Mainstreaming Integrated Assessment Models by embedding behavioural change and actor heterogeneity, and increasing their outreach to citizens, communities and industrial actors

CHOICE D5.1 Release of the scenario narratives and their quantitative drivers

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1.0	29/08/2024	Marta Kozicka – IIASA	Final submitted version

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Glossary of terms

Term	Description
Afforestation	The establishment of a forest or stand of trees in an area where there was no recent tree cover.
Agriculture, Forestry, and Other Land Uses (AFOLU)	A collective term that refers to human use of and influence on land areas.
Bioenergy	Energy derived from biological sources such as plants and waste.
Demand-side mitigation	Actions aimed at reducing greenhouse gas emissions by influencing consumption patterns and behaviour.
EAT-Lancet Commission	A group pf world-leading scientists from 16 countries from various scientific disciplines. The goal of the Commission was to reach a scientific consensus by defining targets for healthy diets and sustainable food production.
Emulator Approach	A method that uses simplified models to generate projections for more complex models.
Environmental Flow Requirement (EFR)	A constraint to ensure sufficient water is reserved for ecosystems, preventing its use for irrigation.
FABLE Calculator	An open Excel tool to compute mid-century pathways of the food and land-use systems, and track progress towards food security, climate mitigation, and biodiversity conservation.
FeliX	Full of Economic-Environment Linkages and Integration dX/dt, a model for linking economic and environmental systems.
Food System	System of all the elements and activities related to producing and consuming food, and their effects, including economic, health, and environmental outcomes.
Global Dietary Database (GDD)	A comprehensive database providing information on food and nutrient consumption worldwide.
GLOBIOM	Global Biosphere Management Model, a partial equilibrium model of the global agricultural and forestry sectors.
Greenhouse Gas (GHG)	Gases that trap heat in the atmosphere, contributing to global warming (e.g., CO2, CH4, N2O).
Gross Domestic Product (GDP)	A measure of the economic performance of a country, representing the total value of goods and services produced.
MACC (Marginal Abatement Cost Curve)	A graphical representation of the cost-effectiveness of different emission reduction options.
Purchasing Power Parity (PPP)	A method of converting different currencies into a common unit based on relative purchasing power.
Reforestation	Re-establishing forest that have either been cut down or lost due to natural causes, such as fire, storm, etc.
Representative Concentration Pathways (RCPs)	Scenarios that describe different levels of greenhouse gas concentrations and their impacts on global temperature.
Shared Socio-economic Pathways (SSPs)	Scenarios that explore different socio-economic developments to understand their impacts on sustainability.

List of abbreviations and acronyms

Abbreviation	Meaning
AFOLU	Agriculture, Forestry, and Other Land Uses
CO2	Carbon dioxide, a greenhouse gas contributing to global warming.
COP	Conference of the Parties
EFR	Environmental Flow Requirement
FABLE	Food, Agriculture, Biodiversity, Land Use, and Environment
FAO	Food and Agriculture Organization
GDD	Global Dietary Database
GDP	Gross Domestic Product
GHG	Greenhouse Gases, gases that trap heat in the atmosphere and contribute to global warming.
GtCO2	Gigatonnes of carbon dioxide; a measure of large-scale CO2 emissions.
IAM	Integrated Assessment Model
MACC	Marginal Abatement Cost Curve
PPP	Purchasing Power Parity
SSP	Shared Socioeconomic Pathways

Executive Summary

This report presents a comprehensive analysis of various scenarios and their application within Integrated Assessment Models (IAMs) to address climate change mitigation and related challenges in the scope of CHOICE. The CHOICE IAM framework represents a sophisticated approach, integrating advanced modelling tools such as Felix, GLOBIOM, and the FABLE Calculator. This framework is designed to explore and develop detailed scenarios and pathways for achieving critical climate stabilization targets while considering the intricate interplay between climate policies, land use, food demand, and socio-economic factors.

The first part of the report introduces the shared socioeconomic pathways (SSPs), which will be the core socioeconomic inputs underlying scenarios in CHOICE. The introduction includes the background and history of SSP pathway development, the most recent version of SSP data update in 2024, the five different SSP narratives that span a wide range of possible socioeconomic futures, and the quantitative drivers under each SSP scenario.

The second section of this report provides an overview of the IAM framework to be applied in CHOICE. Three models with different mechanisms and focuses are introduced: the partial equilibrium land-use model GLOBIOM, the system dynamic model Felix, and the agricultural sector and land use simulator FABLE Calculator. The sectoral coverage, key modelling mechanisms, model applications of these models are introduced.

Following the model description, multiple potential IAM scenario elements in CHOICE are listed and described in detail. The scenario dimensions include:

Climate change mitigation scenarios: The CHOICE framework employs IAMs to craft and evaluate scenarios aimed at meeting specific global temperature targets, such as 1.5 °C and 2.0 °C above pre-industrial levels. These scenarios are grounded in the application of global carbon pricing, which influences all sectors of the economy, including energy, industry, and transportation. By incorporating a comprehensive approach to carbon pricing, the framework assesses how these prices impact land use, agricultural practices, and forestry management. This analysis provides a detailed understanding of how different mitigation strategies can be employed to achieve desired climate outcomes and the associated trade-offs involved.

Food demand scenarios: A significant advancement of the CHOICE framework is its improved representation of consumer behaviour. The model incorporates variations in dietary patterns based on age, sex, and education, enabling more precise projections of future food demand. This nuanced representation allows for the assessment of how dietary changes—such as shifts towards plant-based diets or reductions in food waste—can affect overall sustainability and public health. By analysing these factors, the framework offers insights into the potential impacts of dietary interventions on both environmental outcomes and nutritional security.

Additional scenario dimensions: Beyond climate and food demand, the CHOICE framework explores several other critical scenario dimensions. These include:

- Land protection and biodiversity conservation: Scenarios are developed to evaluate the effects of various land protection strategies and biodiversity conservation measures. This includes assessing the impact of increasing protected areas and implementing biodiversity-friendly land-use regulations.

- Environmental flow constraints: The framework introduces scenarios that consider environmental flow requirements for sustainable water use. This involves restricting irrigation water withdrawals to preserve riverine ecosystems and ensure the availability of water for ecological functions.

- Trade adjustments: The impact of international trade policies is also explored. Scenarios are modelled to assess how trade liberalization or barriers affect land use, food security, and environmental outcomes across regions.

By integrating these diverse modelling elements, the CHOICE framework provides a robust toolbox for analysing potential pathways for addressing climate change. It facilitates targeted policy design by offering a detailed evaluation of trade-offs and co-benefits associated with various strategies. This comprehensive approach equips decision-makers with valuable insights necessary for making effective policies that balance climate goals, food security, and sustainability, ultimately guiding efforts towards a more resilient and sustainable future.

Introduction

Background

To stabilize the climate and significantly reduce climate change related risks, the Paris Agreement was adopted at the United Nations Climate Change Conference (COP) 21 in 2015. It aimed to limit global temperature increases to well below 2.0 °C and to strive for a 1.5 °C limit (Schleussner et al., 2016). However, this would require a rapid decarbonisation of the energy system at unprecedented speed over the next decades (Rogelj et al., 2015; Rockström et al., 2017; Rogelj et al., 2018) as cumulative emissions by the end of the century should not exceed 400-1000 $GtCO_2$ (Schellnhuber et al., 2016; Millar et al., 2017). Despite this urgency to reduce emissions, countries fall short with their current climate mitigation commitments and adopted mitigation policies point towards a 2.8 °C temperature rise by the end of the century (UNEP, 2022). Hence, the remaining carbon budget is shrinking fast and the allowable CO_2 emissions to stay with a 50% chance within the 1.5°C is equivalent to only about six years of current CO_2 emissions (Lamboll et al., 2023).

Integrated Assessment Models (IAM) typically underpin the forward-looking chapters of the IPCC and are used to develop cost-efficient climate stabilization pathways across economic sectors including agriculture (IPCC, 2018; Rogelj et al., 2018). The food system, including its value chains, accounts for around one third of global anthropogenic GHG emissions (16-18 $GtCO_2$eq/yr) (Crippa et al., 2021; Tubiello et al., 2021) and the speed and ambition of climate action in the sector is vital to stabilize the climate. It will not only determine the level of residual GHG emissions and hence the requirement for negative emissions once carbon neutrality has been achieved (Rogelj et al., 2018), but lack of mitigation action in the food system may preclude reaching the 1.5°C target in the first place (Clark et al., 2020; Reisinger et al., 2021). While IAMs traditionally focused on supply-side mitigation measures e.g., increased use of renewables, adoption of carbon-capture-and-storage or changes in land-use such as afforestation and reforestation, less attention has been paid to demand-side and food system representation, due to the inherent complexity and actor heterogeneity.

However, demand side options may also significantly contribute to GHG savings with potential co-benefits for health and food security (Stehfest et al., 2009; Popp et al., 2010; Bajzelj et al., 2014; Herrero et al., 2016; Springmann et al., 2016; van Vuuren et al., 2018), but have been scrutinized less systematically and applying rather simplified dietary change scenario in economic models.

Here CHOICE, will provide a more realistic representation of behaviour change and actor heterogeneity aspects that will be included in IAMs and bridge social science and marketing tools, with the aim of accelerating climate action.

Purpose and scope

The objective of this deliverable is threefold:

1. First, we will present the most recent set of quantitative scenario drivers and main scenario assumptions (Shared Socioeconomic Pathways - SSPs) used in Integrated Assessment Models.
2. Second, we will introduce briefly the IAM modelling framework (FeliX, GLOBIOM, FABLE-Calculator) that is going to be applied and improved within CHOICE.
3. Third, we will present a comprehensive overview of scenarios that can be covered by the CHOICE modelling framework.

Shared Socio-economic Pathways

In CHOICE, the demand-side intervention scenarios to be quantified by the IAMs will be based on a set of shared socioeconomic pathways (SSPs) (O'Neill et al., 2014). The SSPs are five comprehensive socioeconomic scenario narratives that are widely and consistently applied (i.e., "shared") in the community efforts of assessing climate change and climate change mitigation. The SSP narratives span wide ranges of socioeconomic development patterns and climate change mitigation ambitions. It is worth noting that SSPs are not meant to provide "predictions" of future socioeconomic and climate trends but are representative alternative "storylines" on future changes in multiple aspects of society to facilitate addressing the "what-if" questions in climate change scenario assessments.

The SSPs were collectively designed by the climate change research community and have been consistently adopted in most publications on climate change scenario assessments over the past. Compared with earlier generations of community scenarios by the Intergovernmental Panel on Climate Change (IPCC), including SA90, IS92, and SRES scenarios (which were used in the first to fourth IPCC assessment reports), a unique advantage of SSP scenario narratives is its combined comprehensiveness and flexibility. On one hand, SSPs have wide coverage of policy-relevant socioeconomic development (and corresponding mitigation and adaptation challenges) space with varying assumptions about human developments, which were condensed into five alternative storylines (labelled as SSP1 through SSP5, see Table 1). On the other hand, the SSPs only define qualitative narratives (socioeconomic and demographic patterns, and trends in technological, lifestyle, and policy development) plus basic quantitative projections of basic socioeconomic drivers in line with the five SSPs narratives (including population, GDP, and urbanization rates). This offers to the IAMs high degrees of flexibility to quantify the full SSP-based scenario profiles, and to simulate the policy instruments (for example, supply-side intervention to promote higher penetration of renewable energies, or demand-side interventions to reduce mitigation challenges) to achieve certain mitigation targets under specific SSPs.

Initially, the SSPs were designed during the years 2013-2017, with the synthesized SSPs concepts, ideology, as well as detailed narratives and representative (="marker") IAM quantifications of SSP1-5 published in the *Special Issue of Global Environmental Change (van Vuuren et al., 2017)*. After release, the SSPs narratives become a standard set of scenarios used across the climate research community. Typically, they are applied in combination with the representative concentration pathways (RCPs), which were previously designed also by the climate research community to depict different future levels of climate change (van Vuuren et al., 2011). The SSPs-RCPs scenario matrix represents different combinations of socioeconomic pathways and climate change levels (or viewing from another perspective, mitigation targets), and form the basis for impacts, adaptation, vulnerability (IAV) and mitigation analysis. This SSP-based scenario framework is applied in the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) [1], which is the updated phase of a highly successful global climate model intercomparison project coordinated by the World Climate Research Programme (WCRP) (Eyring et al., 2016). SSPs also provides the basic inputs into IPCC Fifth Assessment Report (AR5) (IPCC, 2014) and Sixth Assessment Report (AR6) (IPCC, 2023).

While the SSPs narratives are successful in supporting the extensive climate scenario assessments in the past 10 years, the previous SSP scenario framework assumes future projections and scenario span (=deviation across different SSP scenarios) start from the year 2005 and is therefore to some extent outdated, considering that the world is approaching year 2025 with about 20 years new development that were not accounted and calibrated in the 2005-2025 quantifications of SSP1-5 narratives. Therefore, starting 2023, the climate research community has been working on updating the basic elements and scenario quantifications of

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[1] Program for Climate Model Diagnosis & Intercomparison. CMIP6 - Coupled Model Intercomparison Project Phase 6. https://pcmdi.llnl.gov/CMIP6/

the SSPs. In January 2024, the 3.0 version of SSP GDP and population projections were released after extensive internal and external reviews. The updated GDP and population projections, with updated parameters and assumptions on technological, societal, and environmental factors, will also be applied in CHOICE scenarios modelling. The following sections describe the SSP narratives and quantitative scenario drivers that are inputs into CHIOCE scenarios.

Narratives

The SSPs describe five different plausible future societal development trends. These five narratives, as described in Riahi et al. (2017), include multiple dimensions of society development including demographic, economic, technological, social, governance, and environmental factors, as well as assumptions on cross-regional inequality (Table 1). In line with each SSP narrative, there is also implicit implications on climate change mitigation and adaptation challenges in accord with such development trends. Scenarios to be quantified in CHOICE will span the SSP1-5 pathways.

Table 1. Summary of SSP narratives **Source: Riahi et al. (2017)**

SSPs	Narratives	Corresponding mitigation and adaptation challenges
SSP1 **Sustainability – Taking the Green Road**	The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.	Low challenges to mitigation and adaptation
SSP2 **Middle of the Road**	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves	Medium challenges to mitigation and adaptation

	only slowly and challenges to reducing vulnerability to societal and environmental changes remain.	
SSP3 **Regional Rivalry – A Rocky Road**	A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.	High challenges to mitigation and adaptation
SSP4 **Inequality – A Road Divided**	Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle- and high-income areas.	Low challenges to mitigation, high challenges to adaptation
SSP5 **Fossil-fueled Development – Taking the Highway**	This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air	High challenges to mitigation, low challenges to adaptation

	pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Quantitative drivers

In CHOICE methodology framework, SSPs-based quantitative drivers will be taken as basic scenario inputs to design demand-side mitigation intervention scenarios for further IAM quantification. The SSP-based scenario inputs cover macroeconomic drivers as well as other land-use related scenario drivers including bioenergy demands. The following parts describe the characteristics of each scenario driver, the processing, and validation steps.

Population trends

The updated population and GDP data for all SSP scenarios are from the SSP3.0 release version, available from the SSP Scenario Explorer database [2]. The SSP3.0 database provides updated population and human capital projections developed by IIASA and Wittgenstein Center (WIC) (KC et al., 2024). This data release replaces the earlier version of SSP population projection (SSP v2.0). This dataset includes population projections for SSP1-SSP5 scenarios between 2020-2100, in 5-year intervals. The data covers population in 200 world countries (excluding countries with population smaller than 80 thousand), which accounts for the majority of the current world population. The dataset includes projections of total population, and projections of population for each combination of sex, age (with 5-year intervals), and education (6 different education levels) profiles.

For scenario implementation in CHOICE, the downloaded SSP population projections by different ages, are merged historical population estimates from World Population Prospects 2022 (United Nations, 2022). To put the SSP population projections into perspective, the SSP1-5 population projections were compared with population time series data from other data sources for population statistic or future projections. Figure 1 compares the updated SSP1-5 population projections with population estimates from other open-source databases (including the central estimates from the World Population Prospects 2022 by United Nations, the statistics database by Food and Agricultural Organization of the United Nations, and the World Development Index database by World Bank). Population data availability in SSP3.0 database for each individual country (or region) in the United Nations database is summarized in Table A1 in Annex 1.1. Comparison of the population projections under each SSP between SSP3.0 database and the last version of SSP data (SSP v2.0) can be found in Figures A1-A5 in Annex 1.2.

[2] SSP Scenario Explorer 3.1.0 Release July 2024. https://data.ece.iiasa.ac.at/ssp IIASA and contributing modelling teams. SSP Scenario Explorer. https://data.ece.iiasa.ac.at/ssp

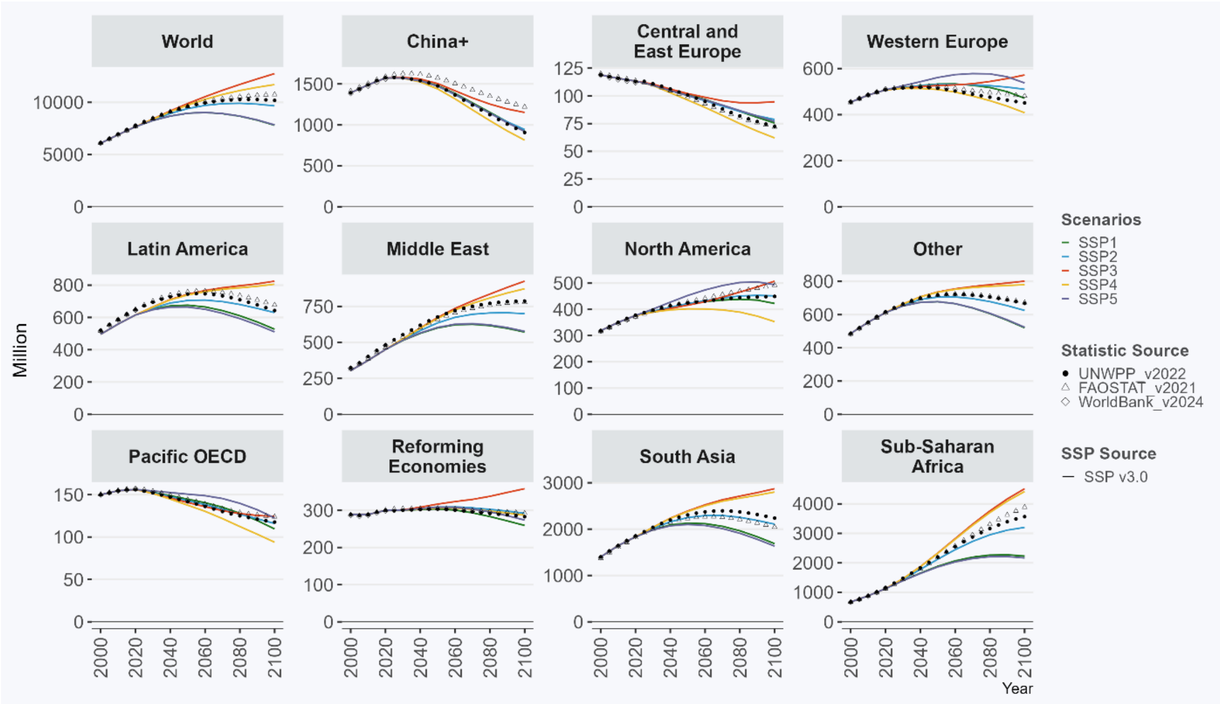

Figure 1. Comparison of updated SSP3.0 population projections with population estimates from other databases

"UNWPP_v2022" indicates projections from United Nations World Population Prospects 2022 central estimates of population trends (which can be interpreted as "the most likely future trend among the various projections published by the United Nations in the World Population Prospects" (United Nations, 2022)), "FAOSTAT_v2021" indicates projections from Food and Agricultural Organization of the United Nations (2021 version), "WorldBank_v2024" indicates projections from World Bank World Development Index database (2024 version). In this figure, national population estimates are aggregated into 11 aggregated regions of GLOBIOM model (the land-use model in the applied IAM in CHOICE).

In addition to the total population size, we collected data on the population demographic structure projections for each individual country and each SSP scenario. The SSP3.0 database contains information on age, education level, and sex (Figure 3). This information will be critical in improving representation of consumer behaviour by introducing heterogenous consumer into the GLOBIOM demand structure.

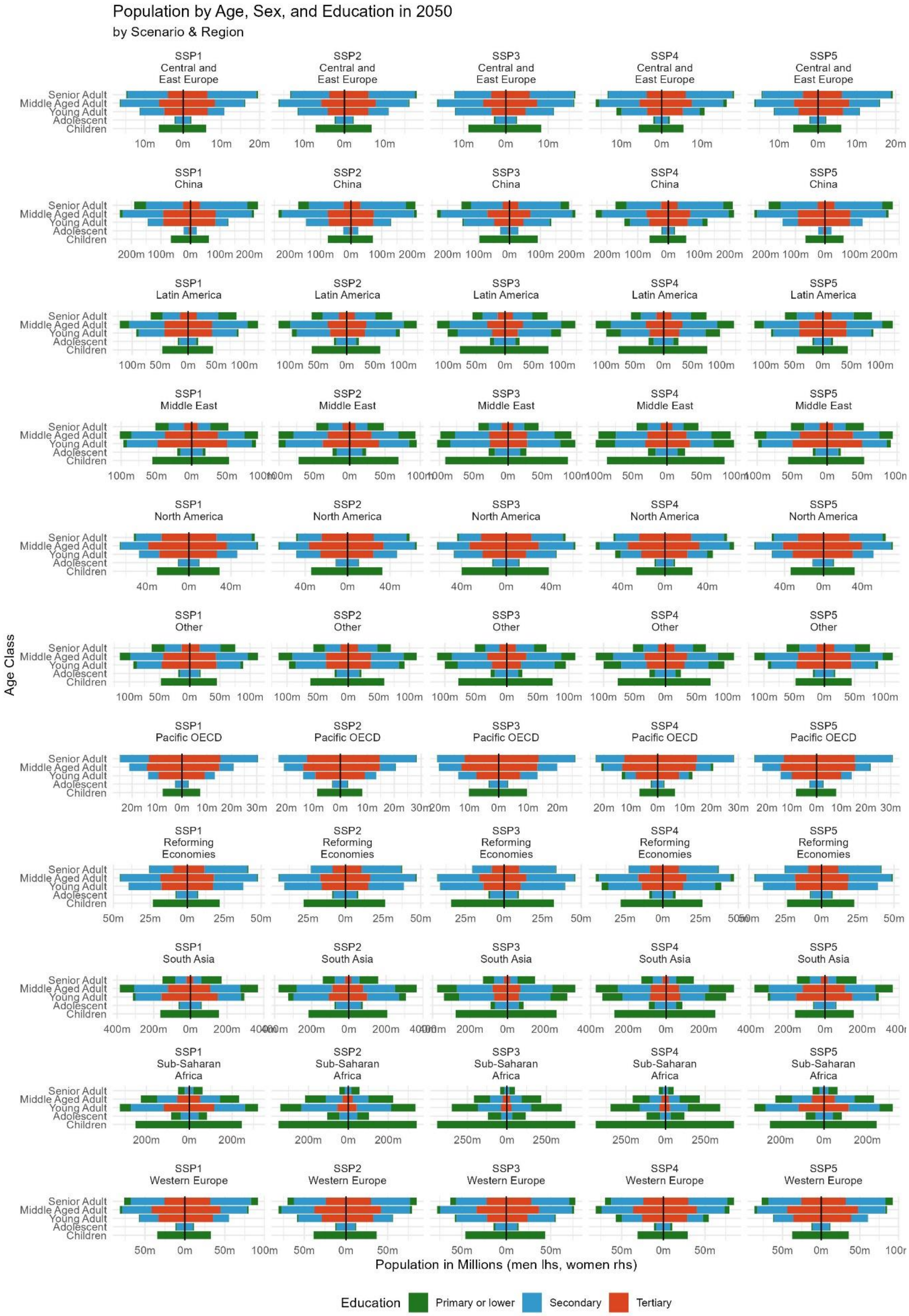

Figure 2 Population structure by age, education, and sex in 2050 under different SSP scenarios

GDP trends

The SSP3.0 database provides updated GDP projections from two sources: one by OECD (Dellink et al., 2017; Chateau et al., forthcoming; Dellink et al., forthcoming journal article), another by IIASA and Vienna University of Economics and Business (Crespo Cuaresma, 2017). These updated GDP projections replace the earlier version of SSP GDP projections (SSP2.0). Both sources provide GDP projections for SSP1-SSP5 scenarios between 2020-2100, in 5-year intervals, in the unit of 2017 PPP$ billion (i.e., billion$ in 2017 constant price, using purchase power parity conversion (=PPP) between different countries/regions' local currency unit and US$). The OECD GDP dataset covers GDP projections for 192 world countries, while the IIASA GDP dataset covers only 170 countries. Given the long-standing economic modelling expertise of OECD, the OECD GDP projection series are recommended to be used in CHOICE.

The original SSP1-5 GDP projections from the SSP3.0 database are processed into different units for flexible choice in IAM modelling. More specifically, the GDP (PPP) projections in 2017 constant price are converted to market exchange rate (MER)-based GDP projections by using the converters between PPP and MER price metrics. They are also converted to GDP projections in 2000, 2005, 2010, 2015 constant prices (Table A2). The converters between PPP and MER prices for each country/region are from the World Bank World Development Index [3]. The converters between different years' constant prices are derived from GDP deflator [4] and the DEC alternative conversion factor [5] for each country/region available in the World Bank WDI database. Corresponding SSP1-5 GDP per capita projections for individual countries/regions are calculated by dividing the GDP projections by total population projection. This will be used as a proxy of income per capita, which is an important driving force in IAM modelling system.

Figure 3 compares the updated SSP1-5 GDP projections from SSP3.0 database (the projections by OECD) with GDP estimates from other open-source databases (including the statistics database by Food and Agricultural Organization of the United Nations and the World Development Index database by World Bank). GDP data availability in SSP3.0 database for each individual country (or region) in the United Nations database is summarized in Table A2 in Annex 1.1. Comparison of the GDP projections under each SSP between SSP3.0 database and the last version of SSP data (SSP v2.0) can be found in Figures A6-A10 in Annex 1.2.

[3] The World Bank. Price level ratio of PPP conversion factor (GDP) to market exchange rate. https://data.worldbank.org/indicator/PA.NUS.PPPC.RF

[4] The World Bank. Price level ratio of PPP conversion factor (GDP) to market exchange rate. https://data.worldbank.org/indicator/PA.NUS.PPPC.RF

[5] The World Bank. DEC alternative conversion factor (LCU per US$). https://data.worldbank.org/indicator/PA.NUS.ATLS

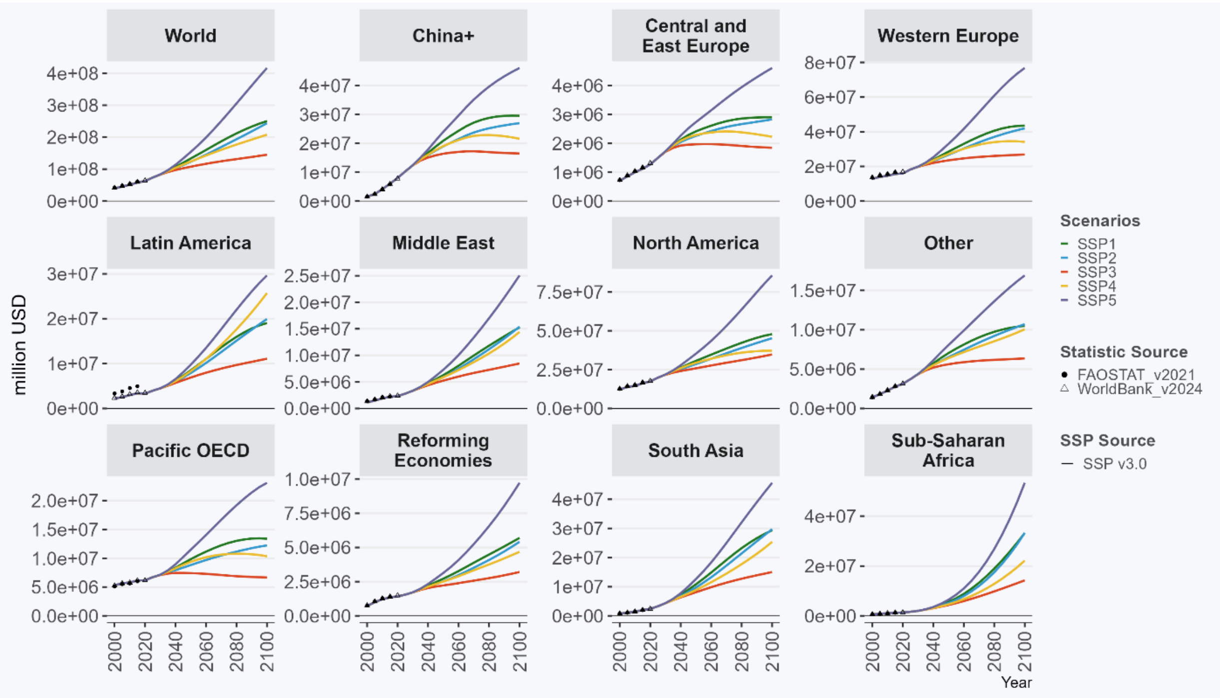

Figure 3. Comparison of updated SSP3.0 GDP projections with GDP estimates from other databases

SSP GDP trends visualized here are the projections by OECD in the SSP3.0 database. “FAOSTAT_v2021” indicates estimates from Food and Agricultural Organization of the United Nations (2021 version), “WorldBank_v2024” indicates estimates from World Bank World Development Index database (2024 version). In this figure, national GDP estimates are aggregated into 11 aggregated regions of GLOBIOM model. Unit: million $ in constant price of year 2005, converted using market exchange rates.

Bioenergy demand

Demand for biomass energy can compete for land with food production and ecosystem protection. Therefore, the level of bioenergy demand is an important input to the land-use modelling part (GLOBIOM model) in the IAM model applied in CHOICE. This input can be estimated by coupling GLOBIOM with the energy system model MESSAGEix and applying an emulator approach. As has been documented in literature (Frank et al., 2021), in this emulator approach, GLOBIOM produces an emulator with large number of pre-defined and pre-simulates. This is fed to MESSAGEix, which can then generate pathways with future trajectories of bioenergy demand and greenhouse gas emission prices for specific combinations of SSP and climate mitigation scenarios. This ensures the consistency between energy and land-use sectors in terms of quantities and prices of biomass energy.

The bioenergy demand in quantitative scenarios varies with SSP narratives and climate change mitigation ambitions. Figure 4Figure 4 takes different RCP scenarios as an example to illustrate the bioenergy demand under different combinations of SSP narratives and climate mitigation efforts. RCP is abbreviation for “representative concentration pathways”, with each RCP corresponding to a different level of radiative forcing and temperature rise in 2100 compared to the preindustrial periods. Here the baseline indicates corresponding baseline bioenergy demand trajectories under different SSPs, which are driven by population-based energy service demand and preference for bioenergy, without any specific climate change mitigation policies. Different RCP scenarios indicate different levels of mitigation ambitions, with RCP1.8 indicating the most ambitious mitigation among the simulated RCPs (least radiative forcing and warming, most stringent mitigation). In applied scenario modelling, other ways of climate mitigation parametrisation except for RCPs are also possible (See “Climate change mitigation scenarios” in Section “Potential IAM scenario elements in CHOICE”).

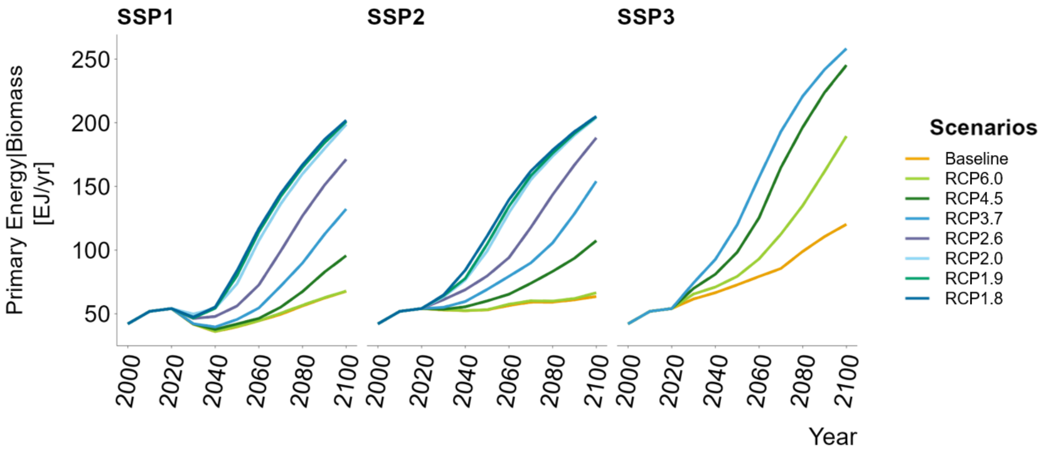

Figure 4 Global total primary bioenergy demand under different SSP-RCP scenarios

Modelling framework

GLOBIOM

GLOBIOM (Global Biosphere Management Model) is a partial equilibrium model of the global agricultural and forestry sectors (IBF-IIASA, 2023). Commodity markets and international trade are modelled at the level of 59 aggregate economic regions where prices are endogenously determined at the regional level to establish market equilibrium. The spatial resolution of the supply side relies on the concept of Simulation Units, which are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and also the same country (Skalský et al., 2008). For crops, livestock, and forest products, spatially explicit Leontief production functions covering alternative production systems are parameterized using biophysical models like EPIC (Environmental Policy Integrated Model) (Williams, 1995), G4M (Global Forest Model) (Kindermann, G.E. et al., 2008; Gusti, 2010), or the RUMINANT model (Herrero et al., 2013). The supply side spatial resolution is typically aggregated to 2 degrees (about 200 x 200 km at the equator). Land and other resources are allocated to the different production and processing activities to maximize a social welfare function which consists of the sum of producer and consumer surplus. Changes in socio-economic and technological conditions, such as economic growth, population changes, and technological progress, lead to adjustments in the product mix and the use of land and other productive resources. By solving the model in a recursive dynamic manner for 10-year time steps, decade-wise detailed trajectories of variables related to supply, demand, prices, land use, and AFOLU emissions are generated. GLOBIOM covers major GHG emissions from AFOLU use including N_2O from the application of synthetic fertilizer and manure to soils, N_2O from manure dropped on pastures, CH_4 from rice cultivation, N_2O and CH_4 from manure management, and CH4 from enteric fermentation, and CO_2 emissions/removals from above- and belowground biomass changes for other natural vegetation. CO_2 emissions/removals from afforestation, deforestation, wood production in managed forests are estimated by geographically explicit (0.5x0.5 degree) model G4M (Kindermann, G. et al., 2008; Gusti, 2010) that is connected with GLOBIOM. Afforestation and deforestation decisions are calculated by comparing net present values of agriculture and forestry land uses. Afforestation occurs where it is more profitable than the agriculture and the environmental conditions are suitable for forest growth. Deforestation, in contrast, happens where agriculture net present value plus profit from one-time selling of deforested wood exceeds the net present value of forestry. The net present values are estimated considering agriculture land rents and wood prices obtained from GLOBIOM and price of carbon stored in biomass. The land transitions in G4M are harmonized with GLOBIOM agriculture land demand. G4M simulates forest management aimed at sustainable production of wood demanded by GLOBIOM on a regional scale.

GLOBIOM explicitly covers biomass feedstocks from energy plantations and existing forests for energy use. Energy plantations are represented through short rotation tree plantations (SRP) of poplar, willow, or eucalyptus with rotation periods of up to 10 years. Productivities are based on NPP maps (Cramer et al., 1999) and the potential for plantation area expansion is determined by land suitability criteria based on aridity, temperature, elevation, population, and land-cover data, as described in Havlík et al. (2011).

GLOBIOM has detailed representation of the forest sector and its supply chains (Lauri et al., 2017). The model includes five primary wood products (pulp logs, sawlogs, other industrial roundwood, fuelwood, and logging residues) that can be used as input for material or energy production processes. The current version of the model includes eight final products (sawn wood, plywood, fiberboard, chemical pulp, mechanical pulp, other industrial roundwood, fuelwood, and energy wood) and five by-products (sawdust, woodchips, bark, black liquor, and recycled wood). Biomass for bioenergy can be sourced from pulp logs, fuelwood, logging residues or forest industry by-products. Detailed information on the forest sector representation is provided in Lauri et al. (2014) and Lauri et al. (2017).

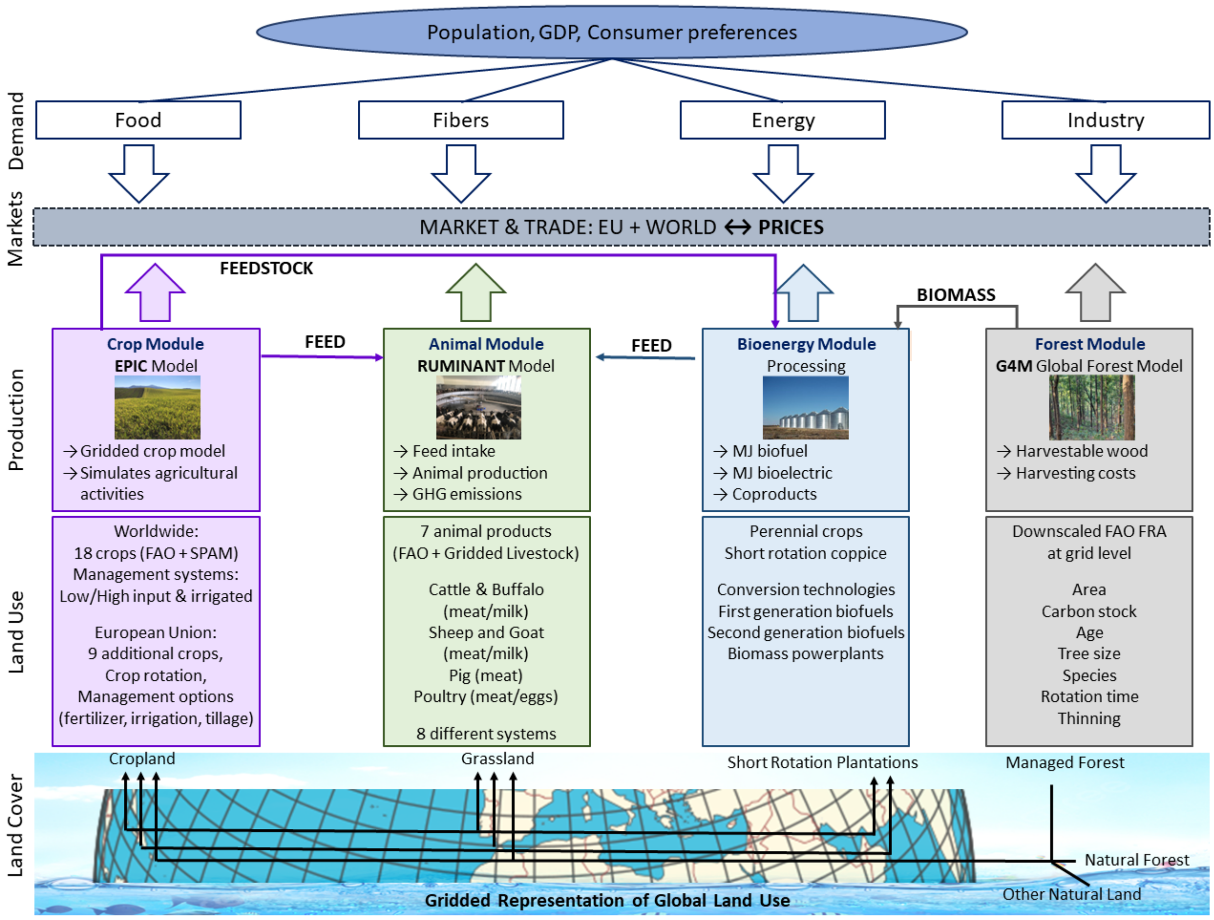

Figure 5 Illustration of the GLOBIOM model. Source: (IBF-IIASA, 2023).

GLOBIOM/G4M represent a comprehensive set of GHG mitigation options for the AFOLU sector (Table 2). Structural mitigation options for agriculture are considered in GLOBIOM via a comprehensive set of management systems. In the crop sector, four different crop management systems are differentiated using the EPIC model (Williams, 1995). In the livestock sector, also various production systems and livestock species are parameterized (Herrero et al., 2013). The detailed representation of production systems allows the model to explicitly represent structural changes in the agricultural sector under a climate policy. Farmers can switch to more GHG efficient management practices on site, reallocate production to more productive areas within a region, or through international trade across regions. In addition, technological options such as anaerobic digesters, animal feed supplements etc. are based on the EPA mitigation option database (Beach et al., 2015). Technical mitigation options (characterized by GHG reduction, productivity changes, and economic costs) are implemented in the model as additional management activities which can be applied on top of a production system. Mitigation options are adopted if the economic benefit i.e., through avoided carbon tax payments or potential productivity changes, exceeds the cost of an option. More detailed information on parameterization of the marginal abatement cost curve for agriculture in GLOBIOM is provided in Frank et al. (2018). G4M considers the following mitigation options for the forestry sector: reduction of deforestation area, increase of afforestation area, change of rotation length of existing managed forests in different locations, change of the ratio of thinning versus final fellings, change of harvest intensity (amount of biomass extracted in thinning and final felling activity), and change of harvest locations.

Table 2. Technical mitigation options for the agricultural sector in GLOBIOM

	Crop sector	Livestock sector
Non-CO_2 emissions	Rice management (different combinations of water, residue, and fertilizer management) Cropping practices (no tillage, residue incorporation) Fertilization practices (nitrogen inhibitors, optimal fertilizer application)	Anaerobic digesters Antibiotics Bovine somatotropin Propionate precursors Anti-methanogen vaccination Anaerobic digesters Algae feeding
CO_2 emissions/removals	Biochar application to soils Improved cropland management	Silvo-pastures Improved pasture management

The estimated AFOLU mitigation potentials include N_2O from the application of synthetic fertilizer, manure to soils and dropped on pastures, and from manure management, CH_4 from rice cultivation, enteric fermentation, and manure management, CO_2 emissions from above- and belowground biomass changes and dead organic matter related to land use changes and forest management as well as soil carbon emissions from deforestation/afforestation.

Food demand in GLOBIOM is endogenous and depends on population, gross domestic product (GDP), and own product price. Population and GDP are exogenous variables, while prices are endogenous. Impacts of price and GDP changes on demand are determined by price and income elasticities respectively. These elasticities are specific for each product and each region and in projections are assumed to decrease exogenously with the level of GDP per capita. Currently, GLOBIOM assumes that for each region, there is one representative consumer – and all demand is calculated through changes occurring to this representative consumer.

FeliX - Full of Economic-Environment Linkages and Integration dX/dt

FeliX is a global system dynamics model of climate, economy, environment and society interactions. It represents the main physical and anthropogenic mechanisms underlying global environmental and economic change with interconnected modules on energy, food and land use, water, population, carbon cycle, climate, biodiversity, and economy (https://iiasa.github.io/felix_docs/) Instead of the techno-economic and biophysical detail in those sectors, the model prioritizes the representation of feedback across different systems. Earlier studies analysed such cross-system feedbacks using the FeliX model, for instance, carbon cycle impacts of global decarbonisation pathways via renewable energy and fossil fuel phase-out (Walsh et al., 2017), and the feedbacks between climate, society and economy leading to dietary shifts at the population level (Eker et al., 2019), synergies and trade-offs between SDGs related to hunger, poverty, economic development, education, climate action, and biodiversity, and the resulting sustainable development pathways (Moallemi et al., 2022), and the specific case of the trade-offs between mitigating environmental pressures and eradicating global poverty (Liu et al., 2023).

FeliX is a descriptive model that answers what-if questions. Therefore, mitigation scenarios are quantified by setting certain values to the parameters that define mitigation measures, for instance, a certain value of carbon price or afforestation. In that way, the mitigation potential is quantified by emission reductions as well as global mean temperature change with respect to the Paris agreement goals.

Below is a summary of FeliX modules that are relevant for the food systems analysis in CHOICE.

Socioeconomic Drivers

Unlike other integrated assessment models, FeliX is often used to quantify custom scenarios that are aligned with SSP narratives, since the main socioeconomic drivers such as population and GDP are endogenously modelled and projected in FeliX. This endogeneity implies that, in a FeliX simulation, population evolves over time depending on developments in economic output, educational attainment, and food supply, and the GDP evolves over time depending on investments in capital and technology (energy and other sectors) and labor force depending on population. Furthermore, FeliX scenarios differ from original SSPs in terms of the climate impacts on population and economy, calibrated according to the economic climate damages estimated by (Burke et al., 2015) and climate mortality estimated by (Bressler et al., 2021). With such assumptions, the baseline demographic and socioeconomic projections of FeliX differs from SSPs as in Figure 6Figure 6. This endogeneity of socioeconomic drivers enables simulating custom scenarios with a wider variety of socioeconomic narratives in FeliX.

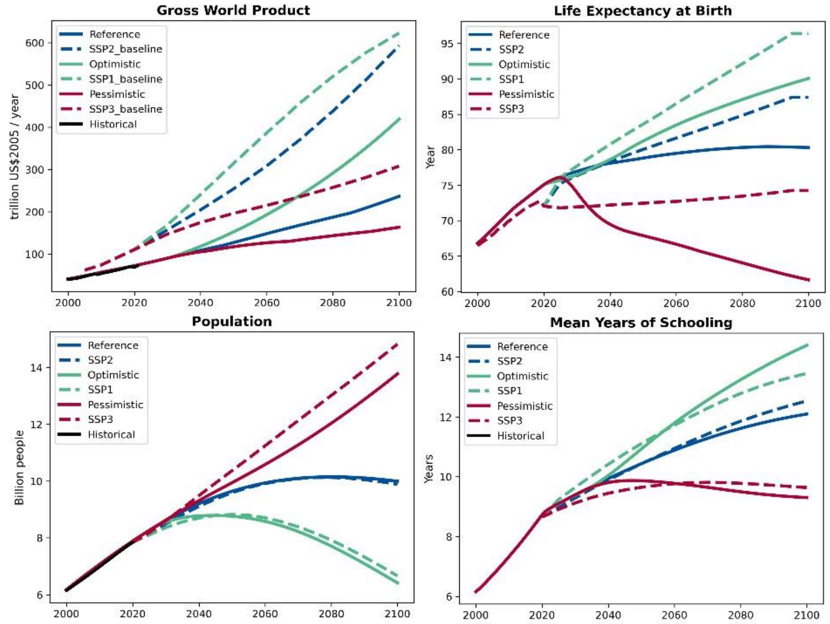

Figure 6: Comparison of the three baselines scenarios of FeliX to the SSP projections for the key socioeconomic drivers.

For the demographic variables, we use the updated SSP projections *(KC et al., 2024) (KC et al., 2023)*, and the gross world product (global GDP) projections are obtained from the AR6 database *(Byers et al., 2022)(Byers et al., 2022)*. The historical trajectories for the period 2000-2020, with the Population and Life Expectancy data from Wittgenstein Centre *(Lutz et al., 2018) (Lutz et al., 2018)*, GDP data from the World Bank statistics.

Land use, land use change, food supply

FeliX represents the global land use and land use change dynamics based on four main categories of land use defined by FAOSTAT (2020): agricultural, forest, urban/industrial, and the other land that does not fall into any of the first three categories. Based on past and expected trends, we assume that agricultural land can be converted to and from forest land, and to and from other land. The rest of land use changes are considered one directional conversion, that is, from agricultural land to urban and industrial land, from forest land to urban and industrial land, and from other land to forest land.

The main underlying driver of land use change is the food system, in addition to bioenergy and forest management practices, as shown in Figure 7Figure 7. Agricultural land requirement increases due to the growing population and income levels which lead to a higher food demand. The discrepancy that emerges between the available agricultural land and the required land is covered by either increasing crop yields, specifically through increased commercial fertilizer consumption, or through agricultural land expansion via deforestation. The resulting agricultural land allocation and crop yields determine the agricultural production and food supply.

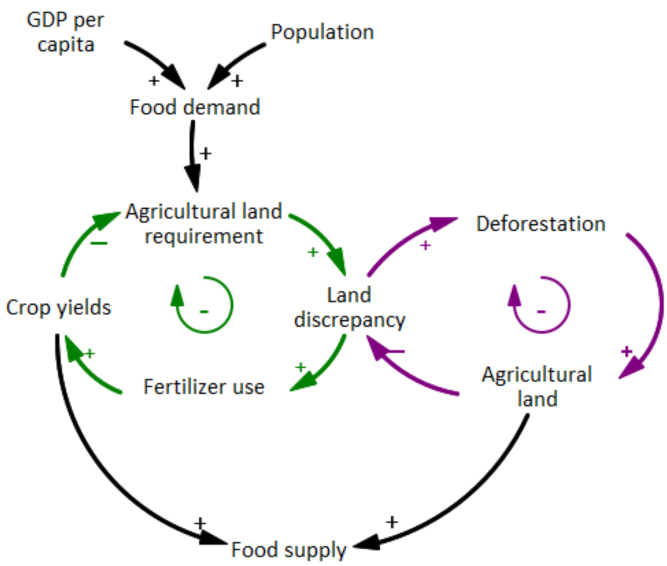

Figure 7: Stylized feedback mechanisms underlying land use change in FeliX

Agricultural land is divided into three sub-categories as *arable land* (cropland), *permanent cropland*, and *permanent meadows and pastures* (grassland). Food demand, supply and land allocation are modelled based on eight categories of food commodities:

- Plant-based food: pulses, grains, vegetables and fruits, and other crops such as sugar and oil crops
- Animal-based food: pasture-based meat, crop-based meat, dairy, and eggs

Red meat sources such as beef, sheep and goat are aggregated into the pasture-based meat category includes, since pasture land constitutes the 96% of the global average land footprint of beef production (Ranganathan, 2016).As for poultry and pork, a large portion of the average land use footprint is on cropland (Ranganathan et al., 2016), since grains provide the 71% of the total feed demand (FAOSTAT, 2020).

The use of nitrogen and phosphorus fertilizers in agriculture, both from commercial sources and livestock manure, is explicitly modelled in FeliX, taking the underlying socioeconomic drivers of fertilizer production (e.g., phosphorus mining) and land pressure into account.

Dietary shifts and food demand

Food demand is quantified based on the total caloric demand for the eight food categories, which depend on dietary choices of different population segments. Dietary choices are represented by two groups of population, that is, the followers of meat-based and vegetarian diet for each 5-year age group and gender (Eker et al., 2019). Further diet compositions, such as EAT-Lancet, vegan, WHO Health guidelines are linked to these population groups to create different possible scenarios. The shifts between these two population groups depend on income, as observed in the case of increasing meat consumption in developing countries, as well as social and behavioural factors such as climate and health risk perception, self-efficacy, and social norms that underly pro-environmental behaviour. Climate risk perception is modelled based on probabilistic extreme events that depend on the global mean temperature change (Beckage et al., 2018), and health risk perception is quantified based on the Global Burden of Disease database, specifically the red meat related mortality (Lopez and Murray, 1998).

Regarding diet compositions, followers of meat-based and vegetarian diets are assumed to consume a standard mix of eight food categories. To understand how meat-based and vegetarian diets differ globally in terms of the proportion of food categories in each group's reference diet, we used typical United States' diets (Pimentel and Pimentel, 2003), and a reference world diet based on the global average supply statistics. By decomposing the global average diet according to the population fraction of the meat-eating and vegetarian groups, we formulated the reference meat-based and vegetarian diets. Besides reference diets, we also built flexibility in the model to run scenario analyses with flexitarian (EAT-Lancet) (Springmann et al., 2018), healthy-eating (WHO guidelines), and vegan diets.

FABLE Calculator

The FABLE Calculator (Mosnier et al., 2020) is an Excel-based model that projects production quantities for more than 80 agricultural products, harvested and planted area by crop, livestock herd number, land use, land use change, GHG emissions from agriculture, water demand for irrigation, food security indicators, on-farm employment and input use, and some biodiversity indicators for each 5-year time step until 2050. It is not an optimisation model, i.e., prices and costs do not influence the solution of the model. It is solved sequentially with each computation steps depending on one or several variables computed in previous steps (Figure 8). The first computation step is human demand for food, bioenergy, and other non-food use. There is one feedback loop: if there is not enough agricultural land to satisfy the targeted demand – because there are expansion constraints or real land scarcity – production, consumption, and exports, are adjusted proportionally.

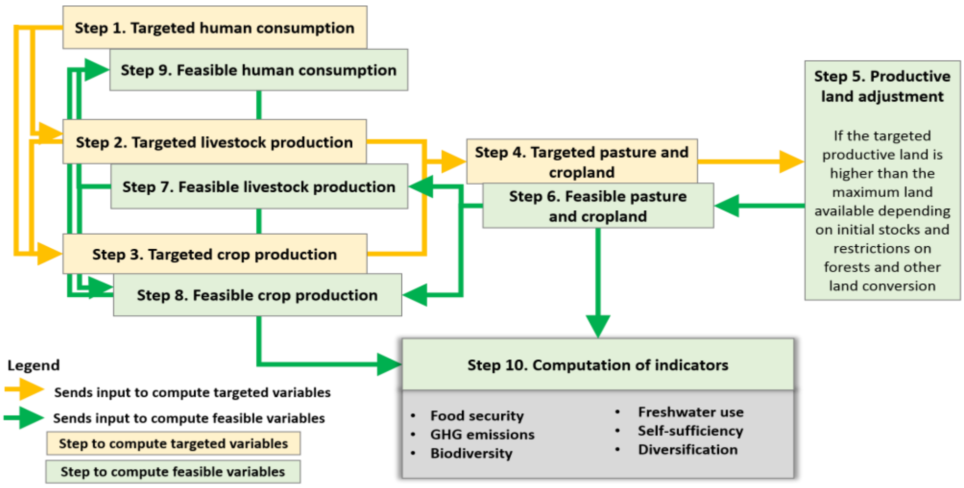

Figure 8 . Overview of the computation steps in the FABLE Calculator (Mosnier et al., 2020)

By-default, there are 23 parameters that can be changed through scenarios leading to thousands possible combinations resulting in alternative trajectories by 2050. The main mitigation options for GHG emissions from agriculture and land use change which are represented in the model are: changes in the level and composition of the demand (e.g., through dietary shifts, food waste reduction), changes in productivity of crops and livestock, changes in the average stocking rate of ruminants by hectare of pasture, and constraints on the expansion of agricultural land (e.g., no deforestation policies). Technical mitigation options are not yet represented in the model, but the most promising options will be implemented during the CHOICE project. Carbon tax cannot be directly implemented in the FABLE Calculator as the result of the model is not driven by the minimization of the costs or the maximisation of the profits. However, it is possible to use the results of certain variables of GLOBIOM for alternative levels of carbon taxes, e.g., level of afforestation, level of adoption of certain mitigation options, level of crop used for bioenergy, etc., and impose a constraint on the level of these variables in the Calculator in alternative mitigation scenarios.

The FABLE Calculator is at national or regional scale but through Scenathons, all national and regional models are connected, international trade is adjusted to ensure balance between total imports and total exports, and results aggregated to the global level. We have just completed the Scenathon 2023. The results and the full set of scenario parameters is publicly available here and can also be used for CHOICE.

Potential IAM scenario elements in CHOICE

In the following chapters we will briefly present different types of scenarios, that can be included in the CHOICE IAM modelling framework.

Climate change mitigation scenarios

Climate stabilization pathways

The IAM community develops the different **climate stabilization pathways** that regularly underpin the forward-looking chapters of the IPCC reports (IPCC, 2022). The implications and contributions to these pathways from a land-use perspective can be modelled with models such as GLOBIOM.

IAMs typically apply a global uniform carbon price on all sectors of the economy to distribute mitigation efforts across regions, sectors, and time. Thereby they develop "least-costly" pathways that achieve a certain climate target (e.g., <1.5 °C, 2.0 °C up to >4 °C warming) by the end of the century (C1 - C8 scenario classification labelled in the IPCC AR6). For the most recent set of climate stabilization scenarios from the ENGAGE project, IAMs quantified scenarios reaching different cumulative CO_2 emission budgets ranging from 300 to 3,000 $GtCO_2$ from 2018‑2100, for example:

- 1.5 °C scenario - carbon budget of approximately 600 $GtCO_2$ (C2 scenario)
- 2.0 °C scenario - carbon budget of approximately 1,000 $GtCO_2$ (C4 scenario)
- 2.5 °C scenario - carbon budget of approximately 1,600 $GtCO_2$ (C5 scenario)
- …

Next to the overall warming levels by the end of the century, these scenarios differ also with respect to temperature trends across the century i.e., implications for temperature overshoot by mid-century (Riahi et al., 2021). Here, two types can be differentiated:

- 'End-of-century budget' scenarios limit cumulative CO_2 emissions over the full course of the century. These scenarios typically comprise higher temperature overshoot by mid-century followed by global net negative CO_2 emissions in the second half of the century to bring down temperatures by the end of the century.
- 'Net-zero budget' scenarios do not require global net negative CO_2 emissions in the second half of the century but require more short-term mitigation action to limit the temperature overshoot by mid-century.

In CHOICE, climate stabilization scenarios can be quantified with the Felix (that represents all sectors of the economy) and GLOBIOM (land-use sectors) models. In GLOBIOM, climate stabilization pathways are typically modelled via different GHG prices on AFOLU emissions/removals and biomass demand trajectories up to 2100 since agriculture is expected to directly reduce GHG emissions and enhance carbon sinks, and to provide additional biomass for bioenergy and fossil fuel substitution to the energy sector. In the model, the imposed GHG price (which acts as a tax on GHG emissions and a subsidy for carbon sequestration) triggers the adoption of mitigation options and adjustment in production systems in the model while the biomass demand for bioenergy increases the demand for land for bioenergy production.

Land-use related mitigation potentials.

Next to climate stabilization scenario that achieve a certain temperature target across all sectors of the economy, also **more stylized mitigation scenarios** or cost-effective mitigation potentials can be quantified using GLOBIOM. The model can be used to quantify so called marginal abatement cost curves (MACC) that depict the cost-effective mitigation potential (how much emission reduction can be achieved at a certain GHG price) for the agricultural sector decomposed either by mitigation technology or by GHG source. To emulate the cost-effective mitigation potential a GHG price is implemented in the model. Different set-ups can be used depending on the scenario narrative and the research question, for example:

- GHG price only active in certain regions e.g., to quantify regional emission reduction potentials and assess potential GHG leakage effects through international trade to other regions.
- GHG price only active for certain crop- or livestock products e.g., beef, pork, rice etc. to mimic policies that target only specific products.
- GHG price only active on individual emission sources e.g., CH_4 from enteric fermentation, synthetic fertilizer N_2O emissions etc. to mimic policies targeting specific emission sources.

Next to the GHG price, also **other scenarios elements** related to GHG mitigation can be implemented to assess implications:

- Taxes/subsidies on agricultural products e.g., testing the socio-economic and environmental impact of a tax on meat or other GHG intensive products.
- Forcing the adoption of certain mitigation technologies/practises e.g., the model represents different technologies for the mitigation of agricultural non-CO_2 emissions and carbon sequestration practises that can be adopted if incentives are in place (e.g., a subsidy or GHG price). This will also be the approach used in the FABLE Calculator to reduce future GHG emissions.

Food demand scenarios

Meeting future food and nutrition security goals while ensuring planetary health will require a complete redesign not only of the supply side of the food system, but also a radical change of our diets as well as a drastic reduction in food waste (Willett et al., 2019; Gerten et al., 2020; Leclère et al., 2020). IAMs allow for scenario analysis that consider both supply- and demand-side developments. As a result, it is possible to quantify the full potential of the mitigation options and to capture possible trade-offs and co-benefits across environmental and socio-economic outcomes.

GLOBIOM model and FABLE Calculator development to improve consumer representation by introducing consumer heterogeneity will be implemented in CHOICE and will allow for consideration of much more refined scenarios on the demand side. Consequently, an array of scenarios that introduce changes to consumer behaviour both in terms of diets and waste reduction while considering differences across socio-demographic consumer groups can be considered.

Consumer heterogeneity in food demand

Several studies have described remarkable differences in food choices between men and women (Wardle et al., 2004; Westenhoefer, 2005). Consistently, women are reported to have higher intakes of fruit and vegetables, higher intakes of dietary fibre and lower intakes of fat. Similarly, people with more education often choose healthier diets with less meat and more vegetables, but fewer sugary foods than those with less education (Fraser et al., 2000). Furthermore, aging significantly affects food consumption patterns and elderly have lower energy intake (Sergi et al., 2017). So far, these factors are not taken explicitly into consideration when projecting food demand in integrated assessment models, for instance in the context of the SSPs. For example, currently in GLOBIOM and in the FABLE Calculator, in each country or region, food demand is modelled for one representative consumer. Differences in consumption patterns between the socio-demographic groups and their impact on the total projected food demand are considered only implicitly (IBF-IIASA, 2023). In CHOICE (WP3), consumer representation in GLOBIOM will be improved by capturing these differences in food demand explicitly.

Differences in demand across various consumer groups in each region and for each food product and food group will be derived from the Global Dietary Database (GDD) (globaldietarydatabase.org/). GDD is a comprehensive compilation of information on food and nutrient consumption levels in countries worldwide. As an intermediate step, food groups and categories from the GDD will be mapped to the GLOBIOM food commodities. Next, food demand projections in GLOBIOM will be informed to reflect these systematic differences in food demand between the consumer groups differentiated by:

- Age (0-14 children, 15-19 adolescent, 20-39 young adults, 40-65 middle-aged adults, 65+ senior adults)
- Sex (male, female)
- Education (no/primary, secondary, post-secondary).

This more detailed consumer representation will enable, on the one hand, more targeted design of healthy diets that will capture heterogenous needs of different groups of people. On the other hand, this will allow for improved assessment of undernourishment and overconsumption in these groups as a result of the consumption deviations from those dietary targets (McNaughton et al., 2008). Furthermore, this development will allow for improved impact assessment of dietary interventions, such as school meals or gender-targeted interventions, on different socio-economic and environmental (Custodio et al., 2021).

Projections of food demand under different SSPs

Scenarios of future diets in GLOBIOM are often based on FAO food demand (Alexandratos and Bruinsma, 2012). These scenarios are adapted to the different storylines for each modelling exercise. For instance, the SSP storylines were adapted to the food consumption context to derive diet assumption for the different scenarios as follows (IBF-IIASA, 2023):

- For SSP2 (Middle of the Road), these future diets follow the projections from FAO at the horizon 2050.
- For SSP1 (Sustainability), future diets are more sustainable than in the FAO baseline. Therefore, some alternative assumptions are made on total consumption per capita and demand for some specific products. First, to reflect the better management of domestic waste in developed countries, consumption per capita in the regions is assumed almost constant, whereas it could increase in SSP2 for some developed regions (North America for example). Second, animal protein demand is reduced in regions where more than 75 grams prot/cap/day are consumed for animal and vegetable products. A minimum consumption of 25 grams prot/cap/day of animal calories is ensured but red meat consumption is reduced to 5 grams prot/cap/day (target remains possible through non ruminant meat, eggs and milk). For developing regions, more nutritious diets are assumed, and this materialized through an increase in protein intake at 75 g prot/cap/day and a reduction of root consumption at a level of 100 kcal/cap/day.
- For SSP3 (Fragmented world), as economic growth is much lower in developing region, the income effects alone lead to a significantly lower demand per capita in these regions.

Thanks to the improved representation of consumer heterogeneity, the information existing in the SSP database on population composition projections will be used to design richer demand scenarios that explicitly consider changes in the population demographic structure. In combination with the updated drivers coming from the SSP3.0 release data, this will lead to improved food demand projections for each SSP scenario.

Alternative dietary change scenarios

While animal sourced foods are essential to the diets of infants and young children, especially in low-resource settings (UN Nutrition, 2021), red and processed meat have been linked to increased probability of cancer and other negative health outcomes (Boada et al., 2016). Consequently, significantly reducing or eliminating consumption of meat and animal sourced food in general has been identified as one of the main pathways towards achieving both human and environmental health (Godfray et al., 2018; Springmann et al., 2018). In addition, in order to achieve healthy diets, in most of the world regions, people should consume more fruits, vegetables, nuts and legumes (Willett et al., 2019).

There are several well-established healthy and sustainable dietary patterns, such as the Mediterranean Diet – a diet heavily plant-based and rich in fruits, vegetables, cereals, beans, nuts, and seeds. Overall, diets rich in plant-based foods and low in processed foods and red meats not only help reduce the risk of non-communicable diseases but are also associated with lower environmental impacts. The EAT-Lancet Commission's "planetary health diet" (EL diet) has been designed to sustainably feed a growing global population by 2050 (Willett et al., 2019). It hence integrates the concept of health and environmental sustainability while considering future population growth. The diet represents a radical transformation of current dietary patterns and aims to achieve a healthy diet within planetary boundaries. This diet significantly increases the global intake of fruits, vegetables, nuts, and legumes while reducing the consumption of foods high in sugars, refined starches, and red meat. The diet is implemented in GLOBIOM to follow these recommendations (Table 3) and limiting the total energy consumption to the healthy energy requirements for each sex- and age-defined groups and established at a national level.

Table 3. Healthy reference diet possible ranges, for an intake of 2500 kcal/day.

	Range (g/day)	
Food	**Min**	**Max**
Fruits	100	300
Red meat	0	28
Fish	0	100
Vegetables	200	600
Legumes	0	100
Soybean	0	50
Nuts and seeds	50	
Sugar	0	31
Milk	0	250
Roots	0	100
Poultry	0	58
Eggs	0	25
Palm oil	0	6.8
Vegetable oil	20	80
Starchy fruits		100

Source: Adapted from (Willett et al., 2019)

Such a global shift in dietary habits will be clearly challenging (Willett et al., 2019; Rust et al., 2020) and necessitates mobilizing a broad range of technological and policy options (Barrett et al., 2020; Herrero et al., 2021). One such emerging technology is the new generation of novel plant-based alternatives for meat and milk. These products are made entirely from plants, but their taste and consistency closely resemble animal products thanks to a sophisticated production process involving haemoglobin and binders extracted from fermented plants (Kearney, 2020). They could potentially shift diets away from meat and dairy without the need to dramatically change food habits. Impact of novel plant-based alternatives for meat and milk adoption on environmental and socio-economic impacts has been already analysed with GLOBIOIM using a range of stylized scenarios (Kozicka et al., 2023). The results show a large potential of this dietary shift to reduce climate and biodiversity pressures from the food system.

A range of scenarios of healthy and sustainable diet adoption, such as the EL diet or substitution to alternative proteins, especially with the reference to the newly established in CHOICE consumer groups can be designed. Specifically, healthy diets that will capture differences in the metabolic needs of consumers in different age and sex categories can be designed. Furthermore, based on the heterogenous consumer groups, scenarios can be refined with different adoption rates across the demographic groups and the design of targeted dietary interventions, such as school meals or gender-targeted campaigns. They could be linked to the CHOICE pilots, allowing for the assessment of scaling of the CHOICE tools and campaigns.

Food loss and waste scenarios

Currently, GLOBIOM uses losses and waste coefficients from (FAO, 2011). It distinguishes between agricultural production loss, storage loss, processing and packaging, distribution and retail, and consumer waste. Projections of future development in food loss and waste have been linked to the SSP narratives (Fricko et al., 2017). In CHOICE, GLOBIOM will be improved to better represent food waste and losses along the value chains. Based on this development, future scenarios of food loss reduction across food products and consumer groups can be developed. This will allow to consider targeted interventions at a product/value chain level, or campaigns aiming at a selected sociodemographic group and assess their environmental and socio-economic impacts. Furthermore, GLOBIOM allows to track potential leakages and spill overs resulting from the reduced food waste. This refined analysis will add to the previous studies that considered reduction of food loss and waste on the aggregate level (Springmann et al., 2018).

Undernourishment scenarios

GLOBIOM and the FABLE Calculator project the under-nourished population (Hasegawa et al., 2018). It is a multiple of the prevalence of under-nourishment and the total population. Following the FAO methodology, the prevalence of under-nourishment is calculated using three key factors: the mean dietary energy availability (kcal per person per day), the mean minimum dietary energy requirement (MDER) and the coefficient of variation of the domestic distribution of dietary energy availability in a country. The food distribution in a country is assumed to obey a log-normal distribution, which is determined by the mean food calorie availability (mean) and the equity of the food distribution (variance). The proportion of the population under the cut- off point (MDER) is then defined as the prevalence of under-nourishment (Hasegawa et al., 2018). The calorie-based food consumption (kcal per person per day) output from the model is used for the mean food calorie availability. The future mean MDER is calculated for each year and country using the mean MDER in the base year at the country, adjusted for the MDER in different age and sex groups and future population demographics to reflect differences in the MDER across age and sex. In GLOBIOM, the future equity of food distribution is estimated by applying the historical trend of income growth and the improved coefficient of variation of the food distribution to the future, such that the equity is improved along with income growth in future at historical rates up to the present best value (0.2).

Thanks to this measure, different scenarios of improved food distribution that link to heterogenous consumers can be designed and analysed with GLOBIOM and the FABLE

Calculator. Furthermore, targeted nutritional interventions, such as elimination of hunger among children can be introduced as elements of other policy scenarios.

Other potential scenario dimensions

Apart from climate change mitigation scenarios and food demand scenarios, there are other scenarios dimensions that can be parameterized and simulated in GLOBIOM and the IAMs that will be used for CHOICE Applying these additional scenario dimensions in combination with mitigation and food demand scenarios can help to address interests on the effects of specific mitigation or demand-side interventions in wider policy contexts.

Land protection and biodiversity conservation scenarios

GLOBIOM and the FABLE Calculator can include additional land protection and biodiversity-friendly land conservation setups in scenario runs. In CHOICE, such scenario setups would act as boundary conditions and affect land availability and land-use change possibilities, and further make a difference in the land-based mitigation potential and the model's reaction to supply or demand-side interventions.

In terms of land protection scenarios, GLOBIOM integrates data of protected area at pixel level from World Database of Protected Areas (IUCN and UNEP-WCMC, 2017), including protected areas (natural land, unmanaged forest, and wetland) in all categories (Ia, Ib, II, III, IV, V, VI and Not Reported). Conversion of protected lands in strictly protected IUCN land categories Ia (Strict Nature Reserve), Ib (Wilderness Area), and II (National part) to agricultural production or other land types is prohibited, i.e., protected other natural vegetation will remains natural land, while protected unmanaged forest will remain forest and not intervened by production activities.

By default, GLOBIOM and the FABLE Calculator apply historically existing land protection (under Ia, Ib and II categories) based on the WDPA data, which accounts for 15.7% of global terrestrial area by 2020. In GLOBIOM, under SSP3 scenarios and in low-income countries under SSP4 scenarios, it is assumed that global land protection area will remain 15.7% throughout the twenty-first century. Under SSP2 scenarios, global land-protection area is assumed to growth to 17% by 2030, which is in line with the AICHI Biodiversity target 11 of increase total surface of protected areas, and the ratio will remain stable for the rest of the century. Under SSP1 and SSP5 scenarios, the land protection ratio by 2030 is assumed to double the AICHI target 11, reaching 34% in 2030 and onwards. Depending on research focus, such variations in land protection extents can also be flexibly parameterised in different scenarios based on a same SSP narrative, to represent the strengthening of land-use protection ambitions in each SSP socioeconomic pathway. Modelling practice with different land-protection has been applied in previous publication (Frank et al., 2021). In the FABLE Calculator, alternative scenarios to increase protected areas can be defined by country at the ecoregion and land cover type level.

In terms of biodiversity conservation scenarios, GLOBIOM can represent more stringent and localized biodiversity-friendly land-use change regulations and land restoration incentives, based on available map layers on potential protected areas, restoration priorities, and modelled impacts of different land-uses on biodiversity in each pixel. As has been analysed and documented as the "C scenario" in (Leclère et al., 2020), this biodiversity conservation scenario is parameterised to include two parts: (i) increased land protection, and (ii) increased land restoration and improved land planning. The former (increased land protection) is implemented as a strict restriction of certain land-use change flows from 2030 onward in those 2-degree pixels identified as biodiversity hot spots. Here "strict restriction" means land-use change flows that would result in negative biodiversity impacts (informed by the data layer of modelled impacts of land-use changes on biodiversity intactness index) are strictly forbidden. "Biodiversity hot spots" are defined as pixels for which the sum of potential protected areas across different land types is larger than 50% of total land area (of these pixels). The potential protected area is derived by overlaying three global datasets – Protected Areas from WDPA, Key Biodiversity Areas from *the World Database of Key Biodiversity Areas*, and the 2009 Wilderness Areas (Watson et al., 2016). Details about the method of deriving the potential protected areas is documented in the supplementary material of (Leclère et al., 2020). The latter (increased land restoration and improved land planning) is implemented as introducing a biodiversity subsidy (or biodiversity tax, depending on the biodiversity effects of corresponding land-use changes) to the impacts of possible land-use changes on biodiversity stock. The land-use changes' impacts on biodiversity stock is defined as the area of land-use change multiplied by biodiversity intactness index coefficient and the value of the regional restoration priority layer – all are grid cell specific. In CHOICE, this biodiversity conservation scenario, when applied based on research needs, can take advantage of recent developments in the GLOBIOM/G4M system which include refined and more consistent representation of land protection and land restoration in GLOBIOM and G4M.

Environmental flow constraints on irrigation water use

Agricultural irrigation water demand and availability is another resource-sustainability dimension represented by GLOBIOM. By default, a monthly irrigation water balance is parameterised and operational in GLOBIOM to regulate local agricultural irrigation activities. This water balance relationship in GLOBIOM depicts the maximum irrigation water consumption at the pixel level, which equals to the sum of available water from available seasonal water, groundwater and other water sources, as well as water storage. This therefore prevents unregulated water withdrawals for agricultural irrigation from exceeding local water availability, representing the consideration given to the local and intra-annual streamflow's availability, but not yet accounting for the potential impacts on environment.

To represent improved sustainability in water resource use, an environmental constraint, called "environmental flow requirement (EFR)", can be activated as an additional scenario dimension. According to literature, the EFR is critical to protect the riverine ecosystem (Arthington et al., 2006; Pastor et al., 2014) and should be reserved from being withdrawn for agricultural production. In GLOBIOM, the EFR scenarios will restrict the water available for irrigation to not exceed the water that can be sustainably taken from surface water sources. The EFRs are binding at the monthly level and calculated under the variable flow method (Pastor et al., 2014). As crop production, food trade, and water use are closely interconnected (Pastor et al., 2019), adding the ERF constraint would also induce impact on food market, nutrient availability, and can further affect land-based mitigation costs and potentials.

Trade adjustments and trade liberalization

Another scenario dimension that can be represented in GLOBIOM is the flexibility in international food trade. As has been extensively studied in literature, international trade could lead to cross-regional spillover impacts, resulting in non-negligible environmental footprints in exporting regions (Sandström et al., 2018; Zhao et al., 2021; Foong et al., 2022). Previous studies with GLOBIOM have also illustrated that applying food or protein self-sufficiency target will massively change the distribution of land related GHG emission patterns and other environmental burden (Ren et al., 2023; Zhao et al., 2024). Meanwhile, international food trade can also act as an important way of adaptation to climate change, which helps to reduce the risk of hunger globally in a changing climate (Janssens et al., 2020; Gouel and Laborde, 2021). Therefore, it is important to consider the trade dimension in scenario setup.

To address the potential leakage impacts and the potential efficiency-improvement-related benefits from international trade, it is possible to setup scenarios with different trade assumptions in GLOBIOM to compare the direct local impact of policy interventions from the indirect and cross-regional impact mediated by international trade. By default, GLOBIOM allows for free trade adjustments in all scenarios (baseline scenarios and policy scenarios), where regions can freely adjust future trade flows and volumes following efficiency principles during the economic optimization. These scenarios can be used to identify the local impacts on sustainable land use, induced by policy interventions. As a comparison, international trade of food commodities under certain policy scenarios (e.g., demand-side intervention, or climate change mitigation scenarios) can be fixed at the corresponding baseline levels (i.e., trade volumes in baseline scenario). The results under fixed-trade setup can be compared the those without restrictions in trade adjustments, to reveal the changes in global market and potential spillover impacts on land use in different regions under the same policy scenarios.

Additionally, scenarios with different levels of trade flexibility can be simulated in GLOBIOM, representing trade liberalization or trade barriers narratives. These scenarios are parameterized as scenarios with different trade costs. For example, in baseline SSP narratives, SSP1 and SSP5 scenarios are assumed to have higher levels of freedom in trade, with lowest trade costs between world regions in different scenarios. Conversely, in the SSP3 “Regional Rivalry” narrative, worldwide trade costs are systematically higher. SSP2 and SSP4 scenarios have medium trade costs. Depending on research needs, similar variations in trade cost parameters can be applied to scenarios with different trade assumptions in a same SSP narrative.

Conclusions

This report provides an overview of the CHOICE Integrated Assessment Modelling (IAM) framework and its application in analysing climate change mitigation and sustainable food system transition strategies, as well as their broader implications for land use, food demand, and socio-economic factors. CHOICE advanced modelling tools—namely GLOBIOM, FeliX, and the FABLE Calculator—offer a comprehensive approach to scenario analysis, allowing for the exploration of various pathways toward achieving climate targets.

The report outlines Shared Socioeconomic Pathways (SSPs) as the foundation for these scenarios, ensuring that they are grounded in comprehensive and updated socioeconomic data. It details the update from the SSP3.0 release version as compared to the SSP2.0. Next, the report discusses a range of scenario elements linked to the key food system interventions across heterogenous actors, their relevance for climate mitigation and sustainability of food systems. It goes on to detail how they could be analysed with the enhanced CHOICE modelling tools. By presenting a variety of potential scenario elements, the report addresses critical dimensions of climate change mitigation, including carbon pricing impacts, dietary shifts, land protection strategies, and the complexities of international trade. The CHOICE models’ ability to model consumer behaviour and dietary changes with greater precision marks a significant advancement in understanding the environmental and socio-economic impacts of different mitigation strategies.

By offering a detailed evaluation of trade-offs and co-benefits associated with various policy options, the CHOICE framework equips decision-makers with the insights necessary to design effective policies. These policies not only aim to meet climate goals but also promote food security, biodiversity conservation, and overall sustainability. Ultimately, this report underscores the critical role of integrated assessment models in guiding global efforts toward a more resilient and sustainable future.

References

Alexandratos, N. and Bruinsma, J. 2012. World Agriculture towards 2030/2050: the 2012 revision. ESA Working Paper.

Arthington, A. H., Bunn, S. E., Poff, N. L., et al. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications, **16**(4): 1311-1318.

Bajzelj, B., Richards, K. S., Allwood, J. M., et al. 2014. Importance of food-demand management for climate mitigation. Nature Clim. Change, **4**(10): 924-929.

Barrett, C. B., Benton, T. G., Cooper, K. A., et al. 2020. Bundling innovations to transform agri-food. Nature Sustainability, **3**(December): 974--976.

Beach, R. H., Creason, J., Ohrel, S. B., et al. 2015. Global mitigation potential and costs of reducing agricultural non-CO2 greenhouse gas emissions through 2030. Journal of Integrative Environmental Sciences, **12**(sup1): 87-105.

Beckage, B., Gross, L. J., Lacasse, K., et al. 2018. Linking models of human behaviour and climate alters projected climate change. Nature Climate Change, **8**(1): 79-84.

Boada, L. D., Henrquez-Hernndez, L. A. and Luzardo, O. P. 2016. The impact of red and processed meat consumption on cancer and other health outcomes: Epidemiological evidences. Food and Chemical Toxicology, **92**: 236--244.

Bressler, R. D., Moore, F. C., Rennert, K., et al. 2021. Estimates of country level temperature-related mortality damage functions. Scientific Reports, **11**(1): 20282.

Burke, M., Hsiang, S. M. and Miguel, E. 2015. Global non-linear effect of temperature on economic production. Nature, **527**(7577): 235-239.

Byers, E., Krey, V., Kriegler, E., et al. Institution. 2022. AR6 Scenarios Database. Series AR6 Scenarios Database Edition. Available from: https://data.ene.iiasa.ac.at/ar6/.

Chateau, J., Dellink, R., Atarody, L., et al. forthcoming. Long-term projections of economic growth for climate change assessments: an economic implementation of the Shared Socioeconomic Pathways. OECD Working Paper Series.

Clark, M. A., Domingo, N. G. G., Colgan, K., et al. 2020. Global food system emissions could preclude achieving the 1.5° and 2° C climate change targets. Science, **370**(6517): 705.

Cramer, W., Kicklighter, D. W., Bondeau, A., et al. 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Global Change Biology, **5**: 1-15.

Crespo Cuaresma, J. 2017. Income projections for climate change research: A framework based on human capital dynamics. Global Environmental Change, **42**: 226-236.

Crippa, M., Solazzo, E., Guizzardi, D., et al. 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, **2**(3): 198-209.

Custodio, M. C., Ynion, J., Samaddar, A., et al. 2021. Unraveling heterogeneity of consumers' food choice: Implications for nutrition interventions in eastern India. Global Food Security, **28**.

Dellink, R., Chateau, J., Atarody, L., et al. forthcoming journal article. Updating economic growth in the SSPs: Integrating observed history with original storylines.

Dellink, R., Chateau, J., Lanzi, E., et al. 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change, **42**: 200-214.

Eker, S., Reese, G. and Obersteiner, M. 2019. Modelling the drivers of a widespread shift to sustainable diets. Nature Sustainability, **2**(8): 725-735.

Eyring, V., Bony, S., Meehl, G. A., et al. 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev., **9**(5): 1937-1958.

FAO. 2011. Global food losses and food waste ‐ Extent, causes and prevention. Available from: https://www.fao.org/sustainable-food-value-chains/library/details/en/c/266053/.

FAOSTAT. Institution. 2020. Food and land-use data. Series Food and land-use data Edition. Available from: http://www.fao.org/faostat/en/#home.

Foong, A., Pradhan, P., Frör, O., et al. 2022. Adjusting agricultural emissions for trade matters for climate change mitigation. Nature Communications, **13**(1): 3024.

Frank, S., Beach, R., Havlik, P., et al. 2018. Structural change as a key component for agricultural non-CO_2 mitigation efforts. Nature Communications, **9**(1): 1060.

Frank, S., Gusti, M., Havlík, P., et al. 2021. Land-based climate change mitigation potentials within the agenda for sustainable development. Environmental Research Letters, **16**(2).

Fraser, G. E., Welch, A., Luben, R., et al. 2000. The effect of age, sex, and education on food consumption of a middle- aged English cohort - EPIC in East Anglia. Preventive Medicine, **30**(1): 26--34.

Fricko, O., Havlík, P., Rogelj, J., et al. 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.

Gerten, D., Heck, V., Jgermeyr, J., et al. 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. Nature Sustainability: 1--9.

Godfray, H. C. J., Aveyard, P., Garnett, T., et al. 2018. Meat consumption, health, and the environment. Science, **361**(6399).

Gouel, C. and Laborde, D. 2021. The crucial role of domestic and international market-mediated adaptation to climate change. Journal of Environmental Economics and Management, **106**: 102408.

Gusti, M. 2010. An algorithm for simulation of forest management decisions in the global forest model. Artificial Intelligence, **N4**: 45-49.

Hasegawa, T., Fujimori, S., Havlk, P., et al. 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change, **8**(8): 699--703.

Havlík, P., Schneider, U. A., Schmid, E., et al. 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy, **39**(10): 5690-5702.

Herrero, M., Havlík, P., Valin, H., et al. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences, **110**(52): 20888.

Herrero, M., Henderson, B., Havlik, P., et al. 2016. Greenhouse gas mitigation potentials in the livestock sector. Nature Clim. Change, **6**(5): 452-461.

Herrero, M., Thornton, P. K., Mason-D'Croz, D., et al. 2021. Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health, **5**(1): 50--62.

IBF-IIASA. Integrated Biospheres Futures International Institute for Applied Systems Analysis (IBF-IIASA). 2023. Global Biosphere Management Model (GLOBIOM) Documentation 2023 - Version 1.0. Available from: https://iiasa.github.io/GLOBIOM/.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available from: https://www.ipcc.ch/report/ar5/syr/.

IPCC. 2018. Global warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Available.

IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Available.

IPCC. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Available from: https://www.ipcc.ch/report/ar6/syr/.

IUCN and UNEP-WCMC. Institution. 2017. The World Database on Protected Areas (WDPA) [On-line]. Series The World Database on Protected Areas (WDPA) [On-line] Edition. Available from: www.protectedplanet.net.

Janssens, C., Havlík, P., Krisztin, T., et al. 2020. Global hunger and climate change adaptation through international trade. Nature Climate Change, **10**(9): 829-835.

KC, S., Moradhvaj, Potancokova, M., et al. (2023). Wittgenstein Center (WIC) Population and Human Capital Projections - 2023.

KC, S., Moradhvaj, P., M., A., S., et al. Institution. 2024. Wittgenstein Center (WIC) Population and Human Capital Projections - 2023 (Version V13). Series Wittgenstein Center (WIC) Population and Human Capital Projections - 2023 (Version V13) Edition. Available from: https://doi.org/10.5281/zenodo.10618931.

Kearney. Kearney. 2020. When consumers go vegan, how much meat will be left on the table for agribusiness? Available from: https://www.de.kearney.com/consumer-retail/article/?/a/when-consumers-go-vegan-how-much-meat-will-be-left-on-the-table-for-agribusiness-.

Kindermann, G., Obersteiner, M., Sohngen, B., et al. 2008. Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America, **105**(30): 10302-10307.

Kindermann, G. E., McCallum, I., Fritz, S., et al. 2008. A global forest growing stock, biomass and carbon map based on FAO statistics. Silva Fennica, **42**(3): 387-396.

Kozicka, M., Havlk, P., Valin, H., et al. 2023. Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives. Nature Communications, **14**(1).

Lamboll, R. D., Nicholls, Z. R. J., Smith, C. J., et al. 2023. Assessing the size and uncertainty of remaining carbon budgets. Nature Climate Change.

Lauri, P., Forsell, N., Korosuo, A., et al. 2017. Impact of the 2° C target on global woody biomass use. Forest Policy and Economics, **83**: 121-130.

Lauri, P., Havlík, P., Kindermann, G., et al. 2014. Woody biomass energy potential in 2050. Energy Policy, **66**(0): 19-31.

Leclère, D., Obersteiner, M., Barrett, M., et al. 2020. Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature, **585**: 551 - 556.

Liu, Q., Gao, L., Guo, Z., et al. 2023. Robust strategies to end global poverty and reduce environmental pressures. One Earth, **6**(4): 392-408.

Lopez, A. D. and Murray, C. C. J. L. 1998. The global burden of disease, 1990‐2020. Nature Medicine, **4**(11): 1241-1243.

Lutz, W., Goujon, A., Kc, S., et al. (2018). Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries[M], Publications Office of the European Union.

McNaughton, S. A., Ball, K., Crawford, D., et al. 2008. An index of diet and eating patterns is a valid measure of diet quality in an Australian population. The Journal of nutrition, **138**(1): 86--93.

Millar, R. J., Fuglestvedt, J. S., Friedlingstein, P., et al. 2017. Emission budgets and pathways consistent with limiting warming to 1.5° C. Nature Geoscience, **10**: 741-747.

Moallemi, E. A., Eker, S., Gao, L., et al. 2022. Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda. One Earth, **5**(7): 792-811.

Mosnier, A., Penescu, L., Perez-Guzman, K., et al. IIASA and SDSN. 2020. FABLE Calculator documentation - 2020 update. Available from: https://fableconsortium.org/publications/fable-calculator-2020-updated-documentation/.

O’Neill, B., Kriegler, E., Riahi, K., et al. 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change, **122**(3): 387-400.

Pastor, A. V., Ludwig, F., Biemans, H., et al. 2014. Accounting for environmental flow requirements in global water assessments. Hydrol. Earth Syst. Sci., **18**(12): 5041-5059.

Pastor, A. V., Palazzo, A., Havlik, P., et al. 2019. The global nexus of food‐trade‐water sustaining environmental flows by 2050. Nature Sustainability, **2**(6): 499-507.

Popp, A., Lotze-Campen, H. and Bodirsky, B. 2010. Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Global Environmental Change, **20**(3): 451-462.

Ranganathan, J., Vennard, D., Waite, R., Lipinski, B., Searchinger, T., Dumas, P. . World Resources Institute. 2016. Shifting Diets for a Sustainable Food Future: Creating a Sustainable Food Future. Available from: https://www.wri.org/research/shifting-diets-sustainable-food-future.

Reisinger, A., Clark, H., Cowie, A. L., et al. 2021. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, **379**(2210): 20200452.

Ren, M., Huang, C., Wu, Y., et al. 2023. Enhanced food system efficiency is the key to China’s 2060 carbon neutrality target. Nature Food, **4**(7): 552-564.

Riahi, K., Bertram, C., Huppmann, D., et al. 2021. Cost and attainability of meeting stringent climate targets without overshoot. Nature Climate Change, **11**(12): 1063-1069.

Riahi, K., van Vuuren, D. P., Kriegler, E., et al. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, **42**: 153-168.

Rockström, J., Gaffney, O., Rogelj, J., et al. 2017. A roadmap for rapid decarbonization. Science, **355**(6331): 1269-1271.

Rogelj, J., Luderer, G., Pietzcker, R. C., et al. 2015. Energy system transformations for limiting end-of-century warming to below 1.5 [deg]C. Nature Clim. Change, **5**(6): 519-527.

Rogelj, J., Popp, A., Calvin, K. V., et al. 2018. Scenarios towards limiting global mean temperature increase below 1.5° C. Nature Climate Change, **8**(4): 325-332.

Rust, N. A., Ridding, L., Ward, C., et al. 2020. How to transition to reduced-meat diets that benefit people and the planet. Science of The Total Environment, **718**: 137208.

Sandström, V., Valin, H., Krisztin, T., et al. 2018. The role of trade in the greenhouse gas footprints of EU diets. Global Food Security, **19**: 48-55.

Schellnhuber, H. J., Rahmstorf, S. and Winkelmann, R. 2016. Why the right climate target was agreed in Paris. Nature Clim. Change, **6**(7): 649-653.

Schleussner, C.-F., Rogelj, J., Schaeffer, M., et al. 2016. Science and policy characteristics of the Paris Agreement temperature goal. Nature Clim. Change, **advance online publication**.

Sergi, G., Bano, G., Pizzato, S., et al. 2017. Taste loss in the elderly: Possible implications for dietary habits. Critical Reviews in Food Science and Nutrition, **57**(17): 3684--3689.

Skalský, R., Tarasovičová, Z., Balkovič, J., et al. International Institute for Applied Systems Analysis (IIASA), Austria. 2008. GEO-BENE global database for bio-physical modeling v. 1.0 - concepts, methodologies and data. The GEO-BENE database report. Available.

Springmann, M., Clark, M., Mason-D'Croz, D., et al. 2018. Options for keeping the food system within environmental limits. Nature, **562**(7728): 519--525.

Springmann, M., Mason-D/'Croz, D., Robinson, S., et al. 2016. Mitigation potential and global health impacts from emissions pricing of food commodities. Nature Clim. Change, **7**: 69-74.

Stehfest, E., Bouwman, L., Van Vuuren, D. P., et al. 2009. Climate benefits of changing diet. Climatic Change, **95**(1-2): 83-102.

Tubiello, F. N., Rosenzweig, C., Conchedda, G., et al. 2021. Greenhouse gas emissions from food systems: building the evidence base. Environmental Research Letters, **16**(6): 065007.

UN Nutrition 2021. Livestock-derived foods and sustainable healthy diets UN Nutrition.

UNEP. UNEP. 2022. Emissions Gap Report 2022: The Closing Window − Climate crisis calls for rapid transformation of societies. Available from: https://www.unep.org/emissions-gap-report-2022.

United Nations. Institution. 2022. World Population Prospects 2022. Series World Population Prospects 2022 Edition. Available from: https://population.un.org/wpp/.

van Vuuren, D., Edmonds, J., Kainuma, M., et al. 2011. The representative concentration pathways: an overview. Climatic Change, **109**(1-2): 5-31.

van Vuuren, D. P., Riahi, K., Calvin, K., et al. 2017. The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. Global Environmental Change, **42**: 148-152.

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., et al. 2018. Alternative pathways to the 1.5 ° C target reduce the need for negative emission technologies. Nature Climate Change, **8**(5): 391-397.

Walsh, B., Ciais, P., Janssens, I. A., et al. 2017. Pathways for balancing CO2 emissions and sinks. Nature Communications, **8**(1): 14856.

Wardle, J., Haase, A. M., Steptoe, A., et al. 2004. Gender differences in food choice: the contribution of health beliefs and dieting. Annals of behavioral medicine : a publication of the Society of Behavioral Medicine, **27**(2): 107--116.

Watson, James E. M., Shanahan, Danielle F., Di Marco, M., et al. 2016. Catastrophic Declines in Wilderness Areas Undermine Global Environment Targets. Current Biology, **26**(21): 2929-2934.

Westenhoefer, J. 2005. Age and gender dependent profile of food choice. Forum of nutrition, **57**(57): 44--51.

Willett, W., Rockstrm, J., Loken, B., et al. 2019. Food in the Anthropocene: the EAT‐Lancet Commission on healthy diets from sustainable food systems. The Lancet, **393**(10170).

Williams, J. R. (1995). The EPIC Model. Computer Models of Watershed Hydrology. V. P. Singh, Water Resources Publications, Highlands Ranch, Colorado**:** 909-1000.

Zhao, H., Chang, J., Havlík, P., et al. 2021. China’s future food demand and its implications for trade and environment. Nature Sustainability, **4**(12): 1042-1051.

Zhao, H., Fan, X., Bai, Z., et al. 2024. Holistic food system innovation strategies can close up to 80% of China’s domestic protein gaps while reducing global environmental impacts. Nature Food, **5**(7): 581-591.

Annex 1: Shared Socioeconomic Pathways (SSP) – additional data and information

1.1 SSP data availability

Table A1 provides a summary of data availability and data application status for each individual country or region defined in United Nation's database, indicating whether the macroeconomic projections for the country/region under different SSP scenarios are available.

Table A1 Regional mapping between country/region names in United Nation's definition, ISO3 code and SSP3.0 database, and data availability

	UN name	ISO3 code	Pop data available in SSP3.0	GDP data available in SSP3.0
1	Afghanistan	AFG	YES	NO
2	Albania	ALB	YES	YES
3	Algeria	DZA	YES	YES
4	American Samoa	ASM	NO	NO
5	Andorra	AND	NO	NO
6	Angola	AGO	YES	YES
7	Anguilla	AIA	NO	NO
8	Antigua and Barbuda	ATG	YES	YES
9	Argentina	ARG	YES	YES
10	Armenia	ARM	YES	YES
11	Aruba	ABW	YES	YES
12	Australia	AUS	YES	YES
13	Austria	AUT	YES	YES
14	Azerbaijan	AZE	YES	YES
15	Bahamas	BHS	YES	YES
16	Bahrain	BHR	YES	YES
17	Bangladesh	BGD	YES	YES
18	Barbados	BRB	YES	YES
19	Belarus	BLR	YES	YES
20	Belgium	BEL	YES	YES
21	Belize	BLZ	YES	YES
22	Benin	BEN	YES	YES
23	Bermuda	BMU	NO	NO
24	Bhutan	BTN	YES	YES
25	Bolivia (Plurinational State of)	BOL	YES	YES
26	Bonaire, Sint Eustatius and Saba	BES	NO	NO
27	Bosnia and Herzegovina	BIH	YES	YES
28	Botswana	BWA	YES	YES
29	Brazil	BRA	YES	YES
30	British Virgin Islands	VGB	NO	NO
31	Brunei Darussalam	BRN	YES	YES
32	Bulgaria	BGR	YES	YES
33	Burkina Faso	BFA	YES	YES
34	Burundi	BDI	YES	YES
35	Cabo Verde	CPV	YES	YES

	UN name	ISO3 code	Pop data available in SSP3.0	GDP data available in SSP3.0
36	Cambodia	KHM	YES	YES
37	Cameroon	CMR	YES	YES
38	Canada	CAN	YES	YES
39	Cayman Islands	CYM	NO	NO
40	Central African Republic	CAF	YES	YES
41	Chad	TCD	YES	YES
42	Chile	CHL	YES	YES
43	China	CHN	YES	YES
44	China, Hong Kong SAR	HKG	YES	YES
45	China, Macao SAR	MAC	YES	YES
46	China, Taiwan Province of China	TWN	YES	YES
47	Colombia	COL	YES	YES
48	Comoros	COM	YES	YES
49	Congo	COG	YES	YES
50	Cook Islands	COK	NO	NO
51	Costa Rica	CRI	YES	YES
52	Cote d'Ivoire	CIV	YES	YES
53	Croatia	HRV	YES	YES
54	Cuba	CUB	YES	YES
55	Curacao	CUW	YES	NO
56	Cyprus	CYP	YES	YES
57	Czechia	CZE	YES	YES
58	Dem. People's Republic of Korea	PRK	YES	YES
59	Democratic Republic of the Congo	COD	YES	YES
60	Denmark	DNK	YES	YES
61	Djibouti	DJI	YES	YES
62	Dominica	DMA	NO	NO
63	Dominican Republic	DOM	YES	YES
64	Ecuador	ECU	YES	YES
65	Egypt	EGY	YES	YES
66	El Salvador	SLV	YES	YES
67	Equatorial Guinea	GNQ	YES	YES
68	Eritrea	ERI	YES	YES
69	Estonia	EST	YES	YES
70	Eswatini	SWZ	YES	YES
71	Ethiopia	ETH	YES	YES
72	Falkland Islands (Malvinas)	FLK	NO	NO
73	Faroe Islands	FRO	NO	NO
74	Fiji	FJI	YES	YES
75	Finland	FIN	YES	YES
76	France	FRA	YES	YES
77	French Guiana	GUF	YES	YES
78	French Polynesia	PYF	YES	YES
79	Gabon	GAB	YES	YES

	UN name	ISO3 code	Pop data available in SSP3.0	GDP data available in SSP3.0
80	Gambia	GMB	YES	YES
81	Georgia	GEO	YES	YES
82	Germany	DEU	YES	YES
83	Ghana	GHA	YES	YES
84	Gibraltar	GIB	NO	NO
85	Greece	GRC	YES	YES
86	Greenland	GRL	NO	NO
87	Grenada	GRD	YES	YES
88	Guadeloupe	GLP	YES	NO
89	Guam	GUM	YES	YES
90	Guatemala	GTM	YES	YES
91	Guernsey	GGY	NO	NO
92	Guinea	GIN	YES	YES
93	Guinea-Bissau	GNB	YES	YES
94	Guyana	GUY	YES	YES
95	Haiti	HTI	YES	YES
96	Holy See	VAT	NO	NO
97	Honduras	HND	YES	YES
98	Hungary	HUN	YES	YES
99	Iceland	ISL	YES	YES
100	India	IND	YES	YES
101	Indonesia	IDN	YES	YES
102	Iran (Islamic Republic of)	IRN	YES	YES
103	Iraq	IRQ	YES	YES
104	Ireland	IRL	YES	YES
105	Isle of Man	IMN	NO	NO
106	Israel	ISR	YES	YES
107	Italy	ITA	YES	YES
108	Jamaica	JAM	YES	YES
109	Japan	JPN	YES	YES
110	Jersey	JEY	NO	NO
111	Jordan	JOR	YES	YES
112	Kazakhstan	KAZ	YES	YES
113	Kenya	KEN	YES	YES
114	Kiribati	KIR	YES	YES
115	Kosovo (under UNSC res. 1244)	-	NO	NO
116	Kuwait	KWT	YES	YES
117	Kyrgyzstan	KGZ	YES	YES
118	Lao People's Democratic Republic	LAO	YES	YES
119	Latvia	LVA	YES	YES
120	Lebanon	LBN	YES	YES
121	Lesotho	LSO	YES	YES
122	Liberia	LBR	YES	YES
123	Libya	LBY	YES	YES
124	Liechtenstein	LIE	NO	NO
125	Lithuania	LTU	YES	YES

	UN name	ISO3 code	Pop data available in SSP3.0	GDP data available in SSP3.0
126	Luxembourg	LUX	YES	YES
127	Madagascar	MDG	YES	YES
128	Malawi	MWI	YES	YES
129	Malaysia	MYS	YES	YES
130	Maldives	MDV	YES	YES
131	Mali	MLI	YES	YES
132	Malta	MLT	YES	YES
133	Marshall Islands	MHL	NO	NO
134	Martinique	MTQ	YES	NO
135	Mauritania	MRT	YES	YES
136	Mauritius	MUS	YES	YES
137	Mayotte	MYT	YES	YES
138	Mexico	MEX	YES	YES
139	Micronesia (Fed. States of)	FSM	YES	YES
140	Monaco	MCO	NO	NO
141	Mongolia	MNG	YES	YES
142	Montenegro	MNE	YES	YES
143	Montserrat	MSR	NO	NO
144	Morocco	MAR	YES	YES
145	Mozambique	MOZ	YES	YES
146	Myanmar	MMR	YES	YES
147	Namibia	NAM	YES	YES
148	Nauru	NRU	NO	NO
149	Nepal	NPL	YES	YES
150	Netherlands	NLD	YES	YES
151	New Caledonia	NCL	YES	YES
152	New Zealand	NZL	YES	YES
153	Nicaragua	NIC	YES	YES
154	Niger	NER	YES	YES
155	Nigeria	NGA	YES	YES
156	Niue	NIU	NO	NO
157	North Macedonia	MKD	YES	YES
158	Northern Mariana Islands	MNP	NO	NO
159	Norway	NOR	YES	YES
160	Oman	OMN	YES	YES
161	Pakistan	PAK	YES	YES
162	Palau	PLW	NO	NO
163	Panama	PAN	YES	YES
164	Papua New Guinea	PNG	YES	YES
165	Paraguay	PRY	YES	YES
166	Peru	PER	YES	YES
167	Philippines	PHL	YES	YES
168	Poland	POL	YES	YES
169	Portugal	PRT	YES	YES
170	Puerto Rico	PRI	YES	YES
171	Qatar	QAT	YES	YES
172	Republic of Korea	KOR	YES	YES

	UN name	ISO3 code	Pop data available in SSP3.0	GDP data available in SSP3.0
173	Republic of Moldova	MDA	YES	YES
174	Reunion	REU	YES	NO
175	Romania	ROU	YES	YES
176	Russian Federation	RUS	YES	YES
177	Rwanda	RWA	YES	YES
178	Saint Barthélemy	BLM	NO	NO
179	Saint Helena	SHN	NO	NO
180	Saint Kitts and Nevis	KNA	NO	NO
181	Saint Lucia	LCA	YES	YES
182	Saint Martin (French part)	MAF	NO	NO
183	Saint Pierre and Miquelon	SPM	NO	NO
184	Saint Vincent and the Grenadines	VCT	YES	YES
185	Samoa	WSM	YES	YES
186	San Marino	SMR	NO	NO
187	Sao Tome and Principe	STP	YES	YES
188	Saudi Arabia	SAU	YES	YES
189	Senegal	SEN	YES	YES
190	Serbia	SRB	YES	YES
191	Seychelles	SYC	YES	YES
192	Sierra Leone	SLE	YES	YES
193	Singapore	SGP	YES	YES
194	Sint Maarten (Dutch part)	SXM	NO	NO
195	Slovakia	SVK	YES	YES
196	Slovenia	SVN	YES	YES
197	Solomon Islands	SLB	YES	YES
198	Somalia	SOM	YES	YES
199	South Africa	ZAF	YES	YES
200	South Sudan	SSD	YES	YES
201	Spain	ESP	YES	YES
202	Sri Lanka	LKA	YES	YES
203	State of Palestine	PSE	YES	NO
204	Sudan	SDN	YES	YES
205	Suriname	SUR	YES	YES
206	Sweden	SWE	YES	YES
207	Switzerland	CHE	YES	YES
208	Syrian Arab Republic	SYR	YES	NO
209	Tajikistan	TJK	YES	YES
210	Thailand	THA	YES	YES
211	Timor-Leste	TLS	YES	YES
212	Togo	TGO	YES	YES
213	Tokelau	TKL	NO	NO
214	Tonga	TON	YES	YES
215	Trinidad and Tobago	TTO	YES	YES
216	Tunisia	TUN	YES	YES
217	Turkiye	TUR	YES	YES
218	Turkmenistan	TKM	YES	YES

	UN name	ISO3 code	Pop data available in SSP3.0	GDP data available in SSP3.0
219	Turks and Caicos Islands	TCA	NO	NO
220	Tuvalu	TUV	NO	NO
221	Uganda	UGA	YES	YES
222	Ukraine	UKR	YES	YES
223	United Arab Emirates	ARE	YES	YES
224	United Kingdom	GBR	YES	YES
225	United Republic of Tanzania	TZA	YES	YES
226	United States of America	USA	YES	YES
227	United States Virgin Islands	VIR	YES	YES
228	Uruguay	URY	YES	YES
229	Uzbekistan	UZB	YES	YES
230	Vanuatu	VUT	YES	YES
231	Venezuela (Bolivarian Republic of)	VEN	YES	NO
232	Viet Nam	VNM	YES	YES
233	Wallis and Futuna Islands	WLF	NO	NO
234	Western Sahara	ESH	YES	YES
235	Yemen	YEM	YES	YES
236	Zambia	ZMB	YES	YES
237	Zimbabwe	ZWE	YES	YES

Table A2 summarizes the available variables and units for data series of macroeconomic projections, after pre-processing of population and GDP projections from SSP3.0 database.

Table A2 Macroeconomic data variables and units, after data processing

Variable	Units
Population	million
GDP|PPP	billion USD_2017, billion USD_2015, billion USD_2005, billion USD_2000
GDP|MER	billion USD_2017, billion USD_2015, billion USD_2005, billion USD_2000
GDP per capita|PPP	USD_2017/yr, USD_2015/yr, USD_2005/yr, USD_2000/yr
GDP per capita|MER	USD_2017/yr, USD_2015/yr, USD_2005/yr, USD_2000/yr

Note: the units in bold format (i.e., population in “million” and GDP|PPP in “billion USD_2017”) indicate available data unit in the original data from SSP3.0 database.

1.2 SSP data update: comparison of socioeconomic projections in SSP3.0 and SSP2.0

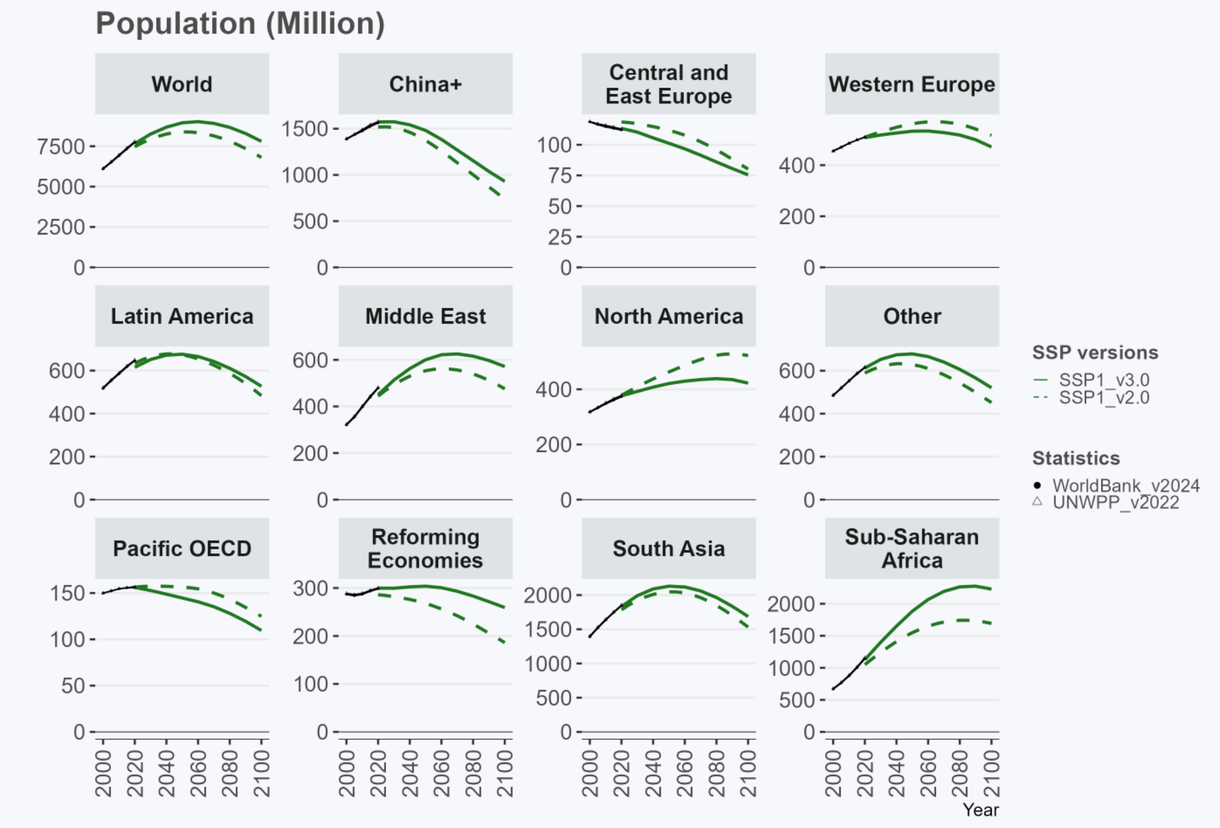

Figure A1 Comparison of population projections for the SSP1 scenario from SSP v3.0 and SSP v2.0 databases

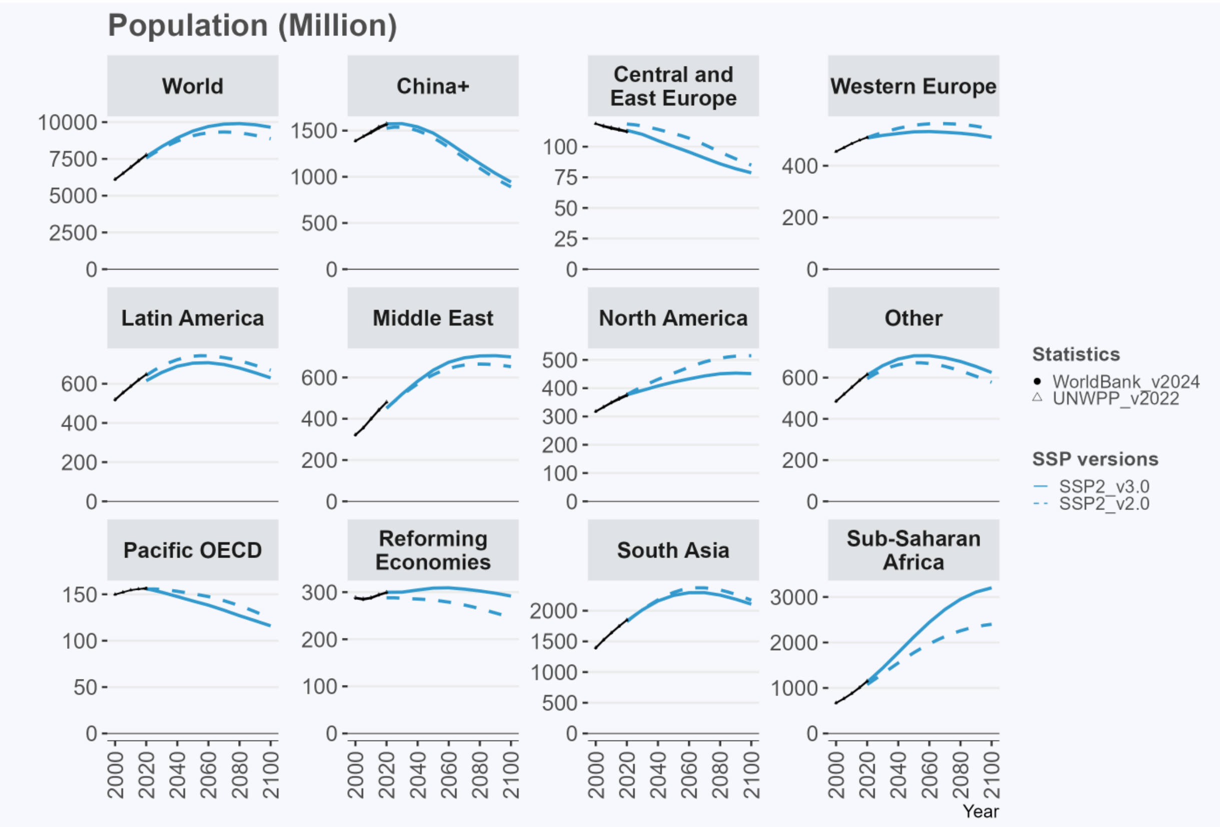

Figure A2 Comparison of population projections for the SSP2 scenario from SSP v3.0 and SSP v2.0 databases

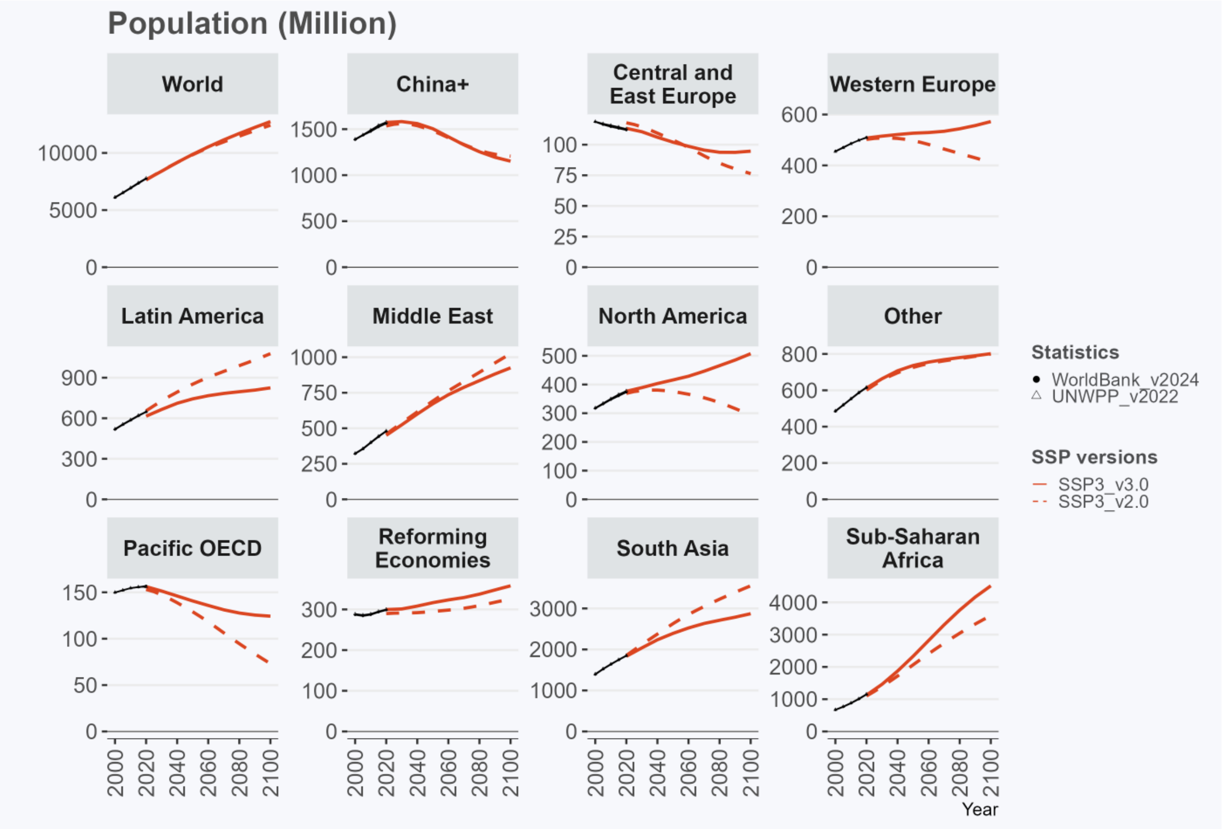

Figure A3 Comparison of population projections for the SSP3 scenario from SSP v3.0 and SSP v2.0 databases

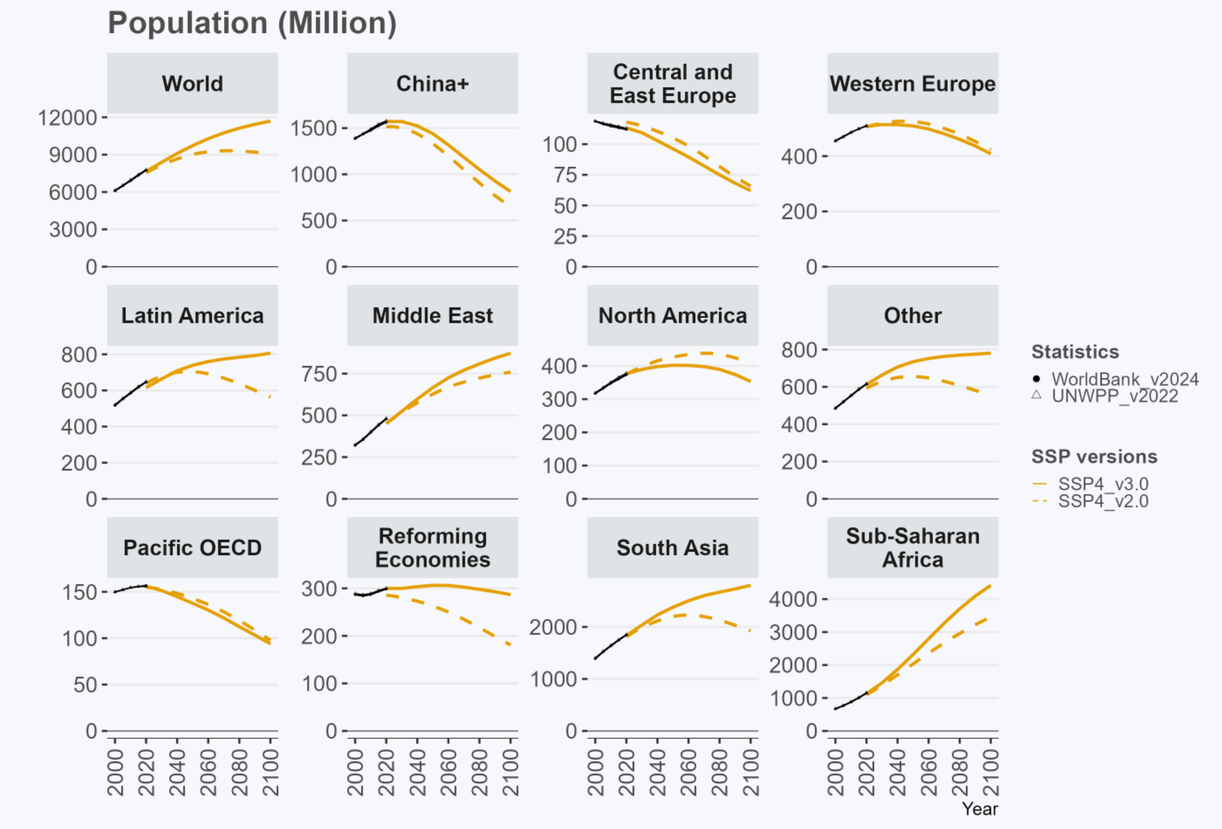

Figure A4 Comparison of population projections for the SSP4 scenario from SSP v3.0 and SSP v2.0 databases

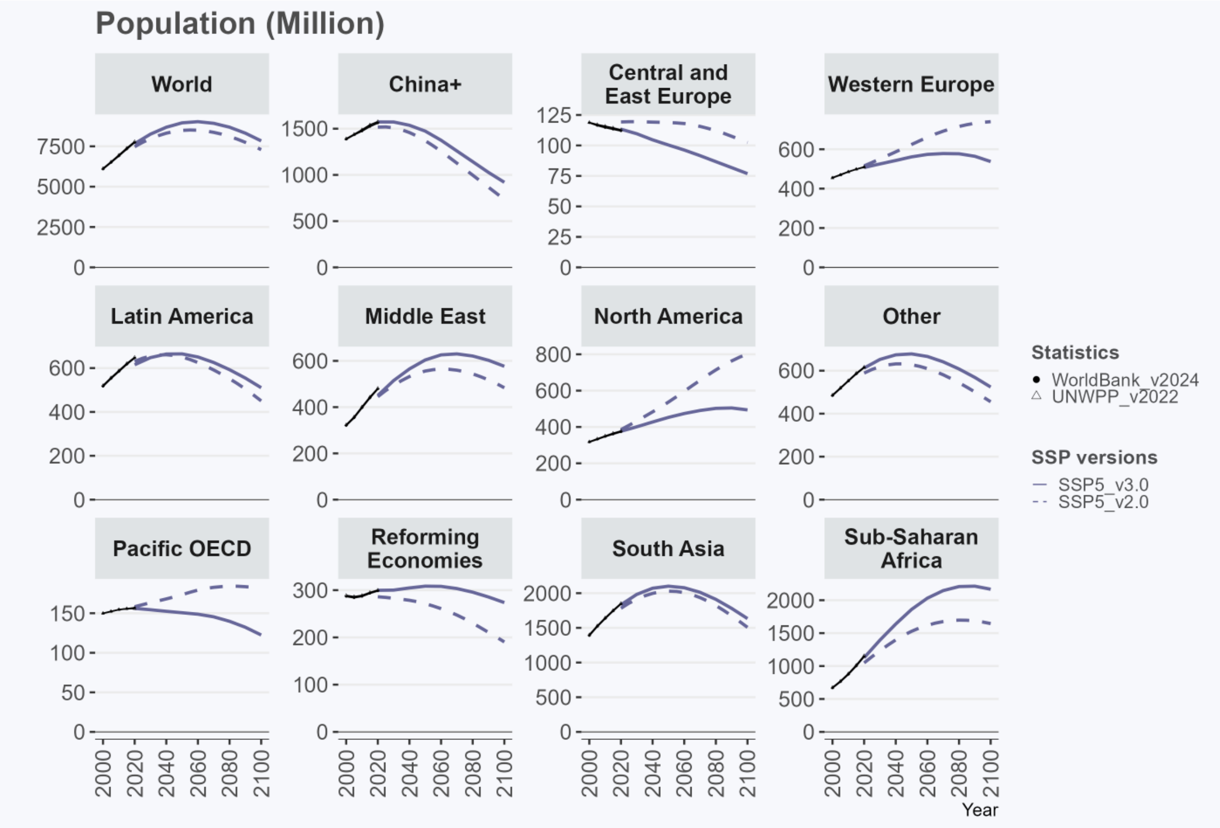

Figure A5 Comparison of population projections for the SSP5 scenario from SSP v3.0 and SSP v2.0 databases

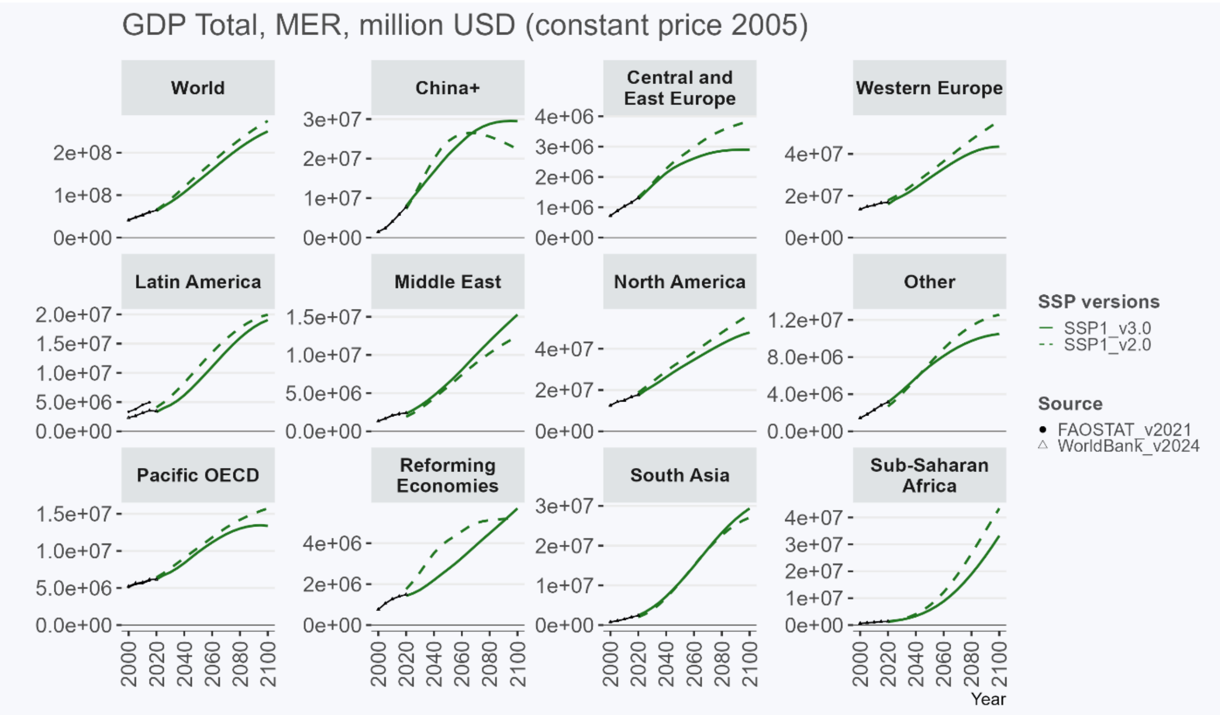

Figure A6 Comparison of GDP projections for the SSP1 scenario from SSP v3.0 and SSP v2.0 databases

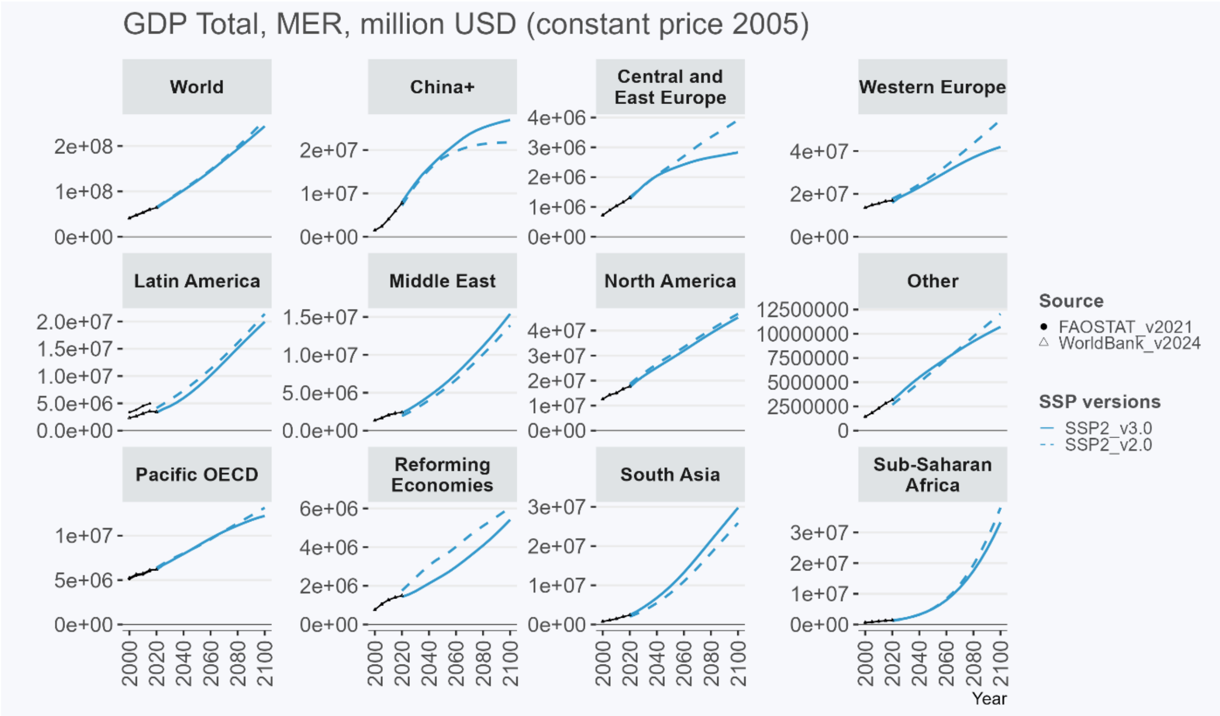

Figure A7 Comparison of GDP projections for the SSP2 scenario from SSP v3.0 and SSP v2.0 databases

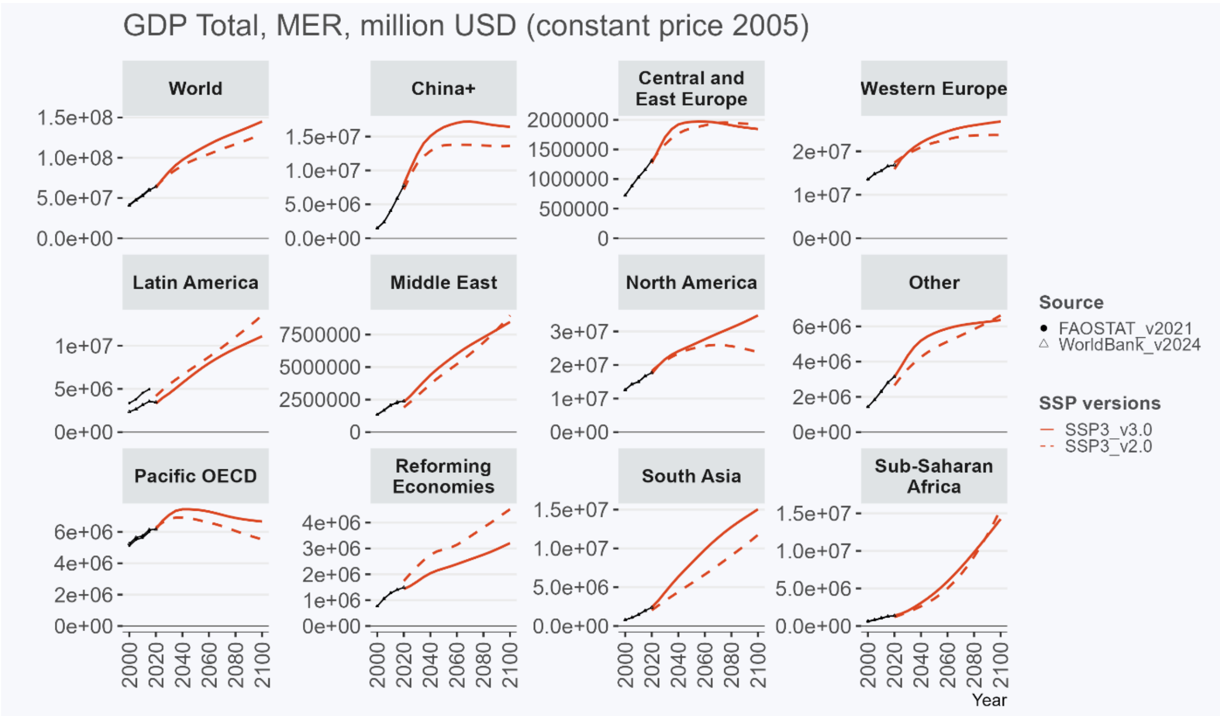

Figure A8 Comparison of GDP projections for the SSP3 scenario from SSP v3.0 and SSP v2.0 databases

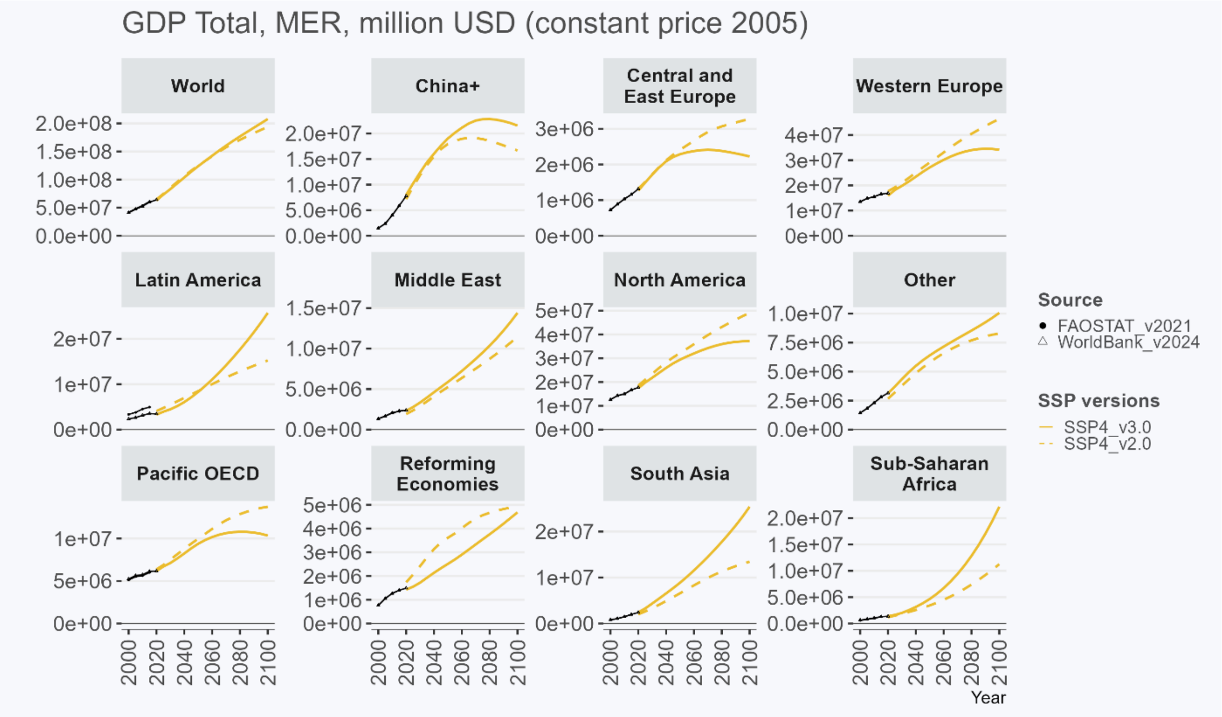

Figure A9 Comparison of GDP projections for the SSP4 scenario from SSP v3.0 and SSP v2.0 databases

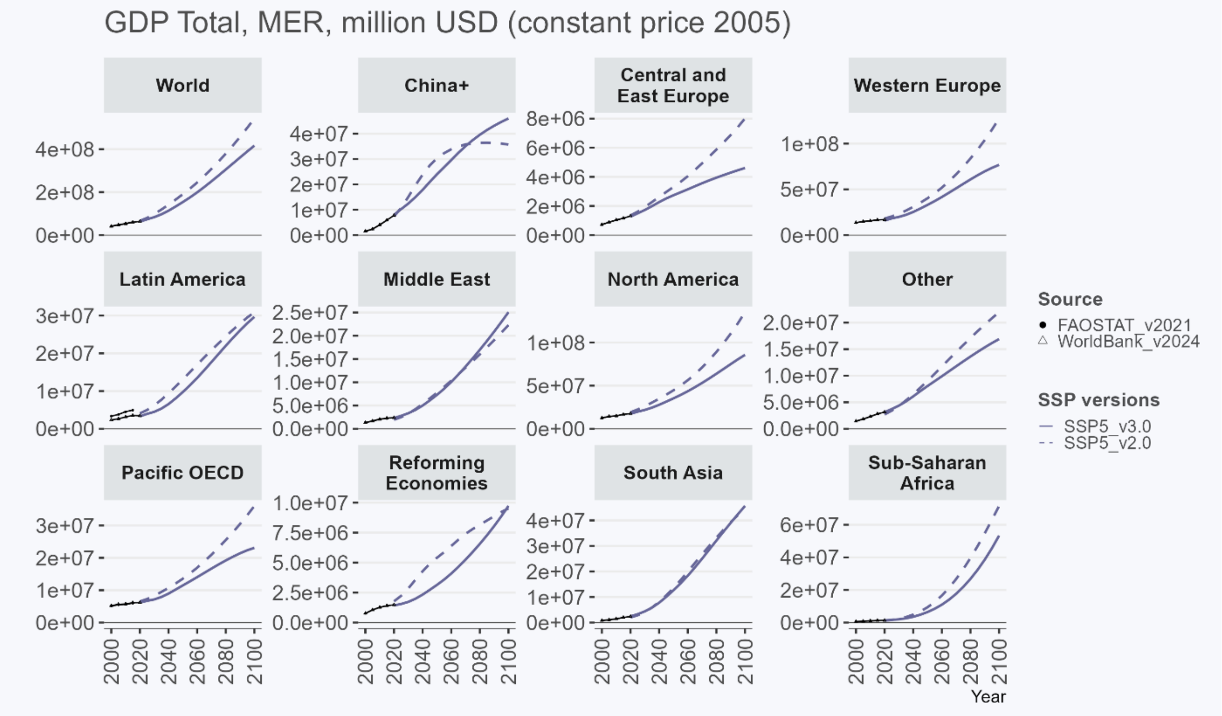

Figure A10 Comparison of GDP projections for the SSP5 scenario from SSP v3.0 and SSP v2.0 databases

Annex 2: Dataset - quantitative scenario drivers

Dataset	Description	Resolution	Format	Contact point	Source
Population growth	Population trends across SSPs including historic time series	Country level	csv, gdx	IIASA	IIASA, SSP Scenario Explorer
GDP growth	GDP trends across SSPs including historic time series	Country level	csv, gdx	IIASA	OECD, SSP Scenario Explorer
Technological progress – crop yields	Econometric estimate of technological change estimates for 18 crops across SSPs based on GDP per capita growth rates	GLOBIOM 37 regions	gdx	IIASA	Own estimate
Primary biomass demand for bioenergy	Primary biomass demand for bioenergy across different SSP x RCP combinations based on MESSAGEix-GLOBIOM	11 aggregated world regions	gdx	IIASA	Own estimate
1st generation biofuel demand	Historic 1st generation biofuel demand from food crops	GLOBIOM 37 regions	gdx	IIASA	AgMIP
GHG price trajectories	GHG price trajectories across different SSP x RCP combinations based on MESSAGEix-GLOBIOM	11 aggregated world regions	gdx	IIASA	Own estimate
Diet trajectories	Baseline diets across SSPs aligned with FAO outlook towards 2050	GLOBIOM 37 regions	gdx	IIASA	Own estimate

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