiple sectors, are more likely to keep carbon prices lower and with greater confidence than scenarios relying on a limited set of measures**, such as greenhouse gas emission market mechanisms applied in only one to three sectors.

In general, the effectiveness of carbon pricing has been questioned and appears to be lower than originally anticipated (Green 2021). Nevertheless, it remains one of the most commonly used instruments in integrated assessment models to simulate climate policy (Kriegler et al. 2015, Harmsen et al. 2021, IPCC 2023c). Several concerns have been raised regarding its application in models, including limited incentives for innovation, potential trade-offs with other sustainability goals, and the widespread use of uniform global carbon prices, where regional carbon prices are assumed to be equal (Keppo et al. 2021). This uniformity fails to reflect the unequal distribution of mitigation costs across regions, raising concerns about fairness and equity. While some of these issues, such as uniform pricing, can be addressed technically (e.g., by incorporating equity-based burden-sharing mechanisms), other criticisms, such as the underrepresentation of innovation dynamics and socio-political feasibility, are more difficult to resolve (Keppo et al. 2021). Consequently, the use of carbon pricing as a climate policy instrument in global models comes with limitations, and results based on such assumptions should be interpreted with caution.

In conclusion, carbon pricing alone is not sufficient to effectively mitigate climate change. It should be strategically combined with other complementary measures to enhance its effectiveness, maximize co-benefits, and minimize potential trade-offs with other sustainability objectives (Bertram et al. 2018, Soergel et al. 2021, IPCC 2023a).

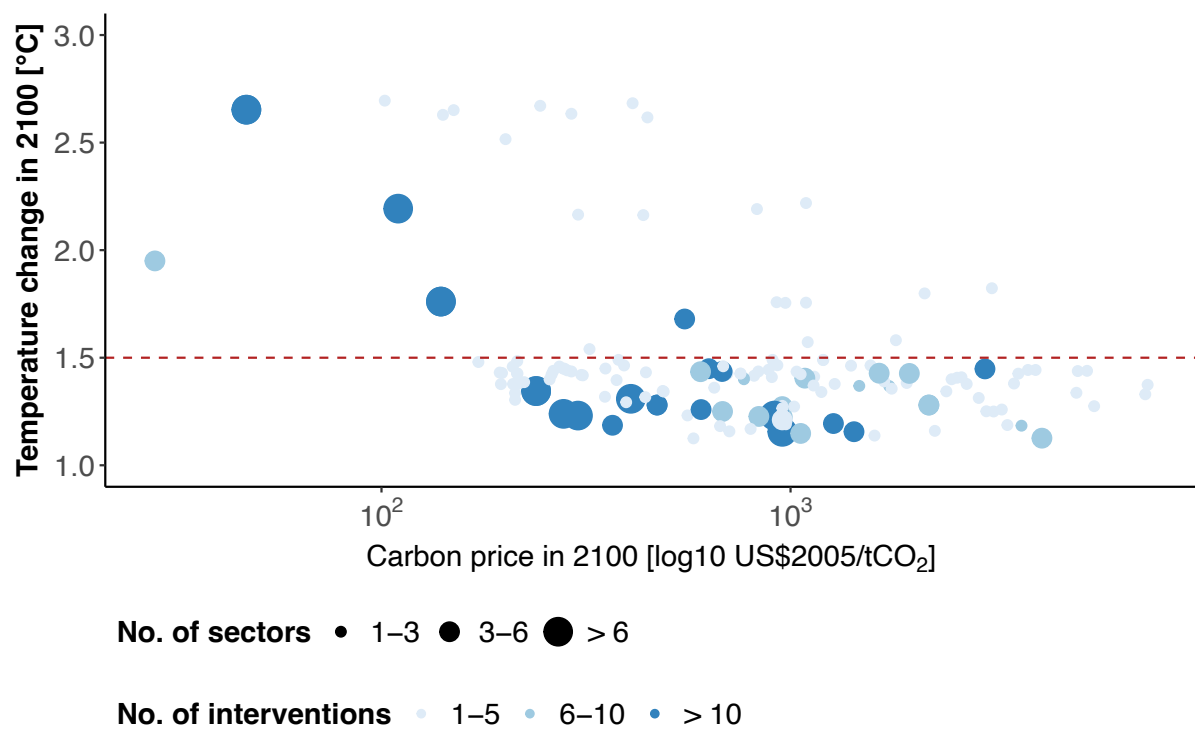


Figure 15: This graph shows the carbon price (x-axis) and the temperature change in 2100 (y-axis) for different scenarios. The colour of the dots indicates the number of interventions applied in a scenario, while the size of the dots indicates the number of sectors used to implement these interventions. The red dashed lines highlight the 1.5°C target. Scenarios with a carbon price greater than or equal to 10,000 US\$2005/tCO₂ in 2100 were excluded from this analysis (8 scenarios).

Conclusion/Outlook

This deliverable comprehensively documents the compilation of a database containing quantitative, model-based, global-scale scenarios for climate change mitigation and/or biodiversity restoration. Based on this database, we have provided a literature synthesis of intervention scenarios by presenting the interventions implemented in global models and the impacts assessed. We provide an impact assessment for different scenario types, different underlying socioeconomic assumptions and the extent to which interventions are integrated into the scenarios. We provide insights into the interventions that have been shown to be essential - from a global perspective - to achieve climate and biodiversity objectives, and we have reiterated that it is the combination of interventions that matters to achieve transformative change, not just the individual instruments.

In summary, climate change impacts are quantified much more frequently than other environmental impacts. This is also reflected in the interventions implemented in the models: climate change mitigation measures are the most common in global models. In contrast, the quantification of biodiversity is characterized by a wide variety of metrics, models and approaches, and most interventions that directly address biodiversity loss can be associated with nature conservation measures. Although most global sustainability scenarios lack explicit social instruments of intervention, they often imply social transformation within their narratives (IPBES 2016, O'Neill et al. 2017). However, initiatives like the Nature Futures Framework are now making these social dimensions more explicit, recognizing that deep, lasting sustainability depends not only on technological and regulatory change, but also on cultural, relational, and ethical shifts in how societies interact with nature (Pereira et al. 2020, Kim et al. 2023).

Furthermore, the results in this report indicate that modest-intervention is not sufficient to mitigate climate change, while target-seeking intervention scenarios outperform the other scenario types in terms of their effectiveness for biodiversity and climate. This is not surprising, as target-seeking scenarios are, by definition, scenarios designed to achieve specific future goals and should therefore have a high positive impact (IPBES 2016). However, implementing modest interventions, such as the pledges in the NDCs, could help to reduce the future investment required for climate change mitigation (McCollum et al. 2018). Therefore, modest intervention could serve as a starting point for further, more in-depth intervention.

Scenarios with a high transformative capacity, such as those following a global sustainable development paradigm or a regional sustainability paradigm, may have a lower positive impact on climate than reformed markets, but this is outweighed by a much higher positive impact on biodiversity.

Our results show that greenhouse gas emission markets and nature protection measures are essential to mitigate climate change and restore biodiversity. However, relying on greenhouse gas emission markets alone can be less efficient and increase the risk of trade-offs with other sustainability objectives (Keppo et al. 2021). Moreover, nature conservation alone is not sufficient to reverse declining biodiversity trends (Leclère et al. 2020, Kok et al. 2023). To increase synergies between different sustainability goals, reduce trade-offs and maximize positive impacts, a range of different measures should be implemented (Figure 12). These should bring about cross-sectoral changes to enable a transformative shift towards a sustainable society. For example, climate change mitigation combined with carefully planned nature conservation, sustainable agricultural land use and reduced meat consumption can help keep global temperature change below 2°C while conserving biodiversity (Kok et al. 2023).

Carbon pricing, combined with other interventions aiming for sustainable development (e.g.: consumption changes, nature conservation, energy access) can further help minimizing negative impacts on other sustainability goals such as increasing food and energy prices and biodiversity (Bertram et al. 2018, Soergel et al. 2021).

Finally, based on our results, we can summarize **three key findings** of this report:

- (i) Interventions in global models are dominated by climate change mitigation measures and conventional conservation measures to protect and restore terrestrial ecosystems. Furthermore, impacts on climate change are quantified more frequently than impacts on biodiversity or other sustainability objectives.
- (ii) Transformative pathways for biodiversity and climate generally belong to the group of target-seeking scenarios. Scenarios that follow a sustainability paradigm, using multiple interventions to transform different sectors simultaneously, have the highest combined positive impacts on climate and biodiversity and offer the greatest potential for transformative change. These scenarios often include measures beyond conventional conservation and climate change mitigation measures such as the sustainable intensification of agriculture, the reduction of food waste, and changes to diets, e.g. reduced meat consumption.
- (iii) The main pillars for global climate change mitigation and biodiversity restoration in current global scenarios are well-known interventions such as carbon markets or nature conservation measures (e.g. protected areas, sparing mechanisms, etc.). However, these do not suffice alone and should be complemented by other measures to create transformative pathways that minimize trade-offs (e.g. carbon pricing) and maximize synergies for biodiversity, climate and society.

In conclusion, while global scenario modelling has improved continuously, there is still a need for future research to develop new scenarios or accompanying narratives that more fully integrate diverse social values, cultural dimensions and equity-focused interventions to reflect the complex, multi-scale realities of sustainability transitions. Initiatives such as the Nature Futures Framework can support the research community by providing guidance on more integrated and value-inclusive scenario-building processes. In addition, future intervention scenarios should move away from siloed approaches and simultaneously quantify cross-sectoral interventions and their impacts on multiple sustainability goals. This will make it possible to assess synergies and trade-offs, as well as the transformative potential of multi-intervention packages.

References

- Affinito, F., Williams, J. M., Campbell, J. E., Londono, M. C. and Gonzalez, A. 2024. Progress in developing and operationalizing the Monitoring Framework of the Global Biodiversity Framework. - *Nat Ecol Evol* 8: 2163–2171. doi: 10.1038/s41559-024-02566-7
- Aguiar, A. P. D., Collste, D., Harmáčková, Z. V., Pereira, L., Selomane, O., Galafassi, D., Van Vuuren, D. and Van Der Leeuw, S. 2020. Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. - *Global Environmental Change* 65: 102198. doi: 10.1016/j.gloenvcha.2020.102198
- Alexander, P., Arneth, A., Henry, R., Maire, J., Rabin, S. and Rounsevell, M. D. A. 2022. High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. - *Nat Food* 4: 84–95. doi: 10.1038/s43016-022-00659-9
- Alexander, P. 2024. War's cascading global effects. - *Nat Sustain* 7: 379–380. doi: 10.1038/s41893-024-01278-x
- Alkemade, R., Van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M. and Ten Brink, B. 2009. GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. - *Ecosystems* 12: 374–390. doi: 10.1007/s10021-009-9229-5
- Ankit Rohatgi 2024. WebPlotDigitizer. url: <https://automeris.io>
- Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley, G. F., Oberdorff, T., Palomo, I. and Saito, O. 2020. Post-2020 biodiversity targets need to embrace climate change. - *Proc. Natl. Acad. Sci. U.S.A.* 117: 30882–30891. doi: 10.1073/pnas.2009584117
- Bertram, C., Luderer, G., Popp, A., Minx, J. C., Lamb, W. F., Stevanović, M., Humpenöder, F., Giannousakis, A. and Kriegler, E. 2018. Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. - *Environ. Res. Lett.* 13: 064038. doi: 10.1088/1748-9326/aac3ec
- Brummitt, N., Regan, E. C., Weatherdon, L. V., Martin, C. S., Geijzendorffer, I. R., Rocchini, D., Gavish, Y., Haase, P., Marsh, C. J. and Schmeller, D. S. 2017. Taking stock of nature: Essential biodiversity variables explained. - *Biological Conservation* 213: 252–255. doi: 10.1016/j.biocon.2016.09.006
- Butchart, S. H. M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., Galloway, J. N., Genovesi, P., Gregory, R. D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M. A., McRae, L., Minasyan, A., Morcillo, M. H., Oldfield, T. E. E., Pauly, D., Quader, S., Revenga, C., Sauer, J. R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S. N., Symes, A., Tierney, M., Tyrrell, T. D., Vié, J.-C. and Watson, R. 2010. Global Biodiversity: Indicators of Recent Declines. - *Science* 328: 1164–1168. doi: 10.1126/science.1187512
- Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., van der Wijst, K., Al -Khourdajie, A., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Stromman, A., Winkler, H., Auer, C., Brutschin, E., Gidden, M., Hackstock, P., Harmsen, M., Huppmann, D., Kolp, P., Lepault, C., Lewis, J.,

- Marangoni, G., Müller-Casseres, E., Skeie, R., Werning, M., Calvin, K., Forster, P., Guivarch, C., Hasegawa, T., Meinshausen, M., Peters, G., Rogelj, J., Samset, B., Steinberger, J., Tavoni, M. and van Vuuren, D. 2022. AR6 Scenarios Database. doi: 10.5281/ZENODO.5886911
- Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., McJeon, H., Patel, P., Smith, S., Waldhoff, S. and Wise, M. 2017. The SSP4: A world of deepening inequality. - *Global Environmental Change* 42: 284–296. doi: 10.1016/j.gloenvcha.2016.06.010
- CBD 2006. Global biodiversity outlook 2. - Secretariat of the Convention on Biological Diversity. ISBN: 978-92-9225-040-9
- CBD and PBL 2007. Cross-roads of Life on Earth. Exploring means to meet the 2010 Biodiversity Target. Solution-oriented scenarios for Global Biodiversity Outlook 2. url: <https://www.cbd.int/doc/publications/cbd-ts-31.pdf>
- CBD 2010. DECISION ADOPTED BY THE CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY AT ITS TENTH MEETING. - UNEP/CBD/COP/DEC/X/2 url: <https://www.cbd.int/doc/decisions/cop-10/cop-10-dec-02-en.pdf>
- CBD 2014. Global Biodiversity Outlook 4. url: <https://www.cbd.int/gbo/gbo4/publication/gbo4-en-hr.pdf>
- CBD 2021. PROPOSED HEADLINE INDICATORS OF THE MONITORING FRAMEWORK FOR THE POST-2020 GLOBAL BIODIVERSITY FRAMEWORK. - CBD/WG2020/3/3/Add.1 url: <https://www.cbd.int/doc/c/d716/da69/5e81c8e0faca1db1dd145a59/wg2020-03-03-add1-en.pdf>
- CBD 2022. Kunming-Montreal Global Biodiversity Framework. - CBD/COP/DEC/15/4 url: <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>
- Chai, L., Liu, A., Li, X., Guo, Z., He, W., Huang, J., Bai, T. and Liu, J. 2024. Telecoupled impacts of the Russia–Ukraine war on global cropland expansion and biodiversity. - *Nat Sustain* 7: 432–441. doi: 10.1038/s41893-024-01292-z
- Chan, K. M. A., Agard, J., Liu, J., Dutra De Aguiar, A. P., Armenteras Pascual, D., Boedhihartono, A. K., Cheung, W. W. L., Hashimoto, S., Hernández-Pedraza, G. C., Hickler, T., Jetzkowitz, J., Kok, M., Murray-Hudson, M. A., O’Farrell, P., Satterfield, T., Saysel, A. K., Seppelt, R., Strassburg, B., Xue, D., Selomane, O., Balint, L. and Mohamed, A. A. A. 2019. Chapter 5. Pathways towards a Sustainable Future. doi: 10.5281/ZENODO.5519483
- Chan, K. M. A., Boyd, D. R., Gould, R. K., Jetzkowitz, J., Liu, J., Muraca, B., Naidoo, R., Olmsted, P., Satterfield, T., Selomane, O., Singh, G. G., Sumaila, R., Ngo, H. T., Boedhihartono, A. K., Agard, J., De Aguiar, A. P. D., Armenteras, D., Balint, L., Barrington-Leigh, C., Cheung, W. W. L., Díaz, S., Driscoll, J., Esler, K., Eyster, H., GREGG, E. J., Hashimoto, S., Hernández Pedraza, G. C., Hickler, T., Kok, M., Lazarova, T., Mohamed, A. A. A., Murray-Hudson, M., O’Farrell, P., Palomo, I., Saysel, A. K., Seppelt, R., Settele, J., Strassburg, B., Xue, D. and Brondízio, E. S. 2020. Levers and leverage points for pathways to sustainability (P Bridgewater, Ed.). - *People and Nature* 2: 693–717. doi: 10.1002/pan3.10124

- Copernicus Climate Change Service 2019. ERA5 monthly averaged data on single levels from 1940 to present. doi: 10.24381/CDS.F17050D7
- Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Becker, W.E., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, J., Rossi, S., Melo, J., Oom, D., Branco, A., San-Miguel, J., Manca, G., Pisoni, E., Vignati, E., and Pekar, F. 2024. GHG emissions of all world countries. - Publications Office of the European Union. url: <https://data.europa.eu/doi/10.2760/4002897>
- Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R. R., Shin, Y.-J., Visseren-Hamakers, I., Willis, K. J. and Zayas, C. N. 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. - *Science* 366: eaax3100. doi: 10.1126/science.aax3100
- Doelman, J. C., Stehfest, E., Tabeau, A., Van Meijl, H., Lassaletta, L., Gernaat, D. E. H. J., Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., Van Der Sluis, S. and Van Vuuren, D. P. 2018. Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. - *Global Environmental Change* 48: 119–135. doi: 10.1016/j.gloenvcha.2017.11.014
- Electric, C., Raskin, P., Rosen, R. and Stutz, J. 2009. The Century Ahead: Four Global Scenarios - Technical Documentation. - Tellus Institute. url: https://www.tellus.org/pub/TheCenturyAhead_TechDoc.pdf
- Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D. L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W. and Riahi, K. 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. - *Global Environmental Change* 42: 251–267. doi: 10.1016/j.gloenvcha.2016.06.004
- Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y. and Kainuma, M. 2017. SSP3: AIM implementation of Shared Socioeconomic Pathways. - *Global Environmental Change* 42: 268–283. doi: 10.1016/j.gloenvcha.2016.06.009
- Gerst, M., Raskin, P. and Rockström, J. 2013. Contours of a Resilient Global Future. - *Sustainability* 6: 123–135. doi: 10.3390/su6010123
- Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., Van Vuuren, D. P., Van Den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E. and Takahashi, K. 2019. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. - *Geosci. Model Dev.* 12: 1443–1475. doi: 10.5194/gmd-12-1443-2019
- Gonzalez, A., Vihervaara, P., Balvanera, P., Bates, A. E., Torrelio, C. Z., et al. 2023. A global biodiversity observing system to unite monitoring and guide action. - *Nat Ecol Evol* 7: 1947–1952. doi: 10.1038/s41559-023-02171-0

- Green, J. F. 2021. Does carbon pricing reduce emissions? A review of ex-post analyses. - *Environ. Res. Lett.* 16: 043004. doi: 10.1088/1748-9326/abdae9
- Gupta, J., Bai, X., Liverman, D. M., Rockström, J., Gentile, G., et al. 2024. A just world on a safe planet: a Lancet Planetary Health–Earth Commission report on Earth-system boundaries, translations, and transformations. - *The Lancet Planetary Health*: S2542519624000421. doi: 10.1016/S2542-5196(24)00042-1
- Harmsen, M., Kriegler, E., Van Vuuren, D. P., Van Der Wijst, K.-I., Luderer, G., Cui, R., Dessens, O., Drouet, L., Emmerling, J., Morris, J. F., Fosse, F., Fragkiadakis, D., Fragkiadakis, K., Fragkos, P., Fricko, O., Fujimori, S., Gernaat, D., Guivarch, C., Iyer, G., Karkatsoulis, P., Keppo, I., Keramidas, K., Köberle, A., Kolp, P., Krey, V., Krüger, C., Leblanc, F., Mittal, S., Paltsev, S., Rochedo, P., Van Ruijven, B. J., Sands, R. D., Sano, F., Strefler, J., Arroyo, E. V., Wada, K. and Zakeri, B. 2021. Integrated assessment model diagnostics: key indicators and model evolution. - *Environ. Res. Lett.* 16: 054046. doi: 10.1088/1748-9326/abf964
- Hunt, D. V. L., Lombardi, D. R., Atkinson, S., Barber, A. R. G., Barnes, M., Boyko, C. T., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R. F. D., Farmani, R., Gaterell, M., Hale, J., Hales, C., Hewitt, C. N., Jankovic, L., Jefferson, I., Leach, J., MacKenzie, A. R., Memon, F. A., Sadler, J. P., Weingaertner, C., Whyatt, J. D. and Rogers, C. D. F. 2012. Scenario Archetypes: Converging Rather than Diverging Themes. - *Sustainability* 4: 740–772. doi: 10.3390/su4040740
- Hurt, G. C., Chini, L. P., Frothingham, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., Van Vuuren, D. P. and Wang, Y. P. 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. - *Climatic Change* 109: 117–161. doi: 10.1007/s10584-011-0153-2
- IEA 2022. World Energy Outlook 2022. - International Energy Agency (IEA). url: <https://www.iea.org/reports/world-energy-outlook-2022>
- IMAGE-team 2001. The IMAGE 2.2 implementation of the SRES scenarios. A comprehensive analysis of emissions, climate change and impacts in the 21st century. - National Institute for Public Health and the Environment.
- International Monetary Fund 2025. Inflation, consumer prices (annual %). url: <https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?end=2010&start=1960>
- IPBES 2016. The methodological assessment report on scenarios and models of biodiversity and ecosystem services. doi: 10.5281/ZENODO.3235429
- IPBES 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. - IPBES. doi: 10.5281/ZENODO.3831673
- IPBES 2022. Thematic assessment of the sustainable use of wild species of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. doi: 10.5281/ZENODO.6448567
- IPBES 2024. IPBES Nexus Assessment: Summary for Policymakers. doi: 10.5281/ZENODO.13850290

- IPCC 2000. Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. - Cambridge University Press. ISBN: 978-0-521-80081-5
- IPCC 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (EEC Buendia, K Tanabe, A Kranjc, B Jamsranjav, M Fukuda, S Ngarize, A Osako, Y Pyrozhenko, P Shermanau, and S Federici, Eds.). ISBN: 978-4-88788-232-4
- IPCC 2023a. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. url: <https://dx.doi.org/10.59327/IPCC/AR6-9789291691647>
- IPCC 2023b. Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. - Cambridge University Press. doi: 10.1017/9781009157926
- IPCC 2023c. Annex III: Scenarios and Modelling Methods. - In: Climate Change 2022 - Mitigation of Climate Change. 1st ed.n. Cambridge University Press, pp. 1841–1908 DOI: 10.1017/9781009157926.022. doi: 10.1017/9781009157926.022
- Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., Fragkos, P., Guivarch, C., Harmsen, M., Lefèvre, J., Le Gallic, T., Leimbach, M., McDowall, W., Mercure, J.-F., Schaeffer, R., Trutnevyte, E. and Wagner, F. 2021. Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. - Environ. Res. Lett. 16: 053006. doi: 10.1088/1748-9326/abe5d8
- Kim, H., Peterson, G. D., Cheung, W. W. L., Ferrier, S., Alkemade, R., Arneth, A., Kuiper, J. J., Okayasu, S., Pereira, L., Acosta, L. A., Chaplin-Kramer, R., Den Belder, E., Eddy, T. D., Johnson, J. A., Karlsson-Vinkhuyzen, S., Kok, M. T. J., Leadley, P., Leclère, D., Lundquist, C. J., Rondinini, C., Scholes, R. J., Schoolenberg, M. A., Shin, Y.-J., Stehfest, E., Stephenson, F., Visconti, P., Van Vuuren, D., Wabnitz, C. C. C., José Alava, J., Cuadros-Casanova, I., Davies, K. K., Gasalla, M. A., Halouani, G., Harfoot, M., Hashimoto, S., Hickler, T., Hirsch, T., Kolomytsev, G., Miller, B. W., Ohashi, H., Gabriela Palomo, M., Popp, A., Paco Remme, R., Saito, O., Rashid Sumalia, U., Willcock, S. and Pereira, H. M. 2023. Towards a better future for biodiversity and people: Modelling Nature Futures. - Global Environmental Change 82: 102681. doi: 10.1016/j.gloenvcha.2023.102681
- Kok, M. T. J., Alkemade, R., Bakkenes, M., Van Eerd, M., Janse, J., Mandryk, M., Kram, T., Lazarova, T., Meijer, J., Van Oorschot, M., Westhoek, H., Van Der Zagt, R., Van Der Berg, M., Van Der Esch, S., Prins, A.-G. and Van Vuuren, D. P. 2018. Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. - Biological Conservation 221: 137–150. doi: 10.1016/j.biocon.2018.03.003
- Kok, M. T. J., Meijer, J. R., Van Zeist, W.-J., Hilbers, J. P., Immovilli, M., Janse, J. H., Stehfest, E., Bakkenes, M., Tabeau, A., Schipper, A. M. and Alkemade, R. 2023. Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. - Biological Conservation 284: 110068. doi: 10.1016/j.biocon.2023.110068
- Kriegler, E., Petermann, N., Krey, V., Schwanitz, V. J., Luderer, G., Ashina, S., Bosetti, V., Eom, J., Kitous, A., Méjean, A., Paroussos, L., Sano, F., Turton, H., Wilson, C. and Van Vuuren, D. P. 2015. Diagnostic indicators for integrated assessment models of

- climate policy. - *Technological Forecasting and Social Change* 90: 45–61. doi: 10.1016/j.techfore.2013.09.020
- Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S. and Edenhofer, O. 2017. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. - *Global Environmental Change* 42: 297–315. doi: 10.1016/j.gloenvcha.2016.05.015
- Kriegler, E., Bertram, C., Kuramochi, T., Jakob, M., Pehl, M., Stevanović, M., Höhne, N., Luderer, G., Minx, J. C., Fekete, H., Hilaire, J., Luna, L., Popp, A., Steckel, J. C., Sterl, S., Yalaw, A. W., Dietrich, J. P. and Edenhofer, O. 2018. Short term policies to keep the door open for Paris climate goals. - *Environ. Res. Lett.* 13: 074022. doi: 10.1088/1748-9326/aac4f1
- Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H. M., Young, L., et al. 2020. Bending the curve of terrestrial biodiversity needs an integrated strategy. - *Nature* 585: 551–556. doi: 10.1038/s41586-020-2705-y
- Luderer, G., Madeddu, S., Merfort, L., Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., Schreyer, F., Bauer, N., Baumstark, L., Bertram, C., Dirnreichner, A., Humpenöder, F., Levesque, A., Popp, A., Rodrigues, R., Strefler, J. and Kriegler, E. 2021. Impact of declining renewable energy costs on electrification in low-emission scenarios. - *Nat Energy* 7: 32–42. doi: 10.1038/s41560-021-00937-z
- Mace, G. M., Barrett, M., Burgess, N. D., Cornell, S. E., Freeman, R., Grooten, M. and Purvis, A. 2018. Aiming higher to bend the curve of biodiversity loss. - *Nat Sustain* 1: 448–451. doi: 10.1038/s41893-018-0130-0
- McCollum, D. L., Krey, V. and Riahi, K. 2012. Beyond Rio: Sustainable energy scenarios for the 21st century: Beyond Rio: Sustainable energy scenarios for the 21st century. - *Nat Resour Forum* 36: 215–230. doi: 10.1111/j.1477-8947.2012.01459.x
- McCollum, D. L., Zhou, W., Bertram, C., De Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., Fricko, O., Fujimori, S., Gidden, M., Harmsen, M., Huppmann, D., Iyer, G., Krey, V., Kriegler, E., Nicolas, C., Pachauri, S., Parkinson, S., Pobleto-Cazenave, M., Rafaj, P., Rao, N., Rozenberg, J., Schmitz, A., Schoepp, W., Van Vuuren, D. and Riahi, K. 2018. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. - *Nat Energy* 3: 589–599. doi: 10.1038/s41560-018-0179-z
- MEA 2005. *Ecosystems and human well-being: synthesis*. - Island Press. ISBN: 978-1-59726-040-4
- MNP 2004. *Integrated modelling of global environmental change. An overview of IMAGE 2.4*. - Netherlands Environmental Assessment Agency (MNP). ISBN: 90-6960-151-6
- Munn, Z., Peters, M. D. J., Stern, C., Tufanaru, C., McArthur, A. and Aromataris, E. 2018. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. - *BMC Med Res Methodol* 18: 143. doi: 10.1186/s12874-018-0611-x

- Neumann, C., Alkemade, R., Van Vuuren, D., Burian, A., Aschi, F. and Seppelt, R. 2025. Trade-offs and synergies between climate change mitigation and biodiversity restoration: A meta-analysis of global intervention scenarios [Manuscript in preparation].
- Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S. and Van Vuuren, D. 2016. Assessing the land resource–food price nexus of the Sustainable Development Goals. - *Sci. Adv.* 2: e1501499. doi: 10.1126/sciadv.1501499
- OECD 2012. OECD environmental outlook to 2050: the consequences of inaction. - *International Journal of Sustainability in Higher Education* in press. doi: 10.1108/ijshe.2012.24913caa.010
- Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Tsuyama, I., Nakao, K., Kominami, Y., Tanaka, N., Hijioka, Y. and Matsui, T. 2019. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. - *Nat Commun* 10: 5240. doi: 10.1038/s41467-019-13241-y
- O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K. and Sanderson, B. M. 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. - *Geosci. Model Dev.* 9: 3461–3482. doi: 10.5194/gmd-9-3461-2016
- O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., Van Ruijven, B. J., Van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. - *Global Environmental Change* 42: 169–180. doi: 10.1016/j.gloenvcha.2015.01.004
- Orbons, K., Van Vuuren, D. P., Ambrosio, G., Kulkarni, S., Weber, E., Zapata, V., Daioglou, V., Hof, A. F. and Zimm, C. 2024. A review of existing model-based scenarios achieving SDGs: progress and challenges. - *Glob. Sustain.* 7: e3. doi: 10.1017/sus.2023.20
- Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S. S. P., Lenferna, A., Morán, N., Van Vuuren, D. P. and Schellnhuber, H. J. 2020. Social tipping dynamics for stabilizing Earth's climate by 2050. - *Proc. Natl. Acad. Sci. U.S.A.* 117: 2354–2365. doi: 10.1073/pnas.1900577117
- Ou, Y., Roney, C., Alsalam, J., Calvin, K., Creason, J., Edmonds, J., Fawcett, A. A., Kyle, P., Narayan, K., O'Rourke, P., Patel, P., Ragnauth, S., Smith, S. J. and McJeon, H. 2021. Deep mitigation of CO₂ and non-CO₂ greenhouse gases toward 1.5 °C and 2 °C futures. - *Nat Commun* 12: 6245. doi: 10.1038/s41467-021-26509-z
- Pereira, H. M., Navarro, L. M. and Martins, I. S. 2012. Global Biodiversity Change: The Bad, the Good, and the Unknown. - *Annu. Rev. Environ. Resour.* 37: 25–50. doi: 10.1146/annurev-environ-042911-093511
- Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., Bruford, M. W., Brummitt, N., Butchart, S. H. M., Cardoso, A. C., Coops, N. C., Dulloo, E., Faith, D. P., Freyhof, J., Gregory, R. D., Heip, C., Höft, R., Hurtt, G., Jetz, W., Karp, D. S., McGeoch, M. A., Obura, D., Onoda, Y., Pettorelli, N., Reyers, B., Sayre, R., Scharlemann, J. P. W., Stuart, S. N., Turak, E., Walpole, M. and Wegmann, M. 2013.

- Essential Biodiversity Variables. - *Science* 339: 277–278. doi: 10.1126/science.1229931
- Pereira, L. M., Davies, K. K., Belder, E., Ferrier, S., Karlsson-Vinkhuyzen, S., Kim, H., Kuiper, J. J., Okayasu, S., Palomo, M. G., Pereira, H. M., Peterson, G., Sathyapalan, J., Schoolenberg, M., Alkemade, R., Carvalho Ribeiro, S., Greenaway, A., Hauck, J., King, N., Lazarova, T., Ravera, F., Chettri, N., Cheung, W. W. L., Hendriks, R. J. J., Kolomytsev, G., Leadley, P., Metzger, J., Ninan, K. N., Pichs, R., Popp, A., Rondinini, C., Rosa, I., Vuuren, D. and Lundquist, C. J. 2020. Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework (B Egoh, Ed.). - *People and Nature* 2: 1172–1195. doi: 10.1002/pan3.10146
- Pereira, H. M., Martins, I. S., Rosa, I. M. D., Kim, H., Alkemade, R., et al. 2024. Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. - *Science* 384: 458–465. doi: 10.1126/science.adn3441
- Peters, M. D. J., Marnie, C., Tricco, A. C., Pollock, D., Munn, Z., Alexander, L., McInerney, P., Godfrey, C. M. and Khalil, H. 2020. Updated methodological guidance for the conduct of scoping reviews. - *JBI Evidence Synthesis* 18: 2119–2126. doi: 10.11124/JBIES-20-00167
- 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., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K. and Vuuren, D. P. V. 2017. Land-use futures in the shared socio-economic pathways. - *Global Environmental Change* 42: 331–345. doi: 10.1016/j.gloenvcha.2016.10.002
- Pörtner, H.-O., Scholes, R. J., Agard, J., Archer, E., Ngo, H., et al. 2021. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. doi: 10.5281/ZENODO.4659158
- Pörtner, H.-O., Scholes, R. J., Arneeth, A., Barnes, D. K. A., Burrows, M. T., Diamond, S. E., Duarte, C. M., Kiessling, W., Leadley, P., Managi, S., McElwee, P., Midgley, G., Ngo, H. T., Obura, D., Pascual, U., Sankaran, M., Shin, Y. J. and Val, A. L. 2023. Overcoming the coupled climate and biodiversity crises and their societal impacts. - *Science* 380: eabl4881. doi: 10.1126/science.abl4881
- Purvis, A. 2025. Bending the curve of biodiversity loss requires a ‘satnav’ for nature. - *Phil. Trans. R. Soc. B* 380: 20230210. doi: 10.1098/rstb.2023.0210
- R Core Team 2023. R: A language and environment for statistical computing. url: <https://www.r-project.org/>
- Raskin, P. D., Electris, C. and Rosen, R. A. 2010. The Century Ahead: Searching for Sustainability. - *Sustainability* 2: 2626–2651. doi: 10.3390/su2082626
- Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N. and Rafaj, P. 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. - *Climatic Change* 109: 33–57. doi: 10.1007/s10584-011-0149-y
- Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., McCollum, D., Pachauri, S., Rao, S., Ruijven, B. V., Van Vuuren, D. P., Wilson, C., Isaac, M., Jaccard, M., Kobayashi, S., Kolp, P., Larson, E. D., Nagai, Y., Purohit, P., Schers, J., Ürge-Vorsatz, D., Van Dingenen, R., Van Vliet, O. and Morgan, G. 2012. Energy Pathways

- for Sustainable Development. - In: Johansson, T. B. et al. (eds), Global Energy Assessment (GEA). Cambridge University Press, pp. 1205–1306 DOI: 10.1017/CBO9780511793677.023. doi: 10.1017/CBO9780511793677.023
- Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. and Tavoni, M. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. - *Global Environmental Change* 42: 153–168. doi: 10.1016/j.gloenvcha.2016.05.009
- Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L. and Rockström, J. 2023. Earth beyond six of nine planetary boundaries. - *Sci. Adv.* 9: eadh2458. doi: 10.1126/sciadv.adh2458
- Rockström, J., Gupta, J., Qin, D., Lade, S. J., Zhang, X., et al. 2023. Safe and just Earth system boundaries. - *Nature* 619: 102–111. doi: 10.1038/s41586-023-06083-8
- Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., Van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlik, P., Humpenöder, F., Stehfest, E. and Tavoni, M. 2018. Scenarios towards limiting global mean temperature increase below 1.5 °C. - *Nature Clim Change* 8: 325–332. doi: 10.1038/s41558-018-0091-3
- Rosa, I. M. D., Pereira, H. M., Ferrier, S., Alkemade, R., Acosta, L. A., Akcakaya, H. R., Den Belder, E., Fazel, A. M., Fujimori, S., Harfoot, M., Harhash, K. A., Harrison, P. A., Hauck, J., Hendriks, R. J. J., Hernández, G., Jetz, W., Karlsson-Vinkhuyzen, S. I., Kim, H., King, N., Kok, M. T. J., Kolomytsev, G. O., Lazarova, T., Leadley, P., Lundquist, C. J., García Márquez, J., Meyer, C., Navarro, L. M., Nesshöver, C., Ngo, H. T., Ninan, K. N., Palomo, M. G., Pereira, L. M., Peterson, G. D., Pichs, R., Popp, A., Purvis, A., Ravera, F., Rondinini, C., Sathyapalan, J., Schipper, A. M., Seppelt, R., Settele, J., Sitas, N. and Van Vuuren, D. 2017. Multiscale scenarios for nature futures. - *Nat Ecol Evol* 1: 1416–1419. doi: 10.1038/s41559-017-0273-9
- Schipper, A. M., Hilbers, J. P., Meijer, J. R., Antão, L. H., Benítez-López, A., Jonge, M. M. J., Leemans, L. H., Scheper, E., Alkemade, R., Doelman, J. C., Mylius, S., Stehfest, E., Vuuren, D. P., Zeist, W. and Huijbregts, M. A. J. 2020. Projecting terrestrial biodiversity intactness with GLOBIO 4. - *Global Change Biology* 26: 760–771. doi: 10.1111/gcb.14848
- Scholes, R. J. and Biggs, R. 2005. A biodiversity intactness index. - *Nature* 434: 45–49. doi: 10.1038/nature03289
- Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., Hofmann, M., Bauer, N., Bertram, C., Bodirsky, B. L., Leimbach, M., Leininger, J., Levesque, A., Luderer, G., Pehl, M., Wingens, C., Baumstark, L., Beier, F., Dietrich, J. P., Humpenöder, F., Von Jeetze, P., Klein, D., Koch, J., Pietzcker, R., Strefler, J., Lotze-Campen, H. and

- Popp, A. 2021. A sustainable development pathway for climate action within the UN 2030 Agenda. - *Nat. Clim. Chang.* 11: 656–664. doi: 10.1038/s41558-021-01098-3
- Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. and Ludwig, C. 2015. The trajectory of the Anthropocene: The Great Acceleration. - *The Anthropocene Review* 2: 81–98. doi: 10.1177/2053019614564785
- Stehfest, E., Van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., Elzen, M., Janse, J., Lucas, P., Minnen, J., Müller, C. and Priens, A. 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications. - PBL Netherlands Environmental Assessment Agency. ISBN: 978-94-91506-71-0
- Streffer, J., Bauer, N., Humpenöder, F., Klein, D., Popp, A. and Kriegler, E. 2021. Carbon dioxide removal technologies are not born equal. - *Environ. Res. Lett.* 16: 074021. doi: 10.1088/1748-9326/ac0a11
- Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E. and Edmonds, J. A. 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. - *Climatic Change* 109: 77–94. doi: 10.1007/s10584-011-0151-4
- Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., Lewin, S., Godfrey, C. M., Macdonald, M. T., Langlois, E. V., Soares-Weiser, K., Moriarty, J., Clifford, T., Tunçalp, Ö. and Straus, S. E. 2018. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. - *Ann Intern Med* 169: 467–473. doi: 10.7326/M18-0850
- UN General Assembly 2015. Transforming our world: the 2030 Agenda for Sustainable Development. - A/RES/70/1 url: <https://documents.un.org/doc/undoc/gen/n15/291/89/pdf/n1529189.pdf>
- UNCCD 2022. The Global Land Outlook, second edition. - United Nations Convention to Combat Desertification (UNCCD). url: https://www.unccd.int/sites/default/files/2022-04/UNCCD_GLO2_low-res_2.pdf
- UNEP 2002. Global environment outlook 3: past, present and future perspectives. - UNEP; Earthscan. ISBN: 978-92-807-2088-4
- UNEP 2007. Global environment outlook: environment for development, GEO 4. ISBN: 978-92-807-2836-1
- UNEP 2019. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People: - Cambridge University Press. doi: 10.1017/9781108627146
- UNEP 2024a. The Sustainable Development Goals Report 2024. - UNEP. ISBN: 978-92-1-003135-6
- UNEP 2024b. Emissions Gap Report 2024: No more hot air ... please! With a massive gap between rhetoric and reality, countries draft new climate commitments. - United Nations Environment Programme. doi: 10.59117/20.500.11822/46404

- United Nations 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. - FCCC/CP/1997/L.7/Add.1 url: <https://unfccc.int/sites/default/files/resource/docs/cop3/107a01.pdf?download>
- United Nations 2018. The Paris Agreement. - FCCC/CP/2015/10/Add.1 url: https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf
- Van Soest, H. L., Aleluia Reis, L., Baptista, L. B., Bertram, C., Després, J., Drouet, L., Den Elzen, M., Fragkos, P., Fricko, O., Fujimori, S., Grant, N., Harmsen, M., Iyer, G., Keramidas, K., Köberle, A. C., Kriegler, E., Malik, A., Mittal, S., Oshiro, K., Riahi, K., Roelfsema, M., Van Ruijven, B., Schaeffer, R., Silva Herran, D., Tavoni, M., Unlu, G., Vandyck, T. and Van Vuuren, D. P. 2021. Global roll-out of comprehensive policy measures may aid in bridging emissions gap. - *Nat Commun* 12: 6419. doi: 10.1038/s41467-021-26595-z
- Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K. 2011a. The representative concentration pathways: an overview. - *Climatic Change* 109: 5–31. doi: 10.1007/s10584-011-0148-z
- Van Vuuren, D. P., Stehfest, E., Den Elzen, M. G. J., Kram, T., Van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., Oostenrijk, R. and Van Ruijven, B. 2011b. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. - *Climatic Change* 109: 95–116. doi: 10.1007/s10584-011-0152-3
- Van Vuuren, D. P., Kok, M. T. J., Girod, B., Lucas, P. L. and De Vries, B. 2012. Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use. - *Global Environmental Change* 22: 884–895. doi: 10.1016/j.gloenvcha.2012.06.001
- Van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and Winkler, H. 2014. A new scenario framework for Climate Change Research: scenario matrix architecture. - *Climatic Change* 122: 373–386. doi: 10.1007/s10584-013-0906-1
- Van Vuuren, D. P., Kok, M., Lucas, P. L., Prins, A. G., Alkemade, R., Van Den Berg, M., Bouwman, L., Van Der Esch, S., Jeuken, M., Kram, T. and Stehfest, E. 2015. Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. - *Technological Forecasting and Social Change* 98: 303–323. doi: 10.1016/j.techfore.2015.03.005
- Van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Doelman, J. C., Van Den Berg, M., Harmsen, M., De Boer, H. S., Bouwman, L. F., Daioglou, V., Edelenbosch, O. Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P. L., Van Meijl, H., Müller, C., Van Ruijven, B. J., Van Der Sluis, S. and Tabeau, A. 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. - *Global Environmental Change* 42: 237–250. doi: 10.1016/j.gloenvcha.2016.05.008
- Van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Van Den Berg, M., Bijl, D. L., De Boer, H. S., Daioglou, V., Doelman, J. C., Edelenbosch, O. Y., Harmsen, M., Hof, A. F. and Van Sluisveld, M. A. E. 2018. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. - *Nature Clim Change* 8: 391–397. doi: 10.1038/s41558-018-0119-8

- Van Vuuren, D., Stehfest, E., Gernaat, D., De Boer, H.-S., Daioglou, V., Doelman, J., Edelenbosch, O., Harmsen, M., Van Zeist, W.-J., Van Den Berg, M., Dafnomilis, I., Van Sluisveld, M., Tabeau, A., De Vos, L., De Waal, L., Van Den Berg, N., Beusen, A., Bos, A., Biemans, H., Bouwman, L., Chen, H.-H., Deetman, S., Dagnachew, A., Hof, A., Van Meijl, H., Meyer, J., Mikropoulos, S., Roelfsema, M., Schipper, A., Van Soest, H., Tagomori, I. and Zapata Castillo, V. 2021. The 2021 SSP scenarios of the IMAGE 3.2 model. doi: 10.31223/X5CG92
- Visconti, P., Bakkenes, M., Baisero, D., Brooks, T., Butchart, S. H. M., Joppa, L., Alkemade, R., Di Marco, M., Santini, L., Hoffmann, M., Maiorano, L., Pressey, R. L., Arponen, A., Boitani, L., Reside, A. E., Van Vuuren, D. P. and Rondinini, C. 2016. Projecting Global Biodiversity Indicators under Future Development Scenarios: Projecting biodiversity indicators. - CONSERVATION LETTERS 9: 5–13. doi: 10.1111/conl.12159
- WMO 2017. WMO Guidelines on the Calculation of Climate Normals. WMO-No. 1203 url: https://www.ncei.noaa.gov/data/normals-old/WMO/Guidelines%20for%20the%20Calculation%20of%20Climate%20Normals.WMO%20No1203_en.pdf
- WWF 2022. Living Planet Report 2022 - Building a nature-positive society. - CBS Library. ISBN: 978-2-88085-316-7
- WWF 2024. Living Planet Report 2024 - A System in Peril. - WWF. ISBN: 978-2-88085-319-8

4 Annex

4.1 Interventions coding overview

Annex table 1: Overview of the interventions identified in the studies. Similar interventions were grouped together for analysis. Based on this, they were classified by intervention type or sector, and a decision was made as to whether an intervention was a physical change or a policy instrument.

ID	Intervention	Intervention group	Intervention type	Physical change or policy instrument	Intervention sector
1	Access to food	Universal access to basic needs and services	Social instruments	Policy instruments	Mixed
2	Afforestation	Forestation	Land management use	Physical interventions	Nature
3	Agricultural subsidies cut	Agricultural trade policies	Economic instruments	Policy instruments	AFOLU
4	Agricultural trade liberalisation	Agricultural trade policies	Economic instruments	Policy instruments	AFOLU
5	Agro-ecological intensification	Sustainable agricultural intensification	Land management use	Physical interventions	AFOLU
6	Agroforestry	Sustainable forest management	Land management use	Physical interventions	AFOLU
7	BECCS	Negative emission technologies	Technologies	Physical interventions	Mixed
8	Best-available building technologies	Building technology and efficiency	Technologies	Physical interventions	Building
9	Best-available energy technologies	Energy technology and efficiency	Technologies	Physical interventions	Energy
10	Bioenergy	Renewable energy	Technologies	Physical interventions	Energy
11	Bioenergy constraints	Energy constraints	Regulatory standards	Policy instruments	Energy
12	Bioenergy phase out	Traditional bioenergy phase out	Regulatory standards	Policy instruments	Energy
13	Bioenergy tax	Energy taxes	Economic instruments	Policy instruments	Energy
14	Biofuel tax	Energy taxes	Economic instruments	Policy instruments	Energy
15	Building efficiency	Building technology and efficiency	Technologies	Physical interventions	Building
16	Building material efficiency	Building technology and efficiency	Technologies	Physical interventions	Building
17	Building material recycling	Recycling and reduced waste	Waste management	Physical interventions	Mixed
18	Carbon budget	Greenhouse gas emission markets	Economic instruments	Policy instruments	Mixed

19	Carbon price	Greenhouse gas emission markets	Economic instruments	Policy instruments	Mixed
20	Carbon tax	Greenhouse gas emission markets	Economic instruments	Policy instruments	Mixed
21	CCS	Negative emission technologies	Technologies	Physical interventions	Mixed
22	CDR	Negative emission technologies	Technologies	Physical interventions	Mixed
23	CDR and sequestration constraints	CDR constraints	Regulatory standards	Policy instruments	Energy
24	Charging infrastructure supply	Energy technology and efficiency	Technologies	Physical interventions	Energy
25	Clean energy preferences	Energy lifestyle changes	Lifestyle	Physical interventions	Energy
26	Coal phase out	Fossil fuel phase out	Regulatory standards	Policy instruments	Energy
27	Conservation agriculture	Sustainable agricultural intensification	Land management use	Physical interventions	AFOLU
28	Conventional biofuel phase out	Traditional bioenergy phase out	Regulatory standards	Policy instruments	Energy
29	Cross-slope barriers	Sustainable agricultural intensification	Land management use	Physical interventions	AFOLU
30	Direct Air Carbon Capture and Storage (DACCS)	Negative emission technologies	Technologies	Physical interventions	Mixed
31	Decarbonized transport vehicle technologies	Transport technology and efficiency	Technologies	Physical interventions	Transport
32	Development assistance	Universal access to basic needs and services	Social instruments	Policy instruments	Mixed
33	Diets	Diet changes	Lifestyle	Physical interventions	Food
34	Electrification technology supply	Energy technology and efficiency	Technologies	Physical interventions	Energy
35	Emission price	Greenhouse gas emission markets	Economic instruments	Policy instruments	Mixed
36	End-of-pipe measures	Industry technology and efficiency	Technologies	Physical interventions	Industry
37	Energy efficiency improvements	Energy technology and efficiency	Technologies	Physical interventions	Energy
38	Energy grid infrastructure	Energy technology and efficiency	Technologies	Physical interventions	Energy
39	Energy subsidies	Energy subsidies and incentives	Economic instruments	Policy instruments	Energy
40	Energy supply-side transformation and	Renewable energy	Technologies	Physical interventions	Energy

	decarbonisation				
41	Energy taxes	Energy taxes	Economic instruments	Policy instruments	Energy
42	Energy technology development	Energy technology and efficiency	Technologies	Physical interventions	Energy
43	Energy trade constraints	Energy trade policies	Economic instruments	Policy instruments	Energy
44	Energy trade liberalisation	Energy trade policies	Economic instruments	Policy instruments	Energy
45	Equal burden sharing	Equal burden sharing	Social instruments	Policy instruments	Mixed
46	Emissions Trading System (ETS)	Greenhouse gas emission markets	Economic instruments	Policy instruments	Mixed
47	Electric vehicles (EV) subsidies	Electrification subsidies	Economic instruments	Policy instruments	Energy
48	Fertilizer efficiency	Agricultural technology and efficiency	Technologies	Physical interventions	AFOLU
49	Foresight energy sector	Renewable energy	Technologies	Physical interventions	Energy
50	Fossil fuel phase out	Fossil fuel phase out	Regulatory standards	Policy instruments	Energy
51	Fossil fuel subsidies phase out	Fossil fuel phase out	Regulatory standards	Policy instruments	Energy
52	GHG tax	Greenhouse gas emission markets	Economic instruments	Policy instruments	Mixed
53	Global grid interconnection	Energy technology and efficiency	Technologies	Physical interventions	Energy
54	Hydrogen	Renewable energy	Technologies	Physical interventions	Energy
55	Hydropower	Renewable energy	Technologies	Physical interventions	Energy
56	Import tax agricultural products	Agricultural trade policies	Economic instruments	Policy instruments	AFOLU
57	Improved wastewater treatment	Recycling and reduced waste	Waste management	Physical interventions	Mixed
58	Increasing bioenergy investment costs	Energy constraints	Regulatory standards	Policy instruments	Energy
59	Industry technology development	Industry technology and efficiency	Technologies	Physical interventions	Industry
60	Industry technology improvement	Industry technology and efficiency	Technologies	Physical interventions	Industry
61	Irrigation efficiency	Agricultural technology and efficiency	Technologies	Physical interventions	AFOLU
62	Livestock efficiency	Agricultural technology and efficiency	Technologies	Physical interventions	AFOLU

63	Lower agricultural demand	Lower demand	non-energy	Lifestyle	Physical interventions	Mixed
64	Lower energy consumption	Energy changes	lifestyle	Lifestyle	Physical interventions	Energy
65	Lower energy consumption residential sector	Energy changes	lifestyle	Lifestyle	Physical interventions	Energy
66	Lower energy demand	Energy changes	lifestyle	Lifestyle	Physical interventions	Energy
67	Manure recycling	Recycling and reduced waste		Waste management	Physical interventions	Mixed
68	Microcredit improved stoves	Energy subsidies and incentives		Economic instruments	Policy instruments	Energy
69	Modern fuel subsidies	Energy subsidies and incentives		Economic instruments	Policy instruments	Energy
70	Multifunctional agricultural landscapes	Sustainable agricultural intensification		Land management use	Physical interventions	AFOLU
71	Nuclear	Nuclear energy		Technologies	Physical interventions	Energy
72	Nuclear energy regulatory standards	Energy constraints		Regulatory standards	Policy instruments	Energy
73	Phase out energy intensive technology	Energy technology and efficiency		Technologies	Physical interventions	Energy
74	Preference public transport	Transport changes	lifestyle	Lifestyle	Physical interventions	Transport
75	Protection	Nature protection		Land management use	Physical interventions	Nature
76	Public transport efficiency	Transport technology and efficiency		Technologies	Physical interventions	Transport
77	REDD	Nature protection		Land management use	Physical interventions	Nature
78	Reduce emissions chemical production	Industry technology and efficiency		Technologies	Physical interventions	Industry
79	Reduced building and industry material demand	Lower demand	non-energy	Lifestyle	Physical interventions	Mixed
80	Reduced building material demand	Lower demand	non-energy	Lifestyle	Physical interventions	Mixed
81	Reduced demand non-energy products	Lower demand	non-energy	Lifestyle	Physical interventions	Mixed
82	Reduced food waste	Reduced food waste		Waste management	Physical interventions	Food

83	Reforestation	Forestation	Land management use	Physical interventions	Nature
84	Regionalised agricultural markets	Agricultural trade policies	Economic instruments	Policy instruments	AFOLU
85	Renewables	Renewable energy	Technologies	Physical interventions	Energy
86	Renewables demand shift	Energy lifestyle changes	Lifestyle	Physical interventions	Energy
87	Replace phosphor-based detergents	Industry technology and efficiency	Technologies	Physical interventions	Industry
88	Restoration	Restoration	Land management use	Physical interventions	Nature
89	Sharing	Sustainable agricultural intensification	Land management use	Physical interventions	AFOLU
90	Slower infrastructure expansion	Slower infrastructure expansion	Land management use	Physical interventions	Building
91	Small-scale energy technologies	Energy technology and efficiency	Technologies	Physical interventions	Energy
92	Sparing	Nature protection	Land management use	Physical interventions	Nature
93	Subsidies on electric produced steel	Electrification subsidies	Economic instruments	Policy instruments	Energy
94	Sustainable agricultural intensification	Sustainable agricultural intensification	Land management use	Physical interventions	AFOLU
95	Sustainable forest management	Sustainable forest management	Land management use	Physical interventions	AFOLU
96	Sustainable grazing management	Sustainable agricultural intensification	Land management use	Physical interventions	AFOLU
97	Sustainable transport	Transport technology and efficiency	Technologies	Physical interventions	Transport
98	Transport efficiency	Transport technology and efficiency	Technologies	Physical interventions	Transport
99	Waste recycling	Recycling and reduced waste	Waste management	Physical interventions	Mixed
100	Water and basic sanitation supply	Universal access to basic needs and services	Social instruments	Policy instruments	Mixed
101	Yield improvements	Agricultural technology and efficiency	Technologies	Physical interventions	AFOLU

4.2 Metric coding overview

Annex table 2: Overview of metrics collected in the database. Percentage of metrics shows the percentage of studies that quantified the corresponding metrics, while percentage of SDGs shows the percentage of studies that quantified the corresponding SDG using one or more of the metrics (Source: Neumann et al. (2025)).

ID	Metric abbreviation	Metric	SDG	Percentage metrics	Percentage SDGs
1	Extreme poverty	Extreme poverty (Mio. people)	SDG1	3.1	4.7
2	Population < 1 \$	Population less than 1 dollar (%)	SDG1	1.6	4.7
3	Hunger risk	Hunger risk (Mio. people)	SDG2	15.6	45.3
4	Undernourishment	Prevalence of undernourishment (Mio. people)	SDG2	1.6	45.3
5	Hunger incidence	Hunger incidence (%) (population)	SDG2	1.6	45.3
6	Malnourished children	Malnourished children (Mio. children)	SDG2	1.6	45.3
7	FPI 2005	Food price index (FPI) (2005)	SDG2	12.5	45.3
8	FPI 2010	Food price index (2010)	SDG2	12.5	45.3
9	FPI 2015	Food price index (2015)	SDG2	1.6	45.3
10	Change food prices	Change average food prices (US\$)	SDG2	3.1	45.3
11	Fertilizer use	Fertilizer use (Input 10 ³ tons/y)	SDG2	4.7	45.3
12	Nitrogen use	Fertilizer use nitrogen (Tg N/yr)	SDG2	25	45.3
13	NO ₂ emissions	Nitrogen dioxide emissions (Mt NO ₂ /yr)	SDG3	53.1	68.8
14	NO _x emissions	Nitrogen oxide emissions (Mt NO _x /yr)	SDG3	10.9	68.8
15	SO ₂ emissions	Sulphur dioxide emissions (Mt SO ₂ /yr)	SDG3	62.5	68.8
16	SO _x emissions	Sulphur oxide emissions (Mt SO ₂ /yr)	SDG3	6.2	68.8
17	BC emissions	Black carbon emissions (Mt BC/yr)	SDG3	60.9	68.8
18	PM2.5 emissions	PM2.5 emissions (Mt PM2.5/yr)	SDG3	1.6	68.8
19	MYS	Mean years of schooling (MYS)	SDG4	9.4	14.1
20	Adults no education	Adults no education (%)	SDG4	3.1	14.1
21	Female education	Female education (%)	SDG4	9.4	14.1
22	Primary education	Primary education (%)	SDG4	1.6	14.1
23	Gender rat. prim. edu.	Gender ratio primary education	SDG5	4.7	4.7
24	Gender rat. sec. edu.	Gender ratio secondary education	SDG5	1.6	4.7
25	Access improved water	Additional access to improved water source (Mio. people)	SDG6	1.6	32.8
26	Access basic sanitation	Additional access to basic sanitation facilities (Mio. people)	SDG6	1.6	32.8

27	Lack improved water	Lacking access to improved water source (Mio. people)	SDG6	1.6	32.8
28	Water stress river bas.	Severe water stress river basins (Mio. people)	SDG6	3.1	32.8
29	Water stress	Water stress (Mio. people)	SDG6	3.1	32.8
30	Agr. irrigation	Agricultural irrigation (km ³ /y)	SDG6	29.7	32.8
31	Share renewables	Share renewables (%)	SDG7	10.9	12.5
32	UE build. tr. p. cap.	UE buildings transport per capita (GJ/cap/yr)	SDG7	3.1	12.5
33	Income convergence	Global income convergence (%)	SDG8	3.1	6.2
34	Unemployment	Unemployment (Mio. people)	SDG8	1.6	6.2
35	Unemployment rate	Unemployment rate (%)	SDG8	3.1	6.2
36	Ind. hydrogen electr. share	Industry hydrogen electricity energy share (%)	SDG9	3.1	3.1
37	International inequity	International inequity	SDG10	1.6	9.4
38	National equity	National equity	SDG10	1.6	9.4
39	International equity	International equity	SDG10	3.1	9.4
40	Rel. poverty	Relative poverty (%)	SDG10	3.1	9.4
41	Rat. GDP/cap	Ratio GDP per capita	SDG10	1.6	9.4
42	10% richest/10% poorest rat.	Richest 10 % to poorest 10 % ratio	SDG10	3.1	9.4
43	GINI coefficient	Gini coefficient (GINI)	SDG10	1.6	9.4
44	Urban PM2.5	Urban PM2.5 concentration (µg/m ³)	SDG11	3.1	3.1
45	Food waste (kcal/cap/day)	Food waste (kcal/cap/day)	SDG12	3.1	6.2
46	Food waste (Mt/yr)	Food waste (Mt/yr)	SDG12	3.1	6.2
47	GHG emissions	Total GHG emissions (Mt CO _{2eq} /yr)	SDG13	60.9	81.2
48	CO ₂ emissions	Total CO ₂ emissions (Mt CO ₂ /yr)	SDG13	67.2	81.2
49	AFOLU CO ₂ emissions	AFOLU CO ₂ emissions (Mt CO ₂ /yr)	SDG13	40.6	81.2
50	AFOLU GHG emissions	AFOLU emissions (Mt CO _{2eq} /yr)	SDG13	6.2	81.2
51	Forcing	Forcing (W/m ²)	SDG13	65.6	81.2
52	CO ₂ concentration	CO ₂ concentration (ppm)	SDG13	28.1	81.2
53	Temperature change	Temperature change (Since pre-industrial age)	SDG13	65.6	81.2
54	Carbon price	Carbon price (US\$/t CO ₂)	SDG13	40.6	81.2
55	River discharge N	River discharges nitrogen (t N/yr)	SDG14	1.6	9.4
56	River discharge P	River discharges phosphorus (t P/year)	SDG14	1.6	9.4
57	MTI	Mean tropic index (MIT)	SDG14	1.6	9.4
58	MSA aquatic	Mean species abundance aquatic (MSA aquatic)	SDG14	3.1	9.4
59	Ocean acidification	Ocean acidification aragonite saturation state	SDG14	4.7	9.4
60	Habitat range size	Habitat range size (%)	SDG15	1.6	42.2

61	Species range loss	Species affected by 50% range loss (%)	SDG15	1.6	42.2
62	GMA	Geometric mean abundance (GMA)	SDG15	1.6	42.2
63	INSIGHTS Index	INSIGHTS index	SDG15	1.6	42.2
64	Habitat loss	Loss suitable habitat (%)	SDG15	1.6	42.2
65	Biodiv. hotspot loss	Biodiversity hotspot loss (%)	SDG15	1.6	42.2
66	Red. vasc. plant sp.	Reduction vascular plant species (%)	SDG15	1.6	42.2
67	Extinction MSY	Extinction per million species years	SDG15	1.6	42.2
68	AOH/ESH	Area of habitat (ESH/AOH)	SDG15	4.7	42.2
69	Species range protection lvl.	Species range protection level (%)	SDG15	1.6	42.2
70	Ecoregions protection lvl.	Ecoregions protection level (%)	SDG15	1.6	42.2
71	Deforestation	Deforestation	SDG15	4.7	42.2
72	NCI-pb	Pressure-based natural capital index (NCI-pb)	SDG15	1.6	42.2
73	LPI	Living planet index (LPI)	SDG15	3.1	42.2
74	RLI	Red list index (RLI)	SDG15	3.1	42.2
75	MSA terrestrial	Mean species abundance terrestrial (MSA)	SDG15	15.6	42.2
76	BII	Biodiversity intactness index (BII)	SDG15	9.4	42.2
77	FRRS	Fraction regionally remaining species (FRRS)	SDG15	1.6	42.2
78	FGRS CB17BDM	Fraction globally remaining species (cSAR CB17BDM)	SDG15	1.6	42.2
79	FGRS US16BDM	Fraction globally remaining species (cSAR US16BDM)	SDG15	1.6	42.2
80	PDF	Potentially disappeared fraction of species (PDF)	SDG15	1.6	42.2
81	Nitrogen fixation	Nitrogen fixation (Mt N/yr)	SDG15	4.7	42.2
82	Mean sp. richness	Mean species richness (Species p. grid cell)	SDG15	1.6	42.2
83	Peace probability	Peace probability below 2005 deaths	SDG16	3.1	3.1
84	Equality	Equality before law and individual liberty (%)	SDG16	3.1	3.1
85	Int. climate finance	International climate finance (US\$)	SDG17	3.1	3.1

4.3 R session info

```

setting  value
version  R version 4.5.0 (2025-04-11)
os       macOS Sequoia 15.5
system   aarch64, darwin20
ui       RStudio
language (EN)
collate  en_US.UTF-8
ctype    en_US.UTF-8
tz       Europe/Berlin
date     2025-06-23
rstudio  2025.05.1+513 Mariposa Orchid (desktop)
pandoc   3.4 @
/Applications/RStudio.app/Contents/Resources/app/quarto/bin/tools/aarch
64/ (via rmarkdown)
quarto   1.6.42 @
/Applications/RStudio.app/Contents/Resources/app/quarto/bin/quarto
Packages
package      * version date (UTC) lib source
abind         1.4-8   2024-09-12 [1] CRAN (R 4.5.0)
backports     1.5.0   2024-05-23 [1] CRAN (R 4.5.0)
broom         1.0.8   2025-03-28 [1] CRAN (R 4.5.0)
cachem        1.1.0   2024-05-16 [1] CRAN (R 4.5.0)
car           3.1-3   2024-09-27 [1] CRAN (R 4.5.0)
carData       3.0-5   2022-01-06 [1] CRAN (R 4.5.0)
cellranger    1.1.0   2016-07-27 [1] CRAN (R 4.5.0)
checkmate     2.3.2   2024-07-29 [1] CRAN (R 4.5.0)
cli           3.6.5   2025-04-23 [1] CRAN (R 4.5.0)
colorBlindness * 0.1.9   2021-04-17 [1] CRAN (R 4.5.0)
colorspace    * 2.1-1   2024-07-26 [1] CRAN (R 4.5.0)
cowplot       1.1.3   2024-01-22 [1] CRAN (R 4.5.0)
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digest        0.6.37  2024-08-19 [1] CRAN (R 4.5.0)
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fastmap       1.2.0   2024-05-15 [1] CRAN (R 4.5.0)
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Formula       1.2-5   2023-02-24 [1] CRAN (R 4.5.0)
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htmltools     0.5.8.1 2024-04-04 [1] CRAN (R 4.5.0)
htmlwidgets   1.6.4   2023-12-06 [1] CRAN (R 4.5.0)
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labeling      0.4.3   2023-08-29 [1] CRAN (R 4.5.0)

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lifecycle	1.0.4	2023-11-07	[1]	CRAN	(R 4.5.0)
lubridate	* 1.9.4	2024-12-08	[1]	CRAN	(R 4.5.0)
magrittr	2.0.3	2022-03-30	[1]	CRAN	(R 4.5.0)
memoise	2.0.1	2021-11-26	[1]	CRAN	(R 4.5.0)
mime	0.13	2025-03-17	[1]	CRAN	(R 4.5.0)
miniUI	0.1.2	2025-04-17	[1]	CRAN	(R 4.5.0)
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nlme	3.1-168	2025-03-31	[1]	CRAN	(R 4.5.0)
NLP	* 0.3-2	2024-11-20	[1]	CRAN	(R 4.5.0)
patchwork	* 1.3.0	2024-09-16	[1]	CRAN	(R 4.5.0)
pillar	1.10.2	2025-04-05	[1]	CRAN	(R 4.5.0)
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pkgconfig	2.0.3	2019-09-22	[1]	CRAN	(R 4.5.0)
pkgload	1.4.0	2024-06-28	[1]	CRAN	(R 4.5.0)
profvis	0.4.0	2024-09-20	[1]	CRAN	(R 4.5.0)
promises	1.3.2	2024-11-28	[1]	CRAN	(R 4.5.0)
psych	2.5.3	2025-03-21	[1]	CRAN	(R 4.5.0)
purrr	* 1.0.4	2025-02-05	[1]	CRAN	(R 4.5.0)
R6	2.6.1	2025-02-15	[1]	CRAN	(R 4.5.0)
RColorBrewer	* 1.1-3	2022-04-03	[1]	CRAN	(R 4.5.0)
Rcpp	1.0.14	2025-01-12	[1]	CRAN	(R 4.5.0)
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remotes	2.5.0	2024-03-17	[1]	CRAN	(R 4.5.0)
rJava	1.0-11	2024-01-26	[1]	CRAN	(R 4.5.0)
rlang	1.1.6	2025-04-11	[1]	CRAN	(R 4.5.0)
rmarkdown	2.29	2024-11-04	[1]	CRAN	(R 4.5.0)
rstatix	0.7.2	2023-02-01	[1]	CRAN	(R 4.5.0)
rstudioapi	0.17.1	2024-10-22	[1]	CRAN	(R 4.5.0)
scales	* 1.4.0	2025-04-24	[1]	CRAN	(R 4.5.0)
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tidyr	* 1.3.1	2024-01-24	[1]	CRAN	(R 4.5.0)
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tidyverse	* 2.0.0	2023-02-22	[1]	CRAN	(R 4.5.0)
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tzdb	0.5.0	2025-03-15	[1]	CRAN	(R 4.5.0)
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wordcloud	* 2.6	2018-08-24	[1]	CRAN	(R 4.5.0)
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xlsxjars	0.6.1	2014-08-22	[1]	CRAN	(R 4.5.0)
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xtable	1.8-4	2019-04-21	[1]	CRAN	(R 4.5.0)
yaml	2.3.10	2024-07-26	[2]	CRAN	(R 4.5.0)

[1] /Library/Frameworks/R.framework/Versions/4.5-arm64/Resources/library

* Packages attached to the search path.

4.4 Publications

The content of this deliverable is based on research performed and prepared in the following publication:

Neumann, C., Alkemade, R., Van Vuuren, D., Burian, A., Aschi, F. and Seppelt, R. 2025. Trade-offs and synergies between climate change mitigation and biodiversity restoration: A meta-analysis of global intervention scenarios [Manuscript in preparation].