BAMBOO

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Biodiversity and trade: mitigating the impacts of non-food biomass global supply chains

The **project's main goals** are to identify trade-offs between biodiversity impacts along global supply chains of non-food biomass and to determine leverage points for transformative change to halt and reverse biodiversity loss, both now and in the future. For this purpose, we develop new biodiversity impact assessment models, create a new, hybrid multiregional input-output (MRIO) model based on the well-known EXIOBASE and the biomass-specific FABIO models, and link the combined models to the integrated assessment model IMAGE for scenario generation. Apart from global assessments and recommendations, we showcase the applicability of our models in two local case studies of global relevance, fishmeal and fish oil production in Peru and cotton production in Tanzania, as well as two case studies with retailers.

Our project is **unique** in that we develop novel models to quantify biodiversity impacts using four indicators - species richness, mean species abundance, functional diversity, and ecosystem services - covering impacts across the terrestrial, freshwater, and marine realms. The hybrid MRIO model combines and extends existing physical and monetary MRIO models, allowing us to comprehensively track global flows of raw and processed non-food biomass in unprecedented detail. Using our system of coupled models, we assess the hotspots and leverage points of the non-food biomass economy and design future scenarios with mitigated impacts on ecosystems, identifying potential pathways for transformative change.

To facilitate transformative change towards protecting biodiversity, we develop an online tool that allows stakeholders to use all models easily. In general, our data will be freely available on Zenodo while safeguarding proprietary information from commercial partners. Overall, BAMBOO provides comprehensive and detailed knowledge of the effects of biomass trade from land and sea on biodiversity and ecosystem services and an improved way of identifying leverage points. This will ultimately contribute to better environmental decision-making by policymakers, retailers and other stakeholders, supporting the achievement of science-based targets and the Sustainable Development Goals.

EXECUTIVE SUMMARY

This deliverable outlines the development of long-term scenarios to be used in the BAMBOO project. The purpose of these scenarios is to form a basis for identifying and assessing leverage points for biodiversity conservation related to non-food biomass supply chains, while also improving the understanding of the interdependencies within and between the climate policies and broader sustainable development. The scenarios provide a framework where different policies or strategies for environmental conservation can be compared and contrasted – thus highlighting the synergies and trade-offs of these strategies, as well as the enabling conditions that maximise the synergies and minimize the trade-offs.

To ensure the relevance, usefulness, and thoroughness of our scenarios we hosted an online stakeholder workshop. During this workshop, 12 stakeholders from different areas of expertise (including impact advisors, economists, and researchers/scientists) and broad actor coverage (including NGOs, private companies and government agencies) gave feedback on an initial set of proposed scenarios. The workshop focused on providing insights on what knowledge gaps stakeholders face regarding non-food biomass supply chains, and what interventions and dynamics were important to represent. As a result of the workshop, the initial scenarios were re-designed to take this advice into account.

The scenarios explore different actions that contribute towards meeting environmental goals (such as climate change, biodiversity conservation, land degradation), whilst also having important implications on biomass demand and biomass supply chains, including biomass used for energy, materials, carbon storage, and feed. These actions are: (i) Increasing the protection of natural biomes, (ii) Reducing demand of energy and agricultural products, (iii) Implementing strong climate mitigation policy. There is also a scenario that combines these three actions. For each action we have two variants: A *Low* variant which assumes an implementation of existing policies, ambitions, or other actions deemed plausible, and a *High* variant which consists of a more structural shift in policy, technology, and behaviours. The baseline scenario upon which we implement these actions is Shared Socioeconomic Pathway 2 (SSP2), including current policies.

The scenarios were projected with the IMAGE model, an integrated assessment modelling framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity loss and human well-being. The model can be used to explore the long-term pathways for future environmental and sustainable development problems, as well as possible response strategies.

The model projections show that climate change mitigation strategies have the greatest impact of the demand of biomass for non-food purposes, particularly due to the need for biomass as a clean energy source, and to provide carbon dioxide removal services. Structural shifts in consumption have very large impacts on land use projections, with land freed up due to dietary shifts vastly outweighing the potential need for land to produce biomass for energy, indicating clear synergies between the different strategies.

This work forms the basis for Task 4.3 of the BAMBOO project, where the potential environmental impact of these scenarios will be investigated in depth by coupling to a multi-regional input-output (MRIO) model. Building upon the work conducted in Task 4.1 (*Develop coupled IAM and MRIO tools to analyse environmental impacts of non-food biomass in future scenarios)*, the quantitative results of these scenarios will be shared with the MRIO, providing an integrated global long term modelling framework to investigate the leverage point for biodiversity conservation.

1 INTRODUCTION AND PURPOSE

This deliverable outlines the development of long-term scenarios to be used in the BAMBOO project. The purpose of these scenarios is to form a basis for identifying and assessing leverage points for biodiversity conservation, while also improving the understanding of the interdependencies within and between the climate policies and broader sustainable development. The scenarios provide a framework where different policies or strategies for environmental conservation can be compared and contrasted – thus highlighting the synergies and trade-offs of these strategies, as well as the enabling conditions that maximise the synergies and minimize the trade-offs.

These scenarios are projected with an integrated assessment model (IAM), incorporating dynamics and interrelationships between the energy, land, and climate systems. The IAM used is the IMAGE model, developed by *PBL Netherlands Environmental Assessment Agency*. The IMAGE model aims to assess and evaluate the global environment by simulating interactions between the human and natural systems. It has been the basis of multiple scientific publications, contributed to several global assessments including the Global Environment Outlook, Global Resource Outlook, OECD Environmental Outlook, Global Energy Assessment, and contributed scenarios assessed by the IPCC across multiple assessment reports. The IAM provides long-term projections of changes in energy supply and demand across different energy carriers and demand sectors, agricultural demand and production across different types of agricultural products, as well as changes in land cover and land use. The results from the IAM are coupled to an Environmentally Extended Multi-Regional Input-Output model (EEMRIO), as part of Tasks 4.1 (*Develop coupled IAM and MRIO tools to analyse the environmental impact of non-food biomass in future scenarios*). This coupling will allow for the identification of hotspots and leverage points of the non-food biomass economy across future scenarios and explore where impacts on biodiversity and ecosystems can be mitigated, thus showcasing options for future leverage points and development pathways. Because non-food biomass includes feed, the food system is also considered in these scenarios.

This deliverable focuses on the process used to design the different scenario storylines, as well as the results of the IAM projections for all scenarios. D4.2 due in M46 will present the results from the EEMRIO integration, building upon the scenarios described and presented here.

This deliverable first outlines the organisation and insights from a stakeholder-engagement workshop organised to aid with the scenario definitions. Subsequently, it qualitatively describes the final scenario selection. Then an overview of the IAM model used is presented, and finally IAM projections of the scenarios are presented together with key results.

2 STAKEHOLDER ENGAGEMENT WORKSHOP

2.1 Objectives

While designing the scenarios we hosted an online stakeholder workshop to ensure we were including all relevant aspects in our scenario design. The purpose of the workshop was to get stakeholder feedback concerning the following questions:

- What are the key knowledge gaps stakeholders face when it comes to evaluating non-food biomass supply chains?
- How can scenario analysis help cover (some of) these?
- What interventions, leverage points, dynamics, and indicators are important to represent?

The goal of the workshop was to make sure that the scenario design would provide results that were useful to stakeholders but were also academically rigorous. To facilitate more productive discussions during the workshop we started with a presentation to inform the participants about the goals of the project and the methods we used, as well as an initial proposal for possible scenarios, acting as a starting point for discussion.

2.2 Workshop methods

2.2.1 Workshop organisation

<u>The participants</u>

We primarily invited people from non-academic backgrounds, i.e. focusing on industry, policymakers, non-governmental organisations (NGOs), consultancies, and think tanks. A total of approximately 100 invitations were sent out via email with the goal of a 20-25% success rate. 22 of the contacted people indicated willingness to participate, with a total of 12 external participants attending. The final attendance achieved gender balance (7 female, 5 male), balance of expertise (impact advisors, economists, managers, analysts, researchers/scientists) and broad actor coverage (NGOs, think tanks, banks, international organisations, private companies, government agencies), and good regional coverage (Europe, North America, Asia, Africa) across affiliations and nationalities, but with a bias towards Europe (6), see Table 1. More details on the external participants' characteristics can be found in appendix 3. Aside from the external participants, 13 BAMBOO consortium partners attended the workshop. These partners were affiliated to NTNU, PBL, WU, Leiden University, ETH Zurich and APRI.

Table 1: Characteristics of the participants of the workshop

Participant type (external)	Number
Policymakers, (non-) governmental and international agencies	8
Retailers, other companies and consultants	3
General public and media	0
Scientists and students	1
Woman	7
Man	5
Non-binary/non-conforming	0
Preference not to respond	0
Africa	3
Americas	3
Asia	2 (by nationality)
Europe	6
Oceania	0

<u>Workshop materials and preparation</u>

One month before the workshop, we shared the initial scenario proposals, presenting one-page qualitative descriptions of the scenarios. These descriptions included (i) the scenario narrative, (ii) its implementation or representation in the models, (iii) the expected insights, and (iv) the purpose of the specific scenario within the scenario set.

2.2.2 Workshop activities

The online workshop was scheduled to last three hours. The first 50 minutes are set to serve as a broad introduction to the meeting, the BAMBOO project, and the specific task to provide context. This was done to accommodate a collaborative spirit and ensure participants had a broad understanding of the overarching research aims. First there was a round of introductions where participants shared their name, affiliation, and expertise. This was followed by a 15-minute presentation containing:

- A summary of the BAMBOO project
- The purpose of the workshop
- An overview of the modelling tools

Following a brief session of clarifying questions, a 15-minute presentation was delivered to provide an overview of the initially proposed scenarios.

The next agenda item consistent of two break-out groups (BoGs), where the participants were split into two smaller groups to discuss a topic in detail. The workshop consistent of two BoGs:

1) "Discussion on scenario requirements", where participants could indicate what they think the scenarios should explore, the research questions they should answer, important dynamics to be elaborated upon, etc.
2) "Discussion on limits of proposed scenarios", where the first scenario proposal was to be critically examined form the perspective of the discussions in BoG1.

After a brief explanation of how the break-out groups (BoGs) would work, we moved to the 1st BoG, focusing on "scenario requirements". The BoGs broke the participants into smaller groups of approximately 6 people; 2 from the BAMBOO project and 4 external participants. With the help of a Miro board, they could indicate, per proposed scenario or in general, their inputs (Figure 1). The miro board was set up in such a way so as to visually remind the participants what the purpose of the BoG was, and to allow participants make comments suggestions using sticky notes. These could be driven by comments on specific scenarios, but also "free" commenting was also allowed and encouraged. Oral discussion was also encouraged and facilitated by the BoG chairs.

The first BoG lasted 30 minutes and was followed by a 10-minute break. After the break, there was a 10-minute plenary session where the main insights from the first BoG were summarised by the respective chairs, and then the participants were led into the second BoG, focusing on the limitations of the initially proposed scenarios. The second BoG also lasted 30 minutes and was also conducted on a separate, already prepared, Miro board. The final 45 minutes were dedicated to (i) summarising the discussion of the second BoG, (ii) an open discussion, and (iii) notifying the participants of how their inputs would be used.

Figure 1. Screenshot of the Miro board for one of the parallel sessions for the 1st break-out group.

2.2.3 After the workshop

After the conclusion of the workshop, BAMBOO researchers compiled all the content from the Miro boards along with notes from the discussions held during the sessions to synthesise the inputs from the stakeholder participants. This led to a set of recommendations for the scenarios and decisions on how to adjust the initial scenario proposals into final versions. The main take-aways from the workshop were:

1. Choice of baseline is important.
    a. Ideally limit to a single baseline to avoid confusion and overload of scenario variants
    b. Baseline should include currently implemented policies
2. Elements of justice and fairness should be included as much as possible in the scenarios
3. For each scenario “different levels” of implementation should be presented, i.e. *moderate* level of action vs. *high* levels of action
4. It would be good to connect the scenarios to the narratives of the *Nature Futures Framework (Kim et al., 2023a)*

5. For the reduced consumption scenario, it would be good to explore the difference between lifestyle and technological changes
6. Scenarios focusing on different levels of trade will be difficult to assess since trade has a lot of nuances (spatial resolution, different actors, policy, products and intermediates)
7. It is useful to have an "optimal" or "desirable" scenario which provides a path to move forward on. When contrasting this with "partial or incomplete" policy scenarios, the leverage points can be identified

The initial scenarios were re-designed to take these conclusions from the stakeholder engagement process on board. The final scenario descriptions are available in Section 3 of this deliverable.

3 SCENARIO DESCRIPTIONS

3.1 Overview

The scenarios explore different actions that contribute towards meeting environmental goals (such as climate change, biodiversity conservation, land degradation), whilst also having important implications on biomass demand and biomass supply chains, including biomass used for energy, materials, carbon storage, and feed. These actions are: (i) Increasing the protection of natural biomes, (ii) Reducing demand of energy and agricultural products, (iii) Implementing strong climate mitigation policy. There is also a scenario that combines these three actions. For each action we have two variants: A *Low* variant which assumes an implementation of existing policies, ambitions, or plausible to implement actions, and a *High* variant which consists of a more structural shift in policy, technology, and behaviours. In this sense, the *High* variants present an extremely ambitious transition, which is beyond current policy discussion and levers. The purpose of this scenario is mostly "heuristic", in order to present "maximum" potentials, explore dynamics including synergies and trade-offs, and stimulate discussion on possible ambitious policies. As such we do not present specific policies catered to local circumstances, but rather explore how different systems may interact with each other as a response to major policy efforts or shifts in socio-economic narrative.

Finally, a baseline assuming a continuation of current trends and policies is also projected, to act as a benchmark. Table 2 has an overview of all the scenarios that are run.

Table 2. Overview of the scenarios.

Scenario	Variation	Implementation
Baseline	None	SSP2 with current policies
Ecosystem Restrictions	Low	30% of areas are protected by 2030 in line with the Kunming-Montreal Global Biodiversity Framework
	High	50% of terrestrial areas are conserved in 2050
Reduced Demand	Low	- 10% reduction in per person roundwood demand - limited reduction in food waste
	High	Food waste: extreme food waste reduction, RC Diet: EAT Lancet (Willett et al., 2019) everyone in 2050
Climate Mitigation	Low	Achieve well below 2°C climate goal through carbon prices.
	High	Achieve well below 2°C climate goal through carbon prices and a lower reliance on carbon dioxide removal via bioenergy production.
Mix	Low	Combination of 'low' measures.
	High	Combination of 'high' measures.

A more elaborate description of the scenarios can be found in the subsequent paragraphs. For each scenario we also indicated which narrative from the *Nature Futures Framework* the scenario aligns with. For each scenario we highlight the implications it will have on demand, on supply, and on the supply-chain of non-food biomass products.

3.2 Baseline

The baseline presents a world where no further action is taken to address environmental degradation and biodiversity loss. By contrasting it to the intervention scenarios it is possible to explore the implications of various transformative actions. The Baseline acts as a counterfactual to the various interventions aimed at addressing environmental degradation and biodiversity loss and is also the basis on which the interventions are applied.

The second Shared Socioeconomic Pathways (SSP2) will be used as baseline scenario in BAMBOO. SSP2 provides consistent projections of population growth, economic growth, technological development, trade, and behavioural change, which can be used to provide a socio-economic context for the model runs. SSP2, also known as Middle of the Road, presents a world that doesn't move away from its historic and current course concerning socio-economic development, technological growth, and consumption patterns. International cooperation is maintained but not expanded.

We also include currently implemented climate policies as mandated in different countries (Dafnomilis et al., 2025). Non-food biomass demand and supply is based on expected technological development and cost-competitiveness of this resource relative to other options. Nationally Determined Contributions (NDCs) and other ambitions that have not been implemented in law or practice are not included.

3.3 Ecosystem Restrictions (Nature for Nature)

This scenario assumes significant expansion of terrestrial protected areas, with no land conversion permitted within these areas. This expansion will reduce global biomass supply, thus affecting biomass prices and demand. This scenario will provide insights into the potential trade-off between biodiversity protection and biomass supply. It is generally expected that a scenario that severely constricts biomass supply will thus lead to reduced demand caused by supply constraints. Additionally, this scenario will offer broader insights into regional aspects. Firstly, environmental constraints will have effects on the regional distribution of biomass supply, and therefore the associated logistics and impacts will also be affected. Secondly, biodiversity will likely improve in protected areas, but because of more extensive or intensive use of the unprotected areas, there will be associated impacts there. Thus, this will enable us to highlight how environmental impacts may be displaced in the presence of different ecosystem protection measures.

Low: 30% of areas are protected by 2030 in line with the Kunming-Montreal Global Biodiversity Framework

High: 50% of terrestrial areas are conserved by 2050.

3.4 Reduced Demand (Nature as culture)

In this scenario, the overall demand of land and energy services is limited, especially in richer regions, by assuming significant cultural, lifestyle, and behavioural changes. On the production side, producers adopt practices that allow producing the same amount of output with fewer primary resources, for example through increased recycling and circular use of resources. On the consumption side, there is a willingness to reduce impacts on biodiversity through changes in consumption. As a result, there is a dietary shift towards plant-based diets, reduced material demand (particularly of non-food biomass materials), reduced waste generation and adoption of energy efficiency measures.

Overall, it is expected that reduced demand will lead to several dynamics that affect environmental pressures: (i) Lower food and non-food biomass demand, and thus also lower demand and competition for land, (ii) behavioural shifts that affect specific supply chains due to differential contribution across different products (i.e. how changes in behaviour have different effects across biomass products), and (iii) Associated benefits for biodiversity and ecosystem services.

Low: Food waste reduced by 20% of potential in rich countries and Latin America, 10% reduction in per person roundwood demand, aligned with the nature as culture framework (Kim et al., 2023b) where humans feel part of nature and therefore use resources more consciously.

High: Higher shift to plant-based diet; global adoption of the EAT Lancet diet (Willett et al., 2019) in 2050, food waste reduced to full potential in rich countries and Latin America, 20% reduction in per person roundwood demand, aligned with the nature as culture framework (Kim et al., 2023b) where humans feel part of nature and therefore use resources more consciously.

3.5 Paris Consistent Climate Change Mitigation (Nature for society)

In this scenario there is a specific focus on reducing emissions. Policy to mitigate climate change has significant implications on energy and land use patterns, as well as on supply and demand for non-food biomass and its supply chains. Furthermore, mitigating climate change also affects the environment compared to the baseline, since climate change is projected to play an important role in future biodiversity loss (United Nations Environment Programme, 2025). In this scenario, we want to investigate these effects by projecting alternative versions of the Baseline, including measures that bring its emissions in line with the Paris Agreement. This is achieved by determining and applying a global price on greenhouse gas emissions.

As such, this scenario aims to represent the most cost-effective way to meet climate goals. It describes a narrative where climate change mitigation is addressed through technical fixes, with a large focus on the functioning of markets, and so also reflects current environmental policy which has a focus on climate. Thus, it acts as a counterfactual to the other interventions that have a greater focus on behavioural and consumption shifts or on environmental management.

The uniform pricing of greenhouse gas emissions will lead to significant changes in both food and non-food biomass demand. Bioenergy becomes increasingly attractive as one of the strategies to decarbonise the energy system by replacing fossil fuels and providing Carbon Dioxide Removal via Bioenergy with Carbon Capture and Storage. This leads to a significant increase in bioenergy demand compared to the Baseline. Furthermore, land use strategies aimed to maximise its carbon sequestration potential are likely to lead to changes in agricultural production patterns, which in turn would affect the environmental footprint of non-food biomass due to competing claims on land. The *Low* and *High* variations aim to specifically explore the role of biomass in meeting climate targets, rather than the ambition of the climate target.

Low: Achieve Well below 2C climate goal through carbon prices.

High: Achieve Well below 2C climate goal through carbon prices and a lower reliance on carbon dioxide removal via bioenergy production.

3.6 Mix

The Mix scenario will present a combination of the above scenarios. The Mix scenarios also provide an opportunity to investigate the combined effects and interactions of the individual interventions. Due to changing prices, demand patterns, logistic chains, and competing uses, the Mix scenarios will display results that are not just the summation of the individual measures analysed in the specific intervention scenarios but may also show unique outcomes. This scenario will likely indicate a “best-case” outcome for biodiversity, providing an antithesis to the baseline.

By exploring the differences in the supply and demand of non-food biomass, and the supply chains of all the above scenarios, we will elaborate the possible extent of mitigation action on biodiversity loss, provide comprehensive and detailed knowledge of the effects of biomass supply chains on biodiversity and ecosystem services, and identify critical leverage points for policy making and different actors.

Low: Combination of ‘low’ measures.

High: Combination of ‘high’ measures.

4 THE IMAGE INTEGRATED ASSESSMENT MODEL

4.1 Introduction

The scenarios described above were projected with the IMAGE model. IMAGE is an integrated assessment modelling framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity loss and human well-being. The model can be used to explore the long-term pathways for future environmental and sustainable development challenges, as well as possible response strategies.

A schematic overview of the model is shown in Figure 2. Exogenous drivers on socioeconomic development, assumptions on resource availability, and normative assumptions on technological development and lifestyle change drive the demand for agricultural products and energy supply and demand. These in turn interact with the natural environment via the extraction of resources (including land cover and land use), as well as the emissions of greenhouse gasses and other pollutants.

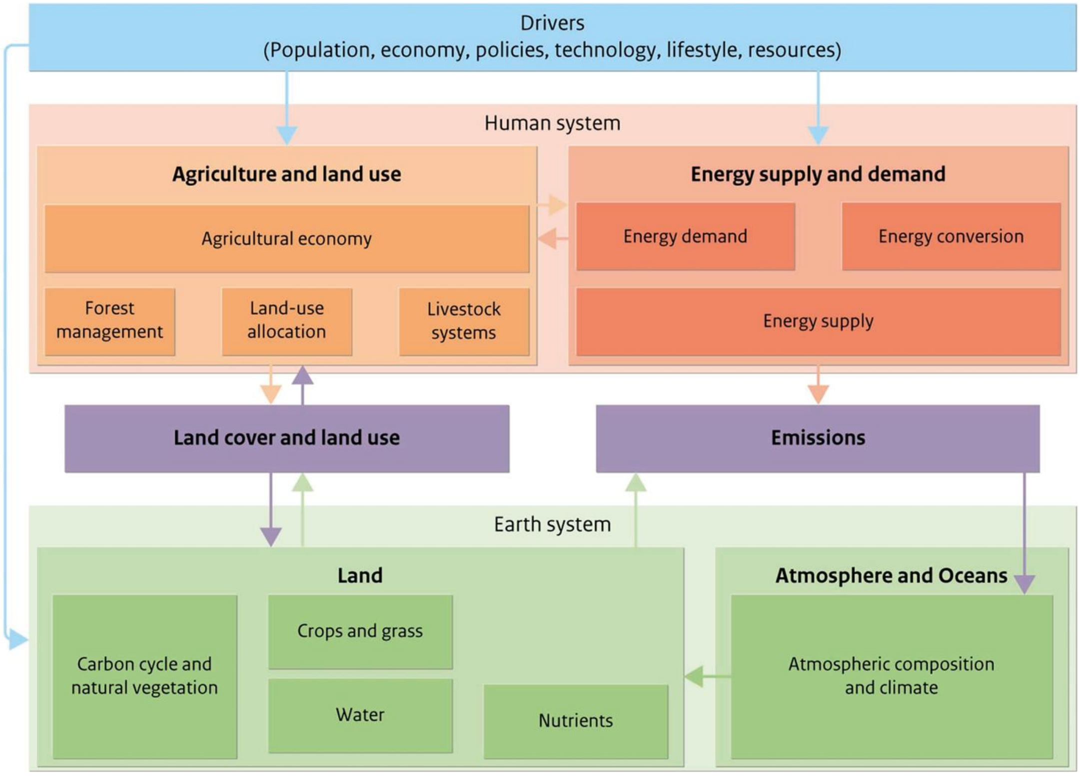

Figure 2. Schematic overview of the IMAGE model.

The model makes projections on an annual timestep until 2100, with 2025 acting as the base year. All biophysical indicators are presented on a 5 arcminute grid basis, while energy, socioeconomic and technological indicators are calculated on a 26 region and global basis[1].

By changing input data, as well as socio-economic or technological assumptions, the IMAGE model can be used to project different normative scenarios. This is how the *Baseline*, *Ecosystem Restrictions* and *Reduced Demand* scenarios were projected. The model can also be used in a target-seeking context, where a specific outcome is prescribed, and the model finds an optimal solution towards that outcome. This is how the *Paris Consistent Climate Change Mitigation* was projected, where a given greenhouse gas emissions constraint to 2100 is set, and the model determines the required changes in the energy and land system to be consistent with that constraint. The *Mix* scenario is a combination of both methods.

[1] For a region definition see: https://models.pbl.nl/image/Region_classification_map

The normative decisions made for the implementation of the scenarios in the IMAGE model are outlined in Appendix 2. Scenario protocol. The following sections give some more details on the representation of the energy and land systems in the IMAGE model.

4.2 Energy System

4.2.1 Overview

The energy system representation aims to analyse long-term trends in energy demand and supply in the context of the sustainable development challenges, including greenhouse gas emissions, access to various energy services, and demand of natural resources. The model simulates long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions.

The energy model is a recursive-dynamic simulation model of the entire energy system spanning of the extraction of primary energy resources to the provision of energy services. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states.

The energy model has three components: energy demand; energy conversion; and energy supply (see Figure 2). The energy demand component describes how energy demand is determined for five economic sectors: industry, transport, residential, services, and other sectors. The energy conversion components describe how carriers such as electricity and hydrogen are produced. Finally, the energy supply modules describe the production of primary energy carriers and calculate prices endogenously for both primary and secondary energy carriers that drive investment in the technologies associated with these carriers. The energy flows in all three main components allow calculation of greenhouse gas and air pollutant emissions.

4.2.2 Use In the BAMBOO scenarios

The energy model is used to project the demand and use of biomass for bioenergy. In the IMAGE model biomass can be used to mitigate the emissions of the energy system by replacing fossil fuels in many different end-uses, but also to provide so-called “negative emissions” by applying bioenergy production of carbon capture and storage. The model also includes the bilateral trade of bioenergy resources based on historic trends as well as the location and cost of potential future biomass resource (Daioglou et al., 2019). Furthermore, the normative assumptions of the energy model allow for a detailed exploration of the implications of reduced demand for energy services. These span the residential, transport and industrial sectors (Edelenbosch et al., 2024; Soergel et al., 2024).

4.3 Land System

4.3.1 Overview

For the land system, the IMAGE model represents the interrelationships between the agricultural economy, livestock-systems, forest management, and a biophysical representation of land use processes.

The agricultural economy is represented via a computable general equilibrium (CGE) model that is connected via a soft link to the biophysical representation of land use processes. Demographic and economic changes are the primary factors driving demand for all agricultural commodities. As agricultural production changes, the model also considers changing prices of production factors, resource availability, and technological progress. Agricultural production may supply domestic markets, and other countries and regions are supplied via international trade, depending on historical trade balances, competitiveness (relative price developments), transport costs, and trade policies. The CGE uses information from the biophysical representation of land concerning the suitability of different land types and changes in crop yields due to climate change, agricultural expansion on heterogeneous land areas, and agricultural management techniques including fertilizer application and irrigation.

The projections of agricultural production drive the biophysical representation of land, specifically concerning land use allocation, forest management, livestock systems, the carbon cycle, and natural vegetation. The output from these components forms a description of gridded global land cover and land use that is used in these and other components of IMAGE. Furthermore, implications on terrestrial carbon stocks affect CO_2 emissions from land use, and different agricultural management techniques affect the emissions of other greenhouse gasses.

Demand for agricultural production from biomass for bioenergy is driven by the Energy model. Land availability for bio-energy production is limited by agricultural production following a 'food-first' principle where agricultural lands are determined first and are off-limits for biomass production. Besides energy crops, residues from agricultural and forestry can also be used as a feedstock – linked to projections of agricultural and forestry demands.

4.3.2 Use in the BAMBOO scenarios

The representation of the land system provides the key results that determine biodiversity outcomes. Assumptions on protected areas (in the form of gridded maps of protected areas) are used to constrain land availability for agricultural production in the *Ecosystem Restrictions* scenarios, while assumptions on dietary preferences and food waste are use in the *Reduced Demand* scenarios. Projections of land use drive the availability of biomass for bioenergy, which affects the energy systems projections.

5 KEY RESULTS

5.1 Scenario projections

Below we present preliminary results for the scenarios as projected by the IMAGE model. The results presented here show macro-trends across the energy and land system, and how these trends may be bent by different measures and actions represented in the different scenarios. In this deliverable we present global results, however all results are also available at 26 world regions.

5.1.1 Energy System

Figure 3 shows projections of primary energy demand across all scenarios. The *Baseline* presents the benchmark to which all other scenarios are compared. The *Ecosystem Restrictions* scenario does not affect total energy demand. Interestingly this scenario slightly increases bio-based primary energy in the 2030-2080 period, driven by slight changes in the agricultural production which increase the availability of residues, however in the long-term bioenergy demand increase is limited.

The *Reduced Demand*, as expected, has a more significant impact of energy demand, especially its “High” variant, with long term primary energy demand being approximately 10% lower than the *Baseline*. Interestingly, reducing demand also enables a greater penetration of renewables in the energy system, since a large aspect of reducing demand comes from increased electrification of energy services. However, like the *Ecosystem Restrictions* scenario, reducing demand does not significantly affect the demand of bioenergy compared to the baseline, slightly increasing demand in the medium term, but being slightly lower in the long term.

The *Climate Mitigation* scenario, which applies relevant emission prices on all energy carriers, leads to a drop in primary energy demand of approximately 10%, as the carbon price stimulates increased energy efficiency, reduced demand for energy services, and increased electrification. While it is close to the *Reduced Demand* scenario on a total energy demand basis, looking at demand of biomass and other renewables, this scenario has a very different energy system setup. In the *Climate Mitigation* scenario, biomass and other renewables become the predominant energy source by 2050, in an effort to limit energy system emissions. The ”High” variant of this scenario leads to significantly lower biomass needs (but still higher than *Baseline, Ecosystem Restrictions,* and the *Reduced Demand* scenarios) since this variant assumes less biomass can be used. The shortfall of biomass is made up by other renewables as the fraction of renewables in primary energy supply is not affected by the choice of variant.

Finally, the *Mix* scenario present the greatest deviation from the *Baseline*. As shown in Figure 3, this scenario which combines all the measures of other scenarios presents the greatest reduction in primary energy demand, and the highest penetration of renewables in energy supply. Interestingly, this reduction in demand means that even though bioenergy does play an important role in the energy system, less of it is needed, especially in the medium term compared to the *Climate Mitigation* scenario. This highlights how reducing the demand for energy services makes it easier to meet climate targets without exacerbating potential risks from the need of biomass to decarbonize energy systems.

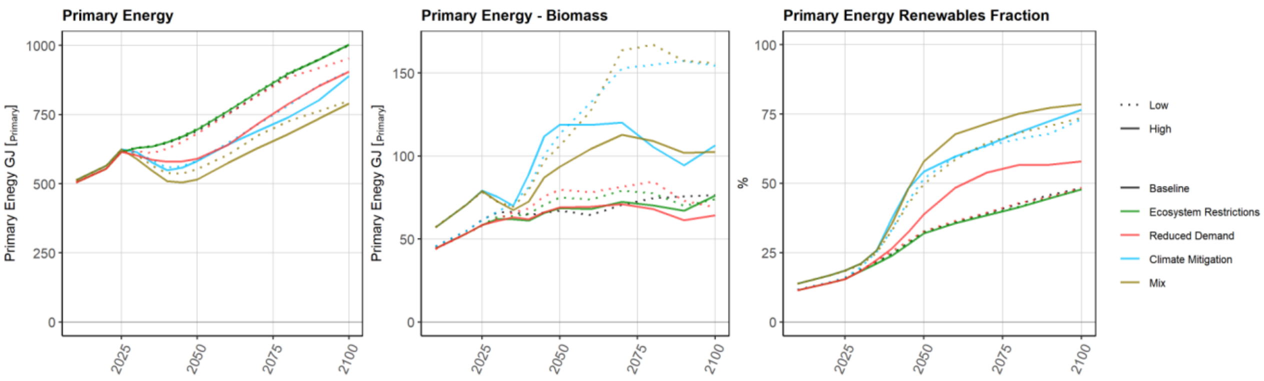

Figure 3. Projections of energy demand across all scenarios. Total primary energy demand (left), biomass primary energy demand (centre), fraction of primary energy demand supplied by renewables (right). Dotted lines present the "Low" variant, while solid lines present the "High". Note that the "Current Policies" doesn't have variants and is presented as a dotted line.

5.1.2 Agricultural and Land Systems

Like the energy system, the different interventions of the scenarios also have a significant influence on the agricultural and land system. Figure 4 shows projections of agricultural demand of different agricultural products across all scenarios. The *Baseline* shows increasing agricultural production across all products, however this growth is dominated by "Feed Crops", and "Food Crops" to a lesser extent. "Energy Crops" and "Livestock" play a comparatively smaller role in total agricultural production, in weight terms.

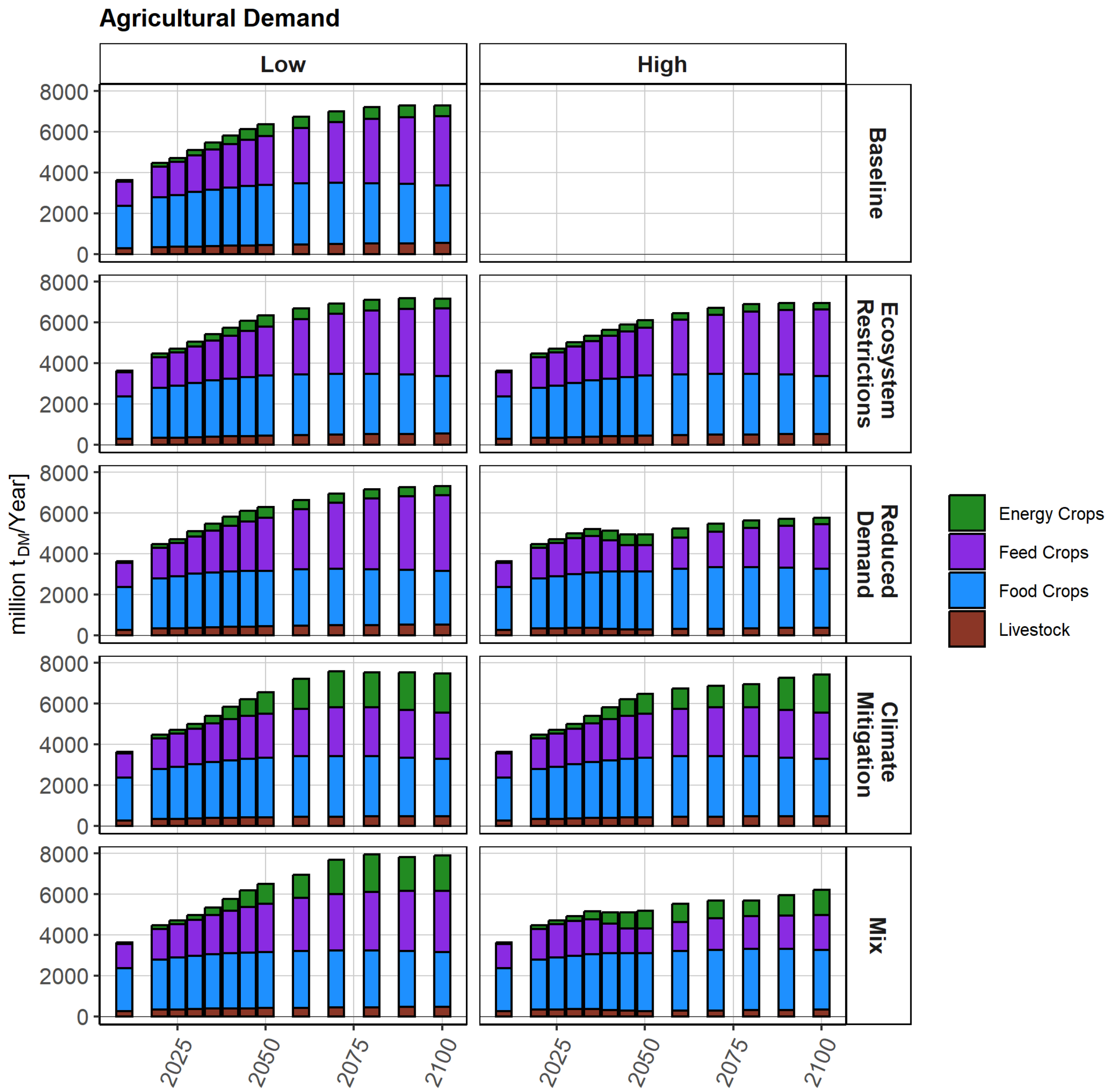

Figure 4. Projections of agricultural demand for different demand categories. Results presented for all interventions (rows) and intervention levels (columns). Note that the "Current Policies" baseline doesn't have a high/low level and its results presented in the "Low" panel.

As shown, increasing protected areas does not affect agricultural production much, except for the production of energy crops - with bioenergy demand shifting towards agricultural and forestry residues as discussed in Section 5.1.1. On the other hand, the "High" variant *Reduced Demand* has a large influence on agricultural production, bending the curve on livestock demand and production of feed crops, indicating the influence of dietary shifts. There is a smaller effect on energy crop production.

The scenario focusing on *Climate Mitigation* shows that energy crop production increases a lot, becoming a major agricultural demand category by the end of the century (increasing in 2100 from 5% in the Baseline to approximately 15%). The “High” variant limits this expansion, especially in the long term as an explicit constraint is added to bioenergy use. Food and feed crop production are also affected but to a lesser extent due to increased land competition with energy crops and afforestation activities.

The *Mix* scenario shows a combination of all the above scenarios. Interestingly, while for the energy system the *Mix* scenario has the lower overall demand for energy resources, this is not the case for the land system in the *Low* variant. This is because while the reduced demand lowers the demand compared to the baseline, the energy crop demand needed to help meet climate targets pushes up total agricultural demand by approximately 8% by 2100, compared to the *Baseline*. However, the “High” variant of the *Mix* scenario has amongst the lowest overall levels of agricultural demand due to important changes in diets, and loser overall energy demand, reducing agricultural demand by 15% compared to the *Baseline* in 2100. It is however important to note that in all these scenarios, and especially in the “Mix”, the modelled interventions may affect food prices, and thus may increase food insecurity, especially for vulnerable populations. This highlights that policies aiming on halting environmental degradation need to also ensure concomitant policies addressing food insecurity.

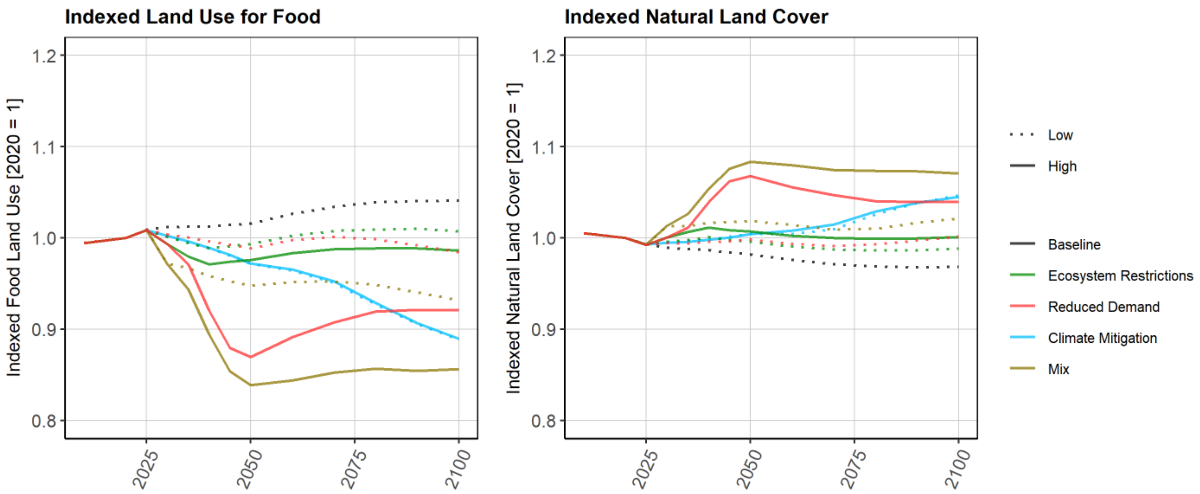

Figure 5. Projections of land cover, indexed to 2025, for all scenarios. Land use for food (left) and natural land cover (right).

The scenario narrative and resultant agricultural demand also has implications on land cover – with associated impacts on biodiversity and other ecosystem services. Figure 5 shows that in the *Baseline* land use for food is projected to increase at the expense of natural land cover, in line with historic trends. Applying protected areas mitigates this trend leading to agricultural land use plateauing to roughly the levels of today, to the benefit of natural areas. It is important to note that the *Protected Areas* scenario only assumes the protection of currently pristine biomes – thus it does not lead to ecological restoration of existing agricultural lands. The *Reduced Demand* scenario (especially the "High" variant) shows how this significantly bends the curve on land use, with land use for food decreasing by approximately 10%, with associated increase of natural land cover. This indicates the important role this measure plays in not just halting natural land cover loss, but leading to an expansion of natural ecosystems. The *Climate Mitigation* scenario shows a gradual decline in land use for food, driven to a large extent due to land competition for re/afforestation (showing an increase in natural land cover – see also Section 5.1.3), and to a lesser extent for bioenergy production. The Mix scenario presents the lowest land use for food, and the highest natural land cover, thus presenting the "best" outcome. However, one has to consider the potential negative aspects on food security mentioned above.

5.1.3 Emissions

The energy and land use projections described above also have important implications on greenhouse gas emissions. Figure 6 shows projections of these emissions, disaggregated across those arising from the energy system, and agriculture, forestry, and other land use (AFOLU). As shown, the current policies represented in the *Baseline* lead to a plateauing of emissions from both the energy and land systems. Increasing protected areas does not affect this significantly, as both the energy and land use systems are not affected a lot as discussed above.

The *Reduced Demand, Climate Mitigation, and Mix* scenarios do have large implications on emissions. As shown, reducing the demand of energy and land use products can lead to total emission reductions of about 20-25%, with reductions in both energy and land systems. The strong climate mitigation policy, in line with the Paris Agreement targets, reduced emissions to net-zero in the second half of the 21st century. This is enabled by the high penetration of renewables, use of bioenergy with carbon capture and storage (especially in the "Low" variant, showing net negative emissions from the energy system), as well as large expansion of re/afforestation. The *Mix* scenario shows a similar projection, as the climate target largely drives the overall emissions – the main difference with the *climate Mitigation* being the more rapid reduction in AFOLU emissions, enabled by reduced demand for agricultural products.

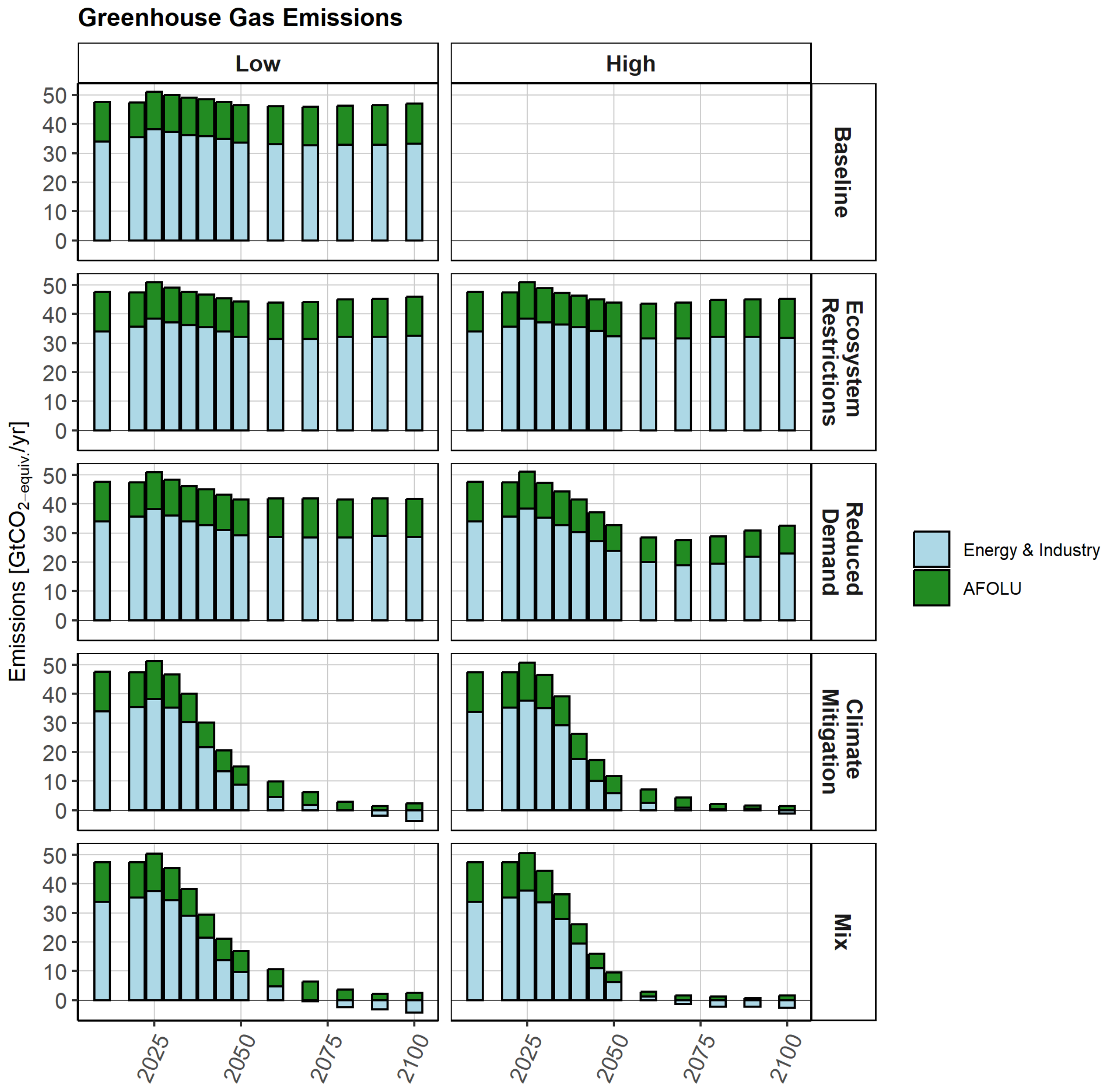

Figure 6. Projections of Greenhouse gas emissions from different sources. Results presented for all interventions (rows) and intervention levels (columns). Note that the "Current Policies" baseline doesn't have a high/low level and its results presented in the "Low" panel.

5.2 Limitations

While this study presents the results of a stakeholder-informed long term scenario analysis, it is important to acknowledge a number of limitations. These are important to fully understand the context of these results, and their usefulness.

One major drawback is the non-exhaustive nature of the stakeholder engagement. This includes the profiles of the stakeholders who participated in the scenario design, as well as their overall engagement. For example, as indicated in Table 1, despite broader interest and willingness to attend, only 12 stakeholders eventually participated in the workshop, with half of the those being based in Europe. This is expected due to the difficulty of organising a workshop spanning multiple time-zones, with voluntary attendance and limited clear and immediate benefits for the stakeholders. Furthermore, while a careful process was designed to get maximum input from the stakeholders, including giving them prior reading material, recap presentations and online infrastructure to share opinions and perspectives, ultimately stakeholder interaction was limited to a single session. While this was as planned, a revised process could include further interaction, with exchange and discussion of preliminary results, and a more regional focus.

Concerning the modelling involved, it is important to note that as integrated assessment models aim to represent global long-term dynamics, they inevitably tend to aggregate a lot of biophysical, technical, and social characteristics. This includes bioenergy technologies, land cover types, and energy demand types, all of which will affect both dynamics, and implications for biodiversity loss. For example, IAMs tend to have poor representation of degraded areas, which may have significant implications for biodiversity and carbon storage – however some of these details may be lost here. By linking to an MRIO (see section 5.3), part of this loss-of-detail is recovered as MRIOs tend to be technologically rich.

A further critique of these results concerns uncertainty. Long term projections from IAMs face multiple forms of uncertainty, including parametric uncertainty (techno-economic parameterisation, elasticities), narrative uncertainty (future economic and demographic changes, technology development), epistemic uncertainty (unknown or unclear system dynamics and interactions and associated model design). While methods exist to assess the above uncertainties (Monte-Carlo analysis, scenario analysis, model intercomparison, etc.), this was beyond the scope of the BAMBOO project. In principle the tools being developed to link the IAM with the MRIO, as well as the scenario protocol provided in Appendix 2 allow for future exercises where different IAMs can run these scenarios in order to better understand uncertainties of this specific scenario set.

All the above imply that the results need to be interpreted within a given scientific context. The scenarios have been designed to present possible outcomes for key indicators of biomass and land use demand across different interventions aiming prevent biodiversity loss. Furthermore, they assume that the interventions are implemented effectively across short timelines with no social or political implications. These scenarios map out a “solution space” of physical indicators and indicate the key dynamics between the energy and land systems. As such, the purpose of the scenarios is heuristic in nature, addressing “what if” questions. They are not predictions or pathways towards specific policy goals.

5.3 Ongoing and future work

The above sections present an overview of global results from IMAGE model. More detailed information concerning energy demand across sectors and processes, energy efficiency and conversion, trade, land use, agricultural demand and production, changes in prices, production of materials, and other aspects are used to couple IMAGE to a multi-region input-output model (MRIO). This data exchange has been standardised as part of Task 4.1, and in total 535 outputs from IMAGE are shared with the MRIO. Preliminary results have been shared with the MRIO to get a first indication of the MRIO implications of these scenarios and further test the IAM-MRIO coupling.

Besides that, all the above results have been shared with the entire BAMBOO consortium via the shared workspace. These results are being evaluated and vetted by all consortium members, and the IMAGE modelling group in addition. A process is set up where /comments on the scenario projections can be made. This evaluation process will result in a list of corrections and adjustments to be made, with final projections being made in February 2026.

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APPENDIX 1. WORKSHOP AGENDA

Date of Workshop: 10th June 2024
Zoom Link: https://pbl-nl.zoom.us/j/84229886825?pwd=Qk1zS0h6ZThmUnRpbmNLNkVJSjkrQT09
Break-out Miro:
https://miro.com/welcomeonboard/bzN4Z2RKbjBzTVd5c3dyV3BwU210NUlnRHVETUVxRGZJTWhHSlZuY25sWDZsNEdBbEtYUUY5Y1NodWozOGJoVnwzNDU4NzY0NTQ4NTg3NDMyOTk2fDI=?share_link_id=951085854897

Time (CEST)	Activity
1400	Entrance & Round of introductions
1415	Background of workshop • BAMBOO project • Overview of modelling tools • Purpose of workshop • Clarifying questions
1435	Overview of Scenarios • Narrative descriptions and their intended purpose • Questions + discussion
1450	1st Break Out Group Session • Discussion on scenario requirements
1520	*Break*
1530	Plenary: Reporting back from 1st BoG Q&A and short discussion
1545	2nd Break Out Group Session • Discussion limits of proposed scenarios
1615	Plenary: Reporting back from 2nd BoG Q&A and open discussion
1655	Wrap up and next steps

APPENDIX 2. SCENARIO PROTOCOL

Scenario	Variation	Implementation
Baseline	None	SSP2 with current policies
Protected Areas Increase	Low	30% of areas are protected by 2030 in line with the Kunming-Montreal Global Biodiversity Framework
	High	50% of terrestrial areas are conserved in 2050
Reduced Demand	Low	- 10% reduction in per person roundwood demand in all regions - Limited food waste reduction in rich countries and Latin America; 20% reduction of potential resulting in about 10% reduction in total - Diet same as baseline
	High	20% reduction in per person roundwood demand in all regions Food waste: maximum food waste reduction in rich countries and Latin America; 100% reduction of potential, resulting in about 50% reduction in food waste Diet: EAT Lancet adopted globally in 2050; this diet emphasises plants and contains only moderate amounts of fish, dairy and meat. It is a diet that is designed to have optimal health in mind (Willett et al., 2019).
Climate Mitigation	Low	Achieve well below 2°C climate goal through carbon prices.
	High	Achieve well below 2°C climate goal through carbon prices and a lower reliance on carbon dioxide removal via bioenergy production. The Bioenergy production is limited to 100 EJ.
Mix	Low	30% of areas are protected by 2030 in line with the Kunming-Montreal Global Biodiversity Framework
	High	50% of terrestrial areas are conserved in 2050

APPENDIX 3. SCENARIO WORKSHOP PARTICIPANTS - AFFILIATIONS

Organisation category	Job title	Gender	Continent
Policymakers, (non-) governmental and international agencies	Global Climate Lead Scientist	Female	US/Asia
Policymakers, (non-) governmental and international agencies	Senior Researcher	Female	Africa
Policymakers, (non-) governmental and international agencies	Science & Impact Advisor	Female	Europe
Policymakers, (non-) governmental and international agencies	Economist	Female	Europe/Global
-Retailers, other companies and consultants	Biodiversity and sustainability researcher	Male	Europe
University	Researcher	Female	Europe/India
Retailers, other companies and consultants	VP Development	Male	Europe
Policymakers, (non-) governmental and international agencies	Senior Research Associate	Female	Europe
Policymakers, (non-) governmental and international agencies	Research Fellow - Energy and Climate Change	Male	Africa
Retailers, other companies and consultants	Sr Manager, Nature & Land Use	Male	North America
Policymakers, (non-) governmental and international agencies	Policy Analyst	Male	North America
Policymakers, (non-) governmental and international agencies	Researcher	Female	Africa