CLEVER

CREATING LEVERAGE TO ENHANCE BIODIVERSITY OUTCOMES OF GLOBAL BIOMASS TRADE

Quantified ex-ante global impacts from selected supply chains on biodiversity and other ecosystem services

Deliverable 7.2

Summary

Work Package	7
Deliverable Nº	7.2
Dissemination Level	Public
Type	Report
Lead Partner	IIASA
Due Date	July 15th, 2025
Submission Date	July 17th, 2025
Status	Draft
Authors	David Leclère, Pekka Lauri, Bettina Meinhart, Amanda Palazzo, Clara Frezal, Fulvio di Fulvio, Niklas Hinkel, Sibylle Rouet-Pollakis, Andrey Lessa Derci Augustynczik

About CLEVER

Project Number	101060765
Project Title	CLEVER: Creating leverage to enhance biodiversity outcomes of global biomass trade
Topic	HORIZON-CL6-2021-BIODIV-01-15
Start date	1st September 2022
End date	31st August 2025
Coordinator	RHEINISCHE FRIEDRICH-WILHELMS-UNIVERSITAT BONN

This project has received funding from the European Research Executive Agency under HORIZON Research and Innovation Actions, grant agreement nº101060765; and from the UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee [grant number 10038491]

Contents

Table of Contents

EXECUTIVE SUMMARY

The CLEVER project sets out to explore the effectiveness of innovative international trade and supply chain governance interventions on non-food biomass supply chains and biodiversity through the use of models and scenarios. This deliverable constitutes the first of two scenario quantification deliverables (D7.2-3), focused on explorative scenarios for three non-biomass supply chains (soy, forestry and crop-based aquafeeds), as part of the Task 7.2.

Overview of methods

The scenarios have been co-designed through literature review and dedicated stakeholder workshops, and quantified with the GLOBIOM land use model, which projects the dynamics of most important agricultural and forestry supply chains and their socio-economic and environmental impacts from the year 2000 into the future with a decadal time step (up to 2050 or even 2100). Impacts are analysed for various indicators related to market balance (demand, supply, trade) as well as environmental (e.g., land and water use, GHG emissions, biodiversity) and economic (e.g., food availability, value of production) outcomes, at global scale with a focus on the EU and Brazil. A particular effort is made to quantify impacts on biodiversity, with multiple ecosystems and impact pathways considered when possible.

A brief introduction to the modelling framework is provided in the deliverable D7.1, while a detailed description of dedicated modelling improvements conducted as part of Work Package 6 activities can be found in the deliverables D6.1, D6.2, D6.3 and D6.4. Some of the modelling developments are still on-going: these are briefly described in the appendix, and will be described in more detail in the upcoming deliverable D6.5.

For all three supply chains, the scenario set contains a baseline scenario (MS15) depicting what these supply chains might look like if historical trends in demand, supply and trade are prolonged in the future. We then consider alternative futures, specific to each supply chains, and varying various aspects related to potential alternative sectorial developments, partly in response to the global climate and biodiversity crisis, but also investigating alternative assumptions about land management strategies, technological progress, demand preferences, and trade networks. Altogether, these scenarios provide contrasted explorative futures, providing a broad picture of what future sectorial trends might look like, and what the contribution of key underlying assumptions are. The literature review underpinning the preliminary scenarios (prior to the stakeholder workshops) are provided in the INTRODUCTION section, while the feedback from the stakeholders and the scenarios for each supply chains are detailed in the METHODS section.

For each supply chain, datasets of the model outputs are provided as separate Zenodo records, listed in the PROJECTS OUTPUTS ACHIEVED section.

Scenario outcomes for soy supply chains

The **baseline scenario** depicts a **business-as-usual future**, based on the ‘Middle of the Road’ Shared Socioeconomic Pathway (SSP2), complemented with key recent land use policies in Brazil. Under this business-as-usual scenario, the global demand for livestock products and crop products keeps growing, and the exports of soy-based products from Brazil increase by 76% over the 2020-2050 period, with increases to the EU but primarily to Asia. While food availability and the value of agricultural production increase globally, further biodiversity losses from agricultural activities are projected. In Brazil, although limited by the Amazon Soy Moratorium and the Forest Code, additional deforestation is projected, primarily through conversion to pastures. The increase in soy production is achieved mainly through an expansion over pastures and yield gains. Biodiversity impacts from agriculture increase for both aquatic and terrestrial ecosystems, although at a slower pace than recent decades for terrestrial biodiversity. Overall, this scenario **points to a clear trade-off between economic and environmental goals in the coming decades, with considerable development opportunities for the soy sector in Brazil and a modest but increased level of imports from soy products to the EU**.

A **first alternative scenario** explores the impact of a **global food systems sustainability transition towards bending global biodiversity loss**. Based on the Bending the Curve study (Leclère et al., 2020), it entails a comprehensive package of increased conservation and restoration, demand-side measures (lower share of animal products in the diets, reduced waste and loss) and supply side measures (sustainably increased yields). It leads to similar outcomes in terms of food availability globally, but large decreases in the value of production for livestock products, and to a more moderate extent, soy. The production and trade of soy is projected increase slightly above 2020 levels, and exports of soy-based products from Brazil increase by about 20% over 2020-2050, while soya imports from the EU decrease to below 2020 levels. As a result, biodiversity losses decrease significantly globally, as well as in Brazil through avoided land conversion and the restoration of low intensity pastures. Overall, this **points to the risks efforts towards the global environmental crisis may pose to the soy and livestock sector, globally and in particular for the soy sector in Brazil**.

A **second alternative scenario** explores the impact of an **idealized ambitious conservation policy in Brazil**. It entails a sensitivity experiment in which, on top of the baseline scenario no conversion of either forest or other natural land to agricultural land is allowed, to better understand the boundary conditions for the soy sector in Brazil. In contrary to the previous scenario, it does not assume any of the global food systems sustainability transition. This scenario leads to very similar outcomes than the baseline scenario, including a very large increase in soy production and exports from Brazil (including some increase to the EU), as well as value of agricultural production. However, it leads a strong decrease in biodiversity impacts, even lower than in the previous scenario for land-use change-mediated impacts on terrestrial ecosystems, for one out of the two related indicators. Although this scenario is projected to lead to much lower levels of pasture restoration as compared to the previous scenario, this points to a **large margin for achieving ambitious biodiversity outcomes in Brazil through halting land degradation without sacrificing potential economic opportunities**. This indicates some potential mutual interest in such a scenario, between producers in Brazil willing to pursue economic growth, and EU consumers not willing to reduce their consumption of animal products.

A **last alternative scenario** explores the **long-term impacts from the US-China trade dispute on the soy markets**. Based on recent developments in soya exports from USA to China, it explores the implications of an assumed cap to USA soya exports to China to 25% below 2020 levels, picturing long-lasting reduced market shares for USA soya exports to China through trust and reliability issues. In this scenario, we project China to turn to Brazil for compensating most of the import shortfall. This is projected to be achieved with limited impacts on other export destination of Brazil soy-based products, while the export shortfall from the USA is not reallocated to other destinations, in a context of very competitive markets. Trends in the import of soya-based products to the EU from different sourcing regions is expected to remain similar to the baseline. Impacts on biodiversity in Brazil and elsewhere, which are significantly increasing in the baseline, are not projected to be significantly higher in this scenario. Moderate losses in soy producer revenues are projected in the USA as compared to the baseline, as a result of both production and price declines. **Under the condition that current key land use policies for the soy sector stay in place, this points to the US-China trade dispute being a much lower risk to Brazilian ecosystems than the growing demand for livestock products, in particular in China.**

Scenario outcomes for forestry supply chains

The **baseline scenario** depicts a **business-as-usual future** where bioenergy demand is fixed at 2020 level, construction material demand is driven by population and GDP growth under the SSP2 socio-economic pathway and plantation forest area is fixed at 2020 level. An **alternative business-as-usual demand scenario**, where plantation forests can expand outside the natural forests area is also considered. Under the business-as-usual scenarios, roundwood harvest volumes are projected to moderately increase by 2100. Net exports of wood-based products are relatively stable, with boreal/temperate regions losing competitiveness and tropical regions gaining some. Afforestation uptake leads to an increase in forest carbon storage in the coming decades, compensating for declining carbon storage in the existing natural/seminatural forest area. The global biodiversity impacts from forestry diminish over time, and slightly reduction is observed more when allowing plantation forest expansion. **This suggests that moderate growth in demand for wood-based products could be achieved with an increase in forest carbon storage and with less pressures on biodiversity.**

A first set of scenarios explores the impact of an increase in demand for construction materials and/or bioenergy without allowing for plantation forests expansion. The global demand for bioenergy is assumed to double between 2020 and 2100 as 90% of the new urban population is assumed to live in wooden buildings, with the related demand increase primarily located in Africa and Asia. Higher demand for construction materials leads to a 50% increase in harvest volumes compared to the baseline, mostly occurring in Asia, Africa and Latin America. Natural forest management is largely intensified, with up to 300Mha of natural forests being taken into production, and negative implications for both forest carbon balance and biodiversity. Higher bioenergy demand, on the other hand, has a limited impact on harvest volumes as it is mainly met through an expansion in energy crops production. Higher bioenergy demand results in an increase in forest carbon storage compared to the baseline due to growing carbon storage of BECSS, and a reduction in biodiversity impacts over time, although at a lower rate than in the BAU scenarios. **This suggests that strong growth in demand for construction materials could exert significant pressure on biodiversity if met through intensified natural forests**

management whereas higher demand for bioenergy has a limited impact as it mainly sourced from energy crops expansion.

A second set of scenarios explores the impact of a similar increase in demand for construction materials and/or bioenergy but with the possibility of expanding plantation forests outside the natural forests area. This leads to an additional increase in harvest volumes as compared to the baseline, due to lower roundwood prices as plantation forests are more efficient than natural/seminatural forests. This also leads to an increase in the share of wood sourced from tropical regions, where the productivity of forest plantations is higher. Importantly, plantation expansion enables the release of 200-300 million hectares of seminatural forests from production and their restoration into natural forests, but leads to some decline in (biodiversity poor) other natural land and agricultural land. Moreover, when considering a joint increase in construction materials and bioenergy demand, available plantation area and therefore spared natural forests area are lower (compared to the scenario with higher material demand only) as energy crops and plantation forests compete for the same land. But overall, plantation forest expansion leads to much better outcomes for forest carbon balance and biodiversity than an intensification in natural forest management (with impacts being closer to baseline levels). **This highlights the potential of a large plantation forests expansion in supporting the development of a wood-based bioeconomy while alleviating pressure on natural forests and biodiversity. However, this also points to a potential trade-offs between wood and bioenergy production growth due to land competition between plantation forests and energy crops.**

Scenario outcomes for crop aquafeed supply chains

The **baseline scenario** depicts **a business-as-usual future**, in which demand trends for blue food products follow historical trends, the level of wild catch remains constant, and technological progress leads to a higher share of waste in fish meal and fish oil reduction, a higher productivity of fed aquaculture systems, and an increased share of crops in aquafeed requirements. As a result, the consumption of blue food products, and in particular, products sourced from freshwater aquaculture (e.g., carps) and unfed aquaculture (e.g., crustaceans, fish and prawns), increase, primarily through fed and unfed aquaculture. While the demand for fish meal and fish oil decrease, the demand for crop aquafeed keep increasing, but at slower pace than the aquaculture supply, and at the same pace than the total demand for concerned crops. The share of aquafeed use in the total consumption of related crops therefore remains constant to a few percentage points. Further loss of terrestrial biodiversity and an increase in nutrient losses from freshwater fed aquaculture systems are projected. **This points to the growth of demand of blue food products, primarily supplied via aquaculture, as contributor to global growth in the environmental impacts from raising food consumption. This trend is however moderated by changes in aquaculture feeding practices, that also redirect pressures from aquafeed demand from marine and pelagic fish stocks to terrestrial ecosystems.**

A second set of **4 sensitivity scenarios** allows to **explore the role of specific assumptions about the development of various forms of aquaculture and related feeding practices**. In particular, potential increase in unfed aquaculture are required for future levels of demand for specific products (e.g., crustaceans) to be met, and it could also slightly alleviate the need for fed aquaculture dedicated to freshwater products. Within fed aquaculture systems, further increases in feed conversion efficiency and further replacement of fish-based aquafeed by crop-based aquafeed will both contribute to averting an increase in the demand for fish-based aquafeed, and could even lead to a large decrease in such demand. The two trends would however play in opposite directions for the demand for crop-based aquafeed, with a net effect projected to moderate increases in crop-based aquafeed demand. In particular, the impact on total crop-based aquafeed of a further substitution of fish-based aquafeed by crop-based aquafeed is projected to be limited, as the share of crop-based aquafeed is already high in 2020. Unsurprisingly, assumptions about the crop mix of crop-based aquafeed play an important role in shaping the aquafeed use biomass demand of both individual and summed across all crops (through differences in nutritional demand), but this parameter is not well constrained. This **points to future changes in aquaculture feeding practices as an important and yet uncertain dimension shaping future interconnections between agricultural and blue food sectors**.

At last, **a counterfactual scenario**, picturing **a hypothetical world in which all components of the blue food sector remain fixed to 2020 levels**. Given how limited the differences between the outcomes projected for the baseline and sensitivity scenarios in terms of regional land use and biodiversity patterns, such a scenario is a necessary tool to understand more precisely the chain of impacts from the various assumptions of the scenarios, to their land use and biodiversity outcomes. Such an analysis confirmed that **the relative contribution of aquaculture in total biodiversity impacts is small, as compared to that of the other trends in the agricultural sector**. Such an analysis also revealed that while future demand for aquafeed demand is primarily located in Eastern Asia, their impacts on land use change can occur in distant regions through trade connections, and the relative proportions across regions crop aquafeed demand, land use change and biodiversity impacts are mediated by several factors related to trade teleconnections, but also background trends in land use, and the spatial heterogeneity of biodiversity and its response to land use change. This **points to the complexities of reliably assessing the interconnections between the blue food and agricultural sectors, and the potential of model and scenario approaches to assess those**.

Next steps

These scenario projections will provide the foundations for exploring further the impact of specific trade and supply chain governance interventions, aimed at reducing the biodiversity impacts of a business-as-usual future and described in an upcoming deliverable (D7.3). Altogether, these model and scenario applications will be further analysed in terms of trade and supply chain governance efficiency and effectiveness, and trade-offs and synergies with the broader sustainable development agenda in another deliverable (D7.4). To support these tasks, further model development and calibration steps are taking place. The scenarios and results presented in this deliverable may thus slightly evolve, as this follow-up work progresses.

INTRODUCTION & OBJECTIVES

Soy supply chains

Soy is the fourth most important crop in terms of global harvested area, and one of the most traded commodities, with over 40% of global production being traded internationally (De Maria et al., 2020; OECD/FAO, 2024). Since 2014, Brazil has become the world's largest soy exporter, overtaking the United States. Together they account for over 60% of global output and over 80% of global exports. Soy imports, in turn, are largely dominated by China (about 60% of global imports) and the European Union (10%)(OECD/FAO, 2024).

Over the past decades, soy production and trade expanded rapidly, mainly driven by strong growth in import demand for protein meals and cooking oil in China due to a rise in living standards (OECD/FAO, 2024; World Economic Forum, 2025). Over the coming decade, soy production and trade are projected to keep growing, although at a slower pace. However, there are uncertainties about the future evolution in soy markets related to the development of animal production in China, raising trade tension between the United States and his trading partners (incl. China) and growing sustainability concerns associated with soy production and trade (OECD/FAO, 2024).

Indeed, the production of soy and other forest-risk commodities (e.g., palm oil, cattle) have been identified as key drivers of deforestation, greenhouse gas (GHG) emissions and biodiversity loss in Brazil and other tropical countries with weak or poorly enforced regulatory frameworks (Curtis et al., 2018; Pendrill, Persson, Godar, Kastner, et al., 2019). A large and increasing share of these environmental impacts has been attributed to international demands, mainly from high-income countries in Europe and Asia (Cabernard et al., 2024; Henders et al., 2015; Pendrill, Persson, Godar, & Kastner, 2019; Pendrill, Persson, Godar, Kastner, et al., 2019). Agricultural imports from Brazil, for instance, were estimated to account for 30% of the EU tropical deforestation footprint between 2007-2015, with soy being the commodity with the largest embedded deforestation impact (WWF, 2021).

There is a growing consensus among public and private actors of the need to better regulate soy production, trade and associated environmental impacts as well as push from consumers and environmental non-governmental organizations (NGOs). Governments and the private sector have been increasingly implementing or considering different mechanisms to govern soy production and trade, including in Brazil and the EU (Schilling-Vacaflor & Lenschow, n.d.; Sotirov et al., 2022; Ziegert & Sotirov, 2024). These include conservation policies in producing countries, demand-side/trade-related policies in importing countries (e.g., dietary shifts, import restrictions on deforestation commodities) and voluntary initiatives by global traders and private companies (e.g., moratoria, zero deforestation commitments)(Frezal & Deuss, 2025). These are expected to increasingly shape soy supply chains and associated environmental footprint in the coming decades.

Beyond soy-specific interventions, there is a push for large-scale food systems transformation to meet global climate and biodiversity goals. This calls for the implementation of ambitious and integrated policy packages acting on the supply-side (e.g., sustainable productivity growth, adoption of environmentally friendly production practices and technologies), on land conservation and restoration but also on the demand-side, including through shift in diets away from animal products (Hadjikakou et al., 2025; Leclère et al., 2020; Popp et al., 2017). These combined policy interventions are expected to impact soy markets, given that soy is an export-orientated commodity and is strongly linked to demand for livestock products.

Soy markets are also being reshaped by trade tensions between key players. In 2018, China imposed 25% retaliatory tariffs on US soybean(Choe et al., 2019; IFPRI, 2025b), leading to a year-on year 75% decline in US exports. In the same year, Brazil soybean exports to China increased by 35% (United Nations, 2025). The first quarter of 2025 has been marked by renewed trade tensions and tariff escalation between the United States and China, and record-breaking development in Brazil-China soy trade (IFPRI, 2025a, 2025b; World Economic Forum, 2025). These trade disruptions could have long term effect on soybean trading patterns by permanently altering the relationship between the United States and China and reducing the competitiveness of US soy exports on Chinese markets. There is uncertainty on whether this would lead to long term reduction in Chinese imports of US soy, given the continuing growth in Chinese import demand. However, Brazil is expected to increasingly absorb China's additional demand for soy, which could have implications for deforestation, and biodiversity loss (Cowley, 2020; World Economic Forum, 2018, 2025).

With regards to the soy supply chain, the objective of WP7 is to develop new scenarios with the GLOBIOM model to explore the potential future evolution of soy trade, production, and associated socio-economic and environmental impacts, as well as the role of various governance mechanisms in regulating those, with a specific focus on Brazil-EU soy supply chains. For this deliverable, we focus on designing and exploring the impacts of stylized intervention scenarios acting on the supply and demand sides, on trade and on land conservation and restoration – and capturing key sources of uncertainties for soy markets. A new set of scenarios considering specific policies in Brazil and the EU (e.g., EUDR, EU-Mercosur trade agreement, private initiatives and domestic policies in Brazil) will be developed in the context of D7.3.

The analysis in D7.2 leverages model and indicators development undertaken in the context of previous CLEVER deliverables. These include improved modelling of vegetable oil supply chains (e.g., crushing, markets for secondary products) and of soy production systems in Brazil (as described in deliverable 6.2, together with on-going developments mentioned in appendix to this report and described in upcoming deliverable D6.5). It also encompasses the development of improved indicators of biodiversity loss based on life cycle assessment (LCA) and their integration into the GLOBIOM model (see D6.3). Finally, for soy production in Brazil, the biodiversity impacts associated with upstream and downstream supply chains stages have been quantified based on LCA and have been introduced into GLOBIOM to capture the impacts of other supply chains activities beyond farming (see D6.4).

Forest supply chains

Forest supply chains are a complex system that starts with silviculture in the forests and ends with wood-based products consumption and recycling/reuse in the urban environment. Hence, forest supply chains modelling calls for a modelling approach that combines ecological, engineering and economic modelling (Fuller et al., 2025).

GLOBIOM (IIASA, 2025) is one of the few models that is able to integrate ecological, engineering and economic modelling in the same modelling framework. Moreover, GLOBIOM is also a land-use model, i.e., it includes a spatially explicit presentation of the woody biomass supply, which is often lacking for other global forest sector models (Riviere et al., 2020). The need for spatially explicit multidisciplinary forest sector analysis has recently grown as nature conservation and biodiversity have received more attention (Azuero-Pedraza et al., 2024).

So far GLOBIOM has mainly been used for analysing agricultural sector since the standard representation of the forest sector is very simple and lacks important aspects of the forest supply chains such as forest management, wood-based final products, woody biomass reuse/recycling, and the tracking of wood-based products carbon flows. On the other hand, GLOBIOM-forest (IIASA, 2025), a sub-model of GLOBIOM, has a detailed representation of the forest managements and wood-based products supply chains, but does not include the agriculture sector (Azuero-Pedraza et al., 2024; Fulvio et al., 2025; Lauri et al., 2021; Schulte et al., 2025).

Wood-based products have been offered as a solution to reduce CO_2 emissions in the energy and material sectors. Woody biomass can be used to produce different final energy carriers such as heat, power and transport fuels as well as different materials such as bioplastic, textiles, packaging and construction materials. Moreover, about 25 % (1150 Mha) of total global forest area (4060 Mha) is currently used for production, so it would be possible to increase woody biomass production by mobilizing the remaining 75% (2910 Mha) of forest area for production(FAO, 2020). However, the remaining forest area consists of biodiversity-rich ecosystems that provide important ecosystem services such as carbon sequestration, soil protection or groundwater filtration. These services are unlikely to be maintained if the production forest area were considerably increased from its current level. Therefore, there is a need for new types of forest supply chain solutions, which do not compromise other forest-based ecosystem services supply.

Traditionally woody biomass (or roundwood) has been produced in natural or seminatural forests, but during the last 30 years an increasing share of roundwood production has moved to plantation forests. Plantation forests are “intensively managed planted forests, which specifically include short rotation plantations and exclude forests planted for protection or restoration”(FAO, 2020).

Currently they cover about 10% of the global production forest area and account for about 30% of the global roundwood supply (Mishra et al., 2021). This highlights the importance of plantation forests with respect to meeting increasing demand of woody biomass for bioenergy and construction materials.

Plantation forests could also play an important role in the sustainability of forest management, as roundwood productivity is 2-5 times higher than in natural or semi-natural forests. Therefore, moving roundwood production from natural/seminatural forest to plantation forests would free up more area for the supply of other forest-based ecosystem services.

However, plantation forests expansion have also raised concern about losing out old-growth grassland and other biodiversity rich natural vegetation areas (Bond, 2016). This may occur directly if plantation forests develop over such ecosystems, but may also occur indirectly if plantation forests develop over agricultural land and triggers the conversion of natural ecosystems into agricultural land elsewhere. To address this issue, in our model development we separate “other natural land” to “abandoned land” and “natural land”, and limit “natural land” conversion to plantations, afforestation or agricultural land.

For forest supply chains, the objective of this deliverable is to analyse the impacts of the wood-based bioeconomy on the forest sector, carbon sequestration, and biodiversity loss by utilizing the Global Biosphere Management Model (GLOBIOM). To conduct this analysis, new features of forest supply chains such as plantation forests, wood-based final products demand, forest managements, age-class dynamics and harvested wood products (HWP) carbon accounting, are included in the model. The role of plantation forests, and the associated potential benefits and trade-offs for both climate mitigation and biodiversity, remain largely unexplored in the literature. As part of CLEVER WP7 Task 7.2, this deliverable provides new scenarios designed to explore these potential interactions, and a quantitative assessment of these at the global scale with the GLOBIOM model, specifically improved in CLEVER WP6 for this purpose.

Aquaculture and aquafeed supply chains

The demand of aquatic food products is expected to increase in the coming decades, as result of increasing population and shifting incomes (Naylor et al., 2021), as well as efforts to reduce the environmental impact of food consumption (Halpern et al., 2022). As marine catch stagnates and may already be beyond sustainable potentials, a large share of the future growth in aquatic food demand is expected to be met by aquaculture (FAO, 2018). Yet, about half of today’s total aquaculture requires feed inputs that were traditionally composed of fish meal and fish oil aquafeeds. These are produced from the reduction of pelagic fish catch, and margins to increase the supply of traditional aquafeeds may be limited by the ecological impacts of the fish reduction sector (Froehlich, Jacobsen, et al., 2018).

While improvements in aquaculture feed conversion efficiencies (Gephart et al., 2021) or the uptake of novel aquafeeds (Cottrell et al., 2020) may contribute to alleviating such a pressure, crop-based aquafeed are increasingly being used as an alternative to traditional aquafeeds (Tacon & Metian, 2015). Future scenarios about dietary changes, food demand and aquaculture and aquafeed developments indicate potentially important land use implications. Blue food demand and crop aquafeeds are therefore considered as one of the main interactions between land and sea supply chains (Cottrell et al., 2018).

For example, (Froehlich, Runge, et al., 2018) estimated that the future increase in land requirements for crop-based aquafeed to sustain demand for blue food products could be significant, although dwarfed by the land requirements for crop-based feed to sustain future demand for livestock products. The study also estimated aquaculture production to be more efficient in crop feed use than livestock production, despite the expected increased reliance of aquaculture on crop feed. The authors found that scenarios assuming a substitution of livestock products by aquaculture products in future food demand might decrease the overall land use pressure from food demand.

Such estimates, however, rely on static representations of the agricultural sector, thereby ignoring potential adjustments in markets and in land use systems expected for such type of scenarios. They also lack a translation of the projected land use impacts into biodiversity impacts. Exploring these questions requires dynamic and integrated modelling of blue food and agricultural sectors, and might be facilitated by a better integration of blue food systems into integrated modelling tools.

As described in CLEVER deliverable D6.2, the GLOBIOM global land use model has recently been extended to cover key blue food supply chains, including an endogenous representation of demand, trade and production for fish products (Spillias et al., 2025). The fish production covers both the catch from marine fisheries and the supply from aquaculture production systems, these two forms of production being connected through the fish reduction sector (i.e., processing marine catch into fish meal and fish oil, used as aquaculture feed). The aquaculture sector is connected to the GLOBIOM crop sector through crop aquafeed, while the demand for blue food final products is explicitly modelled and scenarios of dietary substitutions between blue food and other food products can be considered.

The objective of this deliverable for aquaculture and aquafeed supply chains is to analyse the potential future evolution of blue food demand and supply, alternative aquaculture feeding strategies, and related impacts on land use and terrestrial biodiversity. This relies on new scenarios designed to explore these potential interactions, and a quantitative assessment of these at the global scale with the GLOBIOM model improved in WP6 and undertaken in this deliverable.

METHODS

Soy supply chains

Overall approach

Goal: For soy supply chains, the main objective is to analyse the potential evolution of soy markets and to quantify the potential impact of various governance mechanisms on soy production, trade and associated socio-economic and environmental outcomes. In D7.2, we focus on analysing the impact of stylized intervention scenarios capturing key sources of uncertainties for soy markets around a business-as-usual (BAU) future. An additional set of scenarios, exploring the impact of specific policies in Brazil and EU will be developed in D7.3.

Method summary: The scenarios' design relies on the Story-and-simulation approach (Alcamo, 2001) with an iterative process between expert-led storyline development, quantification with the GLOBIOM model and feedback from stakeholders. The scenarios were primarily developed through a literature review, as well as expert feedback on scenario ideas and key assumptions (including preliminary quantification), gathered during an online workshop.

Literature review: As summarized in the introduction, the literature review suggests that the development of future global demand for animal products and vegetable oils, and well as system-wide interventions across land use and food systems towards global sustainability goals are likely to increasingly shape soy supply chains in the future. Recent trade tensions and tariff escalation between the United States and China are also expected to affect soy trade and environmental outcomes in the coming decades.

Insights from the stakeholder workshop: A two-hour online workshop took place on 14 May 2025. It gathered 23 soy and agriculture experts, from the private sector, public sector, international organizations and NGOs from both Brazil and Europe. The workshop included: 1) a 20min presentation from IIASA on model improvements, potential scenario options and preliminary results, followed by a Q&A; 2) a first 20min breakout session where experts were asked to share their vision for the soy sector by 2050 and a reporting back in plenary; 3) a second 20min breakout session where experts were asked to identify their preferred scenario options and discuss the likely impact of the selected policies/stylized interventions on soy exports and biodiversity, followed by a reporting back in plenary. Experts mentioned population dynamics, the evolution in China's soy demand, dietary shifts away from meat towards plant-based products, deforestation regulations and the United States-China trade war as main factors likely to impact the soy sector in the coming decades. Several of these elements are considered in the stylized scenarios developed in D7.2. Stakeholders also shared feedback on scenarios considering specific policy interventions in Brazil and EU, individually and in various combinations (e.g., ASM, Forest Code, EUDR, and EU-Mercosur) that will be used to inform D7.3.

Scenario description

Based on insights from the literature and the stakeholder workshop, we explore the socio-economic and environmental impacts of a BAU future and of three stylised scenarios capturing key sources of uncertainties for soy markets. The main assumptions behind these scenarios are summarized in Table 1 while a more detailed description is provided below.

Table 1 - Summary of assumptions for soy supply chain scenarios

Scenario name	Assumptions	Questions explored
SSP2	Prolongation of historical trends (no policy change)	What does a BAU future mean for soy markets and biodiversity?
IAP	Conservation and restoration, supply and demand-side efforts aligned with the KMGBF goal of reversing global biodiversity loss from land use change by 2050	What does reaching ambitious biodiversity goals means for soy markets?
Tr.Dis	China's imports of US soy-based products capped at 75% of 2020 value	What could be the long-term consequences of the US-China trade war on soy markets and biodiversity?
ZNL_Bra	Zero absolute conversion of forest and other natural lands to agricultural land use in Brazil after 2020	What strong land conservation in Brazil means for soy production and trade?

As illustrated in Table 1, four scenarios are considered, namely:

- **BAU scenario (SSP2)**: The 'Middle of the Road' Shared Socioeconomic Pathway (SSP) 2 is used as a baseline scenario. It pictures a prolongation of historical trends in population, dietary preferences, trade and agricultural productivity into the future. More specifically, SSP2 represents a world in which the human population peaks at 9.4 billion by 2070, economic growth is moderate and uneven, and globalization continues with slow socioeconomic convergence between countries. Crop yields increase globally with a partial convergence between high- and low-yield regions, while no additional effort are made towards mitigating the triple planetary crisis (i.e., climate change, biodiversity loss, pollution) beyond a reduction in deforestation from other sources than agricultural land use expansion (Popp et al., 2017).
- **Integrated action portfolio (IAP) scenario**: this scenario considers the global implementation of food and land use systems-wide interventions which enables to reverse the global terrestrial biodiversity trends caused by habitat conversion by 2050 while feeding the growing human population (Leclère et al., 2020). The integrated action portfolio includes a mix of supply-side (sustainable increase in crop yields, following the 'Green road' SSP1 scenario instead of SSP2), demand-side (diet shift towards lower share of animal calories than in the baseline in regions of high consumption[1], and waste

[1] It is assumed that the consumption of animal products is decreased by half as compared to the levels assumed in the baseline for 2050, in all regions but the Middle-East and Sub-Saharan Africa (part of the AME aggregated region), India and Pacific islands (part of SAS aggregated region), as well as Southeast Asia (SEA aggregated region), and replaced by an increased consumption of plant-based products to reach the same level of consumption in calorific terms.

reduction from farm to fork) and land conservation and restoration measures (increased extent of protected areas to about 40% of terrestrial areas by 2030, increased effectiveness of protected areas preventing any biodiversity-detrimental additional land use conversion within those after 2020, progressive restoration reaching about 450 million hectares by 2050, and pervasive consideration of biodiversity in land use planning).

- **Trade disruption (Tr.Dis.) scenario**: this scenario caps China's imports of soy-based products from the United States at 75% of 2020 value from 2030 onwards. It represents a plausible assumption about the expected long-term effects of the recent US-China trade dispute, which is expected to erode the competitiveness of US soy exports to China. This represents more than a 25% decline in US soy exports to China after 2020, compared to the BAU scenario. This could be considered as quite pessimistic, given that China's soy import demand is projected to continue increasing in the coming decades.
- **Zero natural land loss (ZNL_Bra) scenario**: this scenario assumes zero absolute conversion from forest and non-forest natural land to agricultural land in Brazil after 2020. It is used to assess the production and export expansion potential of Brazil's soy sector if very ambitious land conservation ambitions were met. It is not meant to represent a realistic policy development but is rather intended to capture the boundary conditions of Brazil's soy sector.

These four scenarios were discussed during the stakeholder workshop and met with interest, as they were considered to capture well the key sources of uncertainties for the future evolution of soy markets. Indeed, soy experts considered the future evolution in China's soy demand, dietary shifts away from meat towards plant-based products, deforestation regulations and the United States-China trade war as key factors likely to impact the soy sector in the coming decades.

As part of an effort to improve the representation of land use dynamics in Brazil, key policy and private sector interventions including the Forest Code and the Amazon Soy Moratorium were parameterized in the model. As further detailed in appendix, the parameterization of the Forest Code assumes restrictions on illegal deforestation in the Amazonia and Cerrado biomes from 2020 onwards, adjusted by enforcement probabilities, together with restoration efforts from 2030 onwards modelled as a conversion of cropland and pasture into protected forest. For the Amazon Soy Moratorium no expansion in the land area dedicated to soy in the Amazon biome is assumed. These features apply both to the BAU scenario and the three explorative scenarios.

Quantification

The GLOBIOM economic model is used to generate projections for market development indicators and environmental and socio-economic indicators from the initial year (2000) until 2050 (with a 10-year time step) for the baseline and the explorative scenarios. Results from 2020 onwards for main global regions, and at subnational scale for Brazil, are analysed in the results section of this deliverable.

Outcomes under the baseline and the stylised policy scenarios are analysed for different indicators of food consumption, production and trade and several environmental indicators including land use, water use, GHG emissions and biodiversity loss. Biodiversity loss indicators are based on life cycle assessment (LCA) methods and have been developed in the context of D6.3. These indicators have been linked to the GLOBIOM model, and their value has already been projected for a BAU SSP2 scenario in D6.4. The analysis for the BAU and the policy scenarios is carried out at the global and regional levels (for five aggregated regions and the EU)[2] as well as at the country and biome level for Brazil.

For soy in Brazil, in addition to the biodiversity impact of farming quantified with GLOBIOM, the model was expanded to also include upstream and downstream supply chain impacts based on the results of LCA (see D6.4). These include biodiversity impacts associated with input production (e.g., fertilizer), soy processing and soy transportation, both domestically and abroad. This enables to get a more complete picture of the full range of impact associated with soy supply chains in Brazil.

Forest supply chains

Overall approach

Goal: For forest-based supply chains, the main goal is to quantify how the potential future developments of wood demands will impact on roundwood harvest volumes, forest management areas, land use changes, forest carbon balance and biodiversity. This includes also understanding how the forest sector competitiveness will develop across different regions and how this would affect global sustainability. In this deliverable, we focus on explorative scenarios picturing plausible future developments in the sectorial demands and land uses impacts, as a complement to more preliminary scenarios presented in D6.2.

Methods summary: To design and quantify the scenarios, we rely on a series of scenarios narratives, designed by sectorial experts and quantified with the GLOBIOM model, including the feedback from stakeholders. The scenarios were firstly developed through literature review and sectorial experts, afterwards they were further refined by integrating stakeholders' input on scenario ideas and key assumptions (including preliminary quantification), gathered during an online workshop. The GLOBIOM model was further improved for accommodating the scenarios specific needs related to carbon dynamics and biodiversity loss. Model improvements, including the addition of forest age-class dynamics, harvested wood products (HWP) and Bioenergy with Carbon Capture and Storage (BECCS) carbon accountings, are described in annex to this report.

[2] The five aggregated regions considered are Northern America (NAM), Other South America (OSA) (excl. Brazil), Africa and Middle East (AME), South Asia (SAS – including China), and the Rest of the World (ROW).

Insights from the literature review: A literature review was used for identifying future major developments that will shape the future bioeconomy in terms of wood demands and carbon storage potentials. The most interesting emerging developments include the growth of wood demands in the building sector, disclosing the potential for storing carbon in long lived harvested wood products (HWP). Accordingly, we developed alternative scenarios for wood use in buildings, one more conservative where timber demands are aligned to GDP/POP growth, and one where we considered also future “timber cities” development and aligned to exploratory scenarios in (Mishra et al., 2022), driven by urbanization in different global regions. Additionally, we considered future alternative growths in demand for BEECS associated with bioenergy scenarios (IIASA, 2021), given that bioenergy demand is another relevant driver of wood-based mitigation.

Insights from the stakeholder workshop: A 90-minute online workshop was conducted on December 5th 2024, involving 10 stakeholders in roughly equal proportions from NGOs, universities and industry & private sector, predominantly based Europe but with participants also based in Latin America. The workshop included an introduction session on the scope of the work, a session dedicated to gathering stakeholder views on the vision for the sector by 2050, and a session dedicated to collecting feedback on the main scenario dimensions, related assumptions and quantified outcomes. More details on the workshop organization can be found in appendix. The stakeholders found the initial scenario scope relevant but also expressed interest in considering more “multi purpose” managements in forests ecosystems together with scenarios that could address protection of primary forests and restoration ambitions in natural ecosystems. Multifunctional forests are included in the management options considered in the modelling of our scenarios. For further expanding the conservation and multipurpose value of natural/seminatural forests, we have refined our preliminary scenarios (D6.2), by focusing on forest plantations expansion outside forest area and establishing new plantations only on abandoned agricultural land (i.e. excluding natural land). This approach is able of incentivizing a win-win solutions able of reducing pressure on primary and seminatural forests without depleting other valuable ecosystems. At the same time, we have considered the expansion of afforestation for carbon and biodiversity as a restoration option. These different assumptions together go in the direction of carbon-oriented forest managements and bio-based solutions as suggested by stakeholders. Interest in more socioeconomic indicators was also raised by stakeholders, while our modelling approach allows to disclose some macroeconomic trends, like the ones related to forest sector competitiveness across different global regions, including wood products production and trade, this approach does not allow to cover in more detailed indicators related to local welfare (i.e. local employment, wages, health), however, the overall regional sectorial development can be used as an indicator for the forest sector economic growth. Suggestions included also to consider native species and local communities; however, this aspect is hardly captured without a substantial refinement of the modelling framework in specific regions and would go beyond the scope of the scenarios presented in this deliverable.

Scenario description

We consider a total of 8 scenarios (Table 2), which differ in terms of the assumptions made regarding forest management and wood demand. All scenarios are consistent with the RCP1p9 climate mitigation target and the SSP2 socio-economic development pathway. The BASE scenario is a "business-as-usual" scenario where forest management is based on current management practices and there is no development for energy use and limited development of material use.

Table 2. Summary of assumption for forest supply chains scenarios

Scenario name	Storyline	Bioenergy	Construction materials	Forest plantations
BASE	"Business as usual"	Fixed 2020 level	SSP2 demand	Fixed 2020 level
BIO	High bioenergy with current management	RCP1p9 net zero	SSP2 demand	Fixed 2020 level
CON	High construction with current management	Fixed 2020 level	Timber cities	Fixed 2020 level
BIO&CON	High bioenergy and construction with current management	RCP1p9 net zero	Timber cities	Fixed 2020 level
PLA	Business as usual with forest plantations	Fixed 2020 level	SSP2 demand	Expansion outside current forest area
PLA BIO	High bioenergy with forest plantations	RCP1p9 net zero	SSP2 demand	Expansion outside current forest area
PLA CON	High construction with forest plantations	Fixed 2020 level	Timber cities	Expansion outside current forest area
PLA BIO&CON	High bioenergy and construction with forest plantations	RCP1p9 net zero	Timber cities	Expansion outside current forest area

The scenarios are based on combinations of three dimensions, including the bioenergy demand (2 variations = fixed 2020 level, RCP1p9 net zero), construction material demand (2 variations = SSP2 demand, Timber cities) and forest plantation area expansion (2 variations = fixed 2020 level, Expansion outside current forest area), as described in the following sections.

Under the BASE scenario, we assume a business at usual development which considers bioenergy demand fixed to 2020 level, construction materials demand following SSP2 demand development (i.e. "middle of the road" socioeconomic growth scenario) and forest plantation area is fixed at 2020 level.

Bioenergy demand

Standard high mitigation bioenergy demand in GLOBIOM is based on the RCP1p9 overshoot scenario, where global bioenergy demand increase from 57 exajoules (EJ) in 2020 to 226 EJ in 2100 (IIASA 2018). This scenario was calculated about 10 years ago under minor sustainability constraints on the land-use sector. Nowadays the general view of the integrated assessment model (IAM) community is that this level of bioenergy demand cannot be reached if stricter land-use sustainability constraints are applied (Wu et al., 2019). Therefore, we apply a lower level bioenergy demand based on the RCP1p9 net-zero scenario.

Specifically, two scenarios are considered for bioenergy demand (Figure 1). In the first scenario (RCP1p9 fix2020) bioenergy demand is fixed at 2020 level 57 EJ. This scenario implicitly assumes that additional renewable energy needed for the RCP1p9 mitigation target comes from other renewable energy sources such as solar and wind power instead of bioenergy. The second scenario (RCP1p9 net zero) is the MESSAGE RCP1p9 net-zero scenario (EN_NPi2050_500) where global bioenergy demand increase from 57 EJ in 2020 to 116 EJ in 2100 (IIASA, 2021).

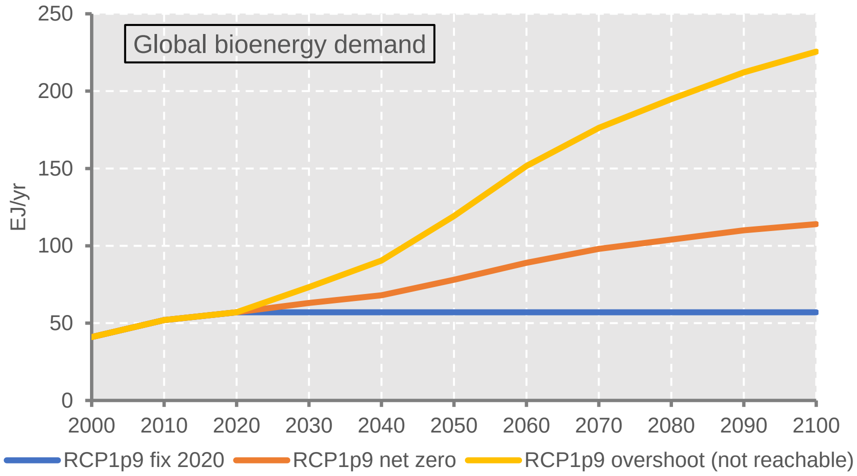

Figure 1. Global bioenergy demand scenarios

Note: 1 EJ primary energy ≈140 Mm3 woody biomass

In 2020, the majority of bioenergy demand is located in Asia and Africa where bioenergy provides the major energy source for heating and cooking for households (Figure 2). In the net zero scenario, bioenergy demand increases most in Asia and Latin America which have the largest biomass potentials for bioenergy production.

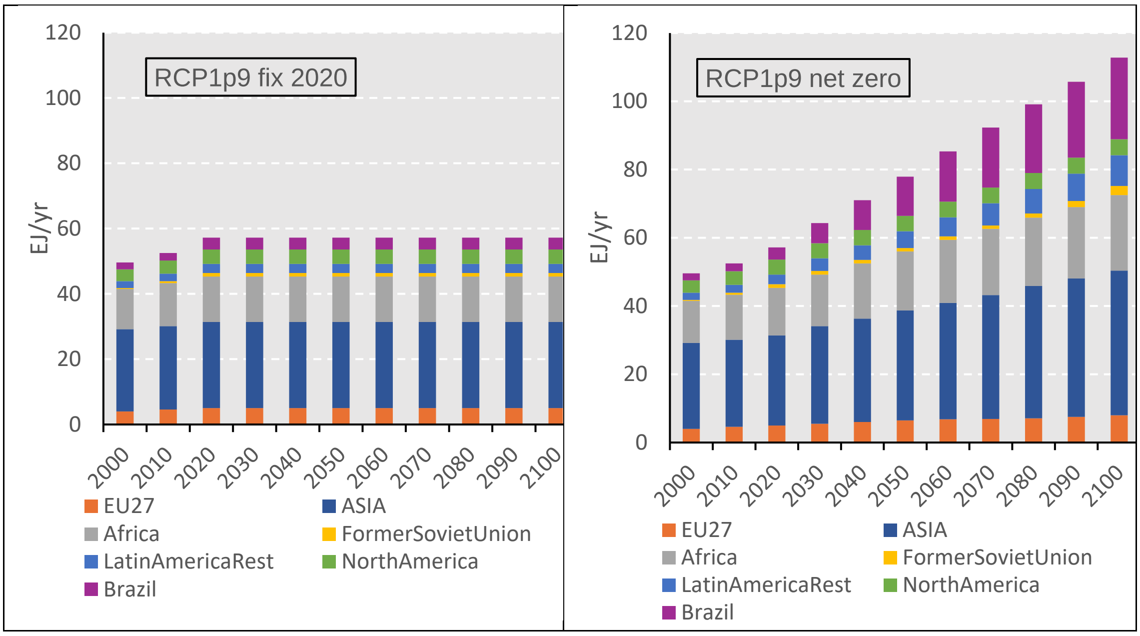

Figure 2. Global bioenergy demand divided by region

Wood-based construction materials demand

Two demand scenarios are considered for wood-based construction materials (Figure 3). In the first scenario, the demand for wood-based construction materials is based on the demand for semifinished products, which is driven by population and GDP growth from the SSP2 scenario. The second scenario is the "Timber Cities" scenario from (Mishra et al., 2022), where 90% of the new urban population is assumed to live in wooden buildings. The number of new urban buildings is based on the amount of people moving from the countryside to cities and is approximated by the regional urbanization rates from to the SSP2 scenario.

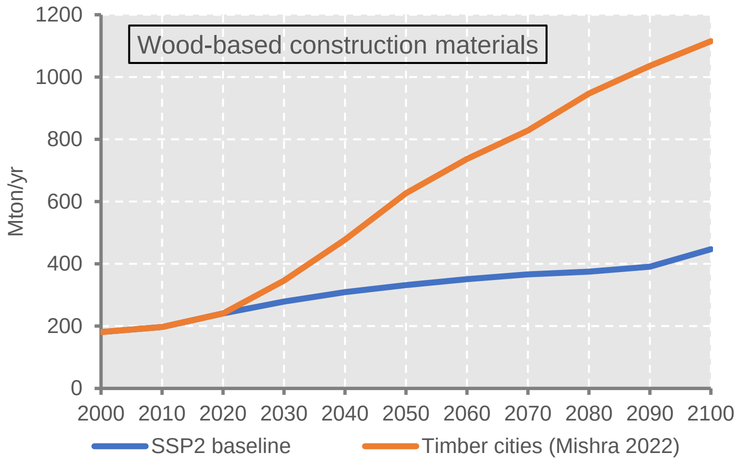

Figure 3. Global wood-based construction materials demand scenarios

Note: 1 Mton construction materials ≈2 Mm3 woody biomass

As showed in Figure 4, in the "Timber Cities" scenario most new wooden buildings are built in Africa and Asia rather than in regions which traditionally have wooden buildings such as the European Union (EU) and North America. This is because urbanization rates are much higher in Asia and Africa than in the EU and North-America.

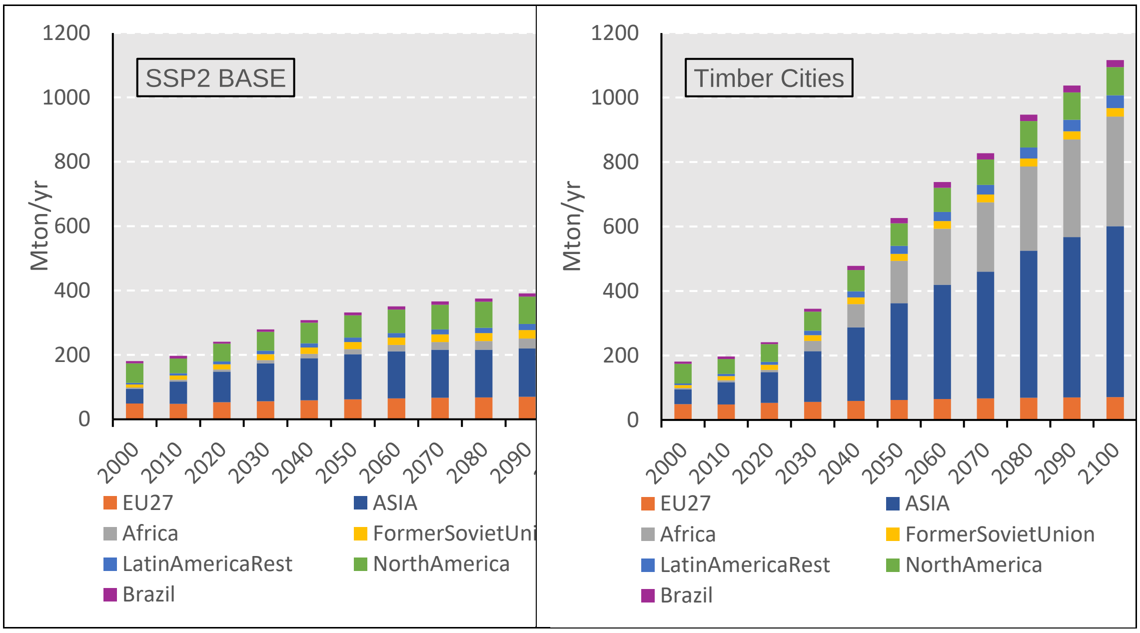

Figure 4. Wood-based construction materials demand by global regions

Plantation forests and energy crops plantations

Two scenarios are considered for plantation forests (Figure 5). The difference to the scenarios presented in D6.2 is that natural forests are not allowed to be converted in plantations and plantations expansion is limited to other natural land. In the first scenario, plantation forests area is fixed at the 2020 level (132 Mha). In the second scenario, plantation forests area can be expanded under the specified land-use change constraints, which allows to increase plantation forests area up to 200-300 Mha in 2100 depending on the demand scenario. New plantations are mostly established in the tropical regions, because biomass yields are higher and land-use competition is lower in tropical zone than in boreal and temperate zones.

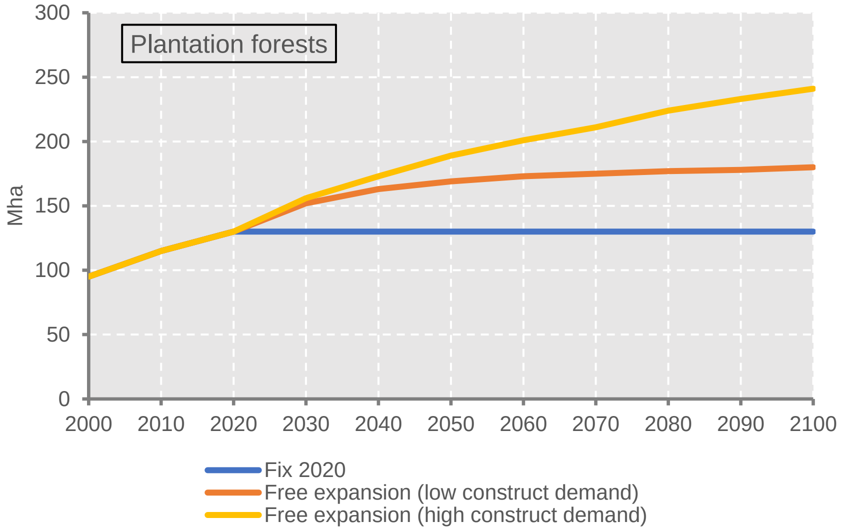

Figure 5. Global plantation forests area according to different plantations scenarios

Besides plantation forests, GLOBIOM also includes energy crops plantations, which compete with plantation forests for the same land areas (Figure 6). The difference between them is that plantations forests produce roundwood and are classified as forest area, while energy crops plantation produce bioenergy crops and are classified as agricultural land area

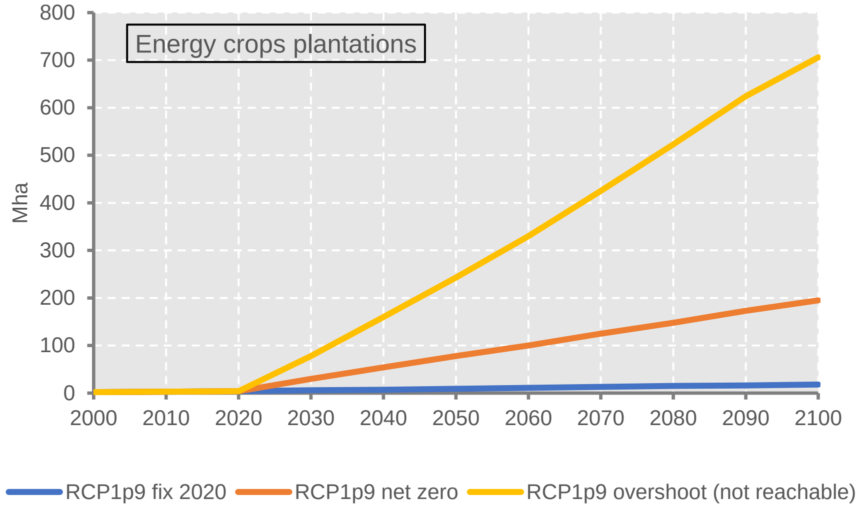

Figure 6. Global energy crops plantation area development according to different bioenergy demand scenarios

Quantification

The scenarios are quantified with a refined version of the GLOBIOM economic model that includes an enhance representation of the forest sector and it is used to generate projections for relevant outcomes until 2100 under the different scenarios. More details on the modelling framework can be found in the deliverable D6.2 and in the appendix. Additional model improvements supporting this deliverable (i.e. inclusion of forest age structure, HWP and BECCS accounting, natural land division) are detailed in appendix. The inclusion of forest age-class dynamics harvested wood products pool (HWP) and bioenergy with carbon capture and storage (BECCS) allows a more comprehensive analysis of forest carbon balance that the previous version of the model. In the updated model forest carbon storage consists of living biomass (aboveground and belowground), HWP and BECCS. Living biomass storage depends on forest area changes as well as on forest management in the existing forest area. Deadwood, soil carbon and wood-based products substitution effects are not included in the carbon accounting, because GLOBIOM does not include a process-based soil carbon model nor life-cycle analysis tools.

Outcomes projected under the various scenarios are analysed for different indicators related to forest management area, wood harvest volume, wood trade volume, carbon balance and biodiversity impacts, based on indicators presented in D6.2. The analysis of projected outcomes is carried out at the level of 7 world regions, and includes outcomes projected for individual scenarios, as well as differences to a business usual scenario (BASE).

Aquaculture and aquafeed supply chains

Overall approach

Goal: For aquaculture and aquafeed supply chains, the main goal is to quantify the potential developments in the demand for blue food products, aquaculture blue food production, fish-based vs crop-based aquafeed requirements, and related risks to the environment. In this deliverable, we focus on explorative scenarios picturing plausible future developments around a business-as-usual (BAU) future. An additional set of scenarios, exploring alternative sustainable demand and supply options will be developed in D7.3.

Methods summary: To design and quantify the scenarios, we rely on the Story-and-simulation approach (Alcamo, 2001) with an iterative process between expert-led storyline development, quantification with the GLOBIOM model and feedback from stakeholders. The scenarios were primarily developed through literature review, as well as feedback from stakeholders on scenario ideas and key assumptions (including preliminary quantification), gathered during an online workshop.

Insights from the literature review: As summarized in the introduction, the literature review highlighted future population and dietary preferences as key aspects leading to future demand growth, a stagnation of wild catch levels and the growing role of aquaculture to sustain recent and future increases in blue food consumption. It also highlighted efficiency gains and a substitution of traditional fish-based aquafeed (fish meal and fish oil) by crop-based aquafeeds as key recent trends mediating the demand for various aquafeed products.

Insights from the stakeholder workshop: A 90-minute online workshop was conducted on December 4th 2024, involving 16 stakeholders from NGOs, universities, and the private sector, predominantly from Europe but with participants from Northern and Latin America. The workshop included an introduction session on the scope of the work, a session dedicated to gathering stakeholder views on their vision for the sector by 2050, and a session dedicated to collecting feedback on the main scenario dimensions, related assumptions and quantified outcomes. More details on the workshop organization can be found in appendix. The stakeholders found the initial scenario scope relevant but also expressed interest in alternative sustainable demand (e.g., towards lower trophic species and bivalves) and supply (e.g., novel feeds, integrated and circular systems) scenarios, which may be tackled in D7.3. They also pointed to the need to vary some of the baseline assumptions (e.g., growth in non-fed aquaculture, maximum substitution potential for fish oil), which was incorporated in the design of scenarios in this deliverable. They identified some additional markets (e.g., seaweed) and sectoral drivers (e.g., legislation to regulate aquaculture development, geopolitics and trade disruption, land competition) that could be important to capture. Doing so would, however, go beyond the scope of what can be modelled within CLEVER. In terms of outcomes quantified, stakeholders expressed interest in GHG emissions impacts from various blue food sourcing strategies, and in social and economic outcomes related to production (e.g., revenue, human rights), consumption (e.g., food security) and nutrient cycle (e.g., nutrient losses from crop aquafeed production). Except for nutrient losses from crop aquafeed (aquaculture on-farm losses are already reported upon, related agriculture on-farm losses might be included in D7.3 if time allows), the model developments required to quantify these aspects are beyond the scope of CLEVER.

Scenario description

Based on insights from the literature review and the stakeholder workshop, we focused on exploring the biodiversity impacts from crop aquafeed under a business-as-usual (BAU) future, together with the impact of key underlying assumptions. As illustrated in Table 3, this led to the creation of six scenarios, that differ along three main dimensions: i) future trends in the demand for blue food products, ii) the contribution of non-fed aquaculture to future blue food production growth, and iii) changes to the aquafeed requirements from fed aquaculture (including feed conversion efficiency, substitutions between fish-based and crop-based aquafeeds, and possible substitutions between aquafeed crops). More details about the assumptions behind each of the scenarios are provided below.

Table 3 - Summary of assumptions for aquaculture and aquafeed scenarios

Scenario name	Scenario rationale	Demand assumptions	Non-fed aquaculture assumptions	Aquafeed requirement assumptions
BAU	Baseline scenario, prolongation of recent	BAU trends beyond 2020	BAU trends beyond 2020	BAU trends beyond 2020

	historical trends to 2050			
BFS20	Counterfactual scenario, blue food sector constant to 2020	2020 levels	2020 levels	2020 levels
AF20	Sensitivity analysis, BAU trends beyond 2020 except for aquafeed requirements	BAU trends	BAU trends	2020 levels for both feed conversion efficiency and share various input products
AFCOMPO20	Sensitivity analysis, BAU trends beyond 2020 except for substitution between fish-based and crop-based aquafeeds	BAU trends	BAU trends	BAU trends for fish conversion efficiency, but static level for the relative shares of fish- and crop-based aquafeeds in total aquafeed input
AFCOMPOCROPMIX	Sensitivity analysis, BAU trends beyond 2020 except for the share of crop composition of crop-based aquafeeds	BAU trends	BAU trends	BAU trends for fish conversion efficiency and fish-based aquafeed, but partial replacement of soy and corn by wheat in crops crop-based aquafeed input for freshwater products
UNFEDAC20	Sensitivity analysis, BAU trends beyond 2020 except for non-fed aquaculture	BAU trends	2020 levels	BAU trends

Baseline scenario (BAU)

This baseline scenario relies on a prolongation of historical trends for various components of blue food supply chains. While a more detailed description can be found in CLEVER deliverable D6.2, the main assumptions are summarised below:

- *Demand trends*: we assume future demand trends to follow i) regional scale future population trends from the shared socioeconomic pathway (SSP) 2, and ii) regional scale future trends in dietary preferences from the SSP2 scenario. The latter reflect SSP2 projections of economic wealth (measured in GDP per capita) combined with a relationship between GDP per capita and the demand for individual blue food products estimated over the historical period.
- *Capacity of various blue food supply sources*: to reflect recent historical trends, we assume that after 2020 the future growth in blue food demand is supplied by both unfed and fed aquaculture, while the levels of wild catches remain at 2020 levels. For unfed aquaculture, the regional capacity cannot exceed a projected regional capacity, which is estimated from historical trends and projected into the future (this was introduced after the stakeholder workshop, see appendix note on model improvements for aquaculture supply chains). For fed aquaculture, capacity is not constrained but the contribution of individual regions to global fed aquaculture supply (i.e., regional market shares) must remain within 20% of 2020 levels.
- *Technological progress in the blue food sector*: we assume both a moderate increase in the share of fish processing waste in fish meal and fish oil production (from about 50% in 2020 to up to 60% by 2050), and a prolongation of recent trends in aquafeed requirements. The latter assume i) further decreases in the economic feed conversion ratio (from 1.3-1.8 in 2020 to 1.1-1.4 in 2050, resulting in less aquafeed requirement per unit of aquaculture output), and ii) further reductions in the share of fish meal and fish oil in aquafeed (from 0.02-0.14 in 2020 to 0.00-0.01 in 2050, resulting in a higher share of crop-based aquafeed in total aquafeed requirements). The share of various crops in total crop-based aquafeed requirements differs across regions but is assumed to remain constant until 2050.

Counterfactual scenario (BFS20)

This scenario provides a counterfactual, designed to differentiate the land use and biodiversity impacts from the blue food sector development from that of other sectors covered in the model (i.e., agriculture, forestry, bioenergy). In this hypothetical scenario, all components of the blue food sector (demand, supply, processing, trade) remains fixed at 2020 levels, while the other sectors follow SSP2 projections (without climate mitigation effort, i.e., low bioenergy demand).

Sensitivity scenarios (AF20, AFCOMPO20, AFCOMPOCROPMIX, UNFEDAC20)

These four scenarios are designed to isolate the impact of specific assumptions from the baseline scenario, but with variation in the assumed post-2020 trends in related parameters:

- AF20: decreases in total aquafeed requirements per unit of fish product projected in the BAU scenario after 2020 are disregarded (i.e., economic feed conversion ratio in each fed aquaculture production system constant to 2020 levels), as well as BAU-projected post-2020 further substitutions between crop-based and fish-based aquafeed (i.e., the share of individual crops in total aquafeed requirements remains constant at 2020 levels for each fed aquaculture production system). This scenario isolates the role of future technological change in fed aquaculture, and emerged from initial model developments (see CLEVER Deliverable D6.2).
- AFCOMPO20: similar to the AF20 scenario, except that decreases in total aquafeed requirements per unit of fish product projected in the BAU scenario after 2020 are included (i.e., the share of individual crops in total aquafeed requirements remains constant at 2020 levels, but the amount of feed requirements per unit of output decreases). This scenario emerged from the stakeholder workshop and complements the AF20 scenario by isolating, within future technological trends in fed aquaculture, the specific role of additional substitution between fish-based and crop-based aquafeeds.
- AFCOMPOCROPMIX: similar to the BAU scenario, except that 50% of the crude protein content from corn and soya feed requirements per unit of aquaculture output for fed aquaculture in China are replaced by a similar crude protein content from wheat. This scenario explores the impact of assuming that aquafeed from crops commonly grown in biodiversity-rich tropical areas is replaced by domestically produced temperate crops in the largest fed aquaculture producing region. This scenario emerged from the discussion of initial model developments (see CLEVER Deliverable D6.2).
- UNFEDAC20: similar to the BAU scenario, except that the supply of unfed aquaculture at regional level cannot exceed 2020 levels. This scenario emerged from the stakeholder workshop discussions.

Quantification

The scenarios are quantified with a version of the GLOBIOM economic model that includes a fish module, and is used to generate projections for relevant outcomes until 2050 for the different scenarios. More details on the modelling framework, the baseline scenario parameterization and illustrative model outputs can be found in the CLEVER Deliverable D6.2. Additional model improvements supporting this deliverable are detailed in appendix. Outcomes projected under the various scenarios are analysed for different indicators related to the demand and supply of various blue food products, aquafeed requirements, land use changes and biodiversity impacts from land use, water use, GHG emissions and biodiversity loss. Biodiversity loss indicators are based on life cycle assessment (LCA) methods and have been developed in the context of D6.3. The analysis of projected outcomes is carried out at the level of 10 world regions[3], and includes outcomes projected for individual scenarios, as well as differences to the counterfactual scenario.

[3] The ten world regions considered Northern America (NAM), Latin America and Caribbean (LAC), Sub-Saharan Africa (SSA), Middle East and Northern Africa (MEN), Europe (EUR), Former Soviet Union (FSU), Eastern Asia (EAS, including China), South-Eastern Asia (SEA), Southern Asia (SAS), Oceania (OCE)

RESULTS AND DISCUSSION

Soy supply chains

Results

Results at the global and regional levels

Food availability

As illustrated in Figure 7, food consumption patterns differ across aggregated regions both in terms of total consumption and diet composition.

In the BAU SSP2 scenario, per capita food availability is projected to increase between 2020 and 2050 in BRA and OSA, ROW, SAS and AME and to stay broadly stable in NAM and EUE where diets have stabilized. The consumption of animal products and their shares in diets are expected to grow in most regions due to growth in per capita incomes, except in NAM and EUE as consumption is already at high levels. However, by 2050, the levels and shares of animal products in the diet in AME and SAS will remain significantly lower than in NAM, EUE and BRA (due to income but also cultural differences).

In the IAP scenario, which assumes the replacement of half of animal calories by plant-based calories in regions with high levels of consumption, the share of plant-based products in diets, but also total food availability in 2050 are higher than in the baseline. Per capita availability of plant-based products increases due to the assumed dietary shift away from animal products but also has a result of a decline in the price of crop products due to a large drop in demand for feed crops and reduced land scarcity.

Zero forest and other natural lands conversion to agriculture in Brazil after 2020, as assumed in the ZNL scenario, is expected to have a limited impact on per capita food availability in both Brazil and other regions, with only a small decline in per capita availability of animal products in Brazil compared to the 2050 BAU.

The Trade disruption scenario, which assumes a cap on China’s imports of US soy-based products from 2020 onwards, has no visible impact on per capita food availability at the regional level, which suggests that this scenario does not generate significant pressures on global markets.

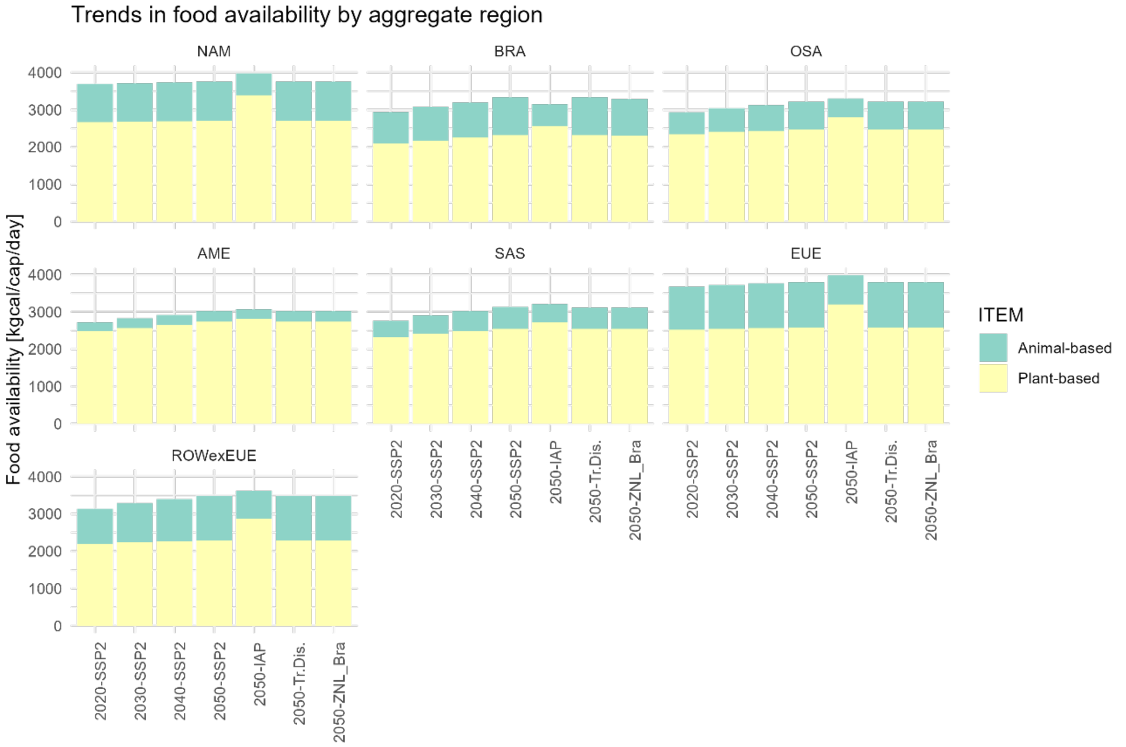

Figure 7. Projected trends in food availability per capita (in energetic content, kcal/cap/day) for five aggregated and two zoomed regions (Brazil BRA and European Union EUE). The colors differentiate animal-based (turquoise) vs plant-based food products (yellow).

Production and net trade

Figure 8 displays trends in production and net trade by aggregated regions for livestock products, soy and other crops.

In the BAU SSP2 scenario, agricultural production is projected to increase globally between 2020 and 2050, with most livestock and crop output growth occurring in SAS, AME and OSA. Soy production is projected to grow in all producing regions (i.e., NAM, BRA and OSA, SAS), but more strongly in Brazil - the world's largest producer - which is expected to account for over half of global output growth.

Net exporters of livestock products are expected to increase their trade surpluses between 2020 and 2050 while for other crops, net exports are projected to increase in Brazil but decline in NAM and OSA. As displayed in Figure 8 for net exports of soya bean only, and in Figure 9 for net bilateral trade in all soy-based products (in soybean equivalent) between aggregated regions, net exporters of soy and soya-based products are projected to increase their trade surpluses, with Brazil consolidating its position as the world's largest exporter and increasing its net exports of soya-based products from 97 Mt in 2020 to over 171 Mt in 2050 (+76%). EUE maintains a surplus for livestock products, a relatively neutral trade position for other crops than soy, and an increased deficit for soy-related products (net imports increase from 25 Mt of soya-equivalent in 2020 to 33 Mt of soya-equivalent by 2050). AME, in turn, is expected to see its agricultural trade deficit widen in the coming decades whereas SAS is projected to reduce its net imports of both livestock and crop products (excl. soy-based products) due to strong production growth. In contrast, SAS imports of soya-based products represent the majority of global increases in net imports of soya-based products, from 120 Mt of soya equivalents to about 200 Mt of soya equivalents in 2050.

In the IAP scenario, livestock production drops in all regions compared to the 2050 BAU scenario, with strong decline in NAM, EUE, BRA and OSA, and ROW (all around 40%). Global soy production - which is mostly used as animal feed - also decrease compared to the baseline (with decline in BRA and OSA, and SAS but some increase in NAM, where soy largely contributes to the increase in vegetable oil consumption required to compensate for losses in animal calories, further incentivized by a decrease in vegetable oil price – see Figure 10). It should be noted that the decrease in soy production is lower than projected with GLOBIOM in (Leclère et al., 2020), due to the improved representation of oilseed supply chains in CLEVER. As soybean meal (used for livestock feed) and soy oil (used for other purposes) are jointly produced through crushing, reductions in feed demand following the assumed dietary shift translate into smaller reductions in soy production. In contrast to the large increase projected between 2020 and 2050 in the BAU scenario (+76%), total net exports of soy-based products from Brazil to other aggregated regions increase by only 20% over the same period in the IAP scenario, and even decrease for exports to the EU (- 34%).

In the IAP scenario, the production of other crops also declines slightly from 2050 baseline levels - although at a lower rate than soy production - as the reduction in demand for feed crops (and associated reduction in production) offsets the increase in demand for plant-based food. In line with the observed trends in production, net trade in livestock and crop products (incl. soy) is below the 2050 BAU (in all regions).

In the Trade disruption scenario, soy production in NAM declines from 2050 baseline level (- 15 Mt), with a corresponding increase in production in Brazil (+ 11 Mt) and OSA (+2.6 Mt). Accordingly, net soy exports from NAM decrease (due to the decline in exports to SAS, slightly compensated by increases in exports to AME, EUE and OSA) and those from Brazil and OSA increase. This is in line with what has been observed during the recent trade wars between the United States and China, where Brazil absorbs China's soy demand that is not met by the United States by increasing its soy production and exports, and limited re-allocation of USA exports to other markets. This confirms the potential risks this trade dispute could have for biodiversity-rich ecosystems in Brazil, and soya producers in the USA. However, it should be noted that the projected increase in soy exports from Brazil to China in the BAU is already very high, thereby highlighting that increased demand for soy in China constitutes a larger source of risk for Brazilian ecosystems.

Zero conversion of forest and other natural lands in Brazil only has a small impact on agricultural production in the country; with soy and livestock output slightly declining from 2050 baseline levels (but increasing from 2020 levels). According, Brazil net exports of soy and livestock products only slightly lower increases than over 2020-2050 than in the baseline, by 4.5 Mt and 162 thousand tons, respectively. This benefits other soy producing regions such as NAM and OSA, whose net exports moderately increase as compared to the 2050 BAU.

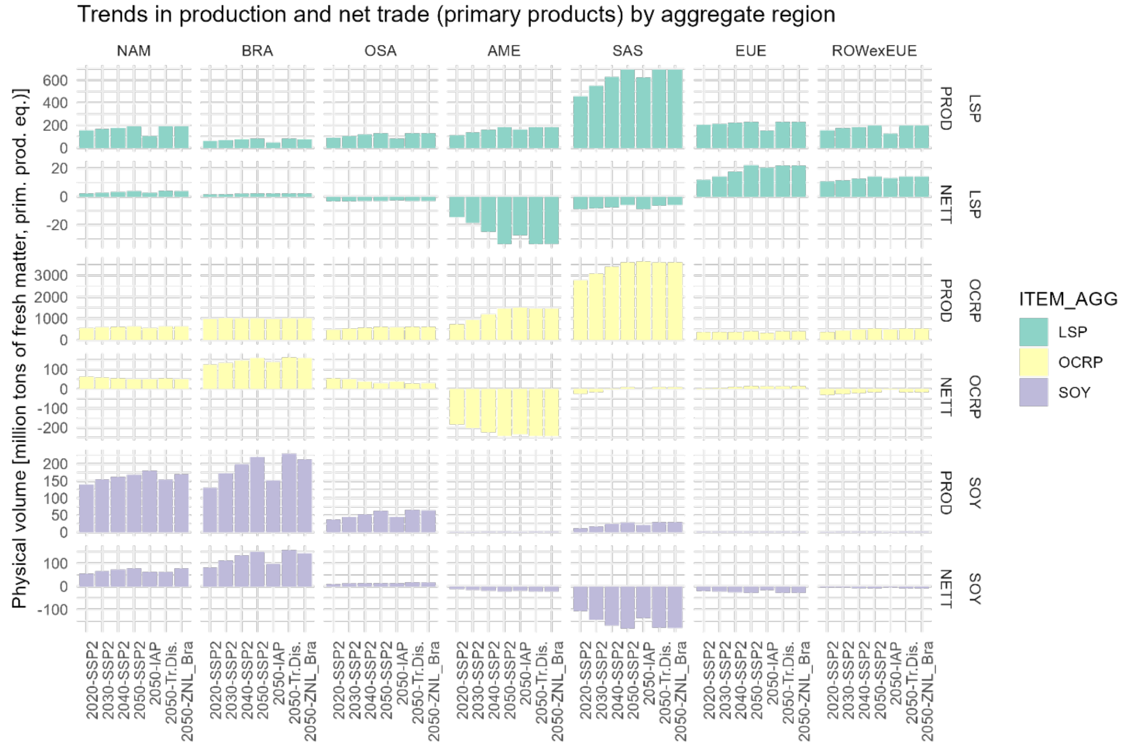

Figure 8. Projected trends in production and net trade (physical volume, in million tons of fresh matter) for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colours differentiate livestock products (LSP, in turquoise) from soy (SOY, in purple) and other primary crops (OCRP, in yellow).

Figure 9. Projected trends in net trade of soy-based products (physical volume, in million tons of primary products equivalent) for five aggregated importing regions and six exporting regions (incl. Brazil).

Substitutions in oilseed markets

Figure 10 shows trends in the consumption of soy oil, other vegetable oils, soy protein meals and other protein meals. It enables us to see potential substitution effects between products.

Vegetable oils: Soy oil is the main cooking oil consumed in NAM and BRA while other vegetable oils dominate in other regions (e.g., palm oil in SAS and AME, sunflower oil, and rapeseed oil in EUE). In a BAU future, global vegetable oils consumption is projected to increase between 2020 and 2050 – with strong growth expected in SAS and AME due to population growth and increase in per capita consumption. In most regions, the consumption of soy oil increases at a higher rate than that of other vegetable oils, with an increase over time in its share in total consumption (incl. in SAS, BRA and OSA, EUE, and ROW). This suggests that gains in soy competitiveness in vegetable oil markets will be a driver of future growth in soy production, partly driven by the demand for soy protein meal for animal feed.

In the IAP scenario, global vegetable oil consumption increases slightly from the 2050 BAU to compensate for the decline in livestock calories, and as a result of an overall decrease in crop commodities prices. However, the share of soy oil in total vegetable oils consumption declines compared to the 2050 BAU, while the consumption of other vegetable oils increases. This substitution is due to the assumed shift in diet away from animal products, which leads to a reduction in demand for all feed products, including soybean meal.

The ZNL and the trade disruption scenarios are projected to only marginally differ from the 2050 BAU in terms of the substitution between vegetable oils.

Protein meals: Soybean meals account for about three quarter of global protein meal consumption. In the BAU scenario, the consumption of protein meals is projected to increase globally between 2020 and 2050, and most notably in SAS, OSA and AME due to an increase in livestock production and feed intensification in developing countries. About 80% of the global increase in protein meal consumption is expected to come from soybean meals.

In the IAP scenario, protein meal consumption declines in all regions compared to the 2050 BAU (except in NAM) due to a shift in diets away from livestock products and associated decline in livestock production (see Figure 8). Most of the global decline in protein meals consumption comes from soybean meals while the consumption of other protein meals increases in some regions (e.g., SAS, OSA, and ROW). In NAM, however, the increase in soy oil consumption leads to an increase in the consumption of soybean meal (although reported as consumption in Figure 10, half of it remains unused due to the drop in domestic and global feed demand).

The ZNL and the trade disruption scenarios are projected to only marginally differ from the 2050 BAU in terms of the substitution between protein meals.

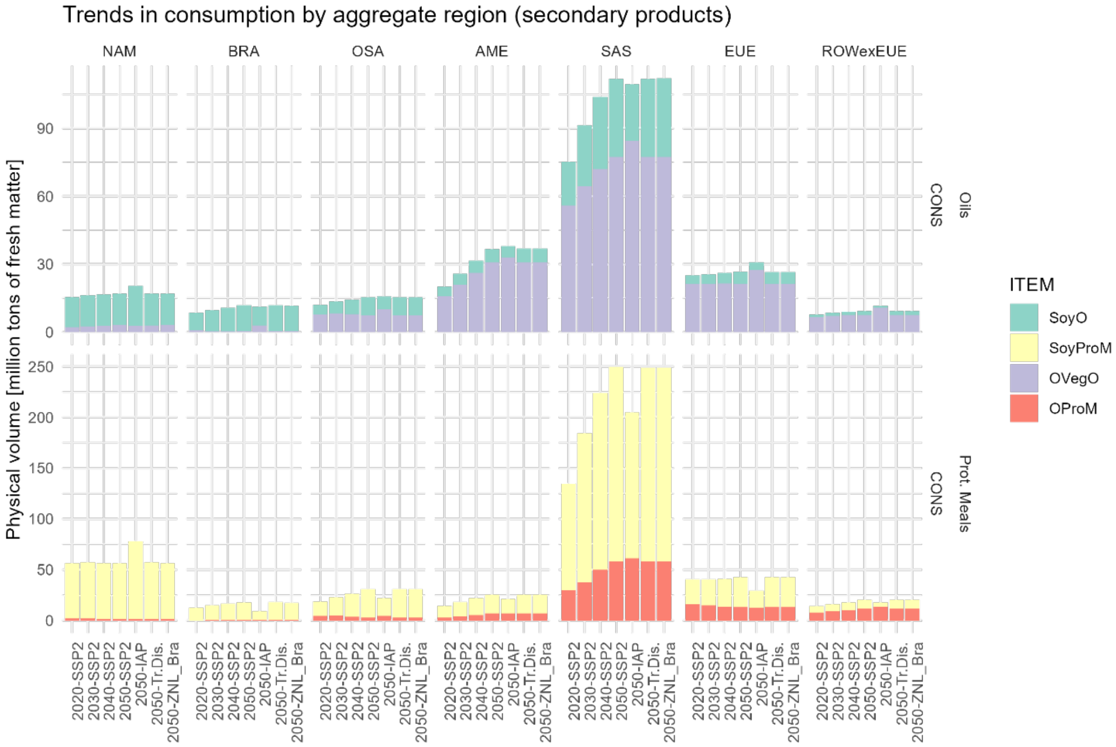

Figure 10. Projected trends in consumption (physical volume, in million tons of fresh matter) for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colors differentiate soy oil (SoyO, in turquoise), from other vegetable oils (OVegO, in purple) and soy protein meals (SoyProM, in yellow) from other protein meals (OProM, in red).

Value of production

The projected value of production (USD 2000) for primary agricultural products (i.e., excluding secondary products such as vegetable oils and protein meals) is displayed in Figure 11. It is calculated as production volume multiplied by producer prices, and provides an understanding of changes in the economic value of agricultural production. In most regions, livestock products represent a larger share in the value of production than in physical volume, due to relatively higher market prices.

In the BAU SSP2 scenario, the total value of agricultural production is expected to increase in all regions between 2020 and 2050, with strong increase in the production value of livestock and crops in AME and SAS. The value of soy production is projected to decline in NAM (due to a projected price decrease) and to increase in BRA and OSA.

In the IAP scenario, the value of production drops in all regions compared to the 2050 BAU mainly driven by a strong decline in the value of livestock production. Livestock production value decreases at a higher rate than physical volume (at around -60% in EUE, NAM, ROW, BRA and OSA) due to a drop in market prices. The value of soy production also declines in BRA and OSA (at a similar rate and slightly higher rate than physical volume, respectively) as well as in NAM, despite an increase in production in this region.

In the Trade disruption scenario, the value of soy production declines at a higher rate than physical volume in NAM (-15% vs -9%) as soy prices drop due to a reduction in Chinese import demand. This illustrates the vulnerability of US soy producers to trade dispute with China. Soy production value, in turn, increases in BRA (+6%) and OSA (+4%) – broadly in line with changes in physical volume, indicating limited price effects on global markets.

In the ZNL scenario, agricultural production value in Brazil slightly increase from the 2050 BAU due to an increase in the value of livestock production as price increases more than production declines. This highlights that, in addition to the impacts on production levels, price reactions are important to consider when estimating the opportunity cost (in terms of sectorial economic output) of ambitious conservation efforts in Brazil. The overall impact in terms of economic output might even be positive at the sectorial level, with limited changes in the distribution of economic opportunities across agricultural sub-sectors.

Figure 11. Projected trends in value of production (in billions of USD2000) for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colors differentiate livestock products (turquoise, LSP) from soy (purple, SOY) and other primary crops (yellow, OCROP).

Land use

As shown in Figure 12, the projected changes in land use from 2020 to 2050 vary across regions, with relatively stable land use in NAM, EUE and ROW and further conversion of forest and other land to cropland and pasture in other regions (BRA and OSA, AME, SAS). This is an expected pattern for SSP2 (e.g., (Fricko et al., 2017; Stehfest et al., 2019)), with proportionally lower increases in total cropland than in production due to projected yield growth (see deliverable D6.3).

In a BAU future, BRA is expected to have a relatively high and increasing share of land dedicated to soy (including both single cropping and soy-corn double cropping, with only half allocated to soy for the latter), and a relatively high forest loss rate. However, from 2030 onwards, there is an increase in restoration land following the implementation of the Forest Codes's Legal Reserve requirements.

In the IAP scenario, pasture drops in all regions from both 2050 and 2020 BAU levels following the shift in diets away from animal products. Cropland also declines slightly from the 2050 BAU in all regions (and from 2020 in most regions), with relatively larger decline in land dedicated to soy in Brazil due to the reduced demand for feed crops and the assumed additional yield growth. Freed up agricultural land is converted to restoration land in all regions (as assumed as part of the policy package)[4], while losses of forest (in BRA, OSA and AME) and other natural lands (mainly in ROW and AME) largely decrease compared to the baseline (preventing the conversion of 80Mha of forest and of 56Mha of other natural land). A large share of the restoration land at global scale is projected to occur in Brazil, which is due to a different representation of pasture in Brazil as compared to other regions[5]. The projected restoration in the IAP scenario reach about 120 million ha, as compared to about 18 million ha restored as part of the Forest Code in 2030.

In the Trade disruption scenario, pasture (and forest to a lower extent) decline slightly in Brazil compared to the 2050 BAU scenario while soy area increases (+4%) to meet the increase in soy import demand from China.

In the ZNL scenario, pasture – soy and other cropland to a lower extent - decline in Brazil compared to the 2050 BAU scenario, preventing the conversion of 50 Mha of forest and 16Mha of other natural lands. However, the decline in agricultural land compared to the 2050 BAU is less pronounced than in the IAP scenario, which also assumes the implementation of other land saving measures (i.e., dietary shift, land restoration and sustainable increase in crop yields) in addition to conservation efforts.

---

[4] In Brazil, restoration efforts as part of the IAP are additional to those as part of the Forest Code (with large increase in restoration land compared to the baseline).

[5] In the standard version of GLOBIOM, only pasture land required to feed ruminants (based on assumptions about the spatial distribution of ruminants, grassland productivity and grazing intensity) is labelled as such, while the remainder of non-forest and non-cropland vegetation is classified as other natural land. This leads to much lower amounts of pasture land than reported by FAOSTAT, and often assumed in other land use models (with a low opportunity cost, as assumed to have very productivity). As pasture is considered eligible for restoration and not other natural land, GLOBIOM usually project lower amounts of restoration than other models. is not considered eligible for restoration, the standard version of GLOBIOM usually projects lower amounts of restoration than most other models. As for CLEVER, the representation of pasture in made closer to that of other models (with a large area identified as pasture and with low opportunity cost for restoration), amounts of restoration are larger for Brazil than for other regions.

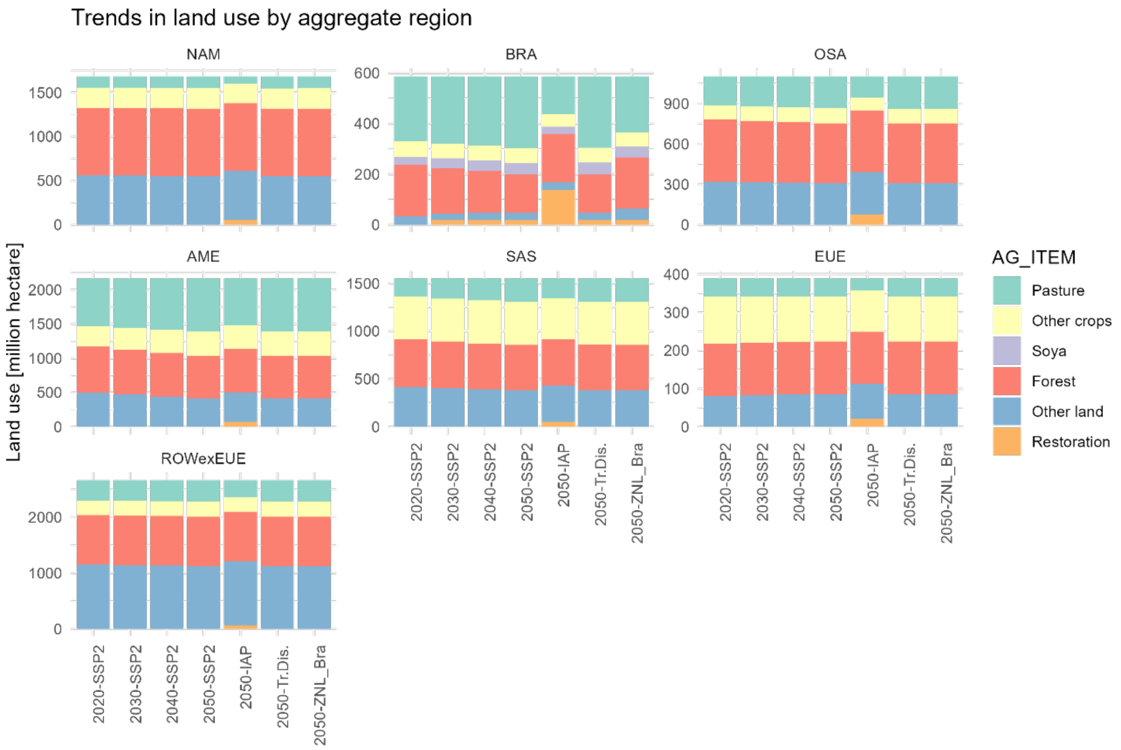

Figure 12. Projected trends in land use (in million hectares) for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colors differentiate pasture (turquoise) from soy crop physical area (purple) and other primary crop physical area (yellow), as well as forest (red), other land (blue) and restoration land (orange).

GHG emissions

Figure 13 shows projected GHG emissions from livestock (through enteric fermentation and manure management), soy and other crops (through cropland soil N_2O emissions and CH_4 emissions from rice cultivation), and LUC (through changes in above ground carbon stocks) in the different scenarios. Overall, livestock accounts for the largest share of AFOLU emissions in most regions, except in BRA and AME where LUC emissions dominates.

In the SSP2 scenario, LUC emissions are projected to remain stable (when low in 2020) or decrease (when high in 2020) in all regions between 2020 and 2050, except in AME where an increase is projected due to the conversion of unmanaged land to agricultural land. Crop and livestock emissions, in turn, are projected to increase globally. Overall, total AFOLU GHG emissions are projected to increase in all regions except in Brazil, where the decline in LUC emissions (following the implementation of the Forest Code) more than offset the increase in direct emissions from agriculture.

In the IAP scenario, GHG emissions decrease in all regions compared to the baseline, mainly due to a large drop in LUC and livestock emissions, and some decline in crop emissions. LUC becomes a carbon sink in most regions. This decline in AFOLU emissions is due to the assumed shift in diets away from animal products (which are more emission intensive than crop products), as well as the land restoration efforts, supported by supply-side and demand-side measures.

In the Trade disruption scenario, no significant changes in GHG emissions are projected compared to the BAU scenario.

In ZNL scenario, Brazil's AFOLU emissions decrease compared to the baseline, mainly due to a large drop in LUC emissions and a small decline in livestock emissions. However, AFOLU emissions are higher than in the IAP scenario, which considers additional measures on the demand and supply sides leading to lower GHG emissions from all sources.

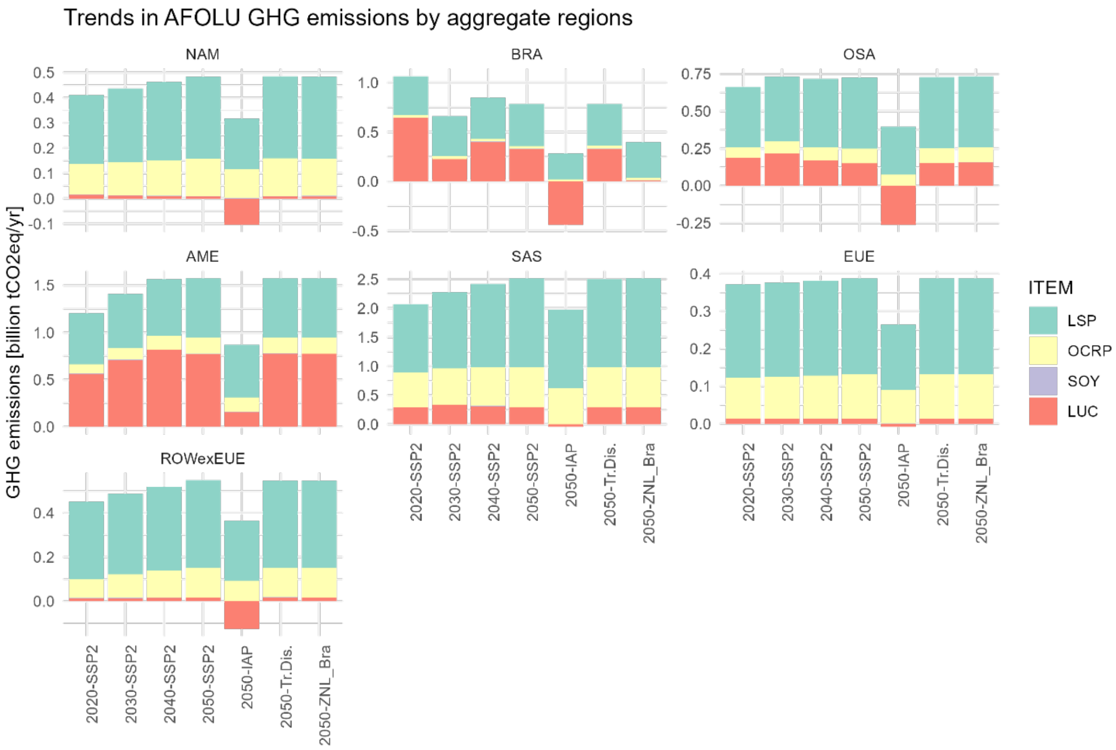

Figure 13. Projected trends in annual GHG emissions (in billion tons of CO_2 equivalents per year) from the agriculture and land use (AFOLU) sectors for aggregated world regions and two zoomed regions (Brazil BRA and European Union EUE). The colours differentiate emissions from livestock production (turquoise, LSP), soy crop production (purple), other crop production (yellow), and land use change (red).

Water use

The projected changes in water use for irrigated crop production are displayed in Figure 14. For most regions, irrigation water use is projected to remain stable or slightly increase, with projected increases in water use efficiency mitigating the increases in irrigated crop production (see deliverable D6.3). Water use for soy production is only significant in NAM (as soy in not irrigated in BRA) and is projected to stay broadly stable over time.

In the IAP scenario, global water use is projected to be broadly in line with the 2050 BAU, with a decline in some regions (SAS, and AME) and an increase in others. Soy water use in NAM is projected to increase compared to the baseline due to an increase in soy production (see Figure 8). In the Trade disruption scenario, soy water use slightly declines from 2050 baseline levels in

NAM (-3%) due to a drop in soy production following a reduction in Chinese import demand (see Figure 8). The ZNL scenario has no clear impact on water use in Brazil.

Figure 14. Projected trends in water use for irrigation (in km3) for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colours differentiate soy crops (purple) from other crops (yellow).

Biodiversity impacts

Biodiversity impacts on terrestrial ecosystems from local agriculture, measured in potentially disappeared fraction of global species per year, are displayed in Figure 15 (see D6.3 for more details on the methodology). They are, in absolute terms, higher in regions with a significant share of tropical ecosystems (e.g., SAS, BRA and OSA, and AME). Land occupation has the largest impact in all regions, followed by land transformation (except in NAM where climate change impacts are higher). It should be noted that this only accounts for biodiversity impacts from the land use and agricultural sectors. While for land occupation and land transformation impacts this may be close to total impacts, significantly larger climate change impacts on biodiversity would be expected if also accounting for biodiversity impacts from other economic sectors.

In the BAU scenario, land transformation impacts are projected to decline between 2020 and 2050, especially in regions where they are currently large (e.g. BRA and OSA, AME, SAS). Land occupation and climate impacts, in turn, are projected to remain broadly stable or increase over time, except for climate impacts in Brazil due the implementation of the Forest Code. It should be noted that, by assumption, restoration does not directly affect biodiversity, as only biodiversity-detrimental impacts are accounted for.

In the IAP scenario, biodiversity impacts on terrestrial ecosystems are expected to be significantly lower than in the BAU scenario in all regions, mainly due to a strong decline in climate change impacts (with LUC becoming a carbon sink in BRA and OSA, AME, ROW, and NAM) but also in land occupation and land transformation impacts.

In the ZNL scenario, biodiversity impacts on terrestrial ecosystems in Brazil are below baseline levels mainly due to strong decline in land transformation impacts as well as some decline in land occupation and climate change impacts. However, the overall impact on terrestrial ecosystems is higher than in the IAP scenario, which includes more comprehensive restoration efforts supported by supply-side and demand-side measures.

The Trade disruption scenario has no clear impact on terrestrial biodiversity, which can be explained by the fact that: i) overall climate change emissions from soy are low and changes in spatial patterns of production do not lead to strong changes in climate impacts on biodiversity, and ii) most of related land use impacts occur in Brazil, where a conversion from pasture to cropland can be observed (which is much less detrimental to biodiversity than a conversion from forest or other natural land to cropland).

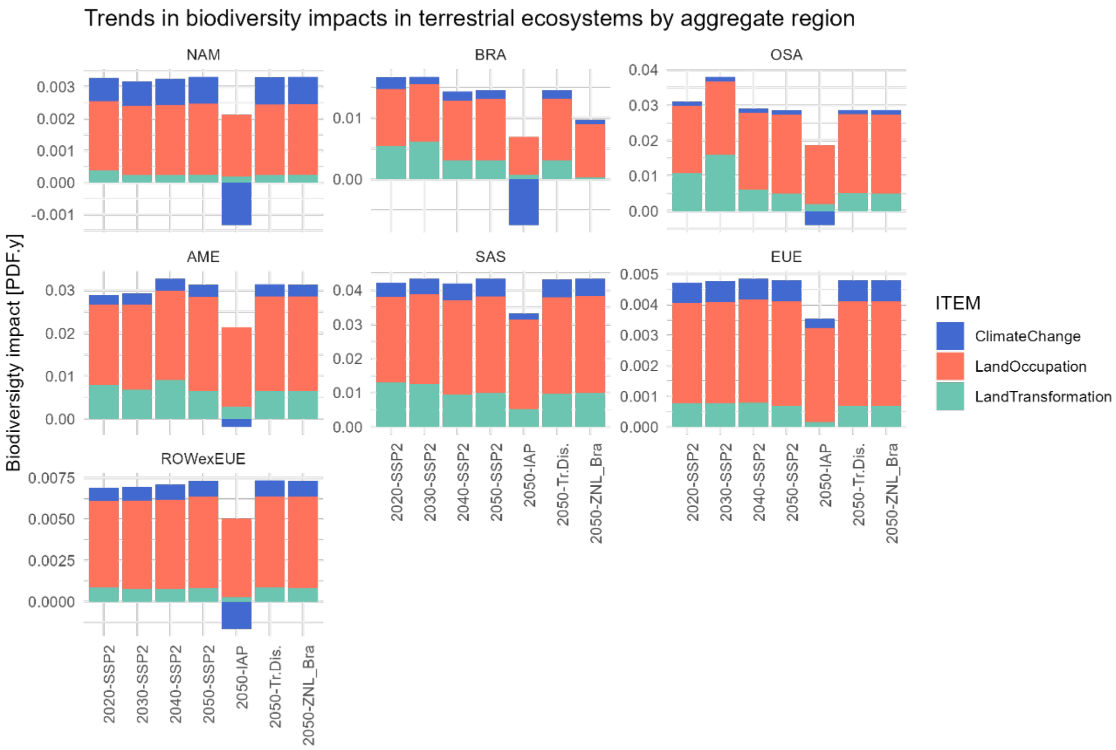

Figure 15. Projected trends in biodiversity impacts on terrestrial ecosystems (in PDF·year) from local production for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colors differentiate impacts through climate change (blue), land occupation (red), and land transformation (green).

The projected biodiversity impacts from local production on freshwater ecosystems also differ across regions (Figure 16). In absolute terms, it is higher in NAM, SAS and ROW than in tropical regions. In terms of pressures, impacts tend to be dominated by water stress (in particular for

NAM), followed by eutrophication (which however is the most important pressure in Brazil) and climate change (which however is the most important pressure in EUE).

In the BAU scenario, impacts on freshwater ecosystems are projected to remain broadly stable in some regions (e.g., NAM, EUE) or increase (e.g., in OSA and AME due to increased water stress, and in BRA due to eutrophication) between 2020 and 2050.

In the IAP scenario, impacts on freshwater ecosystems drop in most regions compared to the 2050 BAU, mainly due to a strong decline in climate change impacts (together with some decrease in water stress in OSA and in eutrophication in BRA and OSA). In ROW, however, the impact on freshwater ecosystems increases from 2050 baseline levels due to an increase in water stress, even though water use remains stable.

In the Trade disruption scenario, impacts on freshwater ecosystems decline slightly in NAM compared to the 2050 BAU due to a decrease in water stress associated with lower water use for soy production, while in BRA they marginally increase mainly due to a small increase in freshwater eutrophication.

In the ZNL scenario, biodiversity impacts on freshwater ecosystems in Brazil are below 2050 baseline levels, mainly due to a decline in climate change and freshwater eutrophication impacts. However, the overall biodiversity impacts are higher than in the IAP scenario, which includes a more complete package of measures.

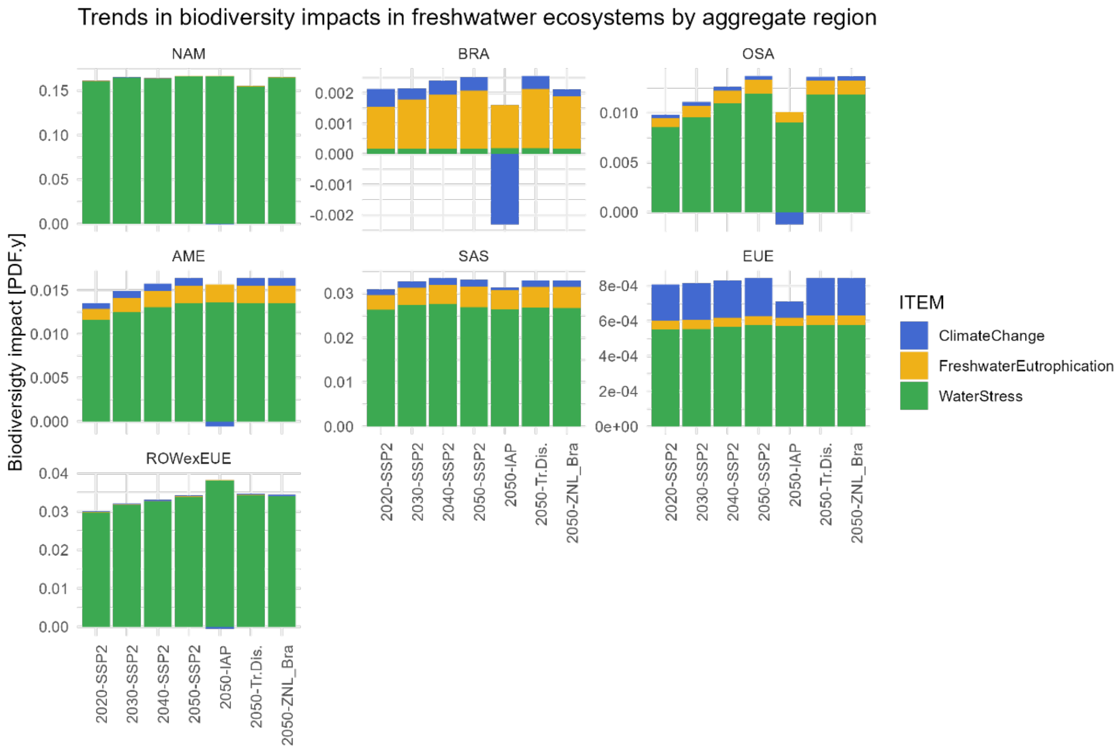

Figure 16. Projected trends in biodiversity impacts on freshwater ecosystems (in PDF·year) from local production for five aggregated regions and two zoomed regions (Brazil BRA and European Union EUE). The colors differentiate impacts through climate change (blue), land occupation (red), and land transformation (green).

Results at the subnational level for Brazil

Crop production

In 2020, the Cerrado and Mata Atlantica biomes hosted 90% of Brazilian crop production. Regarding soy production, over 60% takes place in the Cerrado (Figure 17).

In the BAU SSP2 scenario, crop production is projected to increase in all biomes between 2020 and 2050, with soy production expected to grow at a higher rate than the production of other crops (by 68% and 12%, respectively), and most production growth occurring in the Cerrado.

In the IAP scenario, Brazilian crop production drops compared to the 2050 BAU, with a comparatively much larger decline in soy production - which in mainly used as animal feed - than in the production of other crops. Production levels remain, however, comparable to 2020 levels for other crops, and slightly above 2020 levels for soy, with variation between biomes. Soy production declines below 2020 levels in the Mata Atlantica and Amazon biomes, but remains above 2020 levels in the Cerrado and Pampa biomes.

In the Trade disruption scenario, Brazil's soy production increases by 5% from 2050 baseline level (+11 Mt). Output growth mainly occurs in the Cerrado and Mata Altlantica biomes, where most soy production takes place. As discussed above, Brazil absorbs China's import demand that is not met by the United States by increasing its soy production and exports.

Zero conversion of forest and other natural lands in Brazil from 2020 onwards, as assumed in the ZNL scenario, has a very limited impact on crop production, which is less than 1% below 2050 BAU level, as soy production can expand over pastures. This suggests that Brazil could increase its production well beyond 2020 level without clearing forest and other natural lands.

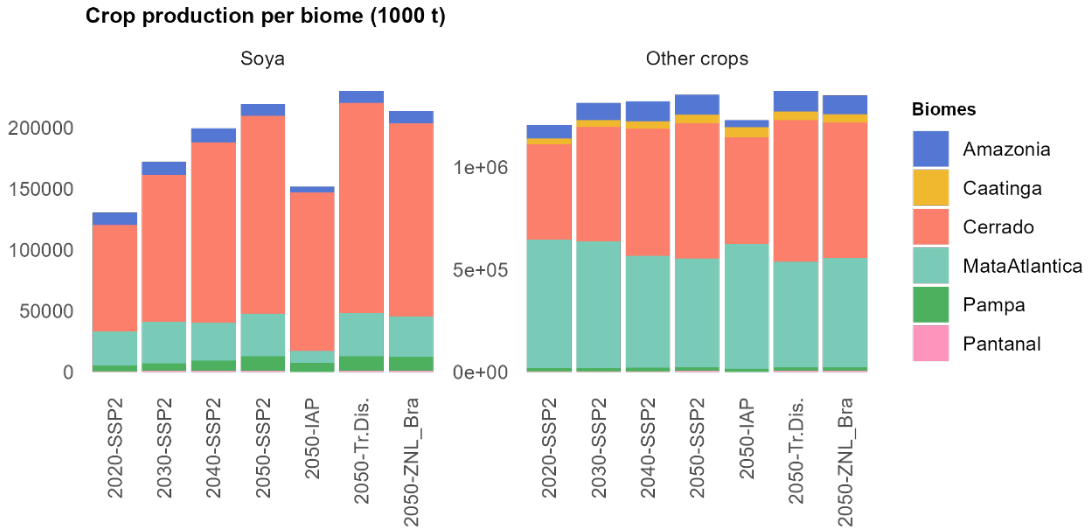

Figure 17. Projected trends in soy and other crop production (in 1000 tons of fresh matter) for the six Brazilian biomes. The colors differentiate the biomes, namely Amazonia (blue), Caatinga (yellow), Cerrado (red), MataAtlantica (turquoise), Pampa (green) and Pantanal (pink).

Land use

As showed in Figure 18, forest area is predominantly located in Amazonia and is projected to decrease between 2020 and 2050 in the BAU scenario, through conversion to pasture. Cropland expansion - mainly for soy production - is projected in the Cerrado and Pampa biomes, where it replaces pasture, and forest to some extent forest (in the Cerrado biome). In the Mata Altlantica biome, forest area stays constant over time.

It should be noted that these trends assume that through the implementation of the Forest Code, legal deforestation (i.e., clearing forest surplus beyond the Legal Reserve not already considered in the Environmental Reserve Quota) is allowed, while illegal deforestation (i.e., additional deforestation) depends on control efforts, with a full enforcement (no illegal deforestation) in the Mata Atlantica biome, and partial enforcement (i.e., some degree of illegal deforestation) in the Cerrado and Amazon biomes. It also assumes no expansion in soy area in the Amazon biome, as a result of the Amazon Soy Moratorium. Finally, restoration land increase in all biomes from 2030 onwards, following the implementation of the Forest Code's Legal Reserve requirements (including the small farm amnesty, see Annex for more details).

In the IAP scenario, following the assumed shift in diets away from animal products and the restoration efforts, pasture declines in all biomes compared to the 2050 BAU, together with land dedicated to soy production (mainly in Cerrado and Mata Atlantica) and to other crops to a lower extent. Land that is freed up from agriculture is primarily restored, while losses to forest are further mitigated (+40Mha of native forests compared to the 2050 BAU, mainly in the Amazonia biome).

In the Trade disruption scenario, a small share of pasture is converted into soy production in the Cerrado biome, with total soy area increasing by 4% (2Mha) compared to the 2050 BAU.

In the ZNL scenario, projected increase in pasture over 2020-2050 are much lower in all biomes compared to the baseline scenario, leading to higher amounts of remaining native forests (+50 Mha by 2050) and other natural land (+16 Mha). These avoided losses of natural lands are higher than in any other scenarios, including the IAP scenario. To a lower extent, the projected increase in areas dedicated to soy and other crops is also mitigated.

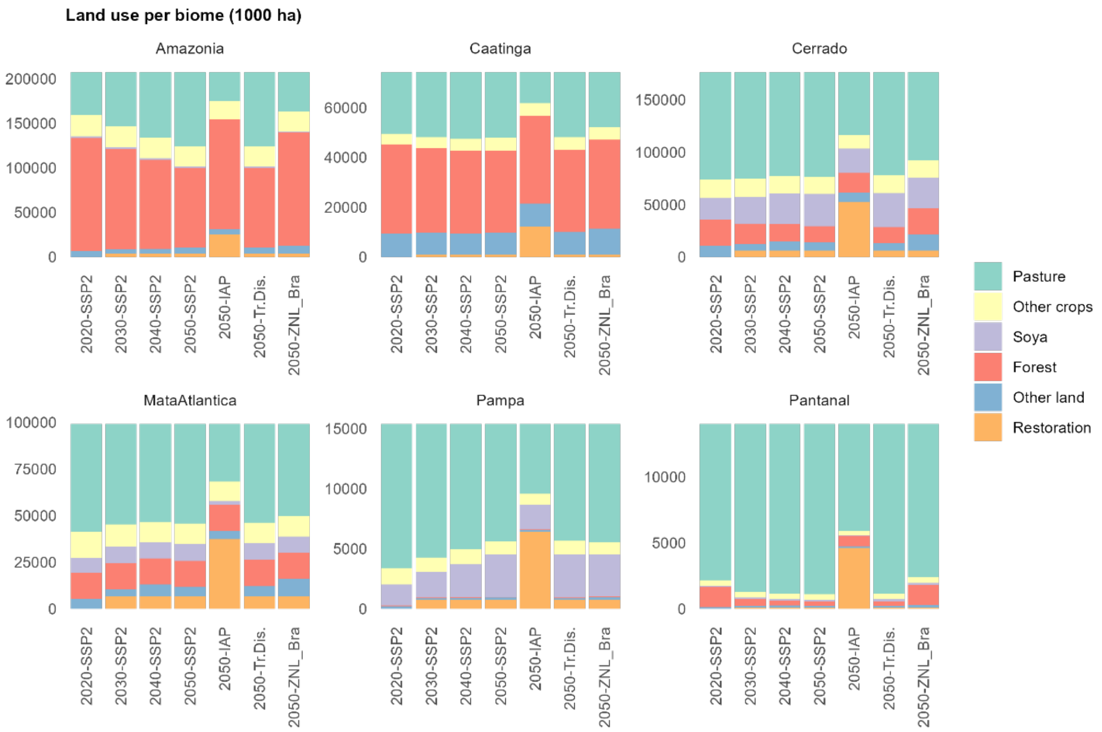

Figure 18. Projected trends in land use (in 1000 ha) for the six Brazilian biomes. The colors differentiate pasture (turquoise) from soy crop physical area (purple) and other primary crop physical area (yellow), as well as forest (red), other land (blue) and restoration land (orange).

GHG emissions

GHG emissions from LUC and livestock production together account for 98% of Brazil's AFOLU emissions (at 60% and 38%, respectively) – crop production accounting for the remaining 2% (Figure 19). Most AFOLU emissions in Brazil occur in the Amazonia and Cerrado biomes, where LUC emissions from deforestation dominates, while direct GHG emissions from agriculture dominate in other biomes.

In the BAU scenario, LUC emissions are projected to drop in all biomes between 2020 and 2050, due to declining rates of land conversion and restoration efforts from 2030 onwards as part of the Forest Code. Crop emissions are also expected to decline due to a decrease in the area of high input use production systems for a few crops (e.g., cotton, sugarcane), that represent a small share of 2020 area (and for corn and sugarcane, a small share of crop area) but the majority of cropland soil emissions. GHG emissions from livestock, however, are expected to continue increasing.

In the IAP scenario, AFOLU emissions drop in all biomes compared to the BAU mainly due to a decline in LUC (which becomes a large carbon sink) and in livestock emissions. This decrease in climate change impact is due to the conservation and restoration efforts, supported by a shift in diets away from animal products (which are more emission intensive than plant-based products), waste reduction and additional yields increases compared to baseline - which all have GHG mitigation benefits.

The Trade disruption scenario does not lead to any noticeable change in GHG emissions, which is consistent with its limited impact on land use and the small contribution of soy to total cropland soil emissions.

In the ZNL scenario, AFOLU emissions also decline compared to the 2050 BAU, mainly due to a drop in LUC emissions (in particular in Amazonia and Cerredo) and some decline in livestock emissions (mainly in Amazonia). However, GHG emissions are higher than in the IAP scenario, in which considerable restoration takes place.

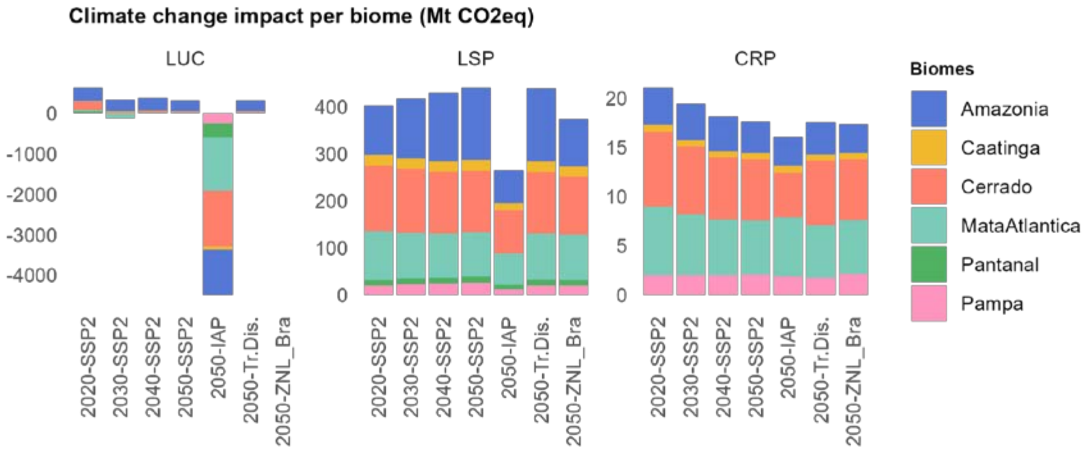

Figure 19. Projected trends in greenhouse gas emissions (in million tons of CO_2eq, Mt CO_2eq) for the six Brazilian biomes split between land use change emissions, livestock and crop emissions. The colours differentiate the biomes, namely Amazonia (blue), Caatinga (yellow), Cerrado (red), MataAtlantica (turquoise), Pampa (green) and Pantanal (pink).

Water use

Water consumption from agriculture in Brazil mainly comes from the cultivation of sugarcane and wheat, which is mostly located in the Mata Atlantica and Cerrado biomes. These two biomes accounted for almost 90% of total water use for irrigated agriculture in Brazil in 2020 (Figure 20).

In the BAU SSP2 scenario, water consumption from agriculture is projected to be broadly stable with an increase in water use in some biomes (mainly in Mata Atlantica for wheat production) and a decline in others (e.g., Cerrado).

In the IAP scenario, agricultural water use slightly increase compared to the 2050 baseline (+5%), with most increase occurring in the Mata Atlantica, Cerrado and Pampa biomes. This is due to an increase in the production of crops that are irrigated – mainly sugarcane and rice – following the shift in diets towards plant-based products.

Although the Trade disruption scenario leads to a slight redistribution of water use from Pampa to Mata Atlantica and Cerrado, the projected level of water use in both the Trade disruption and ZNL scenarios do not differ significantly from the BAU scenario.

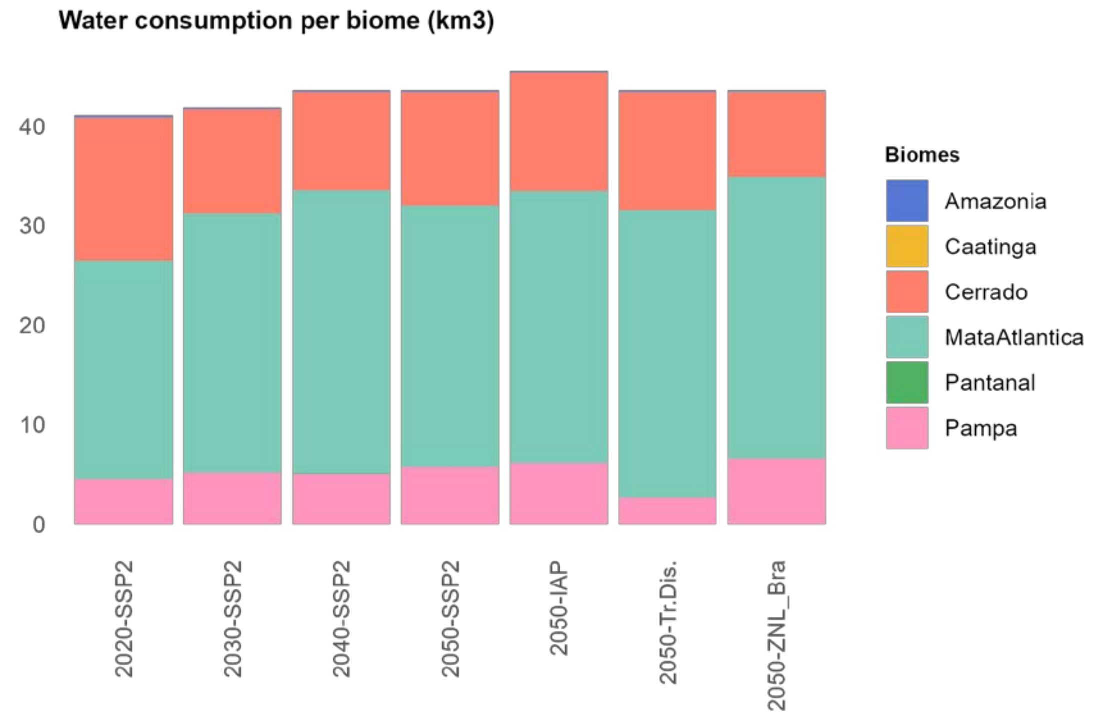

Figure 20. Projected trends in Water consumption (water for irrigation, in km3) for the six Brazilian biomes. The colors differentiate the biomes, namely Amazonia (blue), Caatinga (yellow), Cerrado (red), MataAtlantica (turquoise), Pampa (green) and Pantanal (pink).

Biodiversity impacts

Figure 21 shows the impacts on terrestrial ecosystems from farming activities in the six Brazilian biomes, based on two different LCA methodologies. In the figures in the top panel, biodiversity impacts are calculated based on the LC-IMPACT average characterisation factors (CFs) (Verones et al., 2020) while those in the bottom panel are calculated based on the new CFs developed for South America in the context of D2.4 (hereafter referred to as 'CLEVER CFs') (Oliveira et al., 2019; Oliveira & Pacheco, 2024) It should be noted that results for this figure omit climate change impacts, which are available for the LC-IMPACT CFs but not for the CLEVER CFs.

Both methods predict similar overall trends across scenarios. In the BAU SSP2 scenario, with both approaches, the total land impacts on terrestrial ecosystems are projected to decline over time, due to a drop in land transformation (i.e., LUC) impacts and despite an increase in land occupation impacts. In the IAP scenario, total impact on terrestrial ecosystems decreases compared to the baseline, due to a decline in both land occupation and land transformation impacts. In the ZNL scenario, the total impact on terrestrial ecosystems also declines compared to the BAU mainly due to a drop in land transformation and some decline in land occupation impacts. However, which of the IAP or ZNL scenarios lead to the best outcome for terrestrial biodiversity depends on the method, with the IAP scenario performing better when using LC-IMPACT CFs and the ZNL scenario when using the CLEVER CFs. The Trade disruption scenario, in turn, has no significant impact on terrestrial biodiversity for both metrics.

The main differences between the two methods lie in the scale of the impacts (in particular, for transformation impacts) and the relative contribution of different biomes to the overall impacts. First, the Brazil-level transformation impacts of farming activities on terrestrial ecosystems are more than two times higher when using the CLEVER CFs than when using the LC-IMPACT CFs (in line with what was discussed in D6.3). Then, when using the CLEVER CFs, Amazonia is the biome with the largest overall impact on terrestrial ecosystems (42% of the total in 2020), followed by Cerrado (26%) and Mata Atlantica (17%) while when using the LC-IMPACT CFs, Mata Atlantica has the largest impact (42%), followed by Amazonia (31%) and Cerrado (21%).

Finally, the avoided loss of forest and other natural land in the ZNL scenario (as compared to the BAU scenario) seem to be equally beneficial to biodiversity with both methods (close to full elimination of transformation impacts), while the land use change patterns of the IAP scenario as compared to other scenario seems to result in much higher benefits for biodiversity when using the LC-IMPACT CFs (close to full elimination of transformation impacts) than when using the CLEVER CFs (very limited decrease in transformation impacts). This provides important nuances regarding the best strategies for biodiversity protection in Brazil.

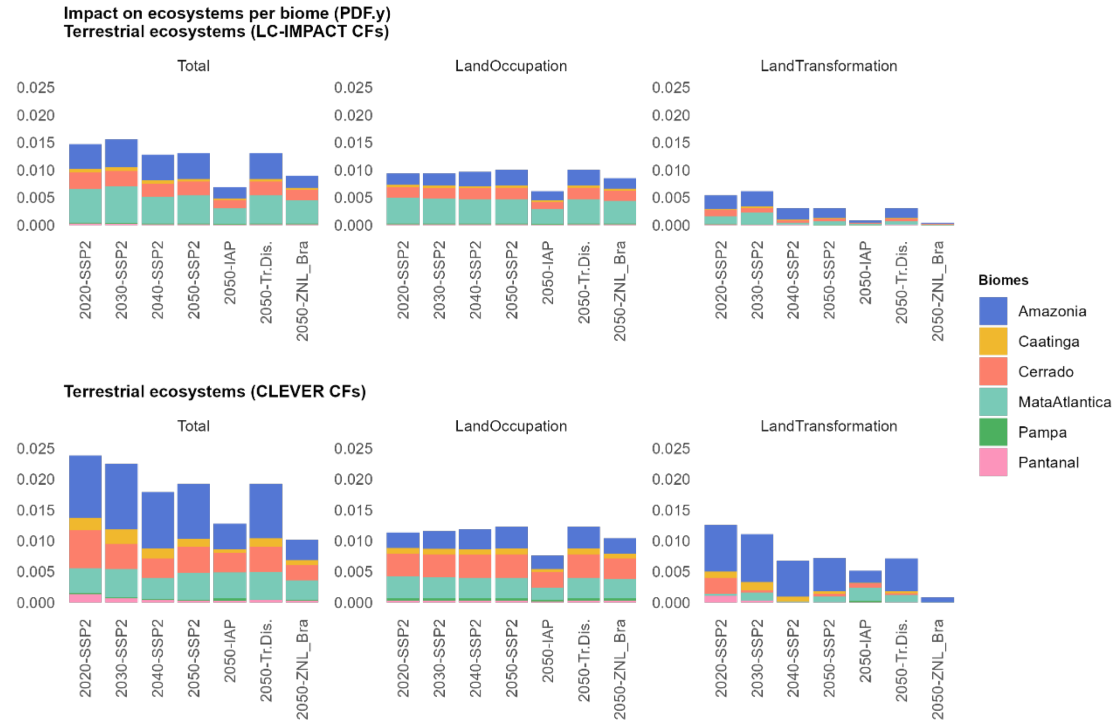

Figure 21. Projected trends in biodiversity impact for terrestrial ecosystems (Potentially disappeared fraction, PDF·y) for the six biomes and split between the different pressures covered in GLOBIOM. The colors differentiate namely Amazonia (blue), Caatinga (yellow), Cerrado (red), MataAtlantica (turquoise), Pampa (green) and Pantanal (pink). The figures in the top panel are based on LC-IMPACT characterisation factors (CFS) while the figures in the bottom panel are based on spatially-explicit CFs developed for South America in CELEVER deliverable D2.4.

As shown in Figure 22, freshwater ecosystems are most affected by farming activities in the Mata Atlantica, Cerrado, and Amazonia biomes.

In the BAU scenario, the total impact on freshwater ecosystems in Brazil is projected to increase between 2020 and 2050, due to a rise in freshwater eutrophication in all biomes, and some increase in water stress in some biomes (mainly Mata Atlantica). Climate change impacts, however, are projected to decline, due to declining LUC emissions.

In the IAP scenario, the impacts on freshwater ecosystems are projected to be lower than in the BAU and become negative, mainly due to strong decline in climate change impacts (with LUC turning into a carbon sink) and some decrease in freshwater eutrophication in all biomes. However, as discussed above, water stress slightly increases from the BAU due to a small increase in water use for irrigated crops (see Figure 20).

In the Trade disruption scenario, biodiversity impacts on freshwater ecosystems slightly increase from the 2050 BAU, mainly due to an increase in freshwater eutrophication (and water stress to a lower extent).

In the ZNL scenario, the total freshwater ecosystems' impacts are projected to be lower than in the BAU scenario, mainly due to lower climate change and eutrophication impacts. However, the total impact on freshwater ecosystems remains higher than in the IAP scenario.

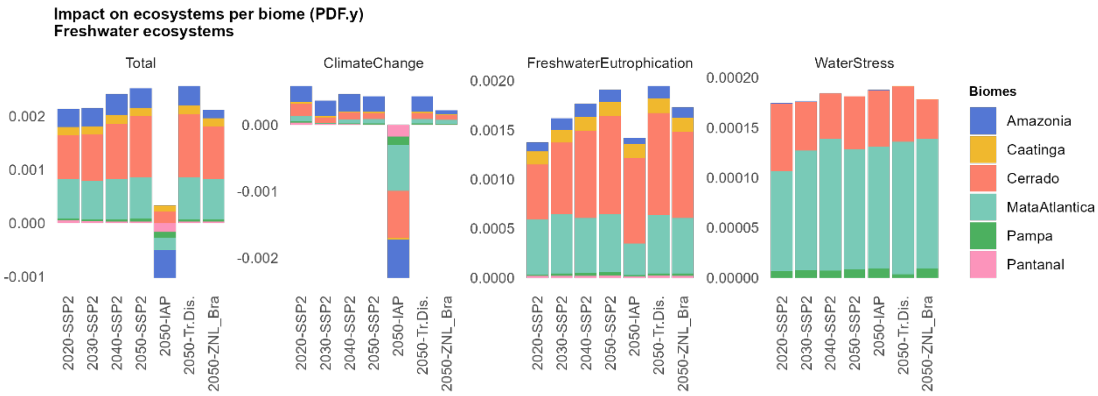

Figure 22. Projected trends in biodiversity impact for freshwater ecosystems (Potentially disappeared fraction, PDF·y) for the six biomes and split between the different pressures covered in GLOBIOM. The colors differentiate the biomes, namely Amazonia (blue), Caatinga (yellow), Cerrado (red), Mata Atlantica (turquoise), Pampa (green) and Pantanal (pink).

Additional impacts from upstream and downstream soy supply chain in Brazil

In the previous sections, the projected environmental impacts of Brazilian agricultural activities have been illustrated, based on the outcome of GLOBIOM for a BAU scenario (SSP2) and three stylised policy scenarios. However, parts of the supply chain of agricultural products are missing in GLOBIOM, the model primarily covering the impact of direct farming activities and related changes in resource use. Based on the results of the LCA developed in D6.4, the model was expanded to include upstream and downstream supply chain impacts of soy production in Brazil. These are estimated by combining LCA-based estimates of impacts per ton of soy produced with GLOBIOM projections for the amount of soy produced. In this section, the additional impacts from these supply chain steps are presented for soy and compared to the footprint from farming presented above.

We analyse the differences in impact in terms of aquatic and terrestrial extinction risk, but also in terms of GHG emissions and freshwater consumption.

Comparison of farming impacts for all crop and livestock products to soy impact from farming and other supply chain steps

The integration of all supply chains impacts into GLOBIOM for soy allows us to put these impacts into perspective by comparing them to the previously calculated Brazilian impacts from farming for all agricultural commodities (i.e., soy and other crops and livestock products) in 2020 (Figure 23). When looking only at the impacts of farming covered in GLOBIOM (in yellow in Figure 23), soy production alone accounts for 3% of GHG emissions and aquatic biodiversity impacts and 13% of terrestrial biodiversity impacts (soy has no impact of freshwater consumption it is not irrigated in Brazil). This highlights the relative importance of soy within all agricultural commodities for the farming impacts covered in GLOBIOM.

However, they are different between biomes regarding the relative contribution of soy to the total farming impacts covered in GLOBIOM. For example, in the Cerrado - where 60% of Brazil's soy production takes place - soy production accounts for a larger share of the total farming impacts than at national scale or than in any other biomes. Conversely, in Amazonia, where GHG emissions and terrestrial ecosystems impacts from farming are the largest, soy production accounts for a smaller portion of these impacts than at the national scale.

Figure 23 also illustrates the contribution of different supply chain steps to soy overall impacts. For terrestrial ecosystem impacts, farming GLOBIOM accounts for 90% of the total impacts, while other supply chains steps are responsible for the remaining 10%. For aquatic ecosystems, farming GLOBIOM accounts for about half of the total impacts, while other supply chains steps (mainly crushing and input production) accounts for the other half. Farming GLOBIOM has no impact on freshwater consumption as soy is not irrigated in Brazil; most of the impacts coming from inputs production (~60%) and crushing (~30%). Finally, for GHG emissions, farming impacts covered in GLOBIOM accounts for about 25% of the total impact while other supply chain steps are responsible for the remaining 75%. This highlights the importance of considering additional supply chain impacts in the standard version of GLOBIOM, as including those for other crops would further increase the overall environmental impacts.

Figure 23. Soy supply chain footprint compared to total farming footprint for Brazil and four soy-producing biomes in 2020 (SSP2). In Yellow, described as "Farming - GLOBIOM" includes all already calculated impacts from GLOBIOM, which are related to direct agricultural and forestry activities. "Farming – other impacts" mainly includes impact associated with input production such as fertilizer.

Evolution of soy supply chain biodiversity impacts

When looking at the evolution of the biodiversity impact of soy production in Brazil (Figure 24), we observe a decline in impact on terrestrial ecosystems over time, due to a decrease in farming impacts, more specifically in land transformation, while upstream and downstream supply chain impacts increase. The impact on aquatic ecosystems, in turn, increases over time, due to an increase in most supply chain impacts (excl. farming), more specifically GHG emissions.

In the BAU scenario, there is a noticeable increase in the biodiversity impacts on aquatic ecosystems, and GHG emissions attributed to non-farming supply chain stages while farming-related impacts decline over time. It should be noted that for other impacts than the farming impacts covered in GLOBIOM, the LCA coefficients used are estimated directly per ton of product and do not evolve dynamically with the scenarios in GLOBIOM to include potential reduction in impacts due to technological progress. By contrast, farming impacts covered in GLOBIOM used coefficient per hectare or per ton of input, and these impacts are affected by long-term increases in yield and input use efficiency. For other impacts than the farming GLOBIOM, and including aquatic biodiversity impacts, this could potentially lead to an overestimation of the impacts in the projections. In contrast, the impacts on terrestrial ecosystems, which are primarily driven by farming impacts covered in GLOBIOM, closely follow the trends observed for Brazil as a whole.

In the IAP scenario, where Brazil's soy production drops compared to the BAU (see Figure 17), the impacts of the soy supply chain on both terrestrial and aquatic ecosystems decline from the BAU levels (with the impact on terrestrial ecosystems becoming negative), mainly due to a decrease in farming impacts. Mid-points impacts (GHG emissions and freshwater consumption) also decline from the baseline, mainly due lower impacts from upstream supply chain activities (i.e., input production) and from crushing.

In the Trade disruption scenario, where Brazil's soy production slightly increases from the 2050 BAU, the impact on terrestrial ecosystems is comparable to 2050 baseline level while the impact on aquatic ecosystems increases mainly due to a rise in farming and upstream supply chain impacts. Mid-points impacts also increase, mainly due to higher impacts from upstream supply chain activities.

In the ZNL scenario, the end-point impacts (aquatic and terrestrial biodiversity) of the soy supply chain are below 2050 BAU levels mainly due to lower farming impacts following a small decline in Brazil soy production. Mid-points impacts are also slightly below baseline levels, mainly due to lower impacts from crushing for freshwater consumption, and from farming and crushing in the case of GHG emissions.

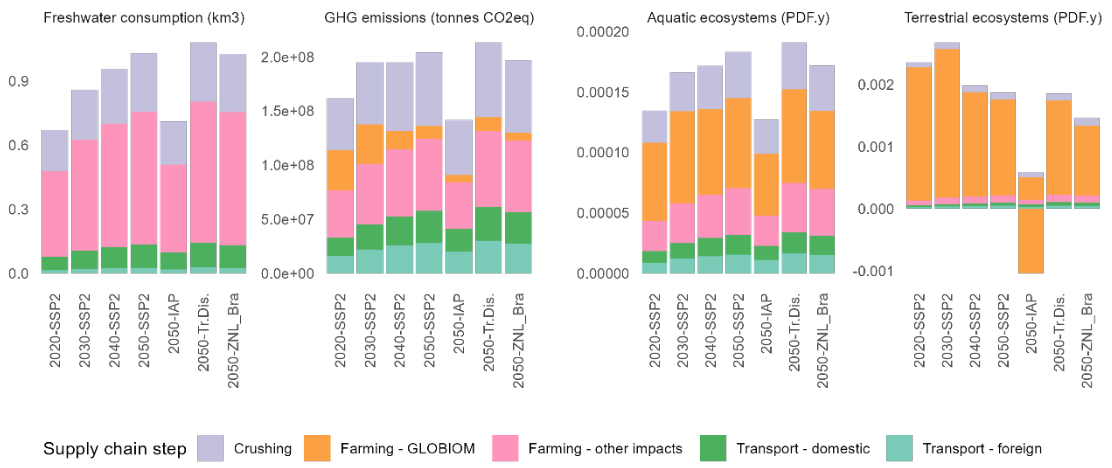

Figure 24. Evolution of the mid-point impacts (GHG emissions and freshwater consumption) and end-point impacts (freshwater and terrestrial biodiversity) of the soy supply chain over time, differentiated per supply chain step.

Discussion

Soy is one of the most internationally traded agricultural commodities. Over the past decades, its production and trade expanded rapidly, mainly driven by strong import demand for protein meals in China and the European Union. These international demands have been associated with land use change, deforestation, and subsequent biodiversity loss in Brazil, the world's largest producer and exporter of soybeans. In this deliverable, we explored alternative future developments in the soy markets, with a focus on Brazil and the EU.

Trends in a business as usual future

When considering the continuation of historical trends in population, diets, trade and productivity, and no change in current policies, the global production, consumption and trade of livestock and crop products are projected to continue increasing by 2050. This includes continuing growth in soy production and trade in soy-based products, with Brazil projected to account for more than half of the global growth in output and net exports. Most of the increase in exports are destinated to Asia, while EU also increases its level of imports. These broad production and consumption patterns are associated with growing environmental pressures, leading to further climate change impacts and increasing extinction risk for aquatic and terrestrial ecosystems, in particular in Latin America, Asia and Africa.

In Brazil, soy production increase is projected to occur primarily in the Cerrado biome, and to some extent, in the Mata Atlantica and Pampa biomes. This growth is achieved in large parts by a conversion of pastures and yield increases. Deforestation is projected to continue until 2050 albeit at a slower pace than in previous decades. Large forest conversions to pasture are projected, in particular in the Amazon biome, while moderate forest restoration efforts take place, in particular in the Mata Atlantica biome. It should be noted that these trends consider the effects from key domestic interventions in Brazil, such as the Amazon Soy Moratorium (limiting soy expansion in the Amazon Biome) and the Forest Code (limiting but not fully eliminating illegal deforestation, and triggering moderate restoration efforts). This leads to a small reduction in GHG emissions from the AFOLU sector, primarily driven by a decrease in land use change emissions partially compensated by an increase in GHG emissions from livestock production. Concomitantly, increases the value of production are projected, in particular for soy, but these remain of a much lower amplitude than projected in increases in production volume.

Extinction risks from agricultural activities increase for aquatic ecosystems of Brazil, in particular due to eutrophication in the Cerrado biome. For terrestrial ecosystems, impacts from agriculture slightly decline for those associated with GHG emissions and land use change (reflecting the slowing rates of deforestation and restoration efforts), but increase for impacts associated with land occupation (indicating that the land sector is still leading to net increases in land-use change mediated terrestrial biodiversity loss).

Although a detailed comparison to the literature would be relevant for aspects such as China's and EU's future demand for soy-based products, these trends are broadly consistent at global scale with the literature of future projections for business as usual scenarios (e.g., for SSP2 scenario (Popp et al., 2017)) and medium-term agricultural outlooks (OECD/FAO, 2024), and similar studies at the scale of Brazil (e.g., (Soterroni et al., 2018)). It might be relevant to consider additional global drivers, such as impacts from climate change, but these are not expected to lead to large changes in Brazil's soy export potential (Zilli et al., 2020).

Impact of alternative futures

We also designed explorative scenarios capturing key sources of uncertainty for soy markets (as identified in the literature and during a stakeholder workshop) and analysed their socio-economic and environmental impacts around the BAU, with a focus on their implications for BRA-EU soy supply chains. This includes scenarios representing a) a global food system transformation (i.e., the IAP scenario), b) the potential long-term implications of the trade dispute between US and China (i.e., the Trade disruption scenario), and c) an idealised ambitious land conservation policy in Brazil (i.e., the ZNL scenario).

Global food system sustainability transition

The IAP scenario assumes the global implementation of a mix of demand-side (incl. dietary shift, waste reduction), supply-side (e.g., sustainable yield increases) and conservation (increased protected area extent and effectiveness, land use planning) and restoration measures. In this scenario, the projected global production and trade of livestock products and feed crops (incl. soy) by 2050 drops compared to the BAU. This leads to a much more limited increase in net exports of soy-related products from Brazil (+20% instead of +76%). Net exports of soy-based products to the EU decrease compared to 2020 levels, while most other importing regions maintain total imports levels slightly above 2020 levels. This scenario is projected to lead to decline in all environmental impacts but also entail important socio-economic trade-offs, with large decreases in the value of livestock production, primarily as a result of changes in consumer preferences.

In Brazil, a significant amount of pasture is restored, while forest and other natural land losses are partially mitigated, as compared to the BAU scenario. Land-use change becomes a large carbon sink, and the biodiversity impacts of local agriculture on both aquatic and terrestrial ecosystems are largely reduced. However, it leads to significant forgone economic opportunities for farmers, with the value of agricultural production declining from 2050 but also from 2020 BAU levels. Decreases are particularly large (more than -50% as compared to 2020 levels) for livestock production. Decrease are very moderate for other crops except for OSA, while for soy, and in particular soy in Brazil, the value of production decrease compared to 2020 levels.

Ambitious conservation in Brazil

Enforcing zero conversion of forest and other natural lands to agriculture in Brazil from 2020 (as assumed in the ZNL scenario) only leads to a slightly lower post-2020 growth in the production and trade of livestock and soy products compared to the BAU, and therefore on agricultural and land use trends in the rest of the world. The halting of land conversion leads to a drop in LUC emissions, and reduced biodiversity impacts on both aquatic and terrestrial ecosystems compared to the BAU. However, biodiversity impacts remain higher than in the IAP scenario, which also considers land restoration and supply and demand-side measures. On the other hand, the value of production is projected to not be significantly affected in the ZNL scenario, in contrast to the stark declines projected in the IAP scenario, primarily in the livestock sector, but also in the soy sector.

This suggests that Brazil could keep supplying domestic and world markets without clearing forest and other natural lands, thereby pursuing both environmental and economic goals, in particular through mobilizing pasture for soy production. However, the same pasture land is also projected to be restored in the scenario pursuing ambitious biodiversity goals, with clear benefits in terms of climate mitigation. In such a scenario, the fate of Brazilian pastures therefore appears at the centre of potential conflicts between economic and environmental goals, while economic opportunities loss would emerge from a shift in global consumption patterns, with potentially large implications for livestock producers. There might be a room for scenarios with more moderate changes in consumption patterns in Brazil, and a mix of restoration and sustainable intensification of the livestock sector (Cohn et al., 2014; De Oliveira Silva et al., 2018).

Long-term impacts of the US-China trade dispute

As compared to other alternative scenarios, the long-term impacts the US-China trade dispute might be limited. In this scenario we assume the trade dispute to result in a long-term decrease in US soy exports to China, capped at maximum 75% of their 2020 levels. This scenario leads to some increase in soy production and trade in Brazil compared to the 2050 BAU, a pattern very similar to the short-term impacts observed in response to the trade shocks in the recent years. However, we projected this scenario to have no impact on deforestation, with an only slightly higher increase soy area (mostly at the expense of pasture in the Cerrado biome) over 2020-2050 as compared to the BAU scenario. We found no significant impact of this scenario on Brazil-level projected biodiversity impacts on aquatic and terrestrial ecosystems as compared to the BAU scenario.

Interestingly, we found the shortfall in USA soya exports to China to be redistributed to other export destination only to a very limited extent, and the Brazil exports to other destinations than China to be very little affected. Although larger efforts from the USA to develop alternative soya export markets could be assumed, this reflects that overall the international market for soy-based products to become very competitive and although slightly increasing its surplus, the USA is projected to become a less important player. In such a context, it will be difficult for soy producers in the USA to recover from short-term drops in export opportunities, which might entail long-term risks.

It should be acknowledged that there is considerable uncertainty in the long-term impacts from the US-China trade dispute, and a broader range of assumptions might be worth testing. It should also be noted that our results reflect two different aspects of the baseline scenario: first, soy exports from Brazil, in particular to China, are projected to already massively increase in the baseline scenario, while exports from the USA to China are projected to undergo limited increases. This makes both the assumed China soya import shortfall, and the potential additional export opportunities for Brazil soya bean to China, limited by 2050 in relative terms. Second, this assumes that that although only partially limiting deforestation, domestic interventions in Brazil such as the Amazon Soy Moratorium and the Forest Code are in place. Should this not be the case, the soy production and export development in Brazil lead to higher rates of deforestation in scenarios with high demand for soya exports.

A rich picture on uncertain future biodiversity impacts

In this deliverable, we rely on multiple indicators to quantify biodiversity impacts, relying on connecting various LCIA-based characterization factors to various outputs the GLOBIOM model (see deliverables D6.3 and D6.4). This included pre-existing characterization factors from the LC-IMPACT project, as well as new characterization factors generated in the CLEVER project and tailored for a more accurate representation of the Brazilian context. These indicators enable us to translate resource use (land, water), input use and GHG emissions (as quantified in GLOBIOM) into biodiversity impacts on both aquatic and terrestrial ecosystems, through multiple impact pathways (e.g., land use, water use, climate change, nutrient pollution).

This provides a significant advancement to the literature, with the few land use models connected to biodiversity models often focusing on terrestrial ecosystems and land use change only (e.g., (Leclère et al., 2020)), and in rare cases including a broader set of impacts (e.g., (Schipper et al., 2020)). We for example explored the impact of future soy supply chains developments on freshwater ecosystems, with an important role of water use (for soy produced in the USA) and nutrient losses and GHG emissions (for soy produced in Brazil). This allowed us enable us to capture, for Brazil soy supply chains, the impacts of supply chain steps not covered by the GLOBIOM model, both upstream (e.g., GHG emissions from fertilizer production) and downstream (e.g., domestic and international transport of soy commodities) of the farming stage. For climate change, for instance, farming accounts for about 25% of the total impact while other supply chain steps (mainly input production and crushing) are responsible for the remaining 75%. Moreover, for aquatic ecosystems and climate change impacts, the share attributed to non-farming supply chain stages is projected to increase over time while farming-related impacts are expected to decline. Finally, for land use impacts, we were also able to compare the projected impacts on terrestrial ecosystems in Brazil between a global set of characterization factors, and a set of characterization factors tailored to Brazil. We found a broad agreement in the overall amplitude and trends of impacts across time horizons and scenarios, but noticeable differences in the amplitude and trends of impacts across scenarios at the scale of individual biomes, and in a few cases at the scale of Brazil. This highlights that the choice of the indicators might influence the diagnosis of what detailed interventions, and sometimes broad scenario might lead to best outcomes for biodiversity, and related patterns of impact.

However, considerable uncertainty remains. While a broader than usual set of impact pathways and ecosystems were considered globally for the impacts of farming, conservation and restoration activities, and the impact other supply chains steps than farming were explored for soy in Brazil, impacts from the full economy are not considered. This complicates the understanding of future trends in biodiversity, and their sensitivity to various scenarios. For example, while land use change remains the largest driver of biodiversity loss for terrestrial ecosystems, the direct and indirect (e.g. through fire) impacts of climate change might become dominant in the coming decades (e.g., (Pereira et al., 2024)), and alter the response of biodiversity trends to policies. In addition, various methods and metrics have each advantages and limits. For example, indicators based on the LCIA framework provides impacts that differ across impacts in terms of time integration (e.g., land occupation vs land transformation), and sensitivity to various types of land use changes (e.g., restoration leads to lower occupation impact, but do not have any transformation impact). This makes it difficult to interpret the temporal trends in such indicators, especially when summed across types of impacts, as compared to other indicators connected to land use models (Leclere et al 2020). This calls for a systematic use of a diverse range of biodiversity indicators to obtain more robust insights.

Forest supply chains

Results

We focus on the following indicators of the forest sector development in the different scenarios: 1) Roundwood harvest volumes 2) Forest management areas 3) Land use changes 4) Wood-based products net exports 5) Forest carbon balance 6) Biodiversity loss. The wood-based bioeconomy tends to increase harvests and forest management intensity, so harvests and management areas provide a rough estimate of the impact of the wood-based bioeconomy on forests. Land-use changes estimate the impact of the wood-based bioeconomy on other land cover types. Net exports trends can be used as a measure of the forest sector regional competitiveness, when considered jointly with corresponding trends in global demand , and compared between the regions. Finally, carbon balance and biodiversity loss provide an estimate of the impact of the wood-based bioeconomy on climate mitigation and nature production.

Roundwood harvest volumes

Harvest volumes moderately increase in the BASE scenario from 3878 Mm3/yr in 2020 to 4112 Mm3/yr in 2100 (Figure 25**Error! Not a valid bookmark self-reference.**). Higher construction materials demand in the CON scenarios based on causes a considerable increase in harvests up to 50% relative to the BASE scenario. On the other hand, higher bioenergy demand in the BIO scenarios only has only a minor 2.5% impact on harvests relative to the BASE scenario. The reason is that additional bioenergy demand is mostly met by increasing energy crops production rather than woody biomass use for energy (Lauri et al. 2019). Harvest volumes are slightly higher in the PLA scenarios (dotted lines) than in other scenarios (solid lines) due to lower roundwood prices in the PLA scenarios. In general, roundwood prices are lower in the PLA scenarios, because plantations are more efficient management system than natural/seminatural forests.

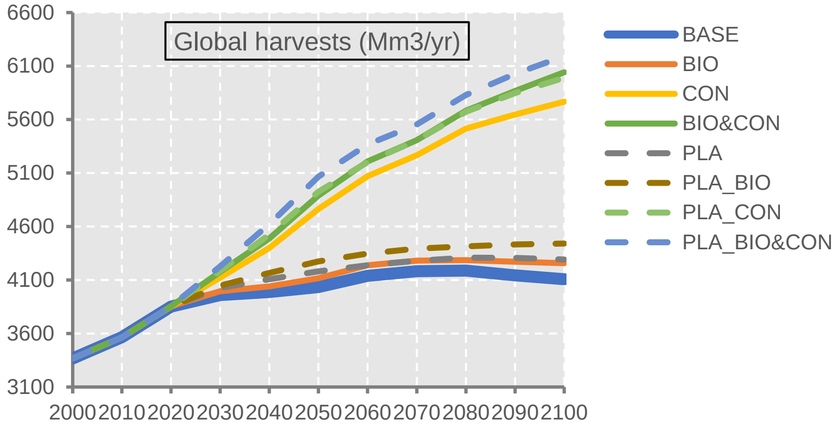

Figure 25. Global roundwood harvest volumes

At the regional level, the wood-based bioeconomy increases harvests mostly in Asia, Africa and Latin America (Figure 26). This increase is driven by higher domestic demand in Asia and Africa and by higher export demand in Latin America. In the PLA scenarios, the additional harvests for the wood-based bioeconomy are coming mainly from plantation forests, which moves logging from traditional forest industry regions (EU, North America, Former Soviet Union) to tropical regions, especially to Brazil.

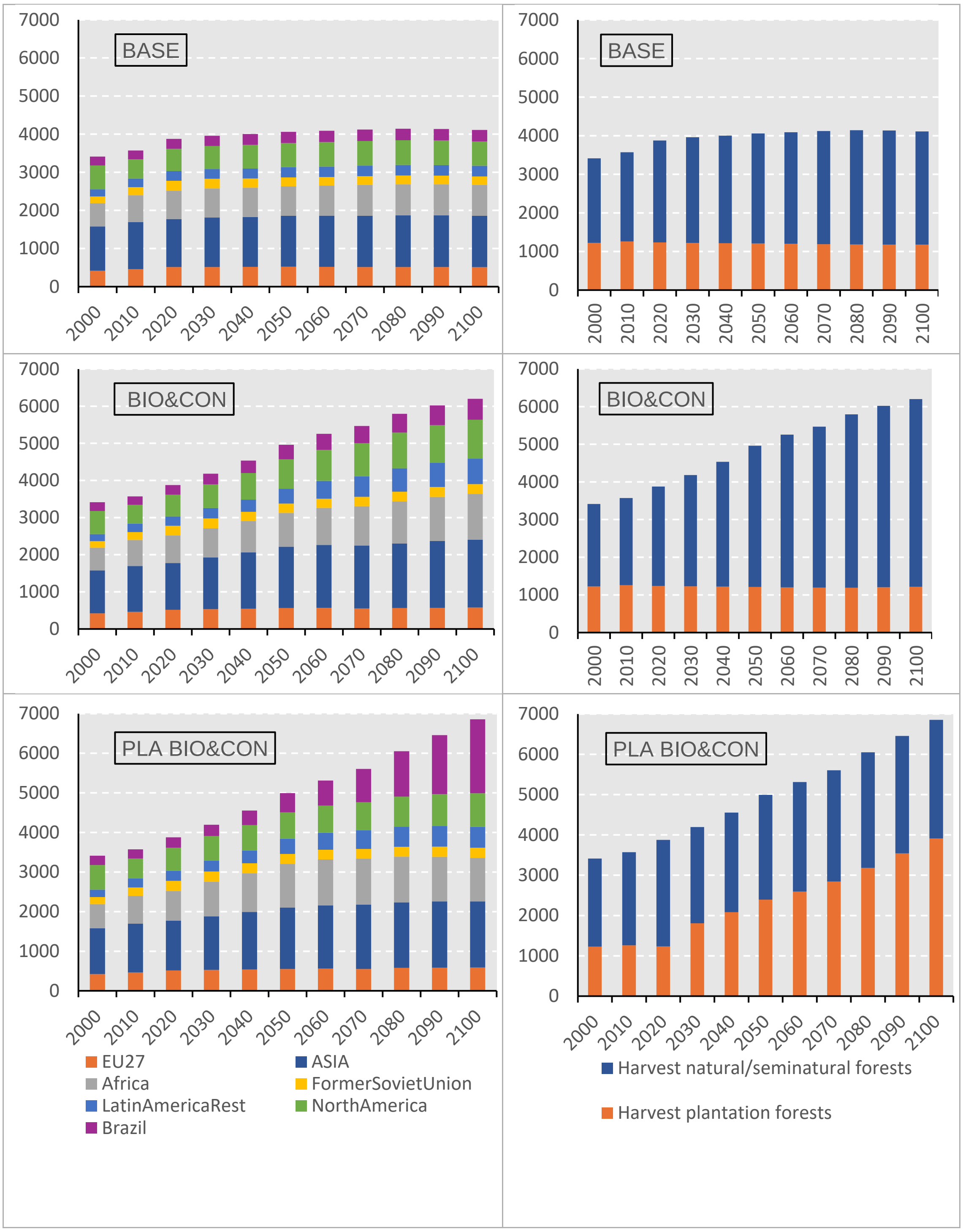

Figure 26. Global roundwood harvest volumes by region and forest type (Mm3/yr)

Wood based products net exports

In the BASE scenario, regional net exports are relatively steady, with boreal/temperate zone regions losing some competitiveness and tropical zone regions becoming more competitive (Figure 27). Bioenergy demand has little impact on net exports, because higher bioenergy demand is mostly met by increasing energy crops, which are not traded in the model. Bioenergy could potentially impact indirectly on net exports by increasing competitions on available land for plantation forests, but this effect remains small except for Brazil in the PLA BIO&CON scenario.

In the CON scenarios, net exports decrease in Asia and Africa while they increase in the other regions. The reason is that Asia and Africa do not have enough domestic resources to match the higher demand for construction materials. This effect is weaker in the PLA scenario, in which Asia and Africa can expand their domestic harvests through plantation expansion. More generally, plantation expansion tends to improve the competitiveness of the tropical zone (especially Brazil) relative to the boreal/temperate zones. This happens in all scenarios independently of the demand assumptions, so the reason is the higher productivity of forest plantations in tropics rather than the higher bioenergy or construction materials demand there.

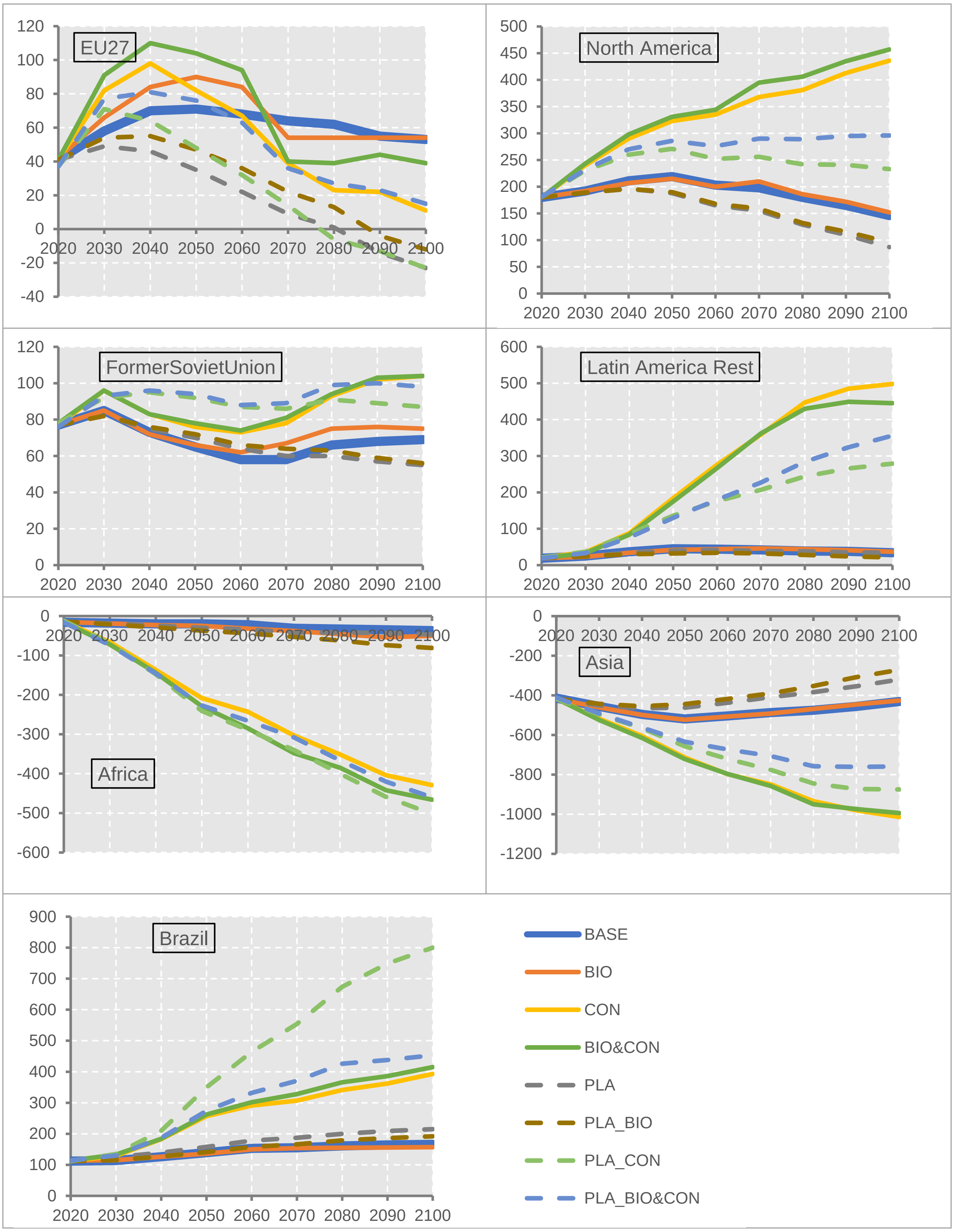

Figure 27. Wood-based products net exports (Mm3/yr RWeq)

Forest management and land-use

In the BASE, BIO, CON and BIO&CON scenarios, plantation forests area is fixed at 2020 level (i.e., 132 Mha) while in the PLA scenarios plantation forests area increases up to 241 Mha in 2100 (Figure 28). This has a considerable impact on natural/seminatural forests management. In the CON scenario, natural forest management is intensified so that up to 300 Mha of natural forests area is taken in production use and converted to seminatural forests. On the other hand, in the PLA scenarios, 200-300 Mha of seminatural forests are released from production use and can be restored back to natural forests.

In the PLA BIO and PLA BIO&CON scenarios, 150-200 Mha additional area is needed for energy crops plantations (Figure 28). This decreases available plantations forests area, because energy crops plantations and plantation forests compete on the same land areas. Therefore, plantations forests and spared natural forests area are lower in the PLA BIO and PLA BIO&CON scenarios than in the PLA and PLA CON scenarios.

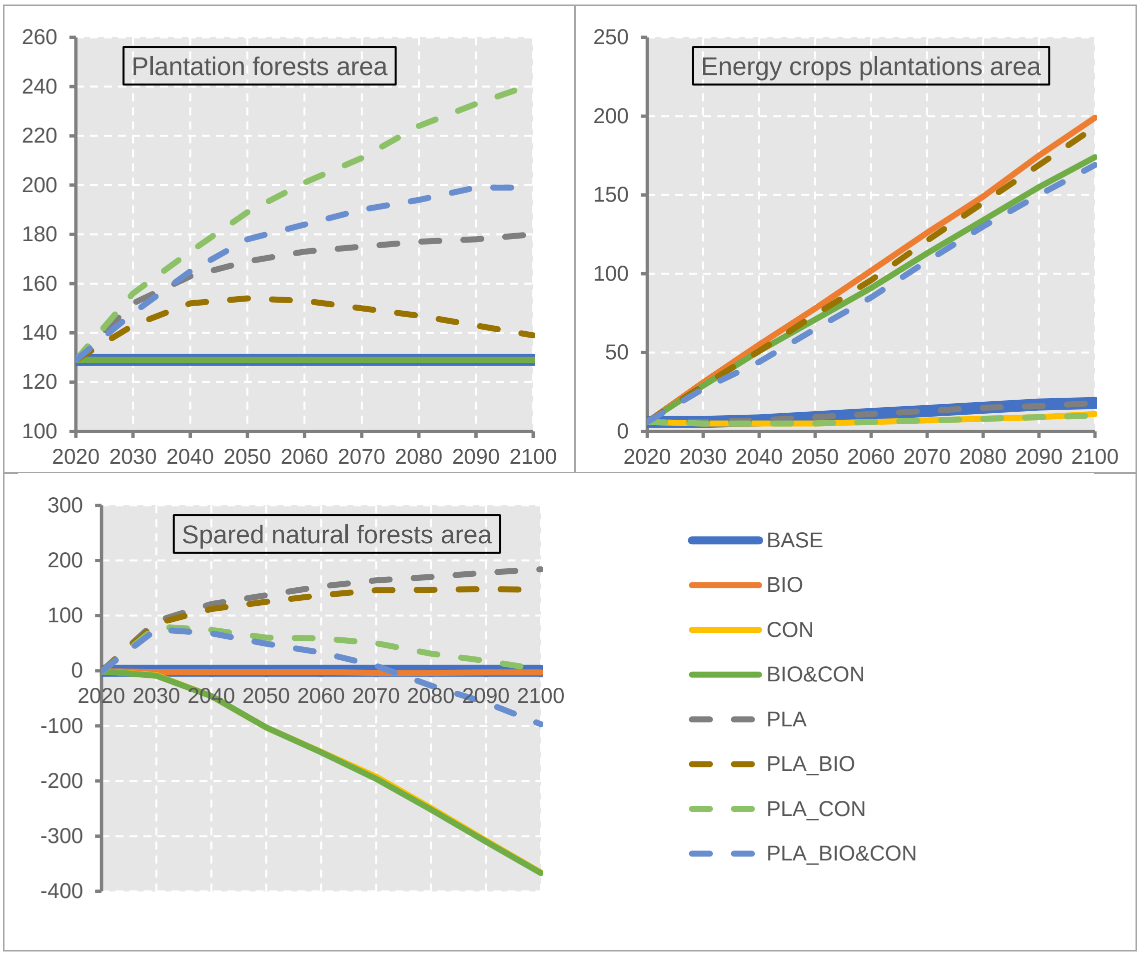

Figure 28. Plantation forests, energy crops plantations and spared natural forests area (Mha)

As shown in Figure 29, plantation forests save natural forests, but at the same time they decrease other natural land and agricultural land. Due to land-use change constraints, the other natural land conversion to plantations (PltLnd) is mostly directed at biodiversity poor abandoned land (AbdLnd) rather than biodiversity rich natural land (NatLnd) (Figure 30). This implies that the direct land-use change impact of plantations expansion on biodiversity remains small and the indirect land-use change impact is positive (i.e., spared natural forests area).

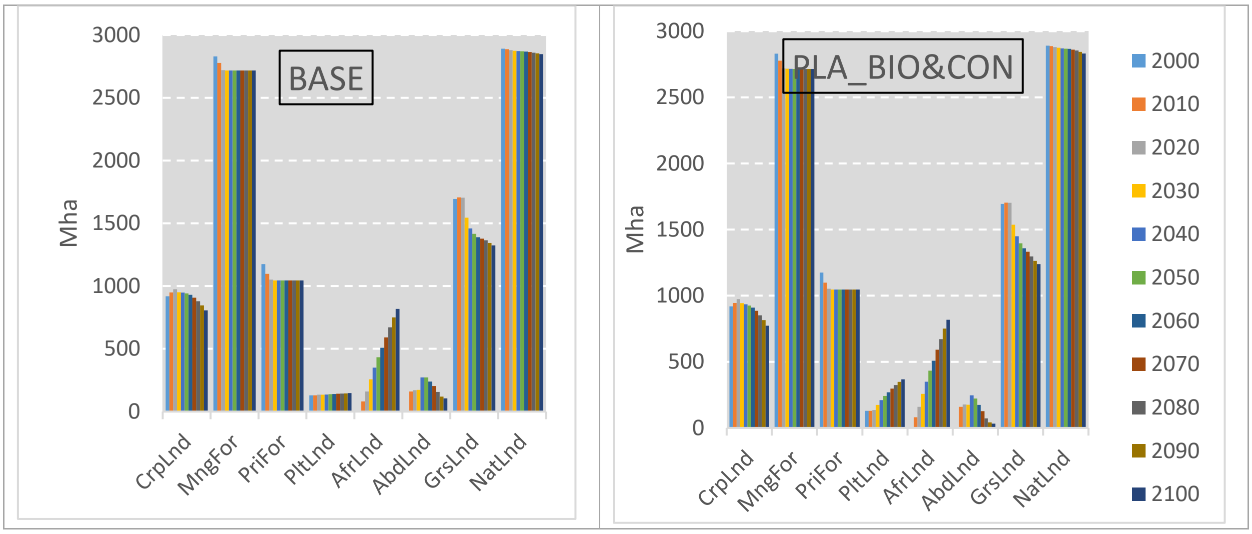

Figure 29. Overall land-use change (Mha)

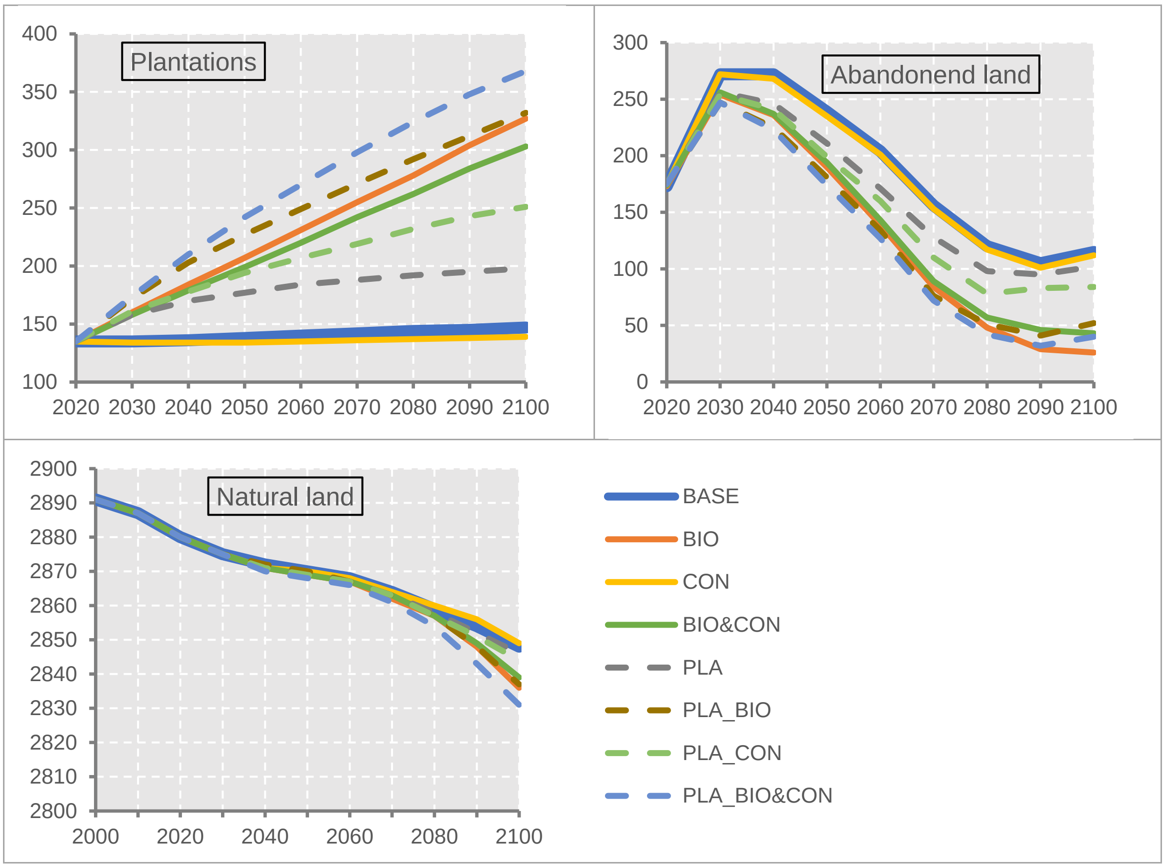

Figure 30. Plantations (energy crops +forests) expansion and decrease in abandoned vs. natural land area (Mha)

Forest carbon balance

In the BASE scenario, forest carbon storage increases over time (Figure 31). The main reason is afforestation uptake, which compensates for carbon storage decrease in the existing forest area. The existing forest area is a sink until 2050, but after 2050 it turns to a source due to increased harvest volumes, natural mortality and the saturation of biomass growth. In addition to afforestation, the carbon changes in the existing forest area are compensated by HWP and BECCS. However, the impact of HWP and BECCS on overall carbon balance is relatively small in the BASE scenario due to "business as usual" bioeconomy development.

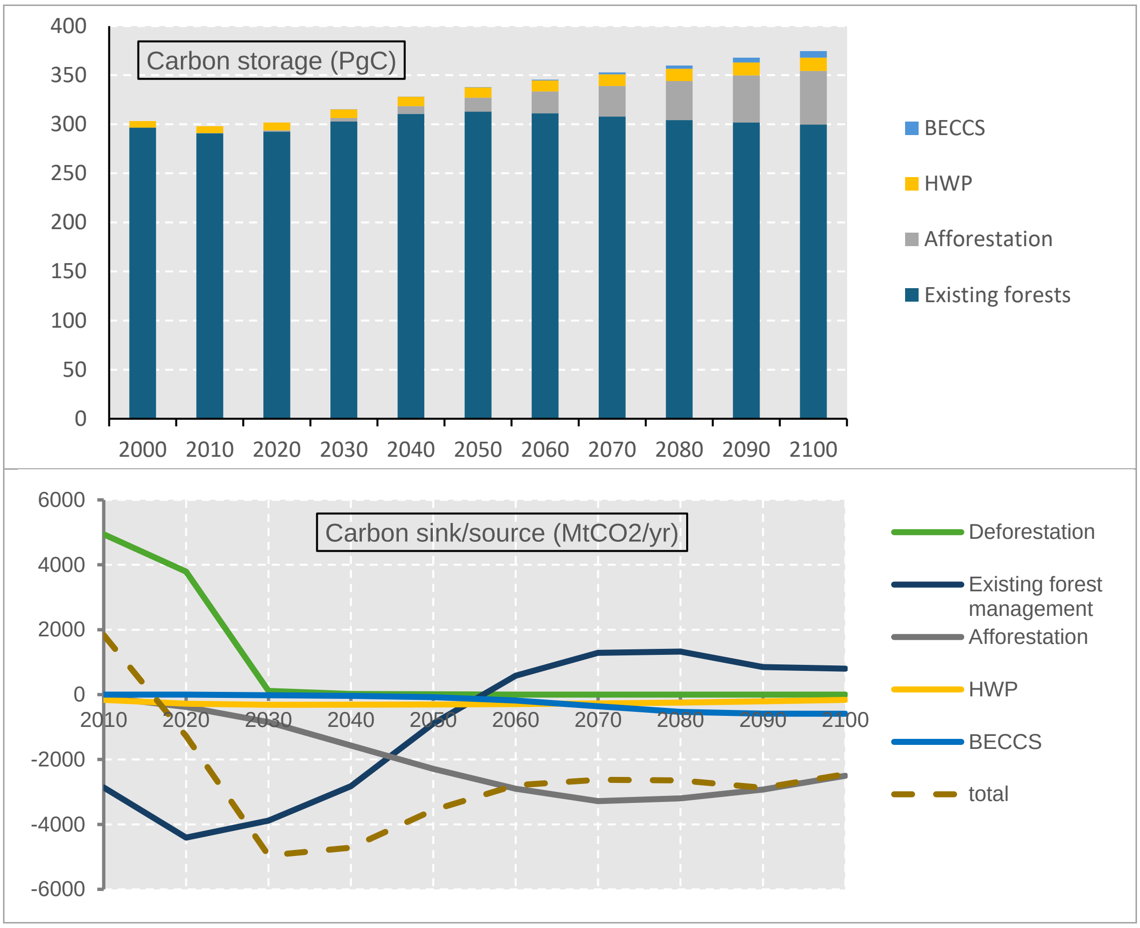

Figure 31. Global forest carbon stock and carbon sink/source in the BASE scenario

In the CON scenario, forest carbon storage remains lower than in the BASE scenario (Figure 32). The reason is higher harvest volumes, which decreases carbon in the existing forests more than is compensated by the increase in HWP carbon storage.

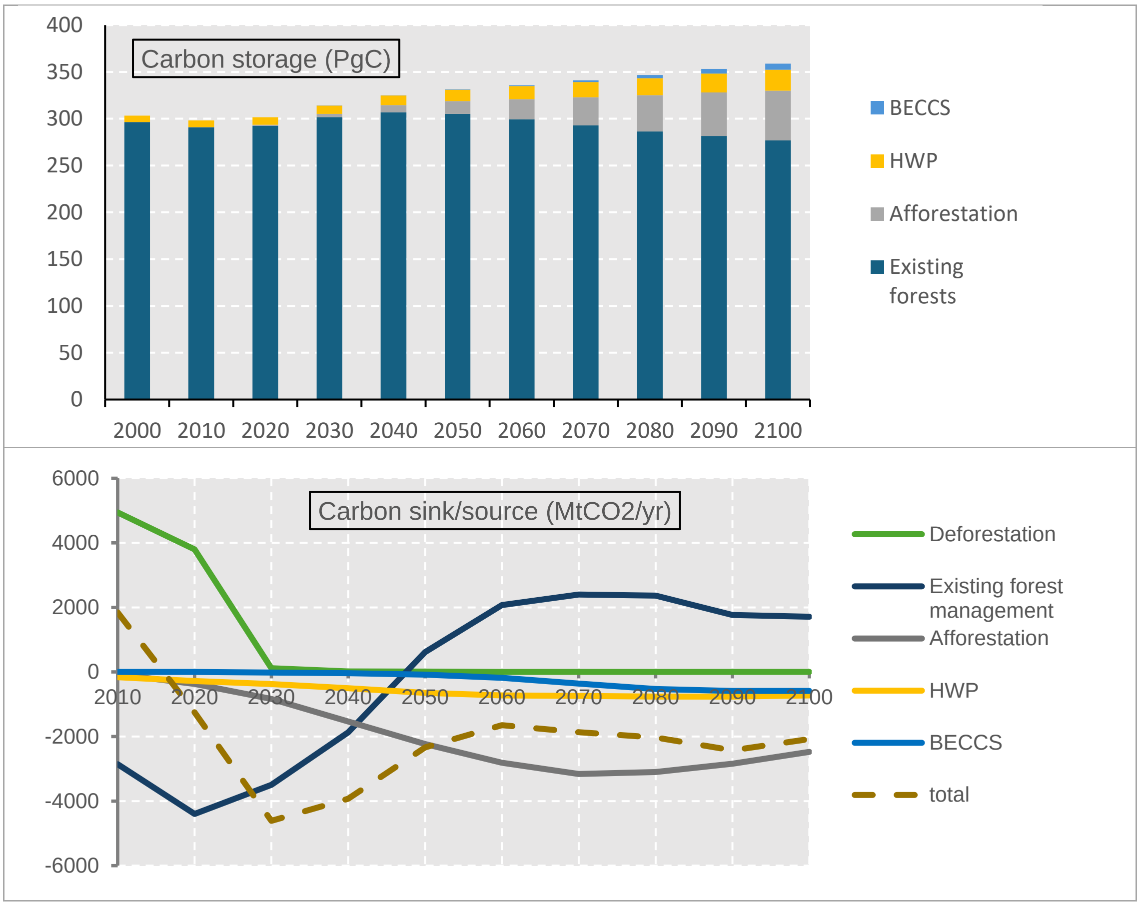

Figure 32. Global forest carbon stock and sink/source in the CON scenario

In the BIO scenario, forest carbon storage is higher than in the BASE and CON scenarios (Figure 33). There are two reasons for this. First, the higher bioenergy demand does not increase harvests and carbon emissions as much as the higher wood-based construction materials demand, because the majority of additional bioenergy demand is satisfied by energy crops. Second, the higher bioenergy demand increases carbon storage of BECSS considerably compared to "business-as-usual" bioenergy demand, especially after 2050 when large scale implementations of BECCS becomes feasible due to high carbon prices.

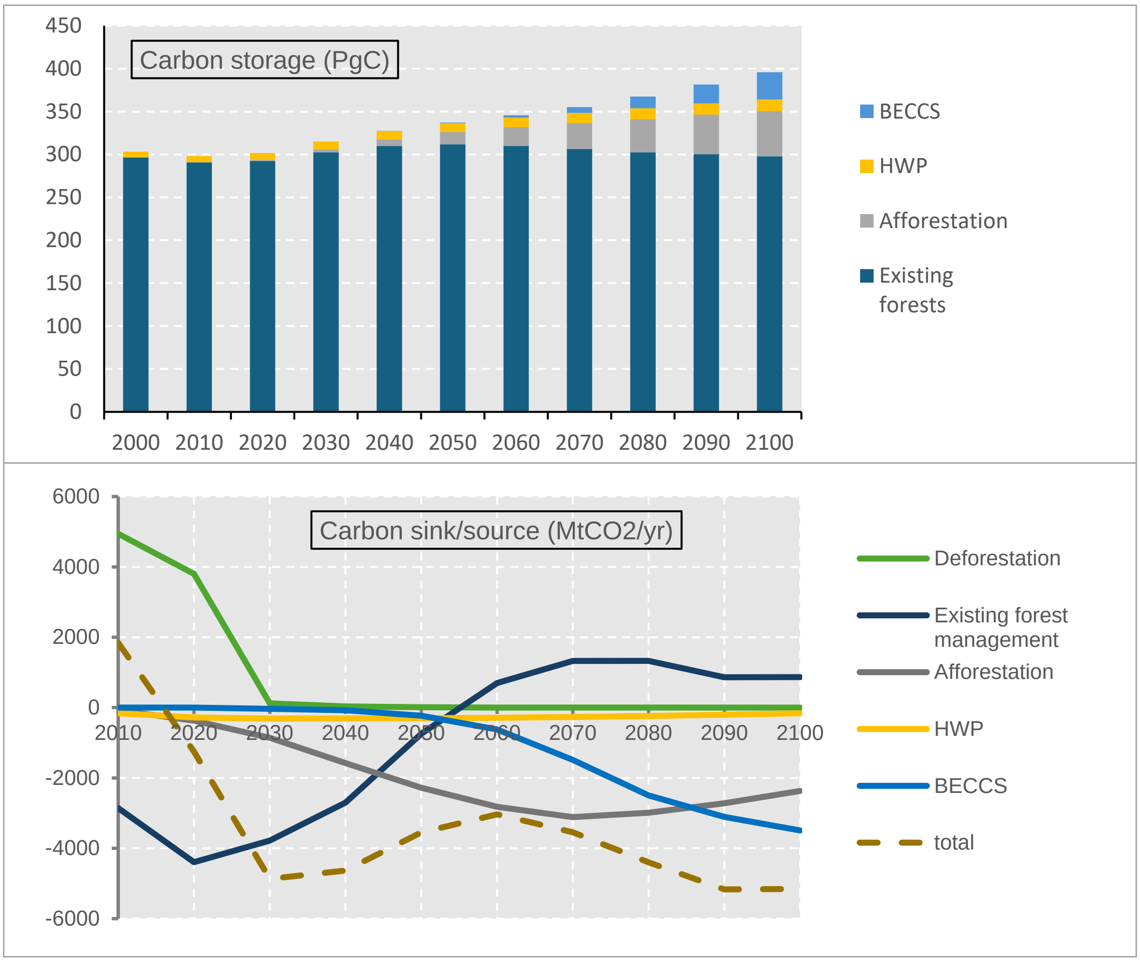

Figure 33. Global forest carbon stock and sink/source in the BIO scenario

In the PLA CON scenario, forest carbon storage is higher than in the BASE and CON scenarios but not as high as in the BIO scenario (Figure 34). There are two reasons for this. First, additional harvests come from forests plantations instead of natural/seminatural forests, which keeps the existing forest area carbon emissions at the BASE scenario level. Second, HWP storage is higher than in the BASE scenario.

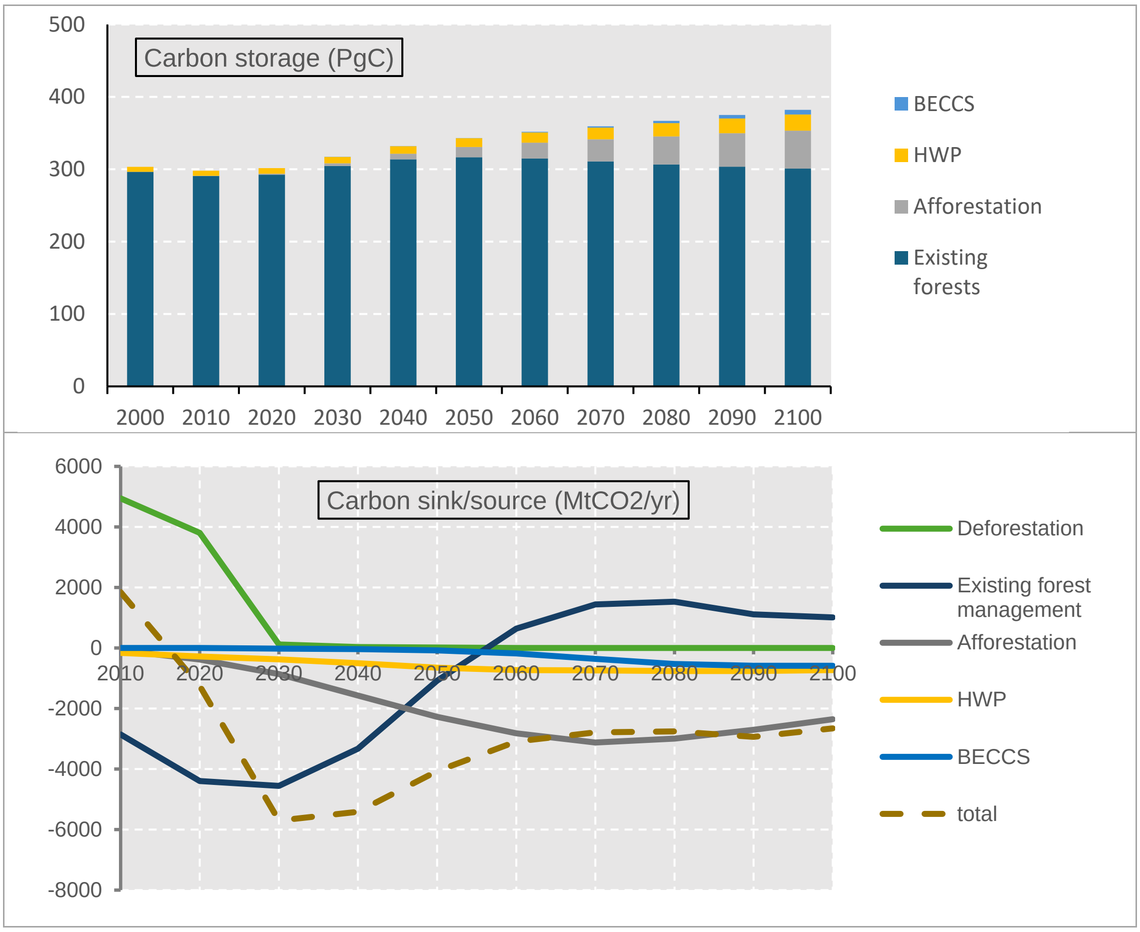

Figure 34. Global forest carbon stock and sink/source in PLA CON scenario

To understand the role of HWP and BECCS in forest carbon balance, we compare forest carbon stock and sink with and without HWP and BECCS. In general, the forest carbon storage is increasing in all scenarios. Without HWP and BECCS, however, the increase starts to saturate after 2050 (Figure 35). Adding HWP and BECCS in the forest carbon storage improves forest carbon balance in all scenarios and tends to eliminate the saturation (Figure 36). The reason is that HWP and BECCS remove old trees and make space for new trees and/or remaining trees regrowth. This has basically a similar effect than natural mortality, but the difference is that HWP and BECCS store the carbon of the removed biomass instead of letting it to decompose and emit in the atmosphere.

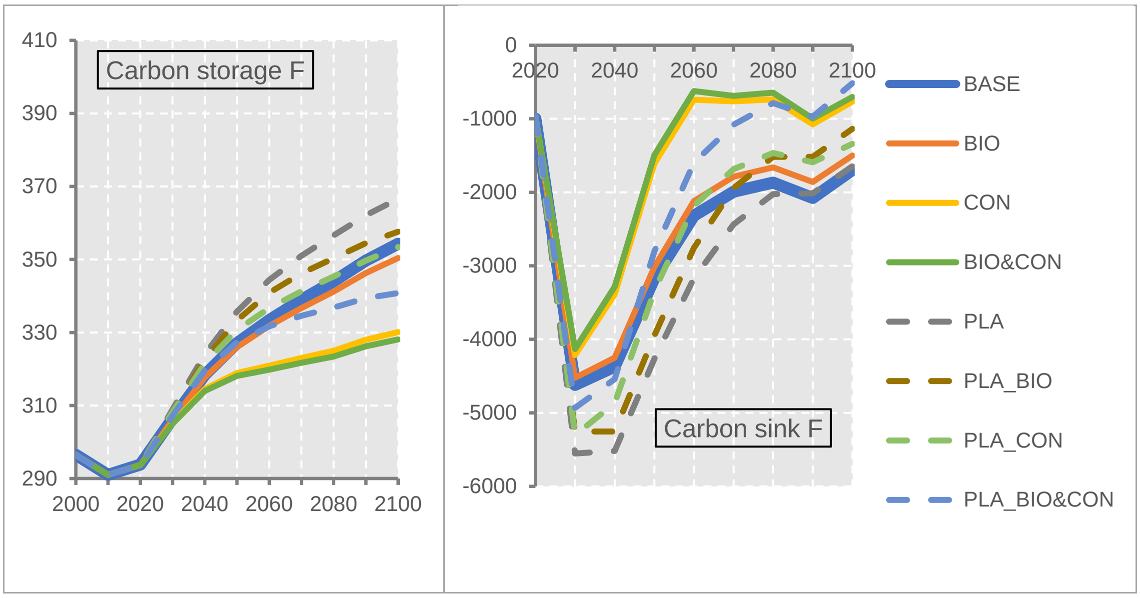

Figure 35. Forest carbon storage (PgC) and sink (MtCO2/yr) including only the biogenic carbon that stays in forests (F)

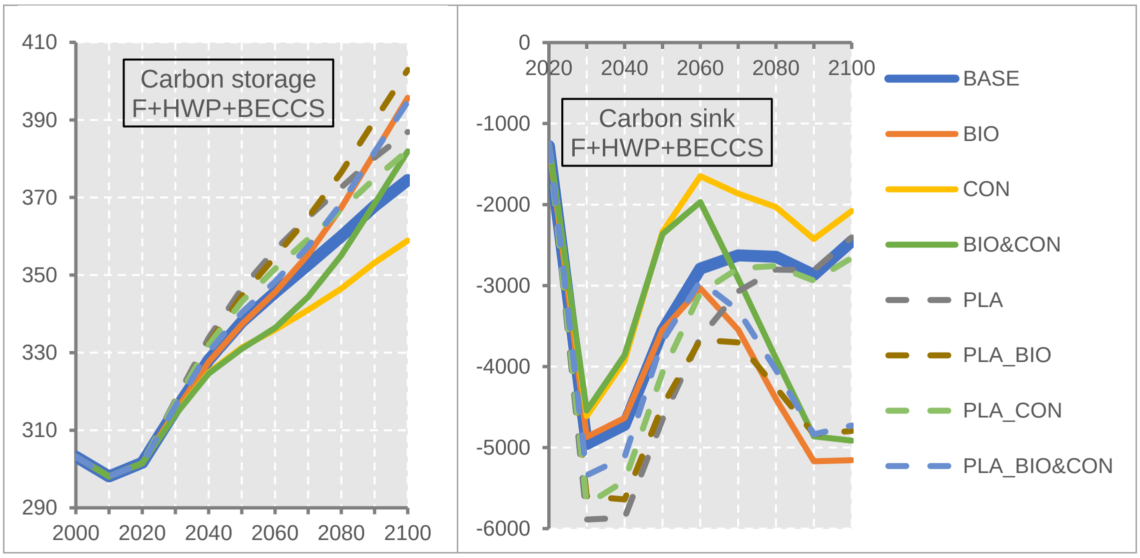

Figure 36. Forest carbon storage (PgC) and sink (MtCO2/yr) including biogenic carbon that stays in forests (F) and biogenic carbon that is stored outside forests (HWP and BECCS)

Biodiversity

Biodiversity loss is measured as in D6.2 by the Potential Disappeared Fraction of global species aggregated over all different taxa (PDF %). Biodiversity loss is lower in the PLA scenarios than in the “business as usual” forest management scenarios (). In particular, biodiversity loss is highest in the CON and BIO&CON scenarios, where increasing demand for wood-base construction materials leads to natural forests extraction for production. In Figure 38, biodiversity loss is divided into different land-uses. It shows the impact of natural forests in the BIO&CON scenario is clearly higher than in the PLA BIO&CON scenario. On the other hand, the plantation expansions in the PLA BIO&CON scenario causes less biodiversity loss than natural forests harvests in the BIO&CON scenario.

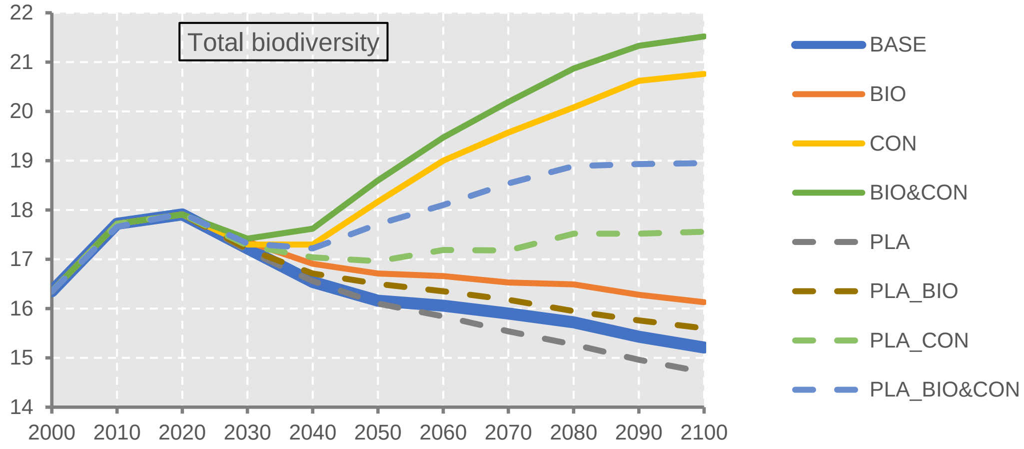

Figure 37. Global biodiversity loss

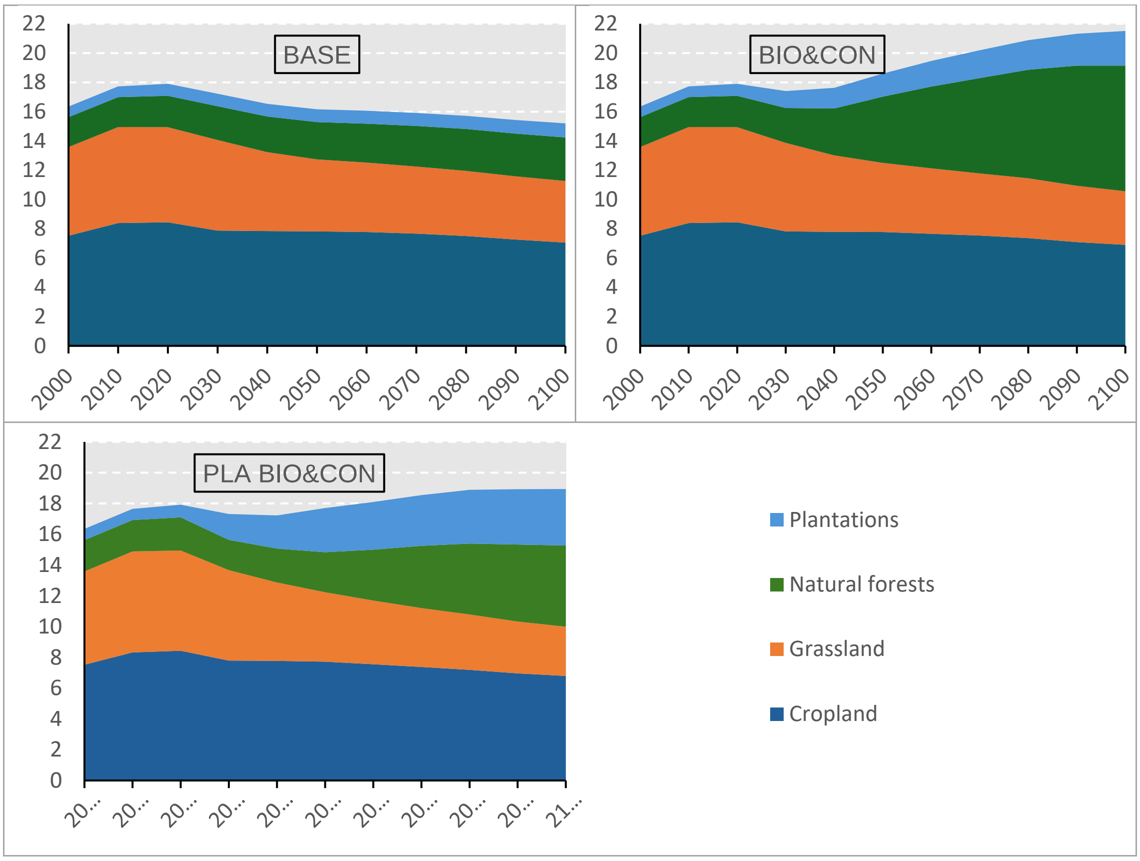

Figure 38. Global biodiversity loss divided into different land-uses

Discussion

The problem of the wood-based bioeconomy is that it tends to increase harvests volumes considerably relative to current harvest volumes, which might have negative impacts on forest carbon balance and biodiversity. Here we consider the possibility of avoiding these effects by shifting logging from natural forests to plantations forests. Currently plantation forests cover about 10% of the global production forest area and account for about 30% of the global roundwood supply. According to our result, the negative effects of the bioeconomy on forest carbon balance and biodiversity could be avoided if we would double the plantation forests area and provide 60% of the global roundwood supply from these plantations.

The question if we should produce woody biomass in natural/seminatural or plantation forests is analogues to the land-sharing vs. land-sparing discussion in conservation ecology and agricultural landscape management (Salles et al., 2017). Land-sharing combines production and nature conservation in the same area while land-sparing separates these objectives in different areas, which implies that our current management scenarios can be interpret as land-sharing while our plantation forests scenarios as land-sparing. According to previous studies focusing on forest landscape management, land-sharing tends to work better in regions with a long history of forest management, low biodiversity and slow biomass growth while land-sparing works better in evolving forest industry regions with high biodiversity and fast biomass growth (Betts et al., 2021).

Our stakeholders emphasized the role of expanding multi-purpose forest managements, which would entail more natural/seminatural forest land managed for maximizing multiple ecosystem services rather than wood production, in the direction of a land-sharing approach. According to our scenario results, land-sharing implies that more natural/seminatural forests area is needed for production use, which tends to increase existing forest area carbon emissions and biodiversity loss. This effect is significantly larger in high construction materials demand scenario than in the high bioenergy demand scenario, because most of the bioenergy increase is met by an increase in energy crops production rather than in roundwood harvesting. Increased carbon emissions can be compensated by higher HWP and BECCS carbon storages. The BECCS carbon storage is typically higher than the HWP carbon storage, since HWP provides a temporary carbon storage while BECCS a permanent carbon storage. On the other hand, BECCS is a new and relatively expensive technology, and becomes economically available only after 2050 when carbon prices are high enough.

Land sparing implies that less natural/seminatural forests area is needed for production use, which tends to decrease existing forest area carbon emissions and biodiversity loss. The spared natural forest area could be used for carbon sequestration and nature conservation, as also demanded by stakeholders. On the other hand, under the land sparing scenario, more land is needed for plantations, which could potentially decrease carbon sequestration and biodiversity, as plantations carbon storage and biodiversity are low. This problem is avoided by locating new plantations mostly in abandoned land rather than biodiversity and carbon rich natural forests or natural land.

Aquaculture & aquafeed supply chains

Results

Demand for final blue food products

Projections for the final demand of blue food products are presented in Figure 39, with different time horizons for the BAU scenario (2010, 2020, 2030, 2040 and 2050), and 2050 values for other scenarios.

In the BAU scenario, the global demand for fish final products remains relatively stable or slightly increases (i.e., salmonoids SALM, less than +15%) between 2020 and 2050 for most products, with a few exceptions. On the one hand, some products are projected to undergo a more significant increase in global demand, for example freshwater (FRSH, +51%) and shrimps & prawns (SHRI, +37%), even though their demand increase at lower speed than in recent decades (e.g., +51% over 2020-2050 vs +41% over 2010-2020). This is compatible with projections from others studies (e.g., Naylor et al 2021), with the level of wild catch expected to stabilize. Countries from Eastern Asia (EAS, including China) are expected to remain the largest consumers of freshwater and crustacean products and undergo moderate demand growth, while countries from South (SAS, e.g., India), South-East Asia (SEA) or Sub-Saharan Africa seeing a large relative increase by 2050. For some wild catch-based fish products (e.g., pelagic fishes PELG, demersal fishes DMRS, marine fishes MARN, tunas TUNA), the globally stable demand hides more contrasted changes at the regional level, with demand often increasing in Sub-Saharan Africa (SSA) and decreasing in Eastern Asia (EAS). On the other hand, demand for fish meal and fish oil are expected to decrease substantially over the 2020-2050 period, by about 90% and 75%, respectively. This follows the assumed prolongation of recent trends in fed aquaculture in terms of feed conversion efficiency gains and substitution of fish meal and fish oil feed by crop-based feed. Most of the trends in final products are related to food use and to some extent other uses, except for fish meal and fish oil, that are used for feed.

In other scenarios, the trends follow the BAU scenario, with a few exceptions. First, in the BFS20 counterfactual scenario, demand remains by design constant at 2020 levels after 2020. Second, in the UNFEDAC20 sensitivity scenario, the capacity of unfed aquaculture systems is assumed to remain constant at 2020 levels after 2020, leading to lower demand by 2050 for some products (freshwater fishes FRSH, crustaceans CRST, shrimps and prawns SHRI). The difference to the BAU demand by 2050 for these products reflects the degree to which they rely on unfed aquaculture systems: high for CRST (2050 demand is close to 2020 levels and well below BAU levels), moderate for FRSH and SHRI (2050 demand is close to BAU levels and well above 2020 levels). Lastly, as opposed to the BAU scenario, the demand for fish meal (FSHM) and fish oil (FSHO) increases to higher levels than 2020 for the AF20 and AFCOMPO20 sensitivity scenarios. This results from the assumed constant share of fish meal and fish oil in aquafeed requirements per unit of output (to 2020 levels, for both scenarios), and constant total aquafeed requirements per unit of output (to 2020 levels, for the AF20 scenario). This highlights the importance of the expected prolongation of recent trends in aquaculture feeding practices (in terms of efficiency and aquafeed composition) in shaping future demands for fish-based aquafeed, in a context of growing demand for aquaculture products.

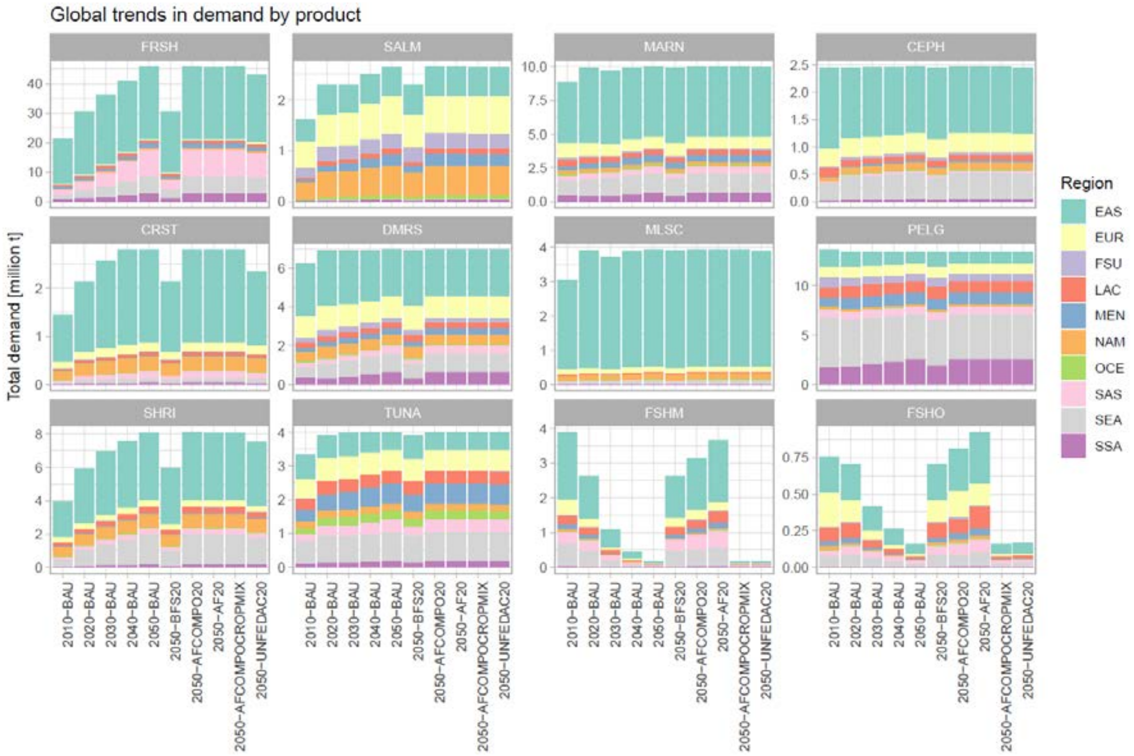

Figure 39 - Projections of demand of blue food final products for food, feed and other use (i.e., excluding input to reduction sector) by product, aggregated to ten world regions.

Primary blue food product supply and aquafeed use

Global-scale projections of primary fish products supply by source (catch, fed and unfed aquaculture) and crop aquafeed requirements (by crop) are presented in Figure 40. By assumption, most of the supply increase is projected to be sourced from fed aquaculture. In the BAU scenario, the total supply of primary blue food products is expected to continue increasing, but at a slower pace than in recent past. It increases from 169 million tons (Mt) t in 2020 to 210 Mt by 2050 (+24%, roughly equal to the relative increase from 2010 to 2020). This translates into a 57% increase in fed aquaculture supply (from 50 Mt in 2020 to 78 Mt in 2050) and a 45% increase in unfed aquaculture (from 29 Mt in 2020 to 41 Mt in 2050). These trends remain below (for fed aquaculture) or nearing (for unfed aquaculture) 2010-2020 rates of increase (+87% for fed aquaculture, +18% for unfed aquaculture). These projections are qualitatively comparable to those from the OECD-FAO Outlook 2024-2033 (OECD-FAO 2024).

Projections of primary fish supply by 2050 for other scenarios are similar to that of the BAU, except for two scenarios. For the BFS20 counterfactual scenario, supply remains by assumption constant at 2020 levels for all three sources. For the UNFEDAC20 sensitivity scenario, unfed aquaculture supply remains by assumption constant at 2020 levels, leading to a slightly higher increases in fed aquaculture (+59% over 2020-2050, instead of +57% in the BAU scenario), reflecting the limited substitution options for CRST and SHRI product groups, for which the demand is projected to be lower than in the BAU scenario (see Figure 39).

As illustrated in Figure 40b, we project an increase in crop-based aquafeed requirements in the BAU scenario over 2020-2050, from 79 Mt in 2020 to about 100 Mt in 2050. This represents a 40% increase over this period, which is lower than the growth in aquaculture supply (+57%) This indicates that the assumed increase in feed conversion efficiency is projected to buffer the future increase in demand for aquafeed, despite the assumed further substitution of fishmeal and fish oil by crop-based aquafeed. The AF20 and AFCOMPO20 scenarios allow disentangling these two factors: the increase in total crop aquafeed requirements would more closely follow aquaculture supply increase if both the composition and the efficiency of feeding practices remained constant at 2020 levels (AF20 scenario, +53%), but would be slightly lower than in the BAU if the share of crops in aquafeed did not increase beyond 2020 levels but efficiency gains still occur (AFCOMPO20 scenario, +35%). It should also be noted that from 2020 to 2050, the projected increase in crop-aquafeed is of lower amplitude than the projected decrease in fish meal and fish oil. The main reason for this is that crop aquafeed already represents a high share of total fed aquaculture requirements by 2020, and the impact of additional substitution is less strong than future trends in demand for aquaculture products and aquaculture feed conversion efficiencies.

By assumption, the proportion of various crops in total crop-based aquafeed differs across regions but remains constant over the different time horizons and scenarios, except for the AFCOMPOCROPMIX scenario. In this simple sensitivity scenario, the assumed substitution of 50% of corn and soya aquafeed requirements in China by wheat leads to a markedly lower increase in feed requirements (+28%, instead of +40% in the same period), primarily due to the higher crude protein content of wheat compared to corn. While this scenario was designed as a simplistic illustration of aquafeed crop mix change rather than as a realistic future evolution, it illustrates that related assumptions can be as important as that of other feeding practices aspects such as feed conversion efficiencies and the share of fish meal and fish oil.

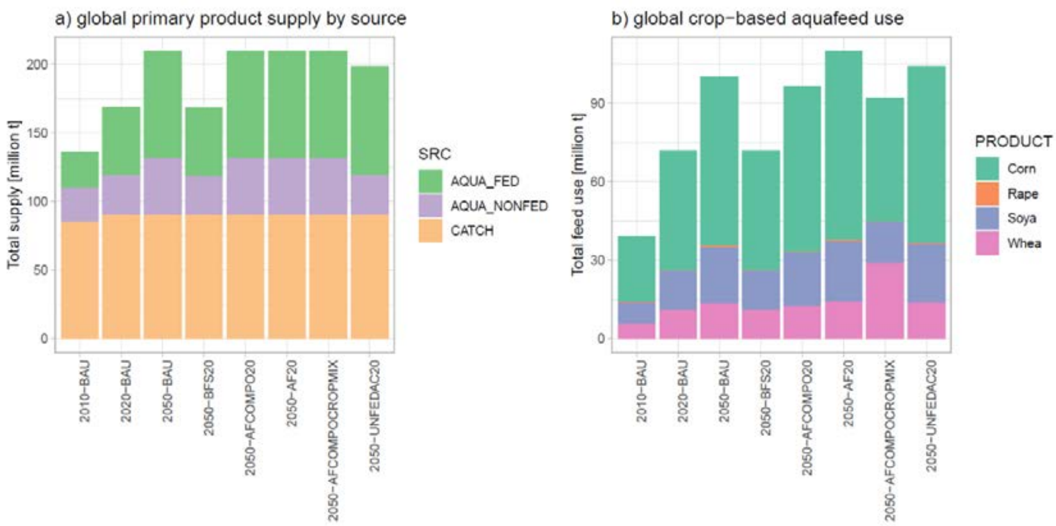

Figure 40 - Projections at global scale of a) total blue food primary products supply by source and b) crop-based aquafeed used by crop.

Land use and biodiversity impacts from crop aquafeed requirements

As shown in Figure 41a, the crops used as aquafeed represent a small share of global crop production projected by 2050: up to 3% for wheat, 5% for corn and 6% for soya. This share is projected to remain relatively stable between 2020 and 2050 for most crops and across the different scenarios, except for the AFCROPOCROPMIX scenario (higher shares for wheat, and lower shares for corn and soya) and the counterfactual BFS20 scenario (decrease for all crops, by design). This means that the demand for crop aquafeed products is not projected to increase faster than the demand for other uses of crops. The AFCOMPOCROPMIX scenario is a simplified experiment picturing changes in the relative contribution of various crops to total crop-based aquafeed, only for one country (China). And yet, at the individual crop level, it differs markedly from other scenarios by 2050: this highlights the importance of crop aquafeed composition assumptions have on land use impacts from aquaculture development.

As displayed in Figure 41b, the overall demand for agricultural products drives an expansion of agricultural land covers (cropland and grassland) from 2020 to 2050 of about 300 million hectares, at the expense of forest and – in larger proportion – other natural vegetation. Differences across scenarios, including for the counterfactual BFS20 scenario, are barely noticeable on Figure 41b, indicating that the impacts of further aquafeed demand play a very marginal role in projected land use expansion globally between 2020 and 2050.

Altogether, results displayed in Figure 41 highlight that the projected future crop aquafeed requirements will occur concomitantly to much larger changes to the agricultural and land use systems. While future increases in crop aquafeed demand may lead to land use-mediated terrestrial biodiversity loss, it indicates that these may only represent a small share of future terrestrial biodiversity losses from the agricultural sector. It also points to the necessity of using dynamic modelling tools to understand such impacts: the impact of additional demand may be very different from those inferred from the current state of the agriculture and land use sectors, due to expected concomitant changes in the land use, productivity, production, demand and trade across regions. Using the GLOBIOM model allows providing an estimate of future dynamics in agriculture and land uses systems, against which the specific impacts of increased crop aquafeed requirements can be estimated. In addition, by comparing production, land use or biodiversity impacts from various scenarios to a counterfactual scenario in which all components of the blue food sector remain fixed at 2020 levels (BFS20 scenario), we can diagnose precisely the impact of post-2020 changes in crop aquafeed requirements, on top of these broader trends in the agricultural and land use systems.

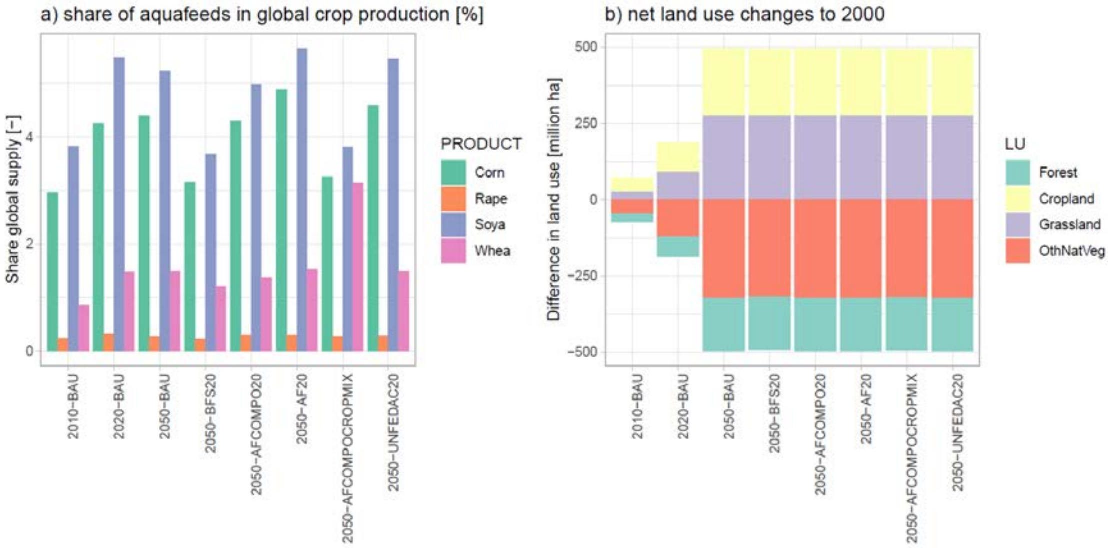

Figure 41 - Projections at global scale of a) the share crop aquafeed represents in total crop supply (%) and b) the net difference to 2000 in the extent of various land covers.

Figure 42 provides the difference between the counterfactual scenario BFS20 and other scenarios by 2050, for crop aquafeed requirements, changes to the natural land cover, and terrestrial biodiversity impacts from land occupation. When it comes to crop aquafeed requirements (left panel), Figure 42 confirms the differences across scenarios in total crop aquafeed requirements shown in Figure 40b, but also highlights that the additional crop aquafeed demand occurs in EAS (including China), SAS and SEA regions, where the additional fed aquaculture production takes place. However, as suggested by the middle panel, due to the trade dependencies of these regions, land use intensification and other market knock-on effects, Latin America and the Caribbean (LAC) appear as a hotspot of natural land loss associated with crop aquafeed production, in particular for soya and corn, to a lower extent. Impacts in EAS and SAS remain high but represent a lower proportion of global impacts for natural land loss than for increased crop aquafeed demand, while to some extent NAM, MEN and EUR show the opposite trends. The spatial patterns of global natural land loss from crop aquafeed requirements are relatively similar across scenarios, except for the AFCOMPOCROPMIX scenario, for which impacts are much lower in EAS where the reduced total crop aquafeed requirement occurs, but also in LAC where export demand for soya – and to some extent, corn – is reduced.

The biodiversity impacts (right panel), however, illustrates that the translation of losses in natural land to terrestrial biodiversity impacts (in terms of global extinction risks) from land occupation is not direct, mainly due to variations at national to subnational scales in species richness and level of endemism, its sensitivity to various land uses, and in land use change patterns. For example, while the AFCOMPOCROPMIX scenario leads in LAC to comparable savings (as compared to the BAU scenario) in terms biodiversity loss and natural land loss, in the same region savings in the AFCOMPO20 scenario (as compared to the BAU scenario) are much higher for biodiversity than for natural land loss. While we found LAC to be a clear hotspot of biodiversity loss from future aquaculture development due to its export-oriented agricultural sector, actual impacts on biodiversity may be particularly sensitive to how additional crop production is achieved. In addition, the share of SAS and SEA regions combined in global additional losses of terrestrial biodiversity (as compared to the BFS20 scenario) is often close to 50% or even higher for the BAU, AFCOMPO20, AF20 and UNFEDAC20 scenarios. Yet, for these scenarios, the share of these two regions combined in global additional natural land loss (as compared to the BFS20 scenario) is often less than 33%. This reinforces the importance of these regions as hotspots of biodiversity loss from future aquaculture development: not only would the local demand for crop aquafeed increase in these regions, but the local ecosystems are particularly important for biodiversity (as measured in terms of global extinction risks).

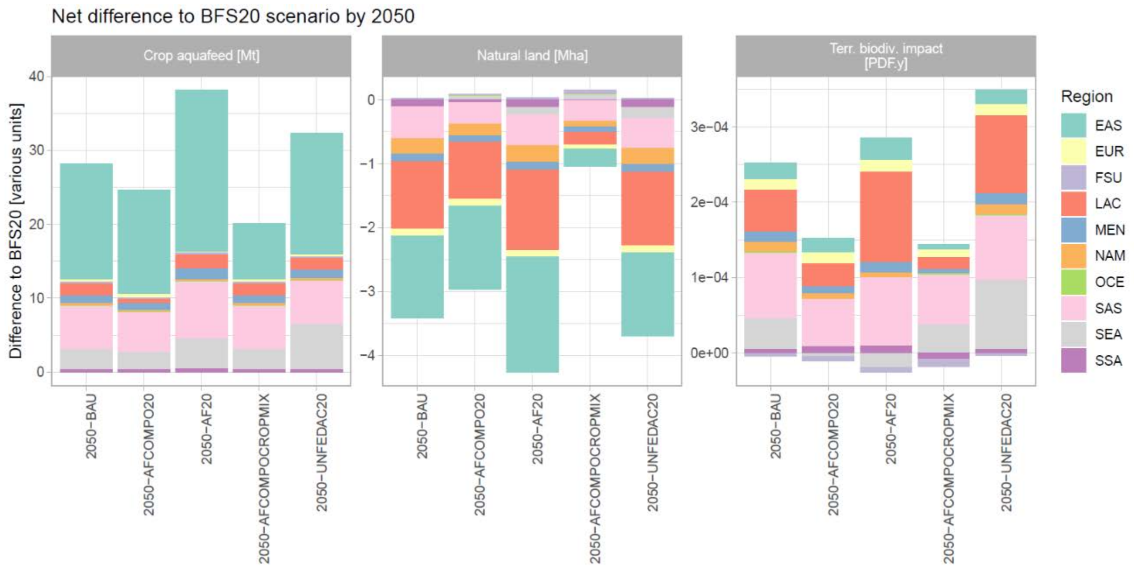

Figure 42 - Net difference between the BAU and AF20 scenarios after 2020, in crop aquafeed use (left panel, million tons), extent of natural land cover (middle panel, million hectares) and total extinction risks impact on terrestrial ecosystems (right panel, potentially disappeared fraction). The stacked bars of different colours indicate the different world regions aggregated from original GLOBIOM regions.

Nitrogen losses from finfish aquaculture

Projected aquaculture on-farm nitrogen waste from the fed aquaculture of finfish species is presented in Figure 43. The projected increase in fed aquaculture production is expected to generate additional reactive nitrogen losses, primarily for freshwater species. In the BAU scenario, total on-site N waste in finfish aquaculture is expected to grow from 0.23 million tons of nitrogen (MtN) in 2020, to about 0.31 MtN by 2050 for the BAU scenario (i.e., +36% over 2020-2050). Similarly to total crop aquafeed requirements displayed in Figure 40b, values projected for the various sensitivity scenarios show that assuming constant feeding practices (in terms of efficiency and aquafeed composition) to 2020 levels would lead to significantly higher losses (+58% over 2020-2050 for the AF20 scenario), while changes to the proportion of various crops in total crop aquafeed requirements could also impact nitrogen waste (e.g., +22% over 2020-2050).

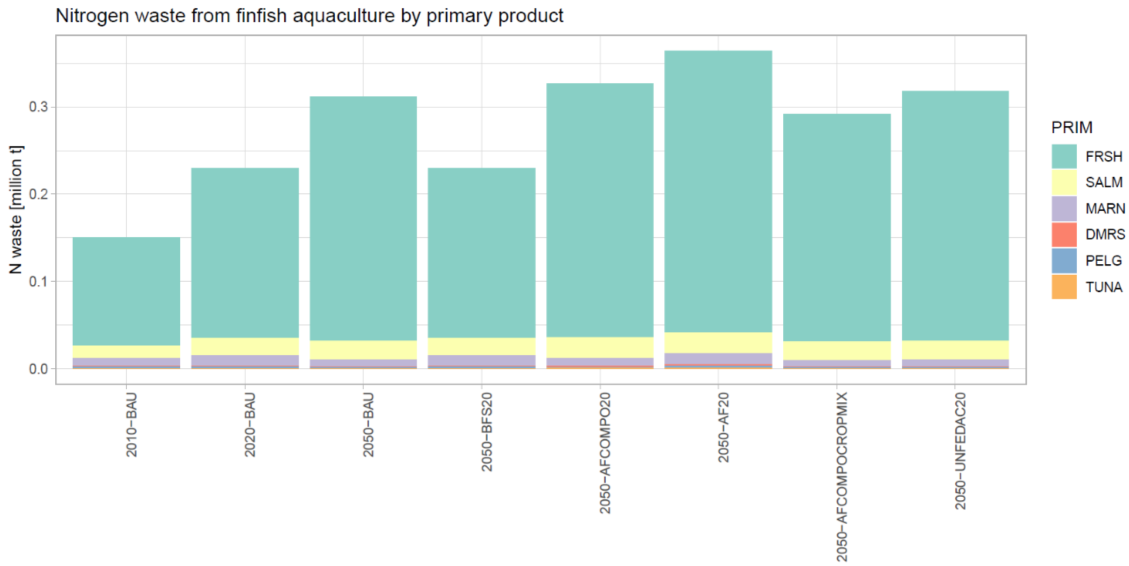

Figure 43 - Projected nitrogen losses in finfish aquaculture at global scale.

Discussion

The projections presented in this deliverable explore various factors that might affect the potential developments of the blue food sector, and their impacts on terrestrial biodiversity through increases in the use of crops as an input to aquaculture. The projections rely on a baseline scenario depicting a prolongation of historical trends, as well as additional scenarios designed to isolate the impact of various assumptions (sensitivity scenarios) or to provide a counterfactual in which the blue food sector remains constant at 2020 level while the land use and agricultural sector follow baseline trends.

One important driver will be the projected future increase in the demand for blue food products. Our BAU projections for population and dietary preferences projects a slowed but prolonged increase in blue food products' demand. The expected increase varies across products, partly driven by expected limitations in supply: in particular, demand is projected to remain stable at the global scale for products groups based on wild catch (despite increases and decreases at regional scale) but to increase significantly for products based on aquaculture production systems (up to +51% over 2020-2050 for freshwater fish). The projected demand increase is particularly important in Eastern Asia (which currently dominates freshwater fish consumption) and in regions with significant future increases in population, like South Asia and Sub-Saharan Africa. The demand for fish meal and fish oil is expected to continue decreasing, unless historical trends in aquaculture feeding practices (in terms of overall feeding efficiency and aquafeed composition) do not continue in the future. These trends are consistent with other studies (Naylor et al 2021; OECD-FAO 2024). As highlighted during the stakeholder workshop, it might be of interest to explore an alternative scenario focusing on a shift in consumer preferences away from historical trends, towards low trophic level-species (e.g., farmed bivalves, seaweed, herbivorous fish species) with higher levels of environmental sustainability (Gephart et al., 2021; Slater & James, 2023).

Another important determinant will be trends in the capacity of various sources and feeding practices in aquaculture. Reflecting historical trends, our baseline projection assumes a stable capacity from wild catch, and a significant increase from unfed (+45% over 2020-2050) and fed (+57% over 2020-2050) aquaculture, although slower than in recent decades. Our baseline scenario also assumes further increases in efficiency (i.e., decreased in economic feed conversion ratio) and aquafeed composition (further replacement of fish meal and fish oil by crop-based aquafeeds) within fed aquaculture, as well as further increases in the use of fish waste in the reduction of fish into fish meal and fish oil. This leads to decreasing demand for fish meal and fish oil, a decrease in the fish reduction-related pressure on marine and pelagic species, and to moderate increases in crop aquafeed requirements compared to projected increases in feed aquaculture supply (e.g., respectively +40% and +57% over 2020-2050).

Projections for the sensitivity scenarios enable to capture the impact of these assumptions, and show for example that assuming the capacity of unfed aquaculture to remain at 2020 levels would lead to slightly higher developments of fed aquaculture (e.g., for freshwater species), but also to reduced demand for products heavily reliant on unfed aquaculture, such as crustaceans. Sensitivity analysis also showed that fish meal and oil demand would increase further if aquaculture feeding practices were maintained at 2020 levels, with however, opposite effects of assumed further feeding efficiency gains (leading to significant savings in crop aquafeed) and replacement of fish-based by crop-based aquafeed (leading to moderate increase in crop aquafeed). The sensitivity scenarios also highlighted that assumptions about the crop mix in crop aquafeed have important implications for projected levels of crop aquafeed requirements, not only for individual crops (which may vary in their place of production and potential impacts on biodiversity) but also for total crop aquafeed biomass requirements (through differences in the nutrition profile of various crops). While our baseline scenario assumes regionally differentiated crop aquafeed mix (based on (Froehlich, Runge, et al., 2018)), those are assumed to remain constant over time. There is limited information available in the literature as such data is not covered in official statistics and is often derived from industry self-reporting.

More broadly, it should be recognised that several parameters related to feeding practices are relatively uncertain. For example, in a review, (Roberts et al., 2024) highlighted a large variation in estimates of the fish in-fish out ratio (related to aquaculture fish-based aquafeed feeding efficiencies, but also reduction sector and wild catch efficiencies). This contributes to uncertainties in overall future trends, and highlights the value of scenario and model-based analysis, as a structured approach to estimating system-wide impacts of variations in these assumptions. Nevertheless, based on feedback from stakeholders, a scenario picturing novel integrated aquaculture systems (Valenti & Ballester, 2024) would be of interest, but might be challenging due to related data needs and model developments. Similarly, it might be of interest to develop scenarios looking into alternative assumptions about the capacity of wild catch, for example around sustainable fisheries management (e.g., (Elleby et al., 2025)) although related data and model improvements might be beyond the scope of the CLEVER project.

Lastly, our projections allow to frame projections of crop aquafeed demand within broader changes to the agricultural and land use sectors by 2050 and isolate the specific impacts of additional crop aquafeed requirements on terrestrial biodiversity through land use change. In our estimates, crop aquafeed requirements represent only a few percents of global crop production in 2020, and this share is not expected to increase by 2050, unless the future changes in feeding practices assumed in the BAU do not materialize. Over the same period, we project more than 300 million hectares of forest and non-forest natural land to be converted to agriculture, with very little variation across scenarios, suggesting that future trends in the blue food sector will have limited impact on land use change at the global scale, and that the specific impacts of future aquafeed requirements maybe challenging to capture. We could isolate these specific impacts by using a counterfactual scenario in which the blue food sector (demand, supply, feeding practices) remains constant at 2020 level, and investigate the role of various assumptions about future trends in the blue food sector by comparing impacts between the counterfactual and not only the baseline scenario, but also to the sensitivity scenarios.

We found the impacts on global terrestrial species extinction risks from land occupation attributable to future crop aquafeed requirements to be negative but moderate, and our results illustrate at least four different sources of complexities when estimating those. First, assumptions about future trends in aquaculture feeding practices such as overall efficiency and share of crop- vs. fish-based aquafeed will modulate the future increase in total crop aquafeed demand, with some of these factors (e.g., increased overall efficiency vs. increased share of crop-based products in total aquafeed) expected to play in opposite direction. Second, the relationship between natural land loss and biodiversity loss is variable, due to spatial differences in biodiversity patterns not only across but within regions. For example, the amount of global species extinction risks relative to natural land loss was systematically higher for Latin America and Caribbean, as well as South Asia and South-Eastern Asia, than for other world regions, and this link can vary across scenarios. Third, trade dependencies might displace the related increase in crop production to biodiversity hotspots, to an amplitude that may change with change with future trade patterns. For example, while less than 10% of the estimated future increases in crop aquafeed requirements is projected to be located in Latin America and the Caribbean, this region was found to host at least a quarter of global attributable natural land loss in most scenarios, in relation to the demand for crops like soya and corn. Fourth, assumptions about the composition of crop-based aquafeed requirements, whose future patterns are generally not well constrained, can have large applications. For example, we found that replacing half of corn and soya crop aquafeed demand by crops like wheat (with high protein content and grown in temperate regions) in China could significantly reduce risks of biodiversity loss in Latin America and the Caribbean.

At last, we also found the projected developments of in crop aquafeed requirements to generate additional nutrient losses on finfish aquaculture farms, in particular for freshwater aquaculture in Eastern Asia. Similar patterns might be expected for non-finfish aquaculture, and losses are also expected for phosphorous nutrients, pointing to both increased eutrophication risks associated with aquaculture developments, and benefits of integrated aquaculture systems with nutrient recycling (e.g., (Xiao et al., 2017)). In addition, the increased demand for crop aquafeed is likely to generate additional nutrient losses within cropland farms, which might be possible to quantify with our modelling framework.

PROJECT OUTPUTS ACHIEVED

List of Zenodo repositories containing model projections:

- Zenodo record for soy supply chains: https://zenodo.org/records/15875871
- Zenodo record for forest supply chains: https://zenodo.org/records/15829433
- Zenodo record for aquaculture & aquafeed supply chains: https://zenodo.org/records/15875624

REFERENCES

Azuero-Pedraza, C., Lauri, P., Lessa Derci Augustynczik, A., & Thomas, V. (2024). *Managing Forests for Biodiversity Conservation and Climate Change Mitigation*. https://pubs.acs.org/doi/10.1021/acs.est.3c07163

Besnard, S., Koirala, S., Santoro, M., Weber, U., Nelson, J., Gütter, J., Herault, B., Kassi, J., N'Guessan, A., Neigh, C., Poulter, B., Zhang, T., & Carvalhais, N. (2021). Mapping global forest age from forest inventories, biomass and climate data. *Earth System Science Data*, *13*(10), 4881–4896. https://doi.org/10.5194/essd-13-4881-2021

Betts, M. G., Phalan, B. T., Wolf, C., Baker, S. C., Messier, C., Puettmann, K. J., Green, R., Harris, S. H., Edwards, D. P., Lindenmayer, D. B., & Balmford, A. (2021). Producing wood at least cost to biodiversity: Integrating Triad and sharing–sparing approaches to inform forest landscape management. *Biological Reviews*, *96*(4), 1301–1317. https://doi.org/10.1111/brv.12703

Bond, W. (2016). *Ancient grasslands at risk*. https://www.science.org/doi/10.1126/science.aad5132

Brus, D. J., Hengeveld, G. M., Walvoort, D. J. J., Goedhart, P. W., Heidema, A. H., Nabuurs, G. J., & Gunia, K. (2012). Statistical mapping of tree species over Europe. *European Journal of Forest Research*, *131*(1), 145–157. https://doi.org/10.1007/s10342-011-0513-5

Cabernard, L., Pfister, S., & Hellweg, S. (2024). Biodiversity impacts of recent land-use change driven by increases in agri-food imports. *Nature Sustainability*, *7*(11), 1512–1524. https://doi.org/10.1038/s41893-024-01433-4

Choe, J., Hammer, A., & Montgomery, C. (2019). *U.S. SOYBEAN EXPORTS TO CHINA CRUSHED AMID RISING TRADE TENSIONS*.

Cohn, A. S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., & Obersteiner, M. (2014). Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. *Proceedings of the National Academy of Sciences*, *111*(20), 7236–7241. https://doi.org/10.1073/pnas.1307163111

Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M., & Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nature Food*, *1*(5), 301–308. https://doi.org/10.1038/s43016-020-0078-x

Cottrell, R. S., Fleming, A., Fulton, E. A., Nash, K. L., Watson, R. A., & Blanchard, J. L. (2018). Considering land–sea interactions and trade-offs for food and biodiversity. *Global Change Biology*, *24*(2), 580–596. https://doi.org/10.1111/gcb.13873

Cowley, C. (2020). Reshuffling in Soybean Markets following Chinese Tariffs. *The Federal Reserve Bank of Kansas City Economic Review*. https://doi.org/10.18651/er/v105n1cowley

Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, *361*(6407), 1108–1111. https://doi.org/10.1126/science.aau3445

De Maria, M., Robinson, E., Kangile, J. R., Kadigi, R. M., Dreoni, I., Couto, M., Howai, N., Peci, J., & Fiennes, S. (2020). *Global Soybean Trade – The Geopolitics of a Bean*. UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC). https://doi.org/10.34892/7YN1-K494

De Oliveira Silva, R., Barioni, L. G., Queiroz Pellegrino, G., & Moran, D. (2018). The role of agricultural intensification in Brazil's Nationally Determined Contribution on emissions mitigation. *Agricultural Systems*, *161*, 102–112. https://doi.org/10.1016/j.agsy.2018.01.003

Elleby, C., Domínguez, I. P., Nielsen, R., Nielsen, M., & Hoff, A. (2025). Introducing maximum sustainable yield targets in fisheries could enhance global food security. *Communications Earth & Environment*, *6*(1), 33. https://doi.org/10.1038/s43247-024-01851-4

FAO (Ed.). (2018). *The State of World Fisheries and Aquaculture 2018—Meeting the sustainable development goals*.

FAO. (2020). *Global Forest Resources Assessment 2020*. FAO ; https://openknowledge.fao.org/handle/20.500.14283/ca9825en

FAOSTAT. (2025). *Forest Production and Trade*. https://www.fao.org/faostat/en/#data/FO

Frezal, C., & Deuss, A. (2025, February 11). *Trade-related measures linked to the environmental sustainability of agriculture*. OECD. https://www.oecd.org/en/publications/trade-related-measures-linked-to-the-environmental-sustainability-of-agriculture_ebfdca09-en.html

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., … 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. https://doi.org/10.1016/j.gloenvcha.2016.06.004

Froehlich, H. E., Jacobsen, N. S., Essington, T. E., Clavelle, T., & Halpern, B. S. (2018). Avoiding the ecological limits of forage fish for fed aquaculture. *Nature Sustainability*, *1*(6), 298–303. https://doi.org/10.1038/s41893-018-0077-1

Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D., & Halpern, B. S. (2018). Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proceedings of the National Academy of Sciences*, *115*(20), 5295–5300. https://doi.org/10.1073/pnas.1801692115

Fuller, M. R., Ganjam, M., Baker, J. S., & Abt, R. C. (2025). Advancing forest carbon projections requires improved convergence between ecological and economic models. *Carbon Balance and Management*, *20*(1), 2. https://doi.org/10.1186/s13021-024-00290-0

Fulvio, F. D., Snäll, T., Lauri, P., Forsell, N., Mönkkönen, M., Burgas, D., Blattert, C., Eyvindson, K., Caicoya, A. T., Vergarechea, M., Antón-Fernández, C., Klein, J., Astrup, R., Lukkarinen, J., Pitzén, S., & Primmer, E. (2025). Impact of the EU biodiversity strategy for 2030 on the EU wood-based bioeconomy. *Global Environmental Change*, *92*, 102986. https://doi.org/10.1016/j.gloenvcha.2025.102986

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. *Nature*, *597*(7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2

Guidotti, V., Freitas, F. L. M., Sparovek, G., Pinto, L. F. G., Hamamura, C., Carvalho, T., & Cerignoni, F. (2017). *Números detalhados do novo Código Florestal e suas implicações para os PRAs*. https://repositorio.usp.br/item/002937819

Hadjikakou, M., Bowles, N. I., Geyik, O., Conijn, S. J. G., Mogollón, J. M., Bodirsky, B. L., Muller, A., Weindl, I., Moallemi, E. A., Shaikh, M. A., Damerau, K., Davis, K. F., Pfister, S., Springmann, M., Clark, M., Metson, G. S., Röös, E., Bajzelj, B., Graham, N. T., … Bryan, B. A. (2025). Ambitious food system interventions required to mitigate the risk of exceeding Earth’s environmental limits. *One Earth*, 101351. https://doi.org/10.1016/j.oneear.2025.101351

Halpern, B. S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J. L., Cottrell, R. S., Froehlich, H. E., Gephart, J. A., Jacobsen, N. S., Kuempel, C. D., McIntyre, P. B., Metian, M., Moran, D., Nash, K. L., Többen, J., & Williams, D. R. (2022). The environmental footprint of global food production. *Nature Sustainability*, *5*(12), 1027–1039. https://doi.org/10.1038/s41893-022-00965-x

Henders, S., Persson, U. M., & Kastner, T. (2015). Trading forests: Land-use change and carbon emissions embodied in production and exports of forest-risk commodities. *Environmental Research Letters*, *10*(12), 125012. https://doi.org/10.1088/1748-9326/10/12/125012

Humpenöder, F., Popp, A., Dietrich, J. P., Klein, D., Lotze-Campen, H., Bonsch, M., Bodirsky, B. L., Weindl, I., Stevanovic, M., & Müller, C. (2014). Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, *9*(6), 064029. https://doi.org/10.1088/1748-9326/9/6/064029

IBF-IIASA. (2023). *Global Biosphere Management Model (GLOBIOM) Documentation 2023—Version 1.0*. International Institute for Applied Systems Analysis. https://pure.iiasa.ac.at/18996

IFPRI. (2025a, April 8). How ‘reciprocal tariffs’ harm agricultural trade. *IFPRI*. https://www.ifpri.org/blog/how-reciprocal-tariffs-harm-agricultural-trade/

IFPRI. (2025b, April 21). U.S.-China trade war 2.0: What are the implications for global oilseed markets? *IFPRI*. https://www.ifpri.org/blog/u-s-china-trade-war-2-0-what-are-the-implications-for-global-oilseed-markets/

IIASA. (2018). *SSP Database—Version 2.0*. https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome

IIASA. (2021). *ENGAGE Scenario Explorer*. https://data.ece.iiasa.ac.at/engage/#/login

IIASA. (2025). *GLOBIOM-forest documentation*. GitHub. https://github.com/iiasa/GLOBIOM_forest/blob/main/GLOBIOM_forest_documentation.pdf

IPCC. (2019). *Harvested wood products—2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Vol. 4). https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch12_HarvestedWoodProducts.pdf

Johnston, C. M. T., & Radeloff, V. C. (2019). Global mitigation potential of carbon stored in harvested wood products. *Proceedings of the National Academy of Sciences*, *116*(29), 14526–14531. https://doi.org/10.1073/pnas.1904231116

Lauri, P., Forsell, N., Di Fulvio, F., Snäll, T., & Havlik, P. (2021). Material substitution between coniferous, non-coniferous and recycled biomass – Impacts on forest industry raw material use and regional competitiveness. *Forest Policy and Economics*, *132*, 102588. https://doi.org/10.1016/j.forpol.2021.102588

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H. M., Chaudhary, A., De Palma, A., DeClerck, F. A. J., Di Marco, M., Doelman, J. C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J. P., Hill, S. L. L., Humpenöder, F., Jennings, N., Krisztin, T., … Young, L. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, *585*(7826), 551–556. https://doi.org/10.1038/s41586-020-2705-y

Lesiv, M., Schepaschenko, D., Buchhorn, M., See, L., Dürauer, M., Georgieva, I., Jung, M., Hofhansl, F., Schulze, K., Bilous, A., Blyshchyk, V., Mukhortova, L., Brenes, C. L. M., Krivobokov, L., Ntie, S., Tsogt, K., Pietsch, S. A., Tikhonova, E., Kim, M., … Fritz, S. (2022). Global forest management data for 2015 at a 100 m resolution. *Scientific Data*, *9*(1), 199. https://doi.org/10.1038/s41597-022-01332-3

Mishra, A., Humpenöder, F., Churkina, G., Reyer, C. P. O., Beier, F., Bodirsky, B. L., Schellnhuber, H. J., Lotze-Campen, H., & Popp, A. (2022). Land use change and carbon emissions of a transformation to timber cities. *Nature Communications*, *13*(1), 4889. https://doi.org/10.1038/s41467-022-32244-w

Mishra, A., Humpenöder, F., Dietrich, J. P., Bodirsky, B. L., Sohngen, B., P. O. Reyer, C., Lotze-Campen, H., & Popp, A. (2021). Estimating global land system impacts of timber plantations using MAgPIE 4.3.5. *Geoscientific Model Development*, *14*(10), 6467–6494. https://doi.org/10.5194/gmd-14-6467-2021

Naylor, R. L., Kishore, A., Sumaila, U. R., Issifu, I., Hunter, B. P., Belton, B., Bush, S. R., Cao, L., Gelcich, S., Gephart, J. A., Golden, C. D., Jonell, M., Koehn, J. Z., Little, D. C., Thilsted, S. H., Tigchelaar, M., & Crona, B. (2021). Blue food demand across geographic and temporal scales. *Nature Communications*, *12*(1), 5413. https://doi.org/10.1038/s41467-021-25516-4

OECD/FAO. (2024, July 2). *OECD-FAO Agricultural Outlook 2024-2033*. https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2024-2033_4c5d2cfb-en/full-report.html

Oliveira, U., & Pacheco, A. (2024). *Deliverable 2.4: Biodiversity impact database including characterization factors and documentation ready for Module C*. Zenodo. https://doi.org/10.5281/zenodo.13640620

Oliveira, U., Soares-Filho, B. S., Santos, A. J., Paglia, A. P., Brescovit, A. D., de Carvalho, C. J. B., Silva, D. P., Rezende, D. T., Leite, F. S. F., Batista, J. A. N., Barbosa, J. P. P. P., Stehmann, J. R., Ascher, J. S., Vasconcelos, M. F., Marco, P. D., Löwenberg-Neto, P., & Ferro, V. G. (2019). Modelling Highly Biodiverse Areas in Brazil. *Scientific Reports*, *9*(1), 6355. https://doi.org/10.1038/s41598-019-42881-9

Pendrill, F., Persson, U. M., Godar, J., & Kastner, T. (2019). Deforestation displaced: Trade in forest-risk commodities and the prospects for a global forest transition. *Environmental Research Letters*, *14*(5), 055003. https://doi.org/10.1088/1748-9326/ab0d41

Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., & Wood, R. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, *56*, 1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002

Pereira, H., Martins, I., Rosa, I., Kim, H., & Leadley, P. (2024). *Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050*. https://doi.org/10.1126/science.adn3441

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

protected planet. (2025). *Protected Areas (WDPA)*. Protected Planet. https://www.protectedplanet.net/en/thematic-areas/wdpa

Riviere, M., Caurla, S., & Delacote, P. (2020). Evolving Integrated Models From Narrower Economic Tools: The Example of Forest Sector Models. *Environmental Modeling & Assessment*, *25*(4), 453–469. https://doi.org/10.1007/s10666-020-09706-w

Roberts, S., Jacquet, J., Majluf, P., & Hayek, M. N. (2024). Feeding global aquaculture. *Science Advances*, *10*(42), eadn9698. https://doi.org/10.1126/sciadv.adn9698

Salles, J.-M., Teillard, F., Tichit, M., & Zanella, M. (2017). Land sparing versus land sharing: An economist's perspective. *Regional Environmental Change*, *17*(5), 1455–1465. https://doi.org/10.1007/s10113-017-1142-4

Schilling-Vacaflor, A., & Lenschow, A. (n.d.). *Bringing the State back in: Exploring new public environmental policy approaches for governing the Brazil-Europe soy chain.*

Schipper, A. M., Hilbers, J. P., Meijer, J. R., Antão, L. H., Benítez-López, A., de Jonge, M. M. J., Leemans, L. H., Scheper, E., Alkemade, R., Doelman, J. C., Mylius, S., Stehfest, E., van Vuuren, D. P., van Zeist, W.-J., & Huijbregts, M. A. J. (2020). Projecting terrestrial biodiversity intactness with GLOBIO 4. *Global Change Biology*, *26*(2), 760–771. https://doi.org/10.1111/gcb.14848

Schulte, M., Lauri, P., & Di Fulvio, F. (2025). Global forest carbon leakage and substitution effect potentials: The case of the Swedish forest sector. *Carbon Balance and Management (in Review)*.

Slater, M., & James, P. (2023). Low trophic species in aquaculture—Growth and research challenges. *Journal of the World Aquaculture Society*, *54*(1), 4–6. https://doi.org/10.1111/jwas.12944

Soterroni, A. C., Mosnier, A., Carvalho, A. X. Y., Câmara, G., Obersteiner, M., Andrade, P. R., Souza, R. C., Brock, R., Pirker, J., Kraxner, F., Havlík, P., Kapos, V., Zu Ermgassen, E. K. H. J., Valin, H., & Ramos, F. M. (2018). Future environmental and agricultural impacts of Brazil's Forest Code. *Environmental Research Letters*, *13*(7), 074021. https://doi.org/10.1088/1748-9326/aaccbb

Sotirov, M., Azevedo-Ramos, C., Rattis, L., & Berning, L. (2022). Policy options to regulate timber and agricultural supply-chains for legality and sustainability: The case of the EU and Brazil. *Forest Policy and Economics*, *144*, 102818. https://doi.org/10.1016/j.forpol.2022.102818

Spillias, S., Blanchard, J. L., Castro-Cadenas, M. D., Cottrell, R. S., Depperman, A., Frank, S., Leclere, D., Tran, N., & Havlik, P. (2025). *Integrating Blue Foods into Future Estimates of Land-Use Change (manuscript in preparation)*.

Stehfest et al. (2019). *Key determinants of global land-use projections*. https://www.nature.com/articles/s41467-019-09945-w

Tacon, A. G. J., & Metian, M. (2015). Feed Matters: Satisfying the Feed Demand of Aquaculture. *Reviews in Fisheries Science & Aquaculture*, *23*(1), 1–10. https://doi.org/10.1080/23308249.2014.987209

United Nations. (2025). *UN Comtrade*. https://comtradeplus.un.org/

Valenti, W. C., & Ballester, E. L. (2024). Integrated Aquaculture and Monoculture of Low-Trophic Species. *Fishes*, *9*(11), 450. https://doi.org/10.3390/fishes9110450

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C. L., Margni, M., … Huijbregts, M. A. J. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. *Journal of Industrial Ecology*, *24*(6), 1201–1219. https://doi.org/10.1111/jiec.13018

World Economic Forum. (2018, May 18). *Brazil's forests could fall victim to the US-China trade war*. World Economic Forum. https://www.weforum.org/stories/2018/05/brazil-forests-could-be-casualties-in-u-s-china-trade-war/

World Economic Forum. (2025, May 15). *How Brazil and China can deliver on sustainability goals*. World Economic Forum. https://www.weforum.org/stories/2025/05/brazil-and-china-can-transform-the-sustainability-of-soy-supply-chains/

Wu, W., Hasegawa, T., Ohashi, H., Hanasaki, N., Liu, J., Matsui, T., Fujimori, S., Masui, T., & Takahashi, K. (2019). Global advanced bioenergy potential under environmental protection policies and societal transformation measures. *GCB Bioenergy*, *11*(9), 1041–1055. https://doi.org/10.1111/gcbb.12614

Xiao, X., Agusti, S., Lin, F., Li, K., Pan, Y., Yu, Y., Zheng, Y., Wu, J., & Duarte, C. M. (2017). Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Scientific Reports*, *7*(1), 46613. https://doi.org/10.1038/srep46613

Zhao, J., Wei, X., & Li, L. (2022). The potential for storing carbon by harvested wood products. *Frontiers in Forests and Global Change*, *5*. https://doi.org/10.3389/ffgc.2022.1055410

Ziegert, R. F., & Sotirov, M. (2024). Regulatory politics and hybrid governance: The case of Brazil's Amazon Soy Moratorium. *Global Environmental Change*, *88*, 102916. https://doi.org/10.1016/j.gloenvcha.2024.102916

Zilli, M., Scarabello, M., Soterroni, A. C., Valin, H., Mosnier, A., Leclère, D., Havlík, P., Kraxner, F., Lopes, M. A., & Ramos, F. M. (2020). The impact of climate change on Brazil's agriculture. *Science of The Total Environment*, *740*, 139384. https://doi.org/10.1016/j.scitotenv.2020.139384

APPENDIX

Stakeholder workshop for soy supply chain scenarios

To support the model and scenario work, a two-hour online stakeholder workshop took place on May 14th 2025.

Potential participants were identified through the CLEVER stakeholder mapping, and 31 participants responded positively to the invitation, of which 23 participated. Of the 23 participating stakeholders, 11 were from NGOs, 6 from the public sector (including both national government and international organizations), and 6 from the private sector. The majority of participating stakeholders were based in Brazil and Europe, and 2 were based in Northern America.

The goal of the workshop was to gather input from stakeholders on relevant scenarios and modelling features for the soy sector and its impact on biodiversity, with a specific focus on Brazil-EU soy supply chains. The workshop consisted of: a) a 10 min welcome and introduction session, b) a 20min presentation from IIASA on model improvements, potential scenario options and preliminary results, followed by a Q&A, c) a first breakout session where experts were asked to share their vision for the soy sector by 2050 (4 breakout groups for 10min followed by a 10min reporting back in plenary, with note taking on the whiteboard), d) a second breakout session where experts were asked to identify their preferred scenario options and discuss the likely impact of the selected policies/stylized interventions on soy exports and biodiversity (4 breakout groups for 10min followed by a 10min reporting back in plenary, with note taking on the whiteboard), and e) a 5min closing session. All participants were provided with the presentation and the whiteboard, as well as a link to a form for any additional feedback they wish to provide.

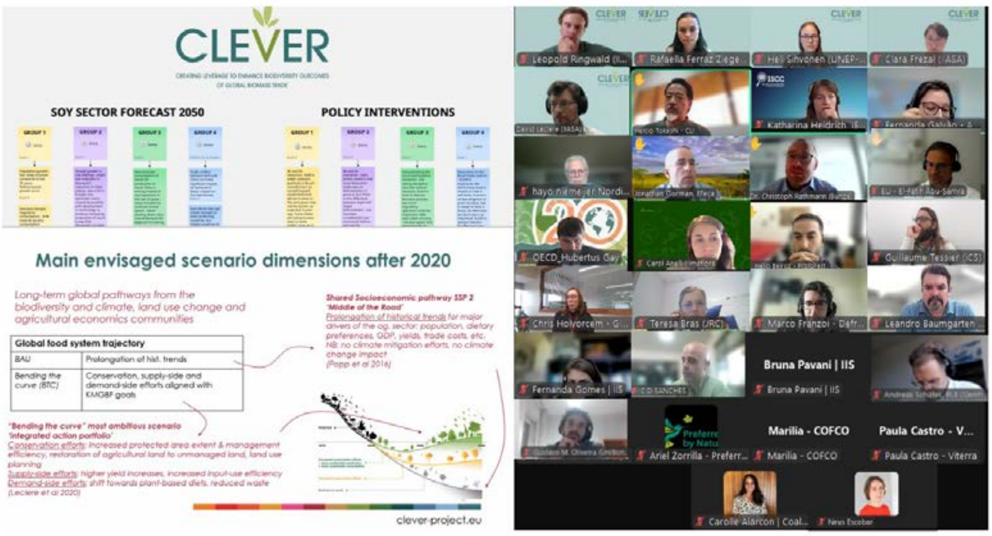

Figure 44. Linkedin post posted after the workshop, which includes a screenshot of the white board, of IIASA presentation and of the zoom participants.

Stakeholder workshop for forestry supply chain scenarios

To support the model and scenario work, a 90 min online stakeholder workshop took place on Dec. 4th. 2024.

Potential participants were identified through the CLEVER stakeholder mapping, and 10 participants responded positively to the invitation, of which 9 participated. Of the 9 participating stakeholders, 4 were from NGOs, 1 from the public sector, 2 from public research organizations, and 2 from the private sector. Almost all participating stakeholders were based in Europe, except for 1 based in Latin America.

The goal of the workshop was to gather input from stakeholders on relevant scenarios and modelling features for the forestry supply chains. The workshop consisted of a 10 min welcome & introduction session, followed by a first session introducing the CLEVER work (15 min presentation from IIASA on research objectives, preliminary scenario ideas and quantification, followed by 10 min for clarification questions), a breakout session in which stakeholders were asked to provide they vision for the sector by 2050 (4 breakout groups for 15 min, 15 for reporting in plenary with note taking on the whiteboard), a plenary moderated discussion on feedback for model and scenario (20 min, focused on missing scenario elements, important indicators to quantify and policies to consider) and a closing session (5 min). All participants were provided with the presentation and the whiteboard, as well as a link to a form for any additional feedback they wish to provide.

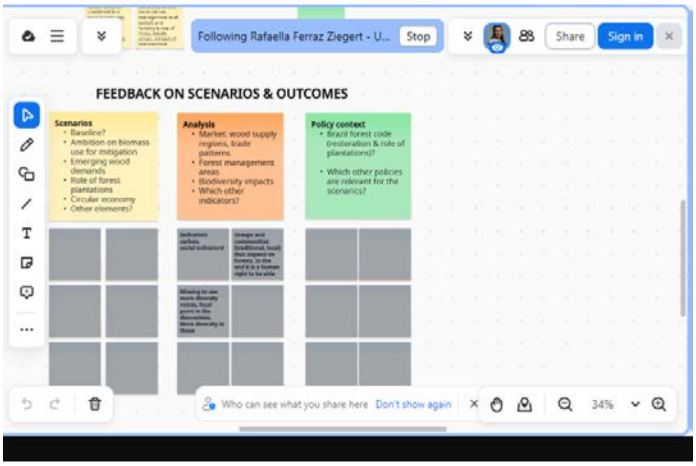

Figure 45. Screen capture of Zoom session screen, sharing the note taking on the whiteboard as participants discuss during the feedback plenary on scenarios, indicators and policies.

Stakeholder workshop for aquaculture & aquafeed supply chain scenarios

To support the model and scenario work, a 90 min online stakeholder workshop took place on Dec. 4th. 2024.

Potential participants were identified through the CLEVER stakeholder mapping, and 18 participants responded positively to the invitation, of which 16 participated. Of the 16 participating stakeholders, 4 were from NGOs, 6 from public research organizations, and 6 from the private sector. The majority of participating stakeholders were based in Europe, while 2 were based in Northern America, 1 in Latin America, and 1 in Africa.

The goal of the workshop was to gather input from stakeholders on relevant scenarios and modelling features for the aquaculture sector and its biodiversity impacts through aquafeed. The workshop consisted of a 10 min welcome & introduction session, followed by a first session introducing the CLEVER work (15 min presentation from IIASA on research objectives, preliminary scenario ideas and quantification, followed by 10 min for clarification questions), a breakout session in which stakeholders were asked to provide they vision for the sector by 2050 (4 breakout groups for 15 min, 15 for reporting in plenary with note taking on the whiteboard), a plenary moderated discussion on feedback for model and scenario (20 min, focused on missing scenario elements and important indicators to quantify) and a closing session (5 min). All participants were provided with the presentation and the whiteboard, as well as a link to a form for any additional feedback they wish to provide.

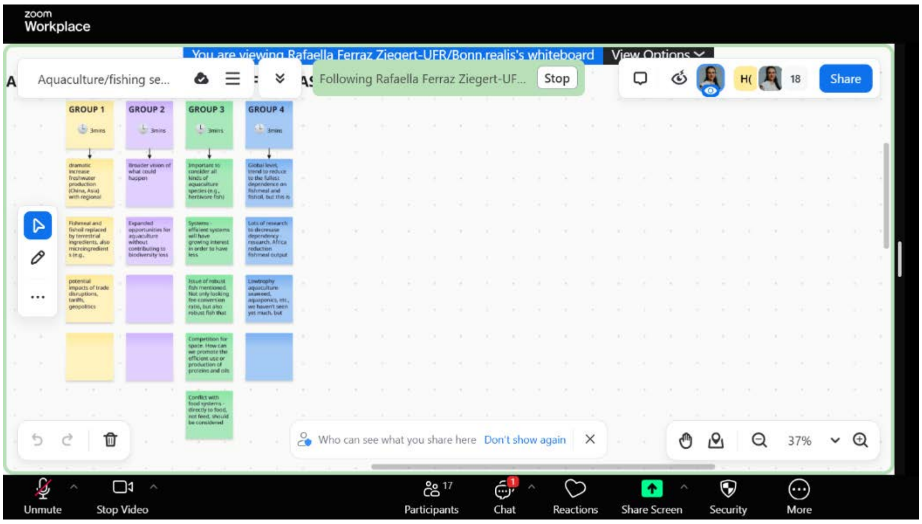

Figure 46. Screen capture of Zoom session screen, sharing the note taking on the whiteboard as participants report on their breakout discussions on their vision for the sector by 2050.

Model improvements for soy supply chains

Implementation of Brazilian environmental protection regulations and land-use restrictions in GLOBIOM

As part of an effort to improve the representation of land use dynamics in Brazil in the CLEVER project, various mechanisms to simulate the land-use restrictions and protection of forests and other natural areas in Brazil have been incorporated into GLOBIOM, largely based on the framework established by (Soterroni et al., 2018). These include representations of the Mata Atlântica law, the Brazilian Forest Code, the Amazon Soy Moratorium, and restrictions on agricultural expansion in the Caatinga biome.

The Mata Atlântica law (law 11.428/2006) is implemented in the GLOBIOM model as a complete prohibition of deforestation in the Mata Atlântica biome from 2010 onwards. In the Amazon and Cerrado biomes, restrictions on deforestation under the Brazilian Forest Code apply from 2020 onwards. These restrictions are modelled as more permissive than the Mata Atlântica law such that the deforestation constraints are adjusted by enforcement probabilities (ranging between zero and one) that are assigned to each simulation unit. The probabilities determine the extent of possible deforestation, ranging from full clearance at one extreme to a more restrictive limit where only surplus forest (including primary forest, managed forest, and regrowth at the start of the simulation period) beyond the Legal Reserve threshold remains open to deforestation. The Brazilian law 12.651/2012 mandates all rural properties to maintain an area covered by native vegetation, as a Legal Reserve. The Legal Reserve requirement and the enforcement probabilities were also used in (Soterroni et al., 2018), where the probabilities were estimated based on historical data on policing deforestation and related costs.

Besides preventing future deforestation, the GLOBIOM model also accounts for the compensation of environmental debt arising from past illegal deforestation. This mechanism is structured around the Legal Reserve requirements and considers the Small Farms Amnesty, which exempts farms below regional size thresholds from compensating for pre-2008 deforestation (Guidotti et al., 2017). Compensation for environmental debt is fulfilled through Environmental Reserve Quotas (*Cotas de Reserva Ambiental*, CRA). The model assumes that surplus forest from other simulation units within the same biome may compensate for this debt, with the exception that only 20% of the surplus forest in the federal state of Amazonas is eligible. This limitation reflects the assumption from (Soterroni et al., 2018) that only 20% of unclaimed public lands in this state will be designated as private properties and thus enter the CRA system. It also safeguards that the large forest surpluses from this state cannot compensate all forest debt within the Amazonia biome. In GLOBIOM, surplus forest is distributed across simulation units within a biome, prioritizing those with the greatest deforestation debt. The unit with the largest debt absorbs as much of the surplus as possible before the remaining surplus is allocated to the next most indebted unit, continuing until either all debt or all surplus is exhausted. The same logic applies to assigning deforestation debt to units with surplus forest, but here the allocation is capped at a fraction of each unit's forest surplus to ensure a broader distribution of the burden. After this process, any remaining debt must be repaid through reforestation during the 2030 simulation period. This reforestation is modelled as the conversion of former cropland (used only for sugarcane and soybean production) or pastureland into protected forest. Once reforested, the land remains protected in all subsequent simulation periods.

The Amazon Soy Moratorium is a voluntary agreement established in 2006 by major soybean traders to prevent deforestation in the Amazon biome for soybean cultivation. Under the moratorium, traders commit to not purchase soy grown on land deforested after July 2008 in the Amazon, using satellite monitoring to enforce compliance. The moratorium is modeled by restricting soybean cultivation in the Amazon biome from 2020 onwards to land already used for growing soy in 2010, the previous simulation period. This timing was selected due to the model's 10-year simulation intervals, with the closest reference year being 2010. The restriction is applied uniformly across all simulation units in the biome. Under this mechanism, the total area of soybean cultivation in the biome remains fixed at 2010 levels, while production increases remain possible via yield trends and endogenous shifts to more efficient management practices.

In addition, the GLOBIOM model limits cropland and grassland expansion in the Caatinga biome based on (Soterroni et al., 2018) to match the historical trends of these landcovers driven by local water scarcity and uncertainty. This corresponds to a maximal expansion of both landcovers of 10% per 10-year simulation period.

The introduction of these mechanisms into GLOBIOM provides a structured representation of forest protection policies and land-use restrictions in Brazil, simulating their implementation and effects within the model's framework.]

Improvement of soy production system dynamics

As detailed in deliverable D6.2, we introduced several changes to the representation of soy production systems in Brazil to better represent their dynamics in terms of area expansion and production volumes at subnational level. This included the introduction of a soy-corn double cropping system (in addition to single soy cropping systems), the increase of the spatial resolution of land use and soy production system area variables to 30 arcminute grid cells, the initialization of related biophysical parameters (e.g., soya and corn yields and input requirements) by production system and grid cell with estimates from the EPIC crop model generated in CLEVER (see D6.1), the initialization of the spatial distribution of land uses and soy planted areas by production system and grid cell with municipality-level data from Brazilian remote sensing products and statistics, and the calibration of planted area expansion rate parameters at the state-level.

Since D6.2, additional developments took place towards the same objective. First, the parameterization of historical yield trends (2000-2020) was adjusted: instead of national level trends for all production systems, we introduced state-level and production system-specific (i.e., single soy vs soy-corn double cropping) trends derived from municipal-level Brazilian statistics. After 2020, national yield trends from the SSP2 scenario applies on top of the state-level 2020/2000 yields trends. Second, we subsequently re-estimated the calibration of state-level parameters for the planted area expansion of individual soy production systems. Third, we also specified a set of simple rules for the post-2020 evolution of the planted area expansion rate parameters, based on an analysis of historical values: a) the rate of soy-corn double cropping expansion per decade decreases as the share of this system in total soy harvested area in previous time step increases, b) the rate of expansion of single soy production system per decade converges to a value of +50%, with a speed that increases with the expansion rate value from the previous time step.

Preliminary results are shown in Figure 47 for soy harvested area and production volume by production system at the state level for 2000, 2010 and 2020, and in Figure 48 in terms of 2000-2020 trends in specific dimensions (total soy harvested area, share of double cropping within soy harvested area, yield, production) of soy production systems at the biome level.

These preliminary results highlight that the main historical developments of harvested areas and yields by production system at the state-level are broadly captured, despite deviations to statistical data at the level of individual states, production system and time horizons. Deviations to the observations can be explained by several reasons. First, despite the improvement of some parameter estimates through revised input data and calibration, several parameters (e.g., differences across grid cells within a state in yields, or in the maximum rate of harvested area expansion by cropping system) remain weakly constrained and/or informed by datasets from various sources that are not necessarily compatible (e.g., soy yields from EPIC and municipal-level harvested area statistics). Second, in such a situation, there are trade-offs in the choice of best parameter at the calibration stage, for example between outcome variables (i.e., harvested area vs production) or between time horizons (e.g., 2010 vs 2020). For these two sources of deviation, a better fit to observation might be achieved via increasing the number of parameters calibrated and/or revised for a finer estimate, or calibrate different values for different time horizons. However, such an improved behaviour over recent historical period might not necessarily lead to of a more realistic simulation of future trends. On the other hand, as shown for example by the underestimation of increases in soy harvested area in the Amazon biome from 2010 to 2020, our assumed effect of Amazon Soy Moratorium (no increase in harvested area after 2010, see previous section) might be improved, and this might lead to better estimates of future trends in the Amazon biome.

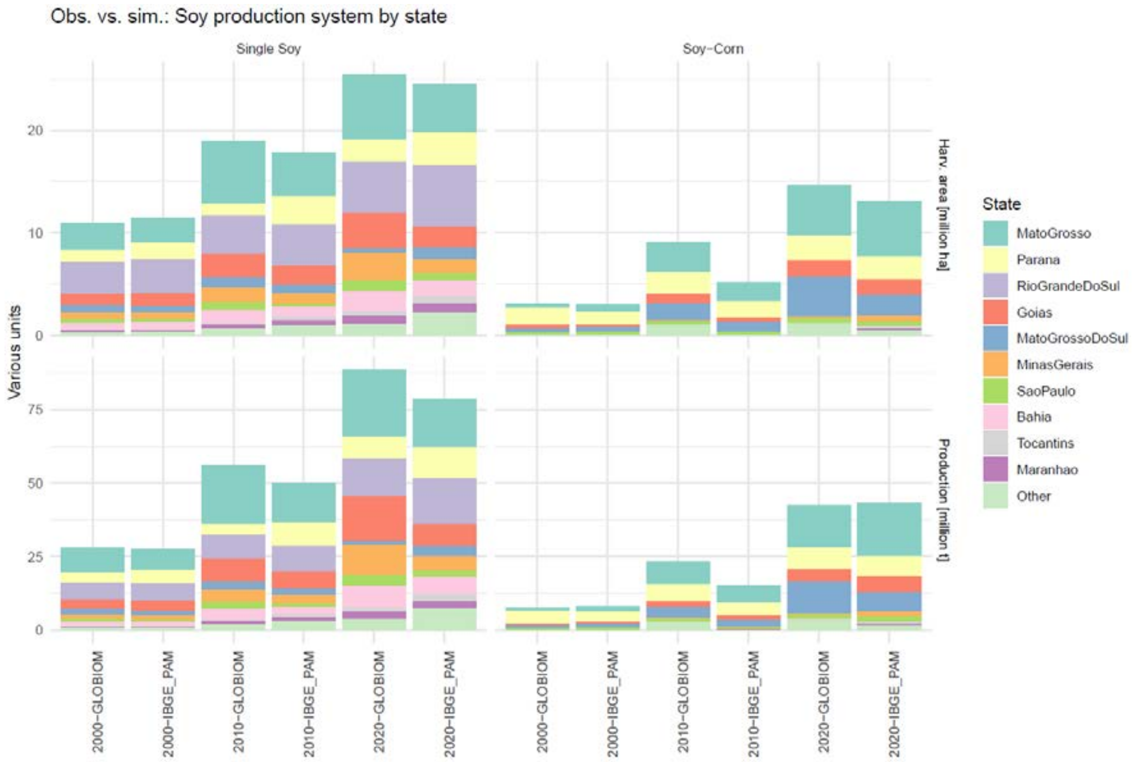

Figure 47 - Comparison of observed (IBGE-PAM) and simulated (GLOBIOM) harvested areas (in million ha) and production volume (in million t) by soy production systems and state over 2000-2020

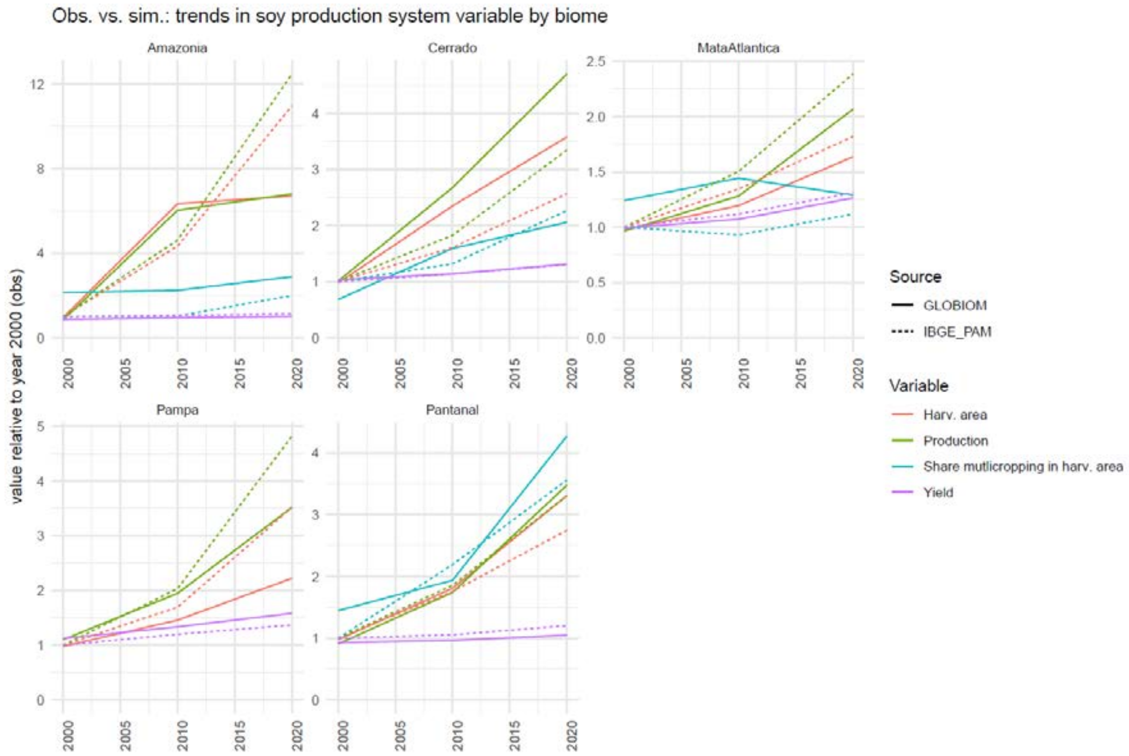

Figure 48 - Comparison of observed (IBGE PAM) vs simulated (GLOBIOM) trends in various aspects (harvested area, production volume, yield and share of soy-corn double cropping in total harvested area) of soy production systems over 2000-2020 at the biome level. For each aspect and biome, values are time horizon- and source-specific (i.e., observed vs simulated) values normalized by the value for year 2000 in the observation dataset.

Model improvements for forest supply chains

Details on the modelling framework for forest supply chains can be found in the deliverable D6.2 while additional model improvements supporting this deliverable (i.e. inclusion of forest age structure, HWP and BECCS accounting, natural land division) are detailed below.

Age-class dynamics and forest management

Forest age-class dynamics in GLOBIOM works similarly than in large-scale area-based matrix models such as the European Forestry Dynamics Model (EFDM) (Packalen et al. 2023) or the European Forest Information Scenario Model (EFISCEN) (Schelhaas et al. 2007). The main difference between GLOBIOM and these models is that harvest decisions and age-class dynamics are based on economic optimization instead of statistical transition probabilities.

In GLOBIOM, the choice over different management systems and age-classes is made separately for each grid. Each grid consists of multiple even-aged stands which are divided to different age-cohorts. Biomass growth happens through age-class dynamics where after each period the stand area is moved to the next age-cohort. The biomass in each age-cohort follows S-shaped growth curves which are determined by the Chapman-Richards biomass growth model, as in (Humpenöder et al., 2014) and (Mishra et al., 2021). If the stand area is harvested or damaged by natural mortality, then it is moved in the first age-cohort. Since the size of the stand is not defined explicitly, the age-class dynamics can be interpreted either as even-or uneven aged managements.

Figure 49 displays an example of age-class dynamics in GLOBIOM. In 2020, the carbon stock of forests is calibrated to (FAO, 2020) data and downscaled to grid level by utilizing G4M data and global age-class database (Besnard et al., 2021) . After 2020, the carbon stock is determined endogenously by the age-class dynamics. The carbon stock of forests is higher in 2100 than in 2020, because the estimated biomass growth exceeds the estimated biomass removals from the forests (harvests, mortality) during this period.

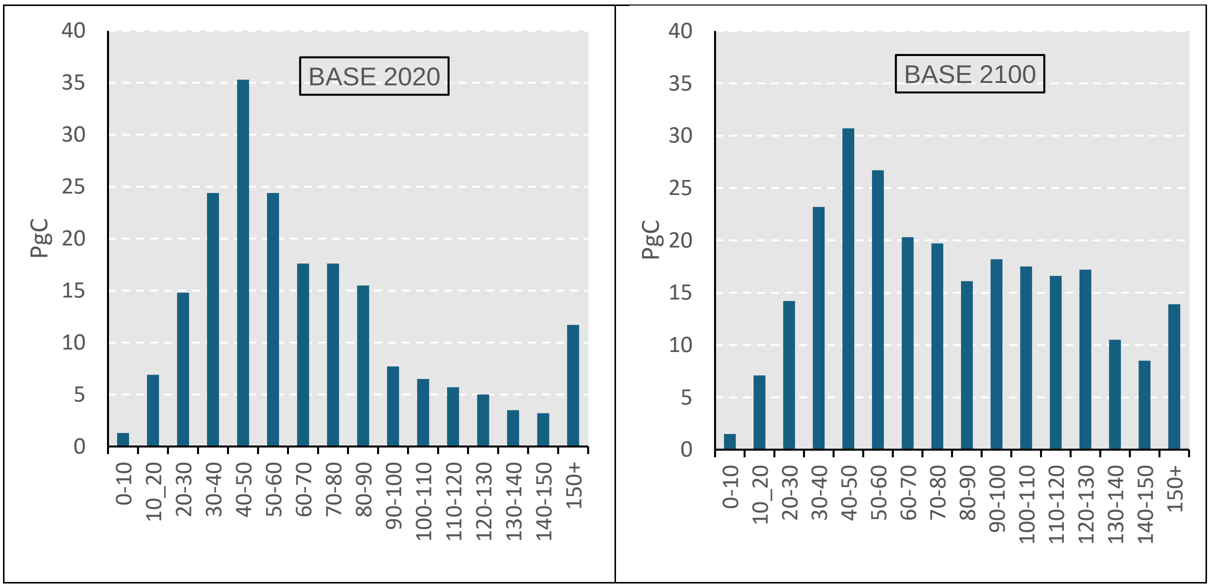

Figure 49. Global carbon stock of forests divided by age-classes in the BASE scenario (excluding primary forests)

In GLOBIOM, forests are divided into three classes: 1) Plantation forests, 2) Seminatural forests and 3) Natural forests. Within each forest class there are different management systems as showed in Table 4. The current formulation of the model includes 9 forest management systems.

Table 4. Forest management systems in GLOBIOM

Management	Description	Forest type	Management intensity	Calibration
CurC_H	Coniferous plantation forest	Plantation forest	3PGmix short rotation	FRA2020+Lesiv2022 plantation forest area
CurNC_H	Non-coniferous plantation forest	Plantation forest	3PGmix short rotation	FRA2020+Lesiv2022 plantation forest area
CurC	Coniferous production forest	Semi-natural forest	G4M EU 75-100% ROW 50-100 %	FRA2020+Lesiv2022 production forest area
CurNC	Non-coniferous production forest	Semi-natural forest	G4M EU 75-100% ROW 50-100 %	FRA2020+Lesiv2022 production forest area
CurC_M	Coniferous multifunctional forest	Semi-natural forest	G4M EU 50-75% ROW 25-50 %	FRA2020+Lesiv2022 production forest area
CurNC_M	Non-coniferous multifunctional forest	Semi-natural forest	G4M EU 50-75% ROW 25-50 %	FRA2020+Lesiv2022 production forest area
CurC_L	Coniferous close-to-nature forest	Natural forest	G4M EU 0-50% ROW 0-25 %	WDPA categories IV-VI
CurNC_L	Non-coniferous close-to- nature forest	Natural forest	G4M EU 0-50% ROW 0-25 %	WDPA categories IV-VI
CurS	Strictly protected secondary forest	Natural forest	0%	WDPA categories I-III
Cur0	Unprotected secondary forest	Natural forest	0%	Residual forest area

PriFor	Primary forest	Natural forest	0%	FRA2020+Lesiv2022 primary forest area, EU Sabatini map

Note: 1) Management intensity=% share of G4M maximum sustainable harvest potential based on NNP maps, local tree species and rotation time that maximizes increment given than carbon stock stays at the current level.
2) The model can choose between coniferous and non-coniferous management option in the limits of tree species distribution based on FRA2020 data (FAO, 2020). In the EU, the model use additional grid level data on tree species from (Brus et al., 2012).

The transition from natural or semi-natural forests to planted forest happens through intensive management, i.e., removing old trees by harvesting and planting new ones. The transition from planted forests to natural or semi-natural forests happens through extensive management, i.e., removing old trees by harvesting or through natural mortality and waiting for new trees to appear by natural regeneration.

The spatially explicit biophysical data for each grid is based on the G4M forest management simulation model (Kinderman et al. 2006,2008). G4M provides GLOBIOM estimates on initial biomass stock, growing stock and sustainable level of harvests (=increment). Using the G4M data and global age-class database (Besnard et al. 2021), the model generates grid level biomass growth curves, i.e., biomass and growing stocks for different stands within each grid.

Within each grid the model can have different management systems with different age-class dynamics, mortality and harvest intensity. The initial areas of different management systems are calibrated to the FRA (2020) data, the World Database of protect areas data (protected planet, 2025) and the Global Forest Management Map (Lesiv et al., 2022). Moreover, for the historical periods 2000-2020 the management areas are matched to FAOSTAT country-level harvest volumes data (FAOSTAT, 2025).

After 2020, the age-class dynamics develops endogenously based on periodic harvests volumes, growth curves, mortality and forest area changes (deforestation/afforestation). To maintain the sustainability of harvest volumes over time in the recursive dynamics, the model includes two additional constraints. First, for each grid cell, the amount of harvested biomass cannot exceed biomass growth. Second, it is not allowed to harvest age-classes that are younger than the optimal rotation time. Optimal rotation times for natural/seminatural forests vary between 30-80 years depending on the management system and climate zone while for plantation forests between 5-30 years.

Finally, the initial calibration of the model for the historical period 2000-2020 has been improved to better match better harvest volumes data (FAOSTAT, 2025), forest biomass stocks and carbon emissions data (FAO, 2020) and forest areas and land-use changes data (FAO, 2020).

HWP and BECCS carbon accounting

Harvested wood products (HWP) carbon accounting follows the IPCC production approach (PA), which is the most commonly used methodology to calculate HWP carbon storage (IPCC, 2019). The initial HWP carbon pool is calculated by using the production and trade data of HWP from FAOSTAT database from 1961 to 2020 (FAOSTAT, 2025). Based on this method the global HWP pool was a sink of about 300 MtCO2/yr in 2020, which is comparable to global HWP pool estimates by (Johnston & Radeloff, 2019). The HWP carbon storage and sink are considerable smaller than to the forest carbon storage and sink, typically HWP carbon storage is about 5% of forest above ground carbon storage and HWP carbon sink about 10% of forest carbon sink (Zhao et al., 2022). There are two reasons for this. First, about 75% of tree biomass is lost for harvest and forest industry residues when woody biomass is moved away from forests and converted to HWP. Second, the lifetime HPW (0-100 years depending on the product) is typically shorter than the lifetime of trees (10-500 years depending on the management).

In addition to HWP carbon storage, we also calculate bioenergy with carbon capture and storage (BECCS) carbon storage. The difference between them is that a half-life HWP vary from 0 to 35 years while BECCS has an infinite half-life, i.e., HWP are temporary carbon storages while BECCS is a permanent carbon storage. The share of bioenergy with BECCS is provided by the MESSAGE model and increases from 5% in 2030 to 75% in 2100 (IIASA, 2018). The BECCS carbon capture rate typically varies between 25-75% depending on the final energy carrier. We assume that BECCS carbon capture rate is 63%, which is an average value estimated from the MESSAGE model outcome.

Deforestation and afforestation

In historical periods 2000-2020, deforestation and afforestation areas are based on (FAO, 2020) country level data, which is allocated in the grid level according to GLOBIOM land-use dynamics. The land-use dynamics is based on land-use change costs, land suitability maps, production potential maps and demand for land on food, feed and fiber production (IBF-IIASA, 2023).

After 2020, deforestation area is endogenous and depends on food and feed demand as well as carbon tax on deforestation emissions. Because carbon prices are relatively high in RCP1p9 scenario, there is very little deforestation after 2020 (Figure 50). Remark that conversion of natural forests to plantations is excluded in the model, i.e., the motive for deforestation in the model is food and feed demand instead of timber demand or some other reason (FAO, 2020).

After 2020, afforestation area is based on G4M SSP2 RCP1p9 country level scenario data, which is allocated in the grid level according to GLOBIOM land-use dynamics. Afforestation competes with energy crops plantations, forest plantations and food production on the same marginal land areas. The difference between afforestation and forest plantations is that afforested areas are managed for carbon sequestration and nature conservation while forest plantations area managed for production use. There are also some differences in afforestation and plantations land suitability maps, i.e., some areas are suitable for afforestation but not for plantations (low productivity areas, deep slopes etc.).

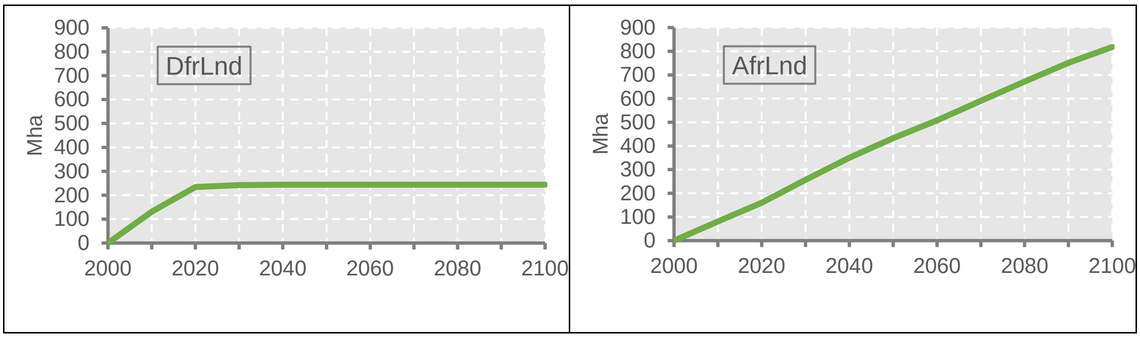

Figure 50. Global deforestation and afforestation

Other natural land division to abandoned land and natural land

In GLOBIOM, other natural land is divided in two land-cover classes: 1) Abandoned land (AbdLnd), and 2) Natural land (NatLnd). AbdLnd is abandoned agricultural land, which typically has low biodiversity value and degraded carbon stock. NatLnd is old-growth natural vegetation land such as savannas, prairies and open forests (not classified as forests), which have high biodiversity value and carbon stock. AbdLnd is allowed to be converted to other land-use according to GLOBIOM usual land-use change constraints (land conversion costs + maximum available land) while NatLnd conversion to other land-use is limited by applying higher land conversion costs for NatLnd than for AbdLnd. Higher land conversion costs eliminate most of NatLnd conversion to other land uses.

Since no good map of historically abandoned lands is available, we let the model decide the level of available AbdLnd for each period. Based on this method, the AbdLnd area increase from zero in 2000 to 270 Mha in 2040, and then starts decreasing depending on the scenario (Figure 51). In general, AbdLnd decreases over time, because it is converted to plantations, forests or agricultural land. On the other hand, some agricultural land area is abandoned due to changes in demand and/or productivity, which increases AbdLnd area over time.

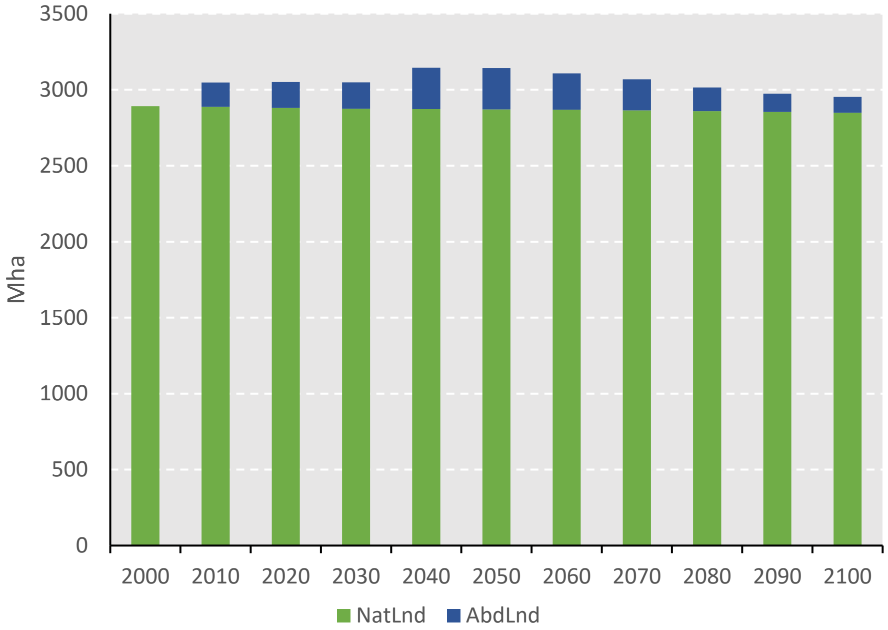

Figure 51. Global abandoned land (AbdLnd) development relative natural land (NatLnd) in the baseline scenario

Wood-based products trade and regional competitiveness

The GLOBIOM model includes 22 traded wood-based products, which differ in units and level of value-addition (i.e., primary, semifinished, final). Remark that energy crops are not included in the traded products in the model. Reason is that energy crops are low value-add products, which are usually not transported longer distances or traded between the countries.

For simplicity, we do not consider here individual wood-based products bilateral trade flows, but only total net exports (i.e. difference between export volume and import volume aggregated over all products). The volume of total net exports reflects regional woody biomass resources, production costs and forest industry development state, and can be used as an indicator of regional economic competitiveness.

Aggregation over different wood-based products requires that they are converted in comparable units. There are different methods to convert wood-based products to comparable units (Lauri et al. 2021). Here we use here so called roundwood equivalent (RWeq) units, which measure wood-based products according to the amount of primary biomass needed for their production. This method is standard in the forest sector analysis and recently applied also in the agricultural sector analysis (Zhao et al. 2025).

Model improvements for aquaculture and aquafeed supply chains

Projecting the capacity of unfed aquaculture beyond 2020

As compared to the description of the BAU scenario in D6.2, and in accordance with the feedback from the stakeholder during the workshop, for all aquaculture and aquafeed scenarios in this deliverable (except for UNFED20), we assume that the capacity of unfed aquaculture can increase beyond 2020 levels.

To constrain the post-2020 capacity of unfed aquaculture, we extrapolated at country- and product-level historical trends using a Generalized Additive Models. Future trends in capacity are provided in Figure 52.

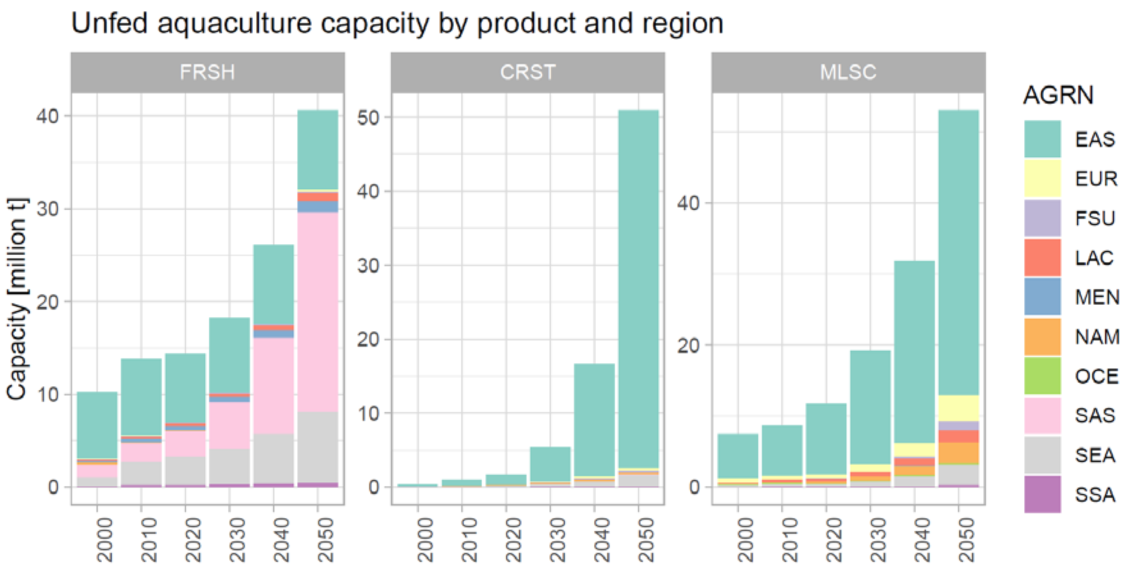

Figure 52 - Projections for the capacity of unfed aquaculture by region and product

Sensitivity analysis of the crop composition of crop aquafeed requirements

For all aquafeed and aquaculture scenarios except for the AFCOMPOCROPMIX scenario, we assumed the proportion of various crops (between soya, corn, rape and wheat) in total crop aquafeed demand to be country-specific (based on Frohlich et al 2018), but invariant across time horizons and scenarios.

As this might not necessarily be a valid assumption, and might affect the potential of impact of crop aquafeed requirements on land use and biodiversity, we tested the impact of an alternative assumption in a simple scenario. In this alternative scenario (AFCOMPOCROPMIX), we focused on the dominant fed aquaculture production system (fed aquaculture in China), for which we assumed that 50% of the crude protein content from corn (which has relatively lower crude protein content) and soya (which is imported) feed requirements per unit of aquaculture output are replaced by a similar crude protein content from wheat. To do so, parameters for corn and soya aquafeed requirements where halved, while that of wheat was increased by the amount necessary to compensate this loss in terms of crude protein intake (while accounting for differences across crops in crude protein content and apparent digestibility, see Table 5).

Table 5 - Nutritional parameters of individual crops as aquafeed. Source: INRAE-CIRAD-AFZ Feed tables (https://www.feedtables.com/, accessed July 2024).

CROP	Crude protein content (gram crude protein per gram of freshmatter)	Apparent digestibility (fraction)
Corn	0.216	0.92
Soya	0.404	0.912
Wheat	0.404	0.95