NGFS

Climate Scenarios Database

Technical Documentation

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Contents

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1. Introduction

This document provides technical information on the two datasets constituting the NGFS reference scenarios (see *NGFS Climate Scenarios for central banks and supervisors* (link)). One dataset includes transition pathways and data on macro-economic impacts from physical risks, both of which available in the NGFS Scenario Explorer provided by IIASA. The other dataset covers the physical impact data collected by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). These datasets are generated with a suite of models including integrated assessment models, general circulation models, sectoral impact models and global macroeconomic damage functions. They are linked together in a coherent way by aligning global warming levels. For each dataset, the most important technical details of the underlying academic work and a short user guide are provided. These are complemented by links to other resources with more detailed information.

This document is intended to answer technical questions for those who want to perform analyses on the datasets themselves, but does not address conceptual questions. For a high-level description of the NGFS scenarios and the rationale behind them, please consult the *NGFS Scenario Presentation*. For a broad overview on how to perform scenario analysis in a financial context, please refer to the *NGFS Guide to climate scenario analysis for central banks and supervisors* (link). This document reflects the status of existing scenarios and datasets that are used in the current NGFS presentation and documents. Please note that the NGFS Work Stream 2 is working on a subsequent product that will make use of further adjusted models and tools.

This document is structured as follows: Section 2 provides an introduction on the key technical features of the NGFS scenarios, sections 3.1.1 - 3.1.3 cover the technical details and assumptions for the modelling of the transition pathways, and section 3.2 details how the outputs from this modelling is used to calculate ex-post macro-economic damage estimates from physical risks based on different macro methodologies.

Section 4 introduces ISIMIP climate impact data which are relevant for assessing physical risks. An overview as well as details on model and scenario assumptions are provided in section 4.1 and 4.1.2. Detailed information on variables available in the datasets and their definitions is provided in section 4.1.3.

User manuals for each of the two datasets are provided at end of their respective sections (see sections 3.3 and 4.2).

2. Key technical features of the NGFS Scenarios

The NGFS reference scenarios consist of 8 scenarios which cover three of the four quadrants of the NGFS scenario matrix (i.e. hot house world, orderly and disorderly) (see Figure 1). From a transition risk perspective, these 8 scenarios were considered by three contributing modelling groups (IIASA, PIK and UMD) and yielded a total of 17 transition pathways (i.e. across different scenarios and models). The number of model variants is indicated in the bubbles in Figure 1.

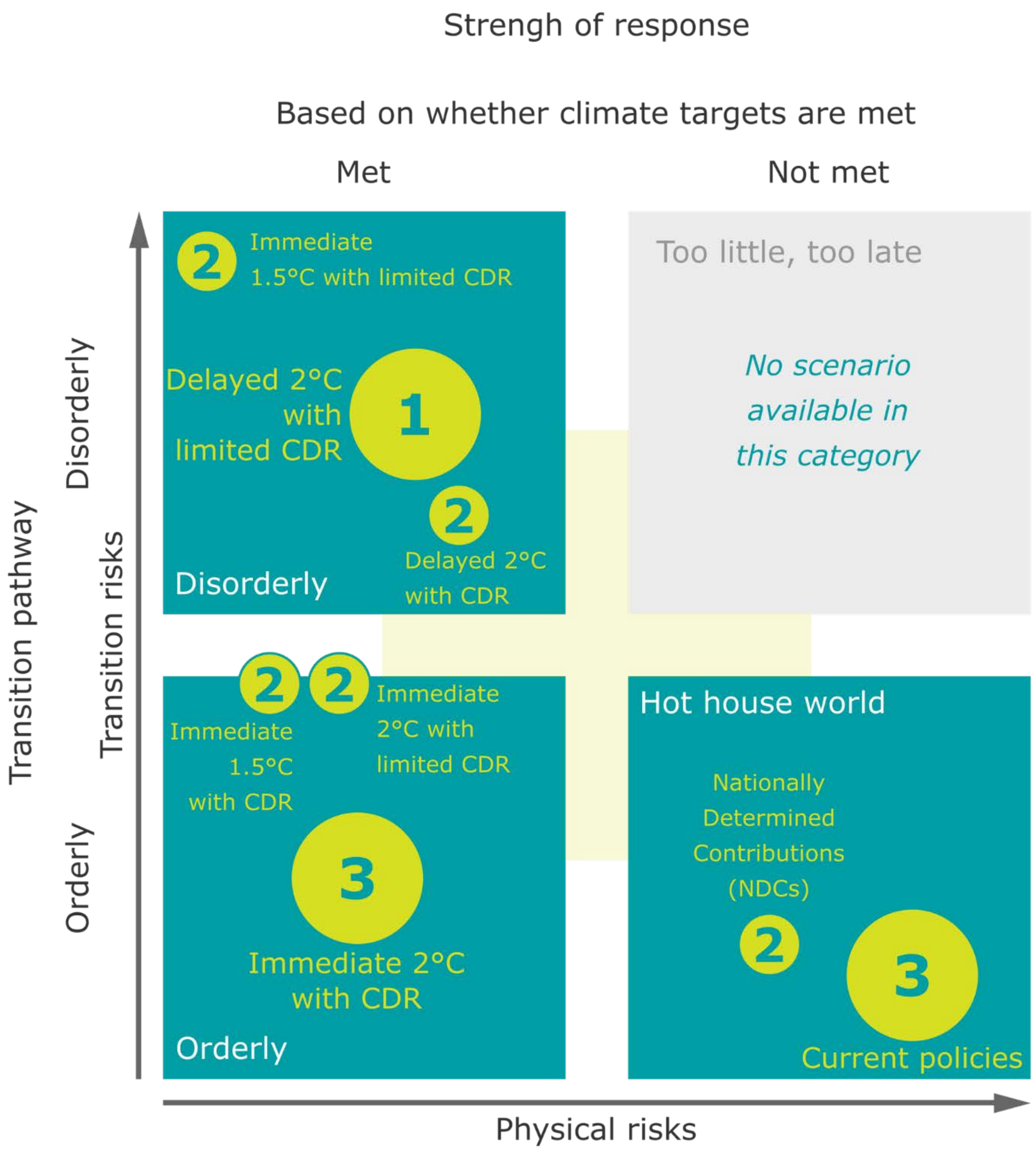


Figure 1 Overview of the NGFS scenarios. Scenarios are indicated with bubbles and positioned according to their transition and physical risks. Representative scenarios are indicated with large bubbles while alternate scenarios are indicated with small bubbles. The number inside bubbles indicates the number of model variants available.

For each quadrant, a representative scenario (large bubble) has been selected by the NGFS to serve as representative of this quadrant. Exploration of inherent uncertainties within each quadrant can thus make use of exploring within one narrative the ranges produced by different models (for further details on model characteristics and differences see section 3.1.1). Additionally, the alternative scenario narratives (small bubbles) in each quadrant allow for a further exploration along defined dimensions.

The transition pathways all share the same underlying assumption on key socio-economic drivers, such as harmonised development of population and economic developments. Further drivers such as food and energy demand are also harmonised, though not at a precise level but in terms of general patterns. All these socio-economic assumptions are taken from the shared socio-economic pathway SSP2 (Dellink et al., 2017; Fricko et al., 2017; KC & Lutz, 2017; O'Neill et al., 2017; Riahi, van Vuuren, et al., 2017), which describes a "middle-of-the-road" future. Many of these input and quasi-input assumptions are reported in the database, see section 3.1.3 for details.

The transition pathways are differentiated by three key design choices relating to long-term policy, short-term policy, and technology availability, see section 3.1.2 for details. Their names reflect these choices and have been harmonised across models. Most of the scenarios come from several existing peer-reviewed publications (Binsted et al., 2020; Kriegler et al., 2018; McCollum et al., 2018; Roelfsema et al., 2020; Rogelj et al., 2019).

The scenarios do not incorporate economic damages from physical risks, so economic trajectories are projected without consideration of feedbacks from emissions and temperature change onto infrastructure systems and the economy. As a step towards more integrated analysis, two approaches for incorporating the physical risk side are possible with the reference scenario set.

Approach 1: Section 3.2 details how estimates of potential macro-economic damages can be computed using simple damage functions, using the temperature outcomes inferred from the emissions trajectories projected by the transition scenarios.

Approach 2: Section 4 offers sectorally detailed impact data, based on various sector models, available for two separate temperature projections. These temperature projections are based on earlier harmonized scenarios but are broadly similar (though not identical) to the transition pathways above. They can be mapped to the NGFS scenarios in the following way: the orderly and disorderly 1.5°C and 2°C scenarios are in the range of the low temperature scenario (Representative Concentration Pathway RCP2.6), whereas the Current policies scenario is close to the high temperature scenario (RCP 6.0) by the end of the century (see section 4.1.1).

3. NGFS Scenario Explorer

3.1. Transition pathways for the NGFS scenarios

3.1.1. Contributing integrated assessment models

The transition pathways for the NGFS scenarios have been generated by well-established integrated assessment models (IAMs), namely GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE. These models have been used in hundreds of peer-reviewed scientific studies on climate change mitigation. In particular, they allow the estimation of global and regional mitigation costs (Kriegler et al., 2013, 2014, 2015; Luderer et al., 2013; Riahi et al., 2015; Tavoni et al., 2013), the analysis of emissions pathways (Riahi, van Vuuren, et al., 2017; Rogelj, Popp, et al., 2018), associated land use (Popp et al., 2017) and energy system transition characteristics (Bauer et al., 2017; GEA, 2012; Kriegler et al., 2014; McJeon et al., 2014), the quantification of investments required to transform the energy system (GEA, 2012; McCollum et al., 2018) and the identification of synergies and trade-off of sustainable development pathways (Bertram et al., 2018; *TWI2050*, 2018). Importantly, their results feature in several assessment reports (Clarke et al., 2014; Forster et al., 2018; Jia et al., In press; Rogelj, Shindell, et al., 2018; UNEP, 2018). Consequently, these models have a long tradition of catering key climate change mitigation information to policy and decision makers. Moreover, MESSAGEix-GLOBIOM and REMIND-MAgPIE were also recently used to evaluate the transition risks faced by banks (UNEP-FI, 2018).

The three models share a similar structure. They combine macro-economic, agriculture and land-use, energy, water and climate systems into a common numerical framework that enables the analysis of the complex and non-linear dynamics in and between these components. In contrast to simple IAMs like DICE and RICE, they cover more systems with a finer granularity and process detail. For instance, they offer more detailed representations of the energy system that include many technologies and account for capacity vintages and technological change. This in turn allows the generation of more detailed transition pathways.

In addition, GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE generate cost-effective transition pathways. That is, they provide pathways that minimises costs subject to a range of constraints that can vary with scenario design like limiting warming to below 2°C and techno-economic and policy assumptions. It is worthwhile to note that these models do not account for climate damages and so cannot be used for cost-benefit analysis or to compute the social cost of carbon.

The models feature many mitigation options including energy-demand-side, energy-supply-side, Agriculture, Forestry and Other Land Uses (AFOLU) and carbon dioxide removal (CDR) measures (see Table 1). The energy sector is expected to play a huge role in the transition to a low-carbon economy as it currently accounts for the highest share of emissions and offers the greatest number of mitigation options. These include solar, wind, nuclear power, carbon capture and storage (CCS), fuel cells and hydrogen on the supply side and energy efficiency improvements, electrification and CCS on the demand side. There are also several mitigation options in the land use sector, such as reduced deforestation/forest protection/avoided forest conversion, forest management, methane reductions in rice paddies, nitrogen pollution reductions. Finally, all models include at least two CDR technologies, namely bioenergy with carbon capture and storage (BECCS) and afforestation and reforestation.

Table 1 **Overview of mitigation options in GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE (adapted from Rogelj et al. (2018) and table 2.SM.6 in Forster et al. (2018))**

	GCAM	MESSAGEix-GLOBIOM	REMIND-MAgPIE
# Demand side mitigation options	14	16	15
Examples of demand side measures	Energy efficiency improvements, electrification of buildings, industry and transport sectors, CCS in industrial process applications	Energy efficiency improvements, electrification of buildings, industry and transport sectors, CCS in industrial process applications	Energy efficiency improvements, electrification of buildings, industry and transport sectors, CCS in industrial process applications
# Supply side mitigation options	18	20	17
Examples of supply side measures	Solar PV, Wind, Nuclear, CCS, Hydrogen	Solar PV, Wind, Nuclear, CCS, Hydrogen	Solar PV, Wind, Nuclear, CCS, Hydrogen
# AFOLU options	8	8	7
Examples of AFOLU measures	Reduced deforestation/forest protection/avoided forest conversion, Forest management, Methane reductions in rice paddies, Nitrogen pollution reductions	Reduced deforestation/forest protection/avoided forest conversion, Forest management, Conservation agriculture, Methane reductions in rice paddies, Nitrogen pollution reductions	Reduced deforestation/forest protection/avoided forest conversion, Methane reductions in rice paddies, Nitrogen pollution reductions

Although the models share similarities, each of them has its own characteristics (see Table 1 and Table 2) which can influence results (i.e. model footprints). For instance, from an economic perspective, both MESSAGEix-GLOBIOM and REMIND-MAgPIE are general equilibrium models solved with an intertemporal optimisation algorithm (i.e. perfect foresight). This allows the models to fully anticipate changes occurring over the 21st century (e.g. increasing costs of exhaustible resources, declining costs of solar and wind technologies, increasing carbon prices). In contrast, GCAM is a partial equilibrium model of the land use and energy sectors with a "myopic" view of the future. At each time step agents in GCAM consider only past and present circumstances in formulating their behaviour including expectations for the future. Prior information includes such factors as existing capital stocks. Expectations for the future are that then current prices and policies will persist for the life of the capital investment. These differences can affect investment dynamics in technologies, e.g. the deployment of carbon dioxide removal technologies.

The models differ also from a technology perspective. Even though, the coverage of mitigation options in the energy system is similar, assumptions in technology costs, efficiencies and innovation vary across models. Models also differ in their treatment of carbon removal. GCAM is the only model to allow the sequestration of carbon in bioplastics.

Table 2 **Overview of key model characteristics (see also reference cards 2.6, 2.15, and 2.17 in Forster et al. (2018))**

Integrated Assessment Model	GCAM 5.2	MESSAGEix_GLOBIOM 1.0	REMIND1.7-MagPIE3.0
Short name	GCAM	MESSAGEix-GLOBIOM	REMIND-MAgPIE
Solution concept	Partial Equilibrium (price elastic demand)	General Equilibrium (closed economy)	REMIND: General Equilibrium (closed economy) MAgPIE: Partial Equilibrium model of the agriculture sector
Anticipation	Recursive dynamic (myopic)	Intertemporal (perfect foresight)	REMIND: Inter-temporal (perfect foresight) MAgPIE: recursive dynamic (myopic)
Solution method	Cost minimisation	Welfare maximisation	REMIND: Welfare maximisation MAgPIE: Cost minimisation
Temporal dimension	Base year: 2015 Time steps: 5 years Horizon: 2100	Base year: 1990 Time steps: 10 years Horizon: 2100	Base year: 2005 Time steps: 5 (2005-2060) and 10 years (2060-2100) Horizon: 2100
Spatial dimension	32 world regions	11 world regions	11 world regions
Technological change	Exogenous	Exogenous	Endogenous for Solar, Wind and Batteries
Technology dimension	58 conversion technologies	64 conversion technologies	50 conversion technologies

The NGFS scenarios have been mainly developed using existing peer-reviewed studies (Kriegler et al., 2018; McCollum et al., 2018; Rogelj et al., 2019). Consequently, the NGFS scenarios are based on 2018/2019 versions for the REMIND-MAgPIE and three of the MESSAGEix-GLOBIOM scenarios. The scenarios from GCAM and the other two MESSAGEix-GLOBIOM scenarios have been updated using the latest 2020 model versions, in order to make sure near-term calibration is in line with historic data. In the next phase of the NGFS work, the three modelling teams will use the latest versions of their models.

Modelling teams strive for a high level of transparency. The models are well documented across several peer-reviewed publications, IPCC assessment reports (e.g. reference cards 2.6, 2.15, and 2.17 in Forster et al. (2018)), publicly-available technical documentations and wikis (e.g. www.iamcdocumentation.eu). At the time of writing this document, the GCAM, and MAgPIE models are fully open-source. The source code of the MESSAGEix-GLOBIOM and REMIND models are available in open access and the modelling teams are currently working on making them fully open-source. The links to these models and their documentation are given in the following sections which provide a more detailed account of the three IAMs.

A comprehensive primer on climate scenarios is available in the SENSES toolkit (https://climatescenarios.org). This web platform also offers learn modules to enhance understanding on a number of topics such as future electrification, fossil fuels risks and closing the emissions gap.

GCAM

GCAM is a global model that represents the behavior of, and interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate. GCAM has been under development for 40 years (Figure 2). Work began in 1980 with the work first documented in 1982 in working papers and the first peer-reviewed publications in 1983 (J. Edmonds & Reilly, 1983a, 1983b, 1983c). At this point, the model was known as the Edmonds-Reilly (and subsequently the Edmonds-Reilly-Barnes) model. The current version of the model is documented at https://jgcri.github.io/gcam-doc/overview.html and at Calvin et al. (Calvin et al., 2019).

GCAM includes two major computational components: a data system to develop inputs and the GCAM core. The GCAM Data System combines and reconciles a wide range of different data sets and systematically incorporates a range of future assumptions. The output of the data system is an XML dataset with historical and base-year data for calibrating the model along with assumptions about future trajectories such as GDP, population, and technology. The GCAM core is the component in which economic decisions are made (e.g., land use and technology choices), and in which dynamics and interactions are modeled within and among different human and Earth systems. The GCAM core is written in C++ and takes in inputs in XML. Outputs are written to a xml database.

GCAM takes in a set of assumptions and then processes those assumptions to create a full scenario of prices, energy and other transformations, and commodity and other flows across regions and into the future. The interactions between these different systems all take place within the GCAM core; that is, they are not modeled as independent modules, but as one integrated whole.

The exact structure of the model is data driven. In all cases, GCAM represents the entire world, but it is constructed with different levels of resolution for each of these different systems. In the version of GCAM used for this study, the energy-economy system operates at 32 regions globally, land is divided into 384 subregions, and water is tracked for 235 basins worldwide. The Earth system module operates at a global scale using Hector, a physical Earth system emulator that provides information about the composition of the atmosphere based on emissions provided by the other modules, ocean acidity, and climate.

The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents indicate their intended supply and/or demand for goods and services in the markets. GCAM solves for a set of market prices so that supplies and demands are balanced in all these markets across the model. The GCAM solution process is the process of iterating on market prices until this equilibrium is reached. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

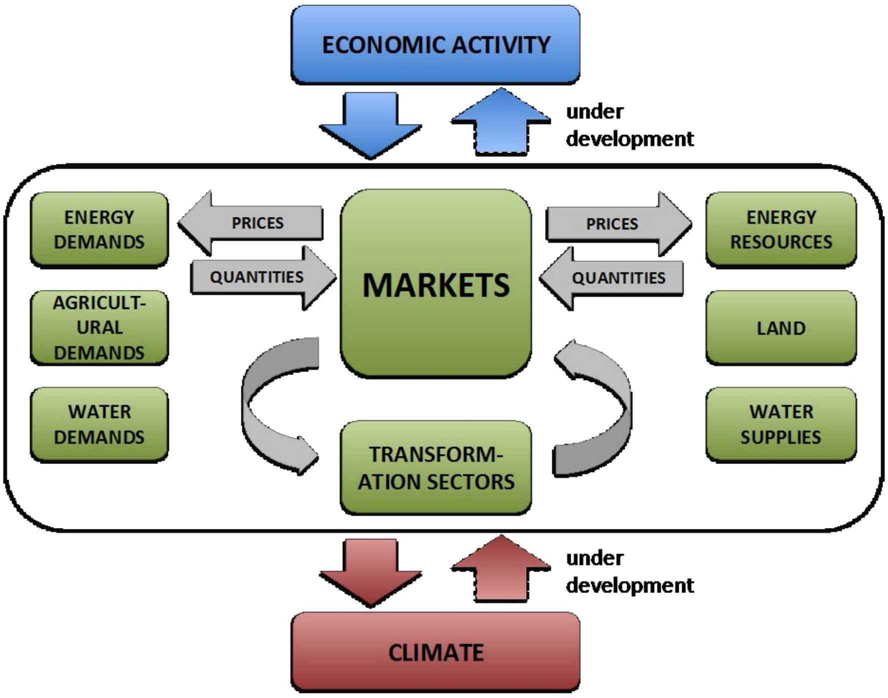


Figure 2 Schematic representation of the GCAM model.

While the agents in the GCAM model are assumed to act to maximise their own self-interest, the model as a whole is not performing an optimisation calculation. Decision-making throughout GCAM uses a logit formulation (J. F. Clarke & Edmonds, 1993; McFadden, 1973). In such a formulation, options are ordered based on preference, with either cost (as in the energy system) or profit (as in the land system) determining the order. However, the single best choice does not capture the entire market.

GCAM is a dynamic recursive model, meaning that decision-makers do not know the future when making a decision. (In contrast, intertemporal optimisation models like MESSAGEix-GLOBIOM and REMIND-MAgPIE assume that agents know the entire future with certainty when they make decisions). After it solves each period, the model then uses the resulting state of the world, including the consequences of decisions made in that period - such as resource depletion, capital stock retirements and installations, and changes to the landscape - and then moves to the next time step and performs the same exercise. For long-lived investments, decision-makers may account for future profit streams, but those estimates would be based on current prices. GCAM is typically operated in five-year time steps with 2015 as the final calibration year. However, the model has flexibility to be operated at different temporal resolutions through user-defined parameters.

A reference card description of this model can be found as section 2.SM.2.5 in (Forster et al., 2018).

A comprehensive documentation of the model is available at this URL:

https://jgcri.github.io/gcam-doc/overview.html

The source code of the model is open-source and available at this URL: https://github.com/JGCRI/gcam-core
A model reference card

MESSAGEix-GLOBIOM

The IIASA IAM framework consists of a combination of five different models or modules - the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC - which complement each other and are specialised in different areas. All models and modules together build the IIASA IAM framework, referred to as

MESSAGE-GLOBIOM historically owing to the fact that the energy model MESSAGE and the land use model GLOBIOM are its central components. The five models provide input to and iterate between each other during a typical scenario development cycle. Below is a brief overview of how the models interact with each other.

Recently, the scientific software structure underlying the global MESSAGE-GLOBIOM model is revamped and called the MESSAGE*ix* framework (Huppmann et al., 2019), an open-source, versatile implementation of a linear optimisation problem, with the option of coupling to the computable general equilibrium (CGE) model MACRO to incorporate the effect of price changes on economic activity and demand for commodities and resources. The new framework is integrated with the *ix modeling platform* (ixmp), a "data warehouse" for version control of reference timeseries, input data and model results. ixmp provides interfaces to the scientific programming languages Python and R for efficient, scripted workflows for data processing and visualisation of results. The IIASA IAM fleet based on this newer framework is named as MESSAGE*ix-GLOBIOM.*

The name "MESSAGE" itself refers to the core of the IIASA IAM framework (Figure 3) and its main task is to optimise the energy system so that it can satisfy specified energy demands at the lowest costs (Huppmann et al., 2019). MESSAGE carries out this optimisation in an iterative setup with MACRO, a single sector macro-economic model, which provides estimates of the macro-economic demand response that results from energy system and services costs computed by MESSAGE. The models run on a 11-region global disaggregation. For the six commercial end-use demand categories depicted in MESSAGE, based on demand prices MACRO will adjust useful energy demands, until the two models have reached equilibrium. This iteration reflects price-induced energy efficiency adjustments that can occur when energy prices change.

GLOBIOM provides MESSAGE with information on land use and its implications, including the availability and cost of bioenergy, and availability and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Other Land Use) sector. To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator which provides an approximation of land-use outcomes during the optimisation process instead of requiring the GLOBIOM model to be rerun iteratively. Only once the iteration between MESSAGE and MACRO has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding analysis with the full-fledged GLOBIOM model. This ensures full consistency of the results from MESSAGE and GLOBIOM, and also allows producing a more extensive set of land-use related indicators, including spatially explicit information on land use.

Air pollution implications of the energy system are accounted for in MESSAGE by applying technology-specific air pollution coefficients derived from the GAINS model. This approach has been applied to the SSP process (Rao et al., 2017). Alternatively, GAINS can be run ex-post based on MESSAGEix-GLOBIOM scenarios to estimate air pollution emissions, concentrations and the related health impacts. This approach allows analysing different air pollution policy packages (e.g., current legislation, maximum feasible reduction), including the estimation of costs for air pollution control measures. Examples for applying this way of linking MESSAGEix-GLOBIOM and GAINS can be found in (McCollum et al., 2018) and (Grubler et al., 2018).

In general, cumulative global carbon emissions from all sectors are constrained at different levels, with equivalent pricing applied to other GHGs, to reach the desired radiative forcing levels (see right-hand side in Figure 3). The climate constraints are thus taken up in the coupled MESSAGE-GLOBIOM optimisation, and the resulting carbon price is fed back to the full-fledged GLOBIOM model for full consistency. Finally, the combined results for land use, energy, and industrial emissions from MESSAGE and GLOBIOM are merged and fed into MAGICC, a global carbon-cycle and climate model, which then provides estimates of the climate implications in terms of atmospheric concentrations, radiative forcing, and global-mean temperature increase. Importantly, climate impacts and impacts of the carbon cycle are – depending on the specific application – currently only partly accounted for in the IIASA IAM framework. The entire framework is linked to an online database infrastructure which allows straightforward visualisation, analysis, comparison and dissemination of results (Riahi, van Vuuren, et al., 2017).

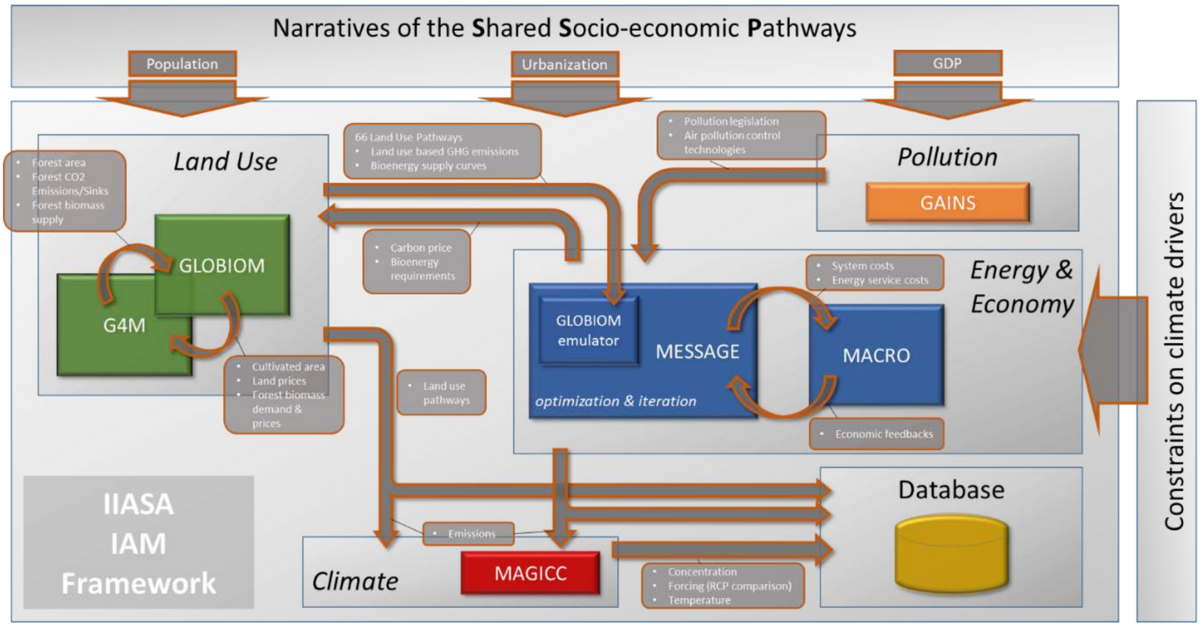


Figure 3 Overview of the IIASA IAM framework. Coloured boxes represent respective specialised disciplinary models which are integrated for generating internally consistent scenarios (Fricko et al., 2017).

A reference card description of this model can be found as section 2.SM.2.15 in (Forster et al., 2018).

A comprehensive documentation of the model is available at this URLs:

https://message.iiasa.ac.at/projects/global/en/latest/overview/index.html

https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_MESSAGE-GLOBIOM

The source code of the model is open-source and available at this URL: https://github.com/iiasa/message_ix

REMIND-MAgPIE

REMIND-MAgPIE is a comprehensive IAM framework that simulates, in a forward-looking fashion, the dynamics within and between the energy, land-use, water, air pollution and health, economy and climate systems. The models were created over a decade ago (Leimbach, Bauer, Baumstark, & Edenhofer, 2010; Lotze-Campen et al., 2008) and are continually being improved to provide up-to-date scientific evidence to decision and policy makers and other relevant stakeholders on climate change mitigation and SDGs strategies.

The REMIND-MAgPIE framework consists of four main components (see Figure 4). First the REMIND model combines a macro-economic module with an energy system module. The macro-economic core of REMIND is a Ramsey-type optimal growth model in which inter-temporal welfare is maximised. The energy system module includes a detailed representation of energy supply and demand sectors. Second the MAgPIE model represents land-use dynamics. The MAgPIE model is linked to the dynamic global vegetation model LPJmL (Bondeau et al., 2007; Müller & Robertson, 2014; Schaphoff et al., 2017). For some applications that do not require detailed land-use information, a MAgPIE-based emulator is used to make the scenario generation process more efficient. The REMIND model is linked to the climate model MAGICC to account for changes in climate-related variables like global surface mean temperature. In addition, REMIND can be linked to other models to allow the analysis of other environmental impacts such as water demand, air pollution and health effects.

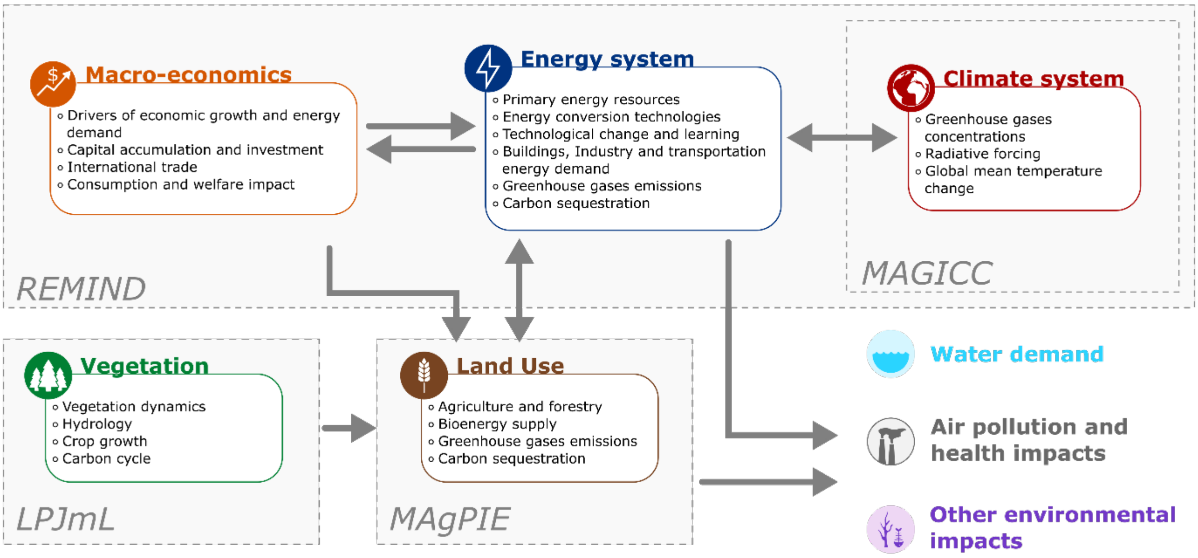


Figure 4 Overview of the structure of the REMIND-MAgPIE framework

Specifically, REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering-based energy system model. It covers eleven world regions (see Figure 5 and Table A1.3 in Appendix 1), differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade (Leimbach, Bauer, Baumstark, & Edenhofer, 2010; Leimbach, Bauer, Baumstark, Luken, et al., 2010; Leimbach et al., 2017; Mouratiadou et al., 2016). A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer et al., 2017; Bauer et al., 2012; Bauer et al., 2016; Klein et al., 2014, 2014; Pietzcker et al., 2014). The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as adjustment costs for rapidly expanding technologies (Pietzcker et al., 2017). The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system (Strefler, Luderer, Aboumahboub, et al., 2014; Strefler, Luderer, Kriegler, et al., 2014). Several energy sector policies are represented explicitly (Bertram et al., 2015, 2018; Kriegler et al., 2018), including energy-sector fuel taxes and consumer subsidies (Jewell et al., 2018; Schwanitz et al., 2014). The model also represents trade in energy resources (Bauer et al., 2015).

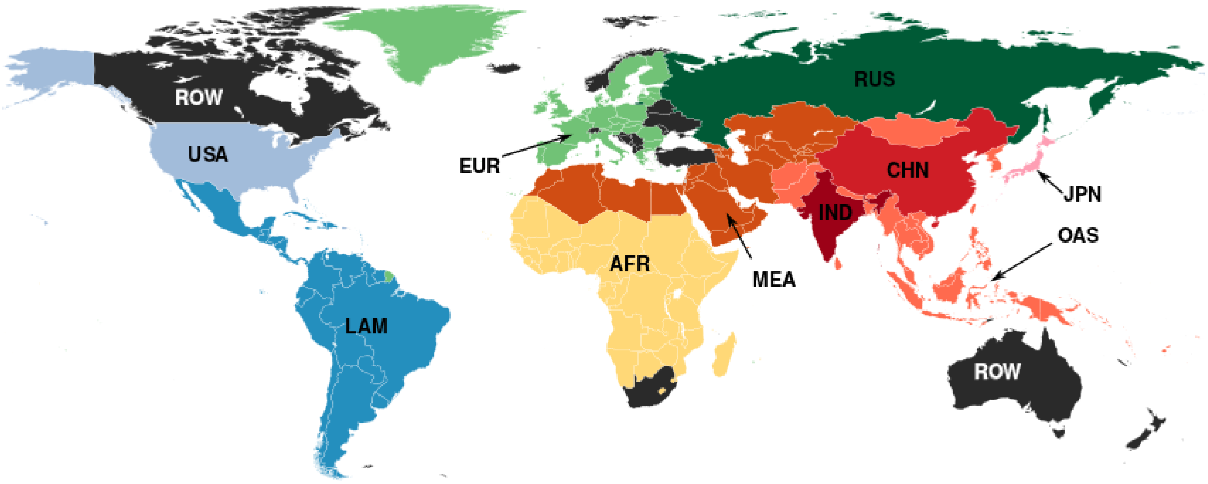


Figure 5 Regional definitions used in the REMIND model

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labour, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL) (Bondeau et al., 2007; Müller & Robertson, 2014; Schaphoff et al., 2017). Agricultural demand includes demand for food (Bodirsky & Popp, 2015), feed (Weindl et al., 2015), bioenergy (Humpenöder et al., 2018; Popp et al., 2010), material and seed. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production, cropland expansion and production relocation (intra-regionally and inter-regionally through international trade) (Dietrich et al., 2014; Lotze-Campen et al., 2010; Schmitz et al., 2012). MAgPIE derives cell specific land-use patterns, rates of future agricultural yield increases(Dietrich et al., 2014), food commodity and bioenergy prices as well as GHG emissions from agricultural production (Bodirsky et al., 2012; Popp et al., 2010) and land-use change (Humpenöder et al., 2014; Popp et al., 2014, 2017).

The coupling approach between REMIND and MAgPIE is designed to derive scenarios with equilibrated bioenergy and emissions markets. In equilibrium, bio-energy demand patterns computed by REMIND are fulfilled in MAgPIE at the same bioenergy and emissions prices that the demand patterns were based on. Moreover, the emissions in REMIND emerging from pre-defined climate policy assumptions account for the GHG emissions from the land-use sector derived in MAgPIE under the emissions pricing and bioenergy use mandated by the same climate policy. The simultaneous equilibrium of bioenergy and emissions markets is established by an iteration of REMIND and MAgPIE simulations in which REMIND provides emissions prices and bioenergy demand to MAgPIE and receives land use emissions and bioenergy prices from MAgPIE in return. The coupling approach with this iterative process at its core is explained elsewhere (Bauer et al., 2014).

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) is a reduced-complexity climate model that calculates atmospheric concentrations of GHGs and other atmospheric climate drivers, radiative forcing and global annual-mean surface air temperature. Emission pathways computed by REMIND are fed to MAGICC to estimate future changes in climate-related variables.

A reference card description of this model can be found as section 2.SM.2.17 in (Forster et al., 2018).

Comprehensive documentations of the models are available at these URLs:

https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND

https://rse.pik-potsdam.de/doc/magpie/4.0/

The source codes of the models are open-source and available at these URLs:

https://github.com/remindmodel/remind

https://github.com/magpiemodel/magpie

3.1.2. Scenario and model input assumptions

The transition pathways for the NGFS Scenarios are differentiated by three key design choices relating to long-term policy, short-term policy, and technology availability.

The first design choice relates to assumptions on **long-term climate policy**, and four different assumptions are covered by the set of scenarios:

1. **Current policies:** existing climate policies remain in place, but there is no strengthening of ambition level of these policies. The detail of policy representation differs across models and even within models across different sectors. Policy implementation has been done as detailed as possible, but due to limited granularity of sector representation, all models also represent some policies as proxies, for example via aggregate final energy reductions instead of explicit implementation of efficiency standards, or a carbon price.
2. **Nationally determined contributions (NDCs)**: This scenario foresees that currently pledged unconditional NDCs are implemented fully, and respective targets on energy and emissions in 2025 and 2030 are reached in all countries. The long-term policy assumption beyond current NDC target times (2025 and 2030) is that climate policy ambition remains comparable to levels implied by NDCs. This however does not clearly constrain the level of policy ambition, so long-term deviations across models are quite high.
3. **2°C**: As an interpretation of the well-below 2°C target of the Paris Agreement, these scenarios keep the 67-percentile of warming below 2°C throughout the 21^{st} century, similar to the Representative Concentration Pathway (RCP) 2.6 (see section 4, Table 7 and Figure 9). Most of those scenarios are defined via a bound on cumulative CO_2 emissions (implemented via iteratively adjusted carbon prices), at 1000 Gt CO_2 from 2011-2100. The exception is the scenario with the model "GCAM 5.2" which has lower cumulative emissions from CO_2, but higher emissions of other greenhouse gases, and the MESSAGE scenario with low CDR, which follows a peak budget design logic (Rogelj et al., 2019). All scenarios achieve mitigation primarily via iterative adjustment of a uniform carbon price across sectors and regions that rises with time. Carbon prices are applied to all greenhouse gases.
4. **1.5°C:** Two alternative scenarios (one in the orderly and disorderly category each) explore a more stringent long-term climate target, allowing median temperature to return to below 1.5°C after a temporary overshoot. These scenarios are defined via a bound on cumulative CO_2 emissions (implemented via iteratively adjusted carbon prices), at 400 Gt CO_2 from 2011-2100, with the

exception of the MESSAGE model with low CDR, which follows a peak budget design logic (Rogelj et al., 2019).

While the first two scenarios do not have further variations in the NGFS scenario set, the latter two scenario options are further differentiated with respect to short-term policy assumptions, and assumptions on technology availability.

Regarding **short-term policy**, two alternative assumptions are explored:

1. **Immediate** scenarios assume that optimal carbon prices in line with the long-term targets are implemented immediately after the 2020 model time step.
2. **Delayed scenarios** in turn assume that the next 10 years see implementation and fulfillment of the conditional NDC targets, but no further strengthening until 2030. After 2030, these scenarios also foresee implementation of a carbon price trajectory in line with long-term targets. Importantly, this sudden shift of policy stringency is not anticipated in the two perfect foresight models REMIND-MAgPIE and MESSAGEix-GLOBIOM.

Regarding technology availability, the literature has explored the sensitivity of results to a range of technological and socio-technical assumptions regarding renewables (Creutzig et al., 2017; Pietzcker et al., 2017), end-use efficiency (Grubler et al., 2018), nuclear (Bauer et al., 2012), bioenergy (Bauer et al., 2018), carbon capture and storage (Koelbl et al., 2014) and various land-use related options (Humpenöder et al., 2018; Popp et al., 2017). Given that each of the three models represented in the NGFS dataset have chosen particular structural and parametric assumptions in the representation of these alternative mitigation options, the comparison of the same scenario narrative within different models allows for an estimation of the order of magnitude that the uncertainties regarding future potentials entail.

One consistent finding of literature with structured comparison of technological sensitivities (Kriegler et al., 2014; Luderer et al., 2013; Riahi et al., 2015) is that the assumptions on availability of carbon dioxide removal (CDR) have a particularly profound impact on mitigation trajectories, as higher availability enables a more gradual phase-out of the use of liquid fuel across various sectors and end-uses. Therefore, the only **technological differentiation** explicitly covered in the NGFS dataset is the assumption on availability of carbon-dioxide removal, with two alternative assumptions:

- **Full availability ("with CDR"):** These scenarios do include the same criteria for constraints on CDR options (especially bioenergy with carbon capture and storage (BECCS) and afforestation) as for other technologies, like biophysical constraints, technological ramp-up constraints, exclusion of unsuitable and protected areas, and geological potentials.
- **Limited CDR ("with limited CDR"):** Given that there are particular challenges associated with the deployment of all CDR options (Fuss et al., 2018), especially at larger scale, these scenarios add explicit, more conservative constraints on maximum potential for CDR. In REMIND, this is done via explicit constraints on the process level (maximum area available for afforestation, max. yearly injection rate for geological sequestration, max. yearly bioenergy potentials. In MESSAGE, a scenario logic that explicitly limits the long-term contribution of net-negative emissions is used (Rogelj et al., 2019), so this limits CDR only indirectly, as CDR can still be used to offset positive emissions from continued use of fossil fuels.

The scenarios and their design have originally been described in different publications. Table 3 provides an overview of the original scenario names, and the details on supporting publications describing the scenarios in more detail are listed below for each model.

GCAM: The two scenarios both are updated versions of scenarios that were developed for a recent publication (Binsted et al., 2020). The NPi2020_1000 scenario builds on the "Straight-to-2°C" scenario shown in this publication, but has been adjusted in order to meet the climate target criteria as defined here (see above).

MESSAGEix-GLOBIOM: The marker scenario of the representative hot-house world scenario and the representative orderly scenario are both recent scenarios developed in the course of the European research project ENGAGE (www.engage-climate.org). The other scenarios are from published papers (McCollum et al., 2018; Roelfsema et al., 2020; Rogelj et al., 2019), and are partly published in the IPCC-IAMC SR1.5 Scenario Explorer (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer) and the CD-Links database (https://db1.ene.iiasa.ac.at/CDLINKSDB).

REMIND-MAgPIE: All scenarios are from a published article (Kriegler et al., 2018) and the scenario data for all but the hot-house world scenarios is available on the IPCC SR1.5 scenario explorer. The two hot-house world scenarios are not explicitly documented in the paper, but built on the basis of the analysis.

Table 3 **Overview of source and original scenario names of NGFS scenarios. The scenarios highlighted in bold are the marker scenarios for the representative scenario narratives. Scenario names with * denote scenarios that are available in the IPCC SR1.5 database**

		Model names		
Category	NGFS scenario name	GCAM 5.2	MESSAGEix-GLOBIOM 1.0	REMIND-MAgPIE 1.7-3.0
Hot house world	Current Policies	NPi	**ENGAGE_NPi**	PEP_NPi
	Nationally determined contributions (NDCs)	-	CD-LINKS_INDCi*	PEP_NDC
Orderly	Immediate 2C scenario with CDR	**NPi2020_1000**	ENGAGE_NPi2020_1000	PEP_2C_full_eff*
	Immediate 2C scenario with limited CDR	-	zero2060_4_0	PEP_2C_red_eff*
	Immediate 1.5C scenario with CDR	-	CD-LINKS_NPi2020_400*	PEP_1p5C_full_eff*
Disorderly	Delayed 2C scenario with limited CDR	-	-	**PEP_2C_red_NDC***
	Delayed 2C scenario with CDR	-	CD-LINKS_INDCi2030_1000	PEP_2C_full_NDC*
	Immediate 1.5C scenario with limited CDR	-	zero2050_4_2	PEP_1p5C_red_eff*

3.1.3. Transition scenario output

The models used to produce the scenarios cover a lot of ground to integrally assess the connections between human activity and the global environment. However, not all aspects reported by the models are determined endogenously. In this section we distinguish between endogenous variables, semi-endogenous variables (which are largely determined by input assumptions or associated demand modules) and exogenous input variables. The latter category covers variables such as population, fossil fuel resources and renewable resource potentials. These inputs are derived from other analysis and only used as input for the models. The category of semi-endogenous variables includes for example GDP (which is calibrated to external projection, but then changes endogenously as result of changes in, for instance, energy system costs) or capital costs for energy technologies (for example, in the case of MESSAGEix-GLOBIOM these are given exogenously to the model and do not change as result of endogenous calculations in the model, but are checked against assumptions of technological development and vary between different scenarios). The category of endogenous variables includes all information that is determined within a model run, such as technology choices, price developments, sectoral shifts, emission prices. In the sections below, it is indicated which variables are endogenous or exogenous to the models.

The scope of the integrated assessment models on long-term developments and global coverage, comes with trade-offs on the temporal and spatial granularity, both in terms of outputs and an in terms of dynamics included in the models. Geographical granularity for both forward-looking models in this project is 11 world regions, and the recursive-dynamic GCAM model includes 32 regions. Still, many of these regions cover large and diverse regions, the development of which can only be derived from the models in broad-brush strokes. Temporally, the models operate on a time step of 5 or 10 years and therefore mainly cover large-scale slow-moving dynamics. For instance, dynamics that are very relevant on the shorter time-scale, such as oil price fluctuations, are less relevant on a 5-year time scale and it becomes arbitrary to include them in a model projection for 2050 or 2100. These considerations should be taken into account when using the output of these models.

The complete list of variables, including their definition and units can also be found on the tab "Documentation" of the NGFS Scenario Explorer.

Socio-economic information

All economic assumptions are taken from the shared socio-economic pathway 2 (SSP 2), designed to represent a "middle-of-the-road" future development. All 3 models have Population as a fully exogenous input assumption. GDP|PPP, denominating the gross domestic product in power-purchasing parity terms, is an exogenous input assumption in the GCAM model, but a semi-endogenous output for REMIND-MAgPIE and MESSAGEix-GLOBIOM. The latter models take the SSP2 GDP trajectories for calibrating assumptions on exogeneous productivity improvement rates in a no-policy reference scenario. GDP trajectories in other scenarios thus reflect the general equilibrium effects of constraints and distortions by policies (so changes in capital allocation and prices, but without taking potential damages from climate impacts into account). The mitigation cost expressed as loss of GDP between two scenarios can thus be calculated for REMIND-MAgPIE and MESSAGEix-GLOBIOM by subtracting the GDP in one scenario from the other (while mitigation costs in GCAM are typically expressed as area under the curve of marginal abatement costs). This enables comparing the impact of stronger climate action compared to the Current Policies scenario. GDP is further reported in market-exchange rate (GDP|MER), but models have different assumption about the dynamics of MER-PPP ratios for the future.

The models employed for detailed analysis of climate change mitigation such as the three in the NGFS set do not have detailed representation of economic sectors beyond energy and land-use. Therefore, the only trade variables reported relate to the four primary energy carriers biomass, coal, oil and gas in energetic terms (named Trade|Primary Energy|Coal|Volume and measured in EJ/year).

Price|Carbon denotes the economy-wide carbon price that is the main policy instrument in all scenarios (though additional sectoral policies are implemented in the "Current Policies" and "NDC" scenarios), and whose value is set so to reach the specified emission targets in the respective scenario. The general equilibrium models REMIND-MAgPIE and MESSAGEix-GLOBIOM recycle the revenues from carbon pricing via the general budget of each region.

Fossil fuel markets

The consumption of fossil primary energy is separated into Primary Energy|Coal, Primary Energy|Oil and Primary Energy|Gas. These three primary energy categories are aggregated into the category Primary energy|Fossil. Primary energy carriers can be used directly or converted to secondary fuels (electricity, gases or liquids, see below), and the use of primary energy carriers in the power sector is reported under Primary Energy|Coal|Electricity (similar for oil and gas). The generation of electricity can take place with or without capturing the CO_2, which is reported separately Primary Energy|Coal|Electricity|w/ CCS and Primary Energy|Coal|Electricity|w/o CCS (similar for oil and gas).

The regional differences in production costs (based on exogenous assumptions on recoverable quantities and extraction costs) of primary energy carriers determine the future development of trade dynamics of primary energy carriers. Dynamics of energy trade are different between the models, for instance whether trade is simulated through a global pool or bilateral trade flows (see the model descriptions in Section 3.1.1 and www.iamcdocumentation.eu).

The long-term price dynamics of fossil primary energy in IAMs are the result of demand changes, resource depletion and development of exploration and exploitation technologies. Long-term prices of primary energy in the models are mainly determined by the marginal production costs of the resources being exploited. Prices are reported as indexed to the model-endogenous price of the year 2020, representing the multi-year average price of 2015-2020.

Renewable and nuclear energy

Primary energy production from renewable source is separated for Primary Energy|Biomass and Primary Energy|non-biomass Renewables. Primary energy from biomass includes energy consumption of purpose-grown bioenergy crops, crop and forestry residue bioenergy, municipal solid waste bioenergy, traditional biomass. For biomass, as for fossil fuels, the use in the power sector and with and without CCS are reported separately under Primary Energy|Biomass|Electricity, Primary Energy|Biomass|Electricity|w/ CCS, and Primary Energy|Biomass|Electricity|w/o CCS.

Primary Energy|Non-Biomass Renewables includes the non-biomass renewable primary energy consumption, reported in direct equivalent (i.e. the electricity or heat generated by these technologies) and includes subcategories for hydroelectricity, wind electricity, geothermal electricity and heat, solar electricity, heat and hydrogen, ocean energy)

Renewable energy generation is determined by a combination of renewable resource potentials, the costs of renewable energy technologies and the system integration dynamics. Renewable resources vary in their quality and therefore the exploitation level determined the marginal costs of renewable energy technologies. The capital costs for renewable energy technologies are semi-exogenously assumed (MESSAGEix-GLOBIOM) or endogenously determined as result of learning dynamics (REMIND-MAgPIE, GCAM). The exact formulation and flexibility or system integration dynamics differ between models, but represent issues such as spinning reserves, flexible capacity, and load-adjustment (Pietzcker et al., 2017).

Nuclear energy is reported as Primary Energy|Nuclear. The accounting for both non-biomass renewables and nuclear energy used for power and heat generation is based on the direct equivalent method, implying that the reported primary energy numbers are identical to the generated electricity and heat (and so a duplication of the reporting in primary and secondary energy, required to be able to do comprehensive assessments on different levels). Shifting from fossil-based power generation to low-carbon fuels thus results in an apparent reduction of primary energy use, even when final and secondary energy consumption is kept constant.

Energy conversion

Primary energy carriers are converted into Secondary Energy|Electricity, Secondary Energy|Gases (all gaseous fuels including natural gas), Secondary Energy|Heat (centralised heat generation), Secondary Energy|Hydrogen, Secondary Energy|Liquids (total production of refined liquid fuels from all energy sources (incl. oil products, synthetic fossil fuels from gas and coal, biofuels)) and Secondary Energy|Solids (solid secondary energy carriers (e.g., briquettes, coke, wood chips, wood pellets).

Electricity and hydrogen can be generated from fossil technologies (Secondary Energy|Electricity|Fossil), renewable energy sources (Secondary Energy|Electricity|Non-Biomass Renewables) or nuclear energy (Secondary Energy|Electricity|Nuclear). Sufficient capacity must be installed to meet demand within the boundaries of the system configurations for the power system and other secondary energy system. The exact formulation of the system properties and boundary conditions differs between models.

Prices of these fuels are reported at the secondary level, i.e. for large scale consumers and include the effect of carbon prices on the production of electricity and other secondary energy carriers. Prices are reported as indexed to the model-endogenous price of the year 2020, representing the multi-year average price of 2015-2020.

Energy investments

Investment numbers are available for various supply technologies, both in the power system for various (sub-) technologies (Investment|Energy Supply|Electricity|*Technology*), for liquids, heat and hydrogen transformations (Investment|Energy Supply|Liquids/Heat/Hydrogen|*Technology*), and for supply of fossil fuels (Investment|Energy Supply|Extraction|*Source*). The latter numbers represent total investments, including mining, shipping and ports for coal, upstream, LNG chain and transmission and distribution for gas, upstream, transport and refining for oil.

On the demand side, there is only an estimated value of overall investments into energy efficiency (Investment|Energy Efficiency), estimated based on policy-induced demand reductions (McCollum et al., 2018).

Energy end-use

Final energy use is the ultimate determinant of the scale of the energy system, and is at the end of the conversion route (Primary energy → Secondary energy → Final energy). Energy end-use dynamics also provide insight into technological or societal changes (e.g., greater use of electricity, shared mobility) that might influence the way that energy is used and the implications for the broader energy system.

In general, final energy is split into three categories: buildings (representing both residential and commercial buildings), industry (representing the remaining stationary energy uses, so especially manufacturing and heavy industries), and transportation. At times, there can be some blurring in the distinction between these classes, depending, for example, on whether industrial buildings are classified in industry or buildings. Another issue is the treatment of on-site electricity generation, which can sometimes be accounted for by decreasing on-site energy demand and other times accounted for as an actual electricity generation source with a corresponding increase in final energy demand. These nuances have only a modest impact on results, however.

Two primary classes of end use information are provided for this scenario assessment. One of these is the fuel mix into any sector. These are found in the variables beginning with Final Energy|Buildings|, Final Energy|Industry|, and Final Energy|Transportation|. The options for fuels include electricity, gaseous fuels, heat, hydrogen, liquid fuels, solids (biomass and coal), and other. These variables allow for consideration of electrification or the increased use of hydrogen or bioenergy, all of which are part of the energy transition associated with deep decarbonisation. Different sums are provided in this set of variables, for example, the sum of final energy across the different sectors for each of the fuels. To the extent that models include it, these variables do not include any increases or decrease in energy use due to a changing climate.

The other type of information is the prices of fuels to end users. The prices represent the prices after the energy has actually been transported one way or another to the particular end use, for example, through power lines or natural gas pipelines. In the current variable, we have included prices for residential building energy and for transportation energy. These are captured in the variables beginning with Price|Final Energy|Buildings|Residential| and Price|Final Energy|Transportation|.

Ultimately, energy demands spring from the demands for actual services, from personal transportation to lighting and social media. For this round, we have included only final energy services associated with passenger transportation and freight transportation (variables starting with Energy Service|Transportation|)

Land use

Land use variables capture a broad range of different dynamics that are associated with agricultural production and with the overall utilisation of land. Land is initially divided into different categories with the variables starting with Land Cover|. Several different types of land cover are included, including agricultural land and forests. These are further divided into different subcategories (e.g., energy crops or managed forests). These variables provide an indication of, for example, the land that is allocated to bioenergy crops in the context of climate mitigation or the forest land that may be added (afforestation) or removed for other uses (deforestation). A special variable for afforestation and deforestation is also provided (Land Cover|Forest|Afforestation and Reforestation). While the categories of afforestation and reforestation are often considered independently, they are, in fact, very hard to distinguish in models operating at relatively aggregate special scales and are therefore combined into a single category.

Actual agricultural production does not scale precisely with the amount of land dedicated to crop production. This is because agricultural yields change over time due to technological change and also in response to policies that might be included in scenarios. Yields are provided for cereal crops, oil crops, and sugar crops (variables starting with Yield|) Agricultural production variables begin with Agricultural Production|. Nitrogen and phosphorous use to support this production are included in the variables that begin with Fertilizer Use|.

Agricultural products are produced to satisfy demands (which are based on the underlying socio-economic assumptions of the SSP 2 scenario), which need to scale with agricultural production and need to map to the different types of agricultural products. These demands overlap with one another. Categories include demand for crops (variables starting with Agricultural Demand|Crops|) and the subcategories associated with energy crops (variables starting with Agricultural Demand|Energy|), livestock (variables starting with Agricultural Demand|Livestock|), and overall non-energy uses (variables starting with Agricultural Demand|Non-Energy|). Actual food demands are given for crops in total and for livestock with variables starting with Food Demand|.

Prices are given for agricultural products. These are internationally-traded prices, meaning that a single price is provided for every agricultural commodity. Because of accounting and measurement issues, absolute values can vary across models. For this reason, international price pathways for agricultural commodities are given in indices that can provide proportional increases or decreases over time. International agricultural prices are given by variables that begin with Price|Agriculture|. Prices are provided for major cereal crops – corn, rice, soy, and wheat – along with livestock and overall indices for non-energy products. (biomass prices are provided under the energy category).

Forestry products are also included the variable list. These represent the roundwood used for industrial applications (e.g, buildings) or for wood fuel. These are captured with Forestry variables starting with Forestry Demand|Roundwood|, and Forestry Production|Roundwood|.

Climate impacts from extreme events or yield changes due to warming are not considered.

Emissions

Energy and land-use related activities release a variety of gases and particles that pollute ambient air and alter the Earth climate. These include long-lived greenhouse gases (i.e. Emissions|CO2, Emissions|CH4, Emissions|N2O, Emissions|F-Gases) as well as greenhouse gas precursors[1] and air pollutants (i.e. Emissions|NOx, Emissions|CO, Emissions|VOC), including aerosols and their precursors (i.e. Emissions|Sulfur, Emissions|NH3, Emissions|BC and Emissions|OC).

IAMs account for all of these compounds but can differ in the way they treat them. Emissions from the energy and land-use sectors are usually modelled explicitly by multiplying activity levels by assumed emission factors (Rao et al., 2017). Some emissions like those released from waste-related activities are often modelled via time-dependent marginal abatement cost curves which estimate the costs associated with different emission reduction levels (Harmsen et al., 2019, p. 201; Lucas et al., 2007). Emissions of fluorinated gases (F-Gases) and biomass burning are taken from exogenous sources (Velders et al., 2015). F-Gases include Emissions|HFC, Emissions|PFC and Emissions|SF6.

The detailed representation of the energy and land-use sectors in IAMs allow emissions to be broken down by sector. For instance, CO_2 emissions can be split into Emissions|CO2|AFOLU and Emissions|CO2|Energy and Industrial Processes. The latter can in turn be further split into Emissions|CO2|Energy and Emissions|CO2|Industrial Processes. CO2 emissions from the energy system are separated between Emissions|CO2|Energy|Supply and Emissions|CO2|Energy|Demand. Sectoral disaggregation in IAM differs from sectoral definitions typically used in national statistical accounts.

Emissions are reported with different units. For example, CO_2 emissions are reported in Mt CO_2/yr while CH_4 and N_2O emissions are reported in Mt CH_4/yr and kt N_2O/yr respectively. Non-CO_2 greenhouse gas emissions can be calculated in CO_2-equivalent units by multiplying them by their respective global warming potential.

From a policy perspective, it is important to keep track of the emissions of the six greenhouse gases included in the Kyoto Protocol (i.e. Emissions|Kyoto Gases). These are provided in Mt CO_2-equivalent/yr using the global warming potentials from the IPCC Fifth Assessment Report (Edenhofer et al., 2014).

In policy scenarios, carbon prices (Price|Carbon, see Economic information section for more details) are applied to all greenhouse gases (i.e. CO_2, CH_4, N_2O and F-Gases). Policies on greenhouse gas precursors and air pollutants follow SSP2 assumptions (Rao et al., 2017). In the SSP2 scenario, air pollution is assumed to decrease over time due to increasingly stringent air pollution control policies (e.g. implementation of the EURO6 standard for road transport).

The engineering of carbon flows offers a complementary option to mitigate climate change, allowing either to continue using fossil fuels without releasing the stored carbon to the atmosphere, or even to remove CO_2 from the atmosphere. The models consider two categories: land-based sequestration (Carbon Sequestration|Land Use) and Carbon Capture and Sequestration (CCS) (Carbon sequestration|CCS). The former includes afforestation and reforestation, i.e. planting trees to store atmospheric carbon in them. The latter includes all technologies that capture CO_2 from flue gases and storing it safely underground in suitable geologic formations. These technologies are divided into any energy transformation technology fitted with CCS (Carbon sequestration|CCS|Fossil), bioenergy with CCS, also known as BECCS, (Carbon sequestration|CCS|Biomass) and industrial activities using CCS (Carbon sequestration|CCS|Industrial Processes).

[1] Emissions of NO_x, CO and VOC react in the atmosphere and yield tropospheric O_3, a greenhouse gas.

Some of these carbon sequestration technologies remove more carbon from the atmosphere than they release. This class of technologies is called Carbon Dioxide Removal (CDR) technologies. It includes land-based sequestration (e.g. via afforestation) and BECCS.

Climate

Global climate outcomes of the scenarios have been estimated with the reduced complexity carbon-cycle and climate *Model for the Assessment of Greenhouse-gas Induced Climate Change* (MAGICC) (M. Meinshausen et al., 2011). The model simulates the change in global mean temperature given a specified evolution of climate-relevant emissions. These emissions include all greenhouse gases (carbon dioxide, methane, nitrous-oxide, and fluorinated gases) as well as aerosols and aerosol precursors like black carbon, organic carbon or sulfur dioxide, and are provided by the IAMs. Scenarios are assessed in a probabilistic setup as used in the Special Report on Global Warming of 1.5°C of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018a; Rogelj, Shindell, et al., 2018) which in turn was consistent with the climate assessment in the IPCC's Fifth Assessment Report (L. Clarke et al., 2014). This ensures backward comparability of the climate outcomes with the latest IPCC reports and assessments. Each scenario is run 600 times, each with an alternative set of model parameters in a way such that a range of responses consistent with the latest climate sensitivity assessment of the IPCC (IPCC, 2013) is captured (Malte Meinshausen et al., 2009; Rogelj et al., 2014). This probabilistic approach enables reporting information beyond an average response only, and allows to understand risks of warming at the higher end of current scientific understanding. For instance, projected temperatures at various percentiles of climate response are reported (5^{th}, 10^{th}, 25^{th}, 33^{rd}, 50^{th}, 67^{th}, 75^{th}, 90^{th}, and 95^{th}) (e.g. Diagnostics|Temperature|Global Mean|MAGICC6|P90). In addition, also the probability of exceeding various temperature thresholds over time is provided for values from 1.0°C to 4.0°C with half-a-degree intervals (e.g. Diagnostics|Temperature|Exceedance Probability|1.5 degC|MAGICC6). The setup clearly highlights the possibility and range of future changes in global mean temperature projections as scientific understanding progresses.

3.2. Economic impact estimates from physical risks

Economic impacts from physical climate change are calculated based on damage functions, i.e. relationships quantifying the effect of a change in global mean temperature on economic output. This is an active research area with very large uncertainties. In particular, it remains an open question if the damages affect the level or the growth rate of output. Here, three different estimates for level damages are chosen to reflect part of the range of estimates available in the literature. Their key features are summarised in Table 4.

Damages are calculated in post-processing using the probabilistic global mean temperature change data from the MAGICC post-processing of the emission pathways of the transition scenarios, thereby reflecting the climate uncertainty. The results are provided as global output loss compared to a world with preindustrial climate, calculated as

$$\Omega_t = \alpha_1 T_t + \alpha_2 T_t^2, \text{ with } Y_t^{net} = \Omega_t Y_t^{gross}.$$

Here, Y_t^{gross} is the pre-damage GDP, Y_t^{net} the GDP net of damage, Ω is the damage term, T is the global mean temperature change compared to preindustrial levels and α_1 and $\alpha_2$are constants. Note that the quadratic from of the relationship is an assumption. Three different specifications are included, taken from the DICE model, based on a statistical analysis of damage estimates from the literature (W. D. Nordhaus, 2017; W. Nordhaus & Moffat, 2017), from a similar meta-analysis by (Howard & Sterner, 2017) and from a new econometric study using subnational GDP data (Kalkuhl & Wenz, 2020). The first two approaches include market and to some degree non-market damages on the level of output, the last one is based on a panel regression, therefore capturing productivity damages (i.e. labor and land productivity, capital depreciation). These results are likely underestimating the actual damages due to missing impact categories like non-monetized effects, effects of sea-level rise, extreme events or large-scale tipping points. However, note that in both the DICE2016 and in the Howard and Sterner specification, a 25% markup is included to account for potentially omitted effects. Furthermore, the global estimates mask very large regional differences as well as differences among income groups. None of the approaches capture effects on the growth rate rather than the level of GDP.

Note that the effects of these physical risks are not reflected in the GDP data available for the transition scenarios, they are pure diagnostic variables at this stage. They are reported, for example, as Diagnostics|GDP change| DICE2016|GMT MED, in %, with losses reported as negative values.

Table 4 **Overview of macro-economic damage functions applied to the NGFS scenarios**

Damage function	DICE2016	KW panel	HS
Source	Nordhaus 2017, Nordhaus and Moffat 2017	Kalkuhl and Wenz 2020	Howard and Sterner 2017
Type	Level	Level	Level
Basis	Statistical analysis of aggregate damage estimates from the literature	Empirical analysis of the effects of temperature change on productivity levels and growth based on subnational data	Meta-analysis of aggregate damage estimates in the literature
Input data	Global mean temperature change	Global mean temperature change	Global mean temperature change
Specification	$\alpha_1 = 0$ $\alpha_2 = -0.00236$	$\alpha_1 = -0.0373$ $\alpha_2 = -0.0009$	$\alpha_1 = 0$ $\alpha_2 = -0.007438$
Comments	Median (quantile), quadratic, weighted regression over 36 damage estimates from 27 studies	These numbers are based on the results from the annual panel regression, which are aggregated from country-level to global using population weighting.	This is the preferred specification of Howard and Sterner, including a 25% markup for potentially omitted impacts. It is based on a weighted least-squares regression with cluster-robust standard errors with a dataset of 21 damage estimates.

3.3. User manual for the NGFS Scenario Explorer

3.3.1. Data availability and license

The transition pathways selected for the NGFS are available in the NGFS Scenario Explorer (NGFS SE), hosted by IIASA: data.ene.iiasa.ac.at/ngfs. The Scenario Explorer is a web-based user interface for scenario results and historical reference data. It provides intuitive visualisations and display of time series data and download of the data in multiple formats. A brief description of the features of the Scenario Explorer is available at the end of this section and tutorial videos of the main features are available at https://software.ene.iiasa.ac.at/ixmp-server/tutorials.html

The NGFS Scenario Explorer data are available under a Public License that is adapted from the Creative Commons Attribution 4.0 International Public License with the aim of keeping the Licensed Material always up-to-date and avoiding the circulation of obsolescent data constituting substantial portions of the Licensed Material.

This license is a balance between making the scenario ensemble available as widely as possible, encouraging broad use of the data for research, science communication and policy analysis and the anticipation of updates of the scenario ensemble. This may be either due to adding more detailed information to available scenarios in response to user requests, or because of reporting issues identified after the release that need to be corrected. While we did take the utmost care to validate all submitted data, such issues can never be fully avoided.

For this reason, we request that downloads of scenario data are routed through the NGFS Scenario Explorer at data.ene.iiasa.ac.at/ngfs, unless the data is made available in relation to a specific figure in a publication or online visualisation tool, for example as supplementary material to a manuscript published in a scientific journal.

We will inform registered users of the scenario ensemble about data updates or any other relevant news.

The details of the legal license are available under https://data.ene.iiasa.ac.at/ngfs/#/license

3.3.2. Data identifiers (Model, Scenario, Region, Variable)

The data from the NGFS Scenario Explorer are available for download in comma separated value (csv) format, organised according to the IAMC data format. The numerical scenario results are provided as time series data. Data is reported for each region and scenario available in the database, organised by variable with additional columns for the available years. Hence, the columns in the data files are:

Model	Scenario	Region	Variable	Unit	2000	...	2100

Model: The transition scenarios for the NGFS are provided by three integrated assessment models: GCAM 5.2, MESSAGEix-GLOBIOM 1.0 and REMIND-MAgPIE 1.7-3.0. In the rest of this document, shorter versions of the full model names are also used to refer to these three models; GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE, respectively.

Scenario: The scenario names are defined in line with Figure 1 on page 4 and Table 3 on page 17:

- Hot house world (Rep) Current policies
- Hot house world (Alt) Nationally determined contributions (NDCs)
- Orderly (Rep) Immediate 2C scenario with CDR
-
- Orderly (Alt) Immediate 1.5C scenario with CDR
- Orderly (Alt) immediate 2C scenario with limited CDR
- Disorderly (Rep) Delayed 2C scenario with limited CDR
- Disorderly (Alt) Delayed 2C scenario with CDR
- Disorderly (Alt) Immediate 1.5C scenario with limited CDR

Region: The transition scenarios for the NGFS are provided for the native model regions as defined by each of the participating models and several aggregate regions (see below). The native model regions are labelled "MODEL NAME|REGION NAME" (e.g. "GCAM 5.2|Africa_Eastern"). The aggregated regions are labelled R5XXXX (e.g. R5ASIA), and some individual G20 countries are labelled by their ISO codes (e.g. CHN, IND, RUS, USA) with the exception of the European Union (EU). Global information is provided under "World".

Variable: The variable names follow a few basic rules.

- Variables are organized in a hierarchical structure which is specified by separators "|"
- Variable names can include none, one or more separators (e.g. "Population", "GDP|PPP", "Emissions|CO2|Energy")
- For variables with one or more separators, the left-most word indicates a broad variable category or an indicator (e.g. "GDP", "Emissions", "Primary Energy")
- The separators define two types of relationships among variables:
    - Relationships for indicators calculated with different metrics or methods: e.g. "GDP|PPP" and "GDP|MER"
    - Aggregate relationships providing disaggregation across sectors, fuels, technologies or gases: e.g. "Emissions|CO2" = "Emissions|CO2|AFOLU" + "Emissions|CO2|Energy" + "Emissions|CO2|Industrial Processes"
- Several alternatives may exist for aggregate relationships (e.g. Final Energy is decomposed by sector and by fuel)
- Elements pertaining to the same hierarchical level can sometimes be aggregates themselves (e.g. "Primary Energy|Fossil" is the aggregate of "Primary Energy|Coal", "Primary Energy|Oil" and "Primary Energy|Gas")

Detailed description and definition of the variables in the database is available in Section 3.1.3, and can also be found on the Explorer on the "Documentation" tab.

Unit: Each variable is specified by its unit, generally specified in the international system of units (SI units, abbreviated from the French Système international (d'unités)).

3.3.3. Time steps and regional granularity

The time steps between two consecutive model output data range between 5 and 10 years and differ across the participating models (Table 5).

Table 5 **Time steps across models**

Model	Time steps
GCAM	• 5-year time steps from 2005 to 2100
MESSAGEix-GLOBIOM	• 5-year time steps from 2005 to 2050 and 10-year timesteps over the period 2050-2100 for the scenarios "Hot house world (Rep) Current policies" and "Orderly (Rep) Immediate 2C scenario with CDR". • For the other scenarios, output is available in 10-year time steps from 2010 to 2100.
REMIND-MAgPIE	• 5-year time steps from 2005 to 2060 and 10-year time steps over the period 2050-2100

Regional granularity differs between the participating models. The MESSAGEix-GLOBIOM and REMIND-MAgPIE models both have 11 model regions, whereas the GCAM model has 32 native model regions. The regional definitions are summarised in Table A1.1, Table A1.2 and Table A1.3 for the individual models and Table 6 for the aggregate regions.

Table 6 **Regional definition of meta regions across models**

NGFS SE identifier	Geography name	GCAM regions	MESSAGEix-GLOBIOM regions	REMIND-MAgPIE regions
BRA	Brazil	Brazil		
CHN	China	China	CPA	CHN
EU	European Union	EU-12, EU-15	EEU, WEU	EUR
IND	India	India	SAS	IND
USA	United States	USA	NAM	USA
JPN	Japan	Japan		JPN
MEX	Mexico	Mexico		
RUS	Russia			RUS
R5ASIA	Asia	Central Asia, China, India, Indonesia, Pakistan, South Asia, South Korea, Southeast Asia, Taiwan	SAS, PAS, CPA	CHN, IND, OAS
R5LAM	Latin America	Brazil, Central America and Caribbean, Mexico, South America_Northern, South America_Southern, Argentina, Colombia	LAM	LAM
R5MAF	Middle East and Africa	Africa_Eastern, Africa_Northern, Africa_Southern, Africa_Western, Middle East, South Africa	MEA, AFR	MEA, AFR
R5OECD90+EU	OECD and EU	USA, Australia_NZ, Canada, EU-15, Europe_Non_EU, European Free Trade Association, Japan	WEU, PAO, NAM, EEU	EUR, JPN, USA, ROW
R5REF	Reform economies	EU-12, Europe_Eastern, Russia	FSU	RUS

3.3.4. Meta-data

The following meta-data categories are available:

Main scenario category:

- Hot house world
- Orderly
- Disorderly

Scenario Status:

- Representative
- Alternative

3.3.5. Scenario Explorer functionalities

The Scenario Explorer has been developed by IIASA and is increasingly used by the research community for outreach and model comparison projects. For example, there are explorer instances accompanying the IPCC SR1.5 and upcoming IPCC Sixth Assessment Report, and many projects funded by the Horizon 2020 EU Research and Innovation programme (such as CD-LINKS www.cd-links.org), the Energy Foundation China, GEIDCO and UNIDO make use of the explorer.

The transition scenarios selected for the NGFS are available in the NGFS Scenario Explorer hosted by IIASA: data.ene.iiasa.ac.at/ngfs.

Tutorial videos of the main features are available at https://software.ene.iiasa.ac.at/ixmp-server/tutorials.html

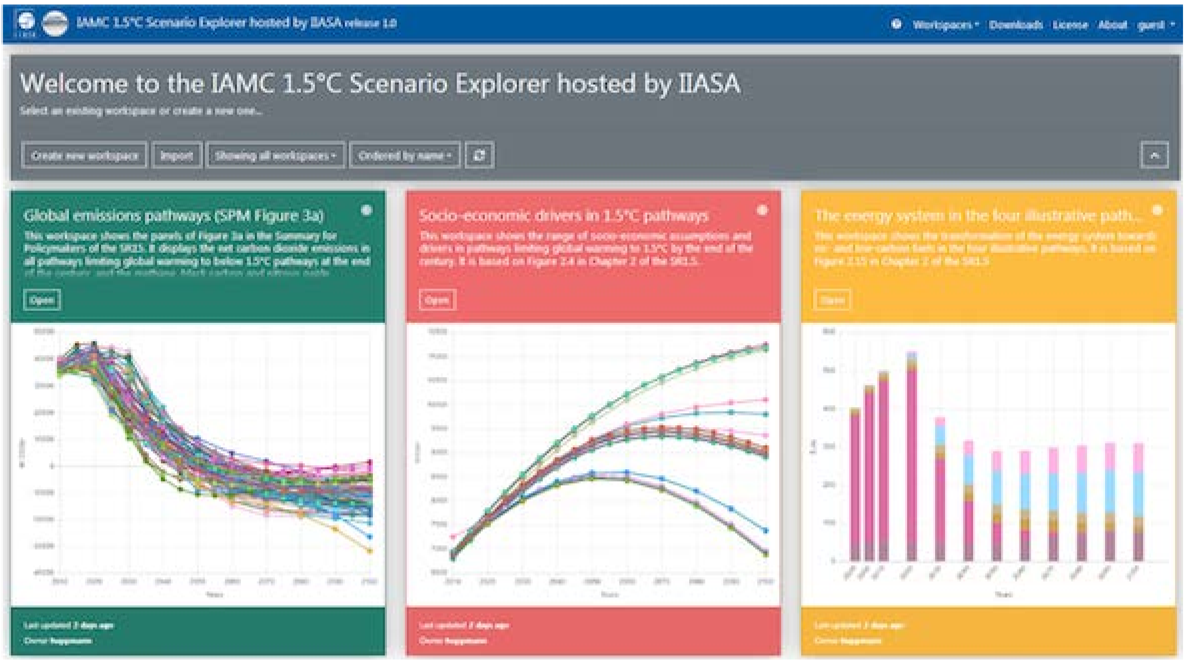


Figure 6 The IAMC 1.5°C Scenario Explorer was the first application of the IIASA modelling platform infrastructure

New user registration

At the bottom of the login box at the landing page of the explorer you find a registration button which will open the new user registration page. Once you fill out this form, at least providing username, email and password, you will receive an email to confirm your registration and you will have access to the NGFS Scenario Explorer.

If you are already registered for one of the other Scenario Explorer instances (such as the IPCC SR1.5), there is no need to register again. Your account should work on the NGFS Scenario Explorer as well. For any questions, please email ngfs.ene.admin@iiasa.ac.at.

It is also possible to use the NGFS Scenario Explorer without registration. In that case, simply click the Guest Login button at the landing page to enter the NGFS Scenario Explorer. When using the Scenario Explorer without registration, it is possible to use all the features of the Scenarios Explorer, except saving and sharing workspaces.

Workspaces

The Scenario Explorer is built around the concept of workspaces, which can be developed, saved and shared between users. Workspaces are interactive, user-customisable environments that can contain charts, data-tables and text descriptions. Any registered user of the Scenario Explorer can create, save and share workspaces. Workspaces can be generated to be public such that every user sees them when accessing the Scenario Explorer instance or they can be shared bilaterally with colleagues or on social-media.

To create a new workspace, click the 'create workspace' button at the top of the Scenario Explorer page. This will create and open a new workspace for you. By clicking on 'edit workspace' the workspace setting page will be opened, allowing to provide a name and description of the workspace and to save the workspace to the server. The three-striped workspace menu on the top-right provides the option to export the workspace code in json file format, to export the workspace as pdf or to clone the workspace. Cloning the workspace will create a copy that can be edited without interfering with the original version. It is possible to clone workspaces that have been shared by other users or to clone workspaces that are already saved to your account. Updating the workspace will reload it from the server and overwrite any changes that have been made locally.

Finally, the workspace setting page allows to reorder the panels in the workspace.

Panels

Any charts, data-tables and text descriptions within a workspace are called 'panels'. New panels can be created with the 'plus' button, or by clicking 'create a new timeseries panel' at the top of the page.

The first step in creating a new data or figure panel is to select scenarios, either from a set of meta-characterisations of the scenarios or by selecting individual scenarios from the full list.

The second step is selection of the variables, either by categories or from selecting individual variables from the full list. It is possible to scroll through the full list, or to search variables by typing part of the variable name in the search box.

The third step is the selection of regions. The default region is 'world', but any of the above-described regions can be selected.

After these selection steps, the plot can be created by clicking the 'apply' button.

After creating the graph, the following features are available:

- Adjusting the ranges shown on the graph, in the 'ranges' tab
- Change the title and add a description under the 'options' tab (and click update after changing title or description)
- The filter panel can be hidden and reopened by clicking on the above-pointing arrow in the top bar of the panel.
- The legend can be shown or hidden with the most left button in the top bar of the panel
- The figure can be converted to line chart, bar chart of data table by clicking the respective buttons in the top bar
- Sub-categories can be shown in stacked format as well.

- The data underlying the panel can be downloaded in several different data formats (such as xlsx, csv) or the figure itself can be downloaded as pdf or other picture format.
- The size of the panel can be adjusted from full-width to half-width using the minimise panel button.

When a workspace contains multiple panels, the chain-button in the top of the workspace allows to cross-highlight the same scenario across multiple panels for easy comparison.

Finally, creating a text panel allows to add text descriptions to a workspace with formatting based on the markdown language.

Documentation

Documentation is provided at the level of individual panels (using the document-icon) or for the full database in the documentation menu at the top of the Scenario Explorer. Definitions and links to more detailed documentation and references are provided for all models, scenarios, variables, regions and metadata categories that are used for scenario categorisation.

Download features

The data of an individual panel can be downloaded in several different data formats (such as xlsx, csv) or the figure itself can be downloaded as pdf or other picture format.

The data contained in the full database can be downloaded through the download menu at the top of the Scenario Explorer. This menu contains snapshots in csv format for all scenarios and variables in the database, the reference data and citation options for the data in different formats.

4. ISIMIP Climate Impact Database

4.1. Overview of ISIMIP

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) is a community-driven initiative launched by PIK and IIASA with the aim to offer a consistent climate change impact modelling framework. Up to date, more than 100 models have contributed to the initiative. The impact models are listed under www.isimip.org/impactmodels where a factsheet for each model is provided.

To participate, impact modelling teams are provided with pre-processed input data and agree to run a minimal set of model runs. The resulting output data becomes open-access after a few months' time and can be downloaded from the Earth System Grid Federation (ESGF) platform.

For further reading on conducted studies, please look at the list of ISIMIP-related publications under: https://www.isimip.org/outcomes/publications-overview-page/.

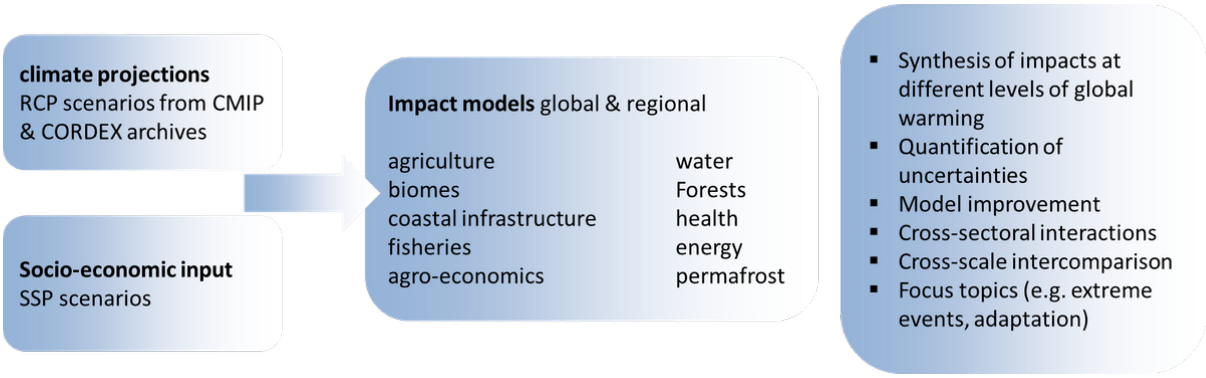


Figure 7 Overview of the ISIMIP framework (ISIMIP website)

Figure 7 provides a visualisation of the ISIMIP framework: For each simulation round, a scenario based on climate and socio-economic projections is designed. The projections on climate change follow the Representative Concentration Pathways (RCP) scenarios which are four greenhouse gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report (AR5). They are named after a possible range of radiative forcing values in the year 2100 with RCP2.6 being the lowest and RCP8.5 the highest emission, respectively high and low mitigation, scenario (Table 7).

Table 7 **Four representative concentration pathways (RCPs) from the IPCC**

Scenario name	Scenario description
RCP2.6	One pathway where radiative forcing peaks at approximately 2.6 $W.m^{-2}$ before 2100 and then declines
RCP4.5	Intermediate stabilisation pathways in which radiative forcing is stabilised at approximately 4.5 $W.m^{-2}$ after 2100
RCP6.0	Intermediate stabilisation pathways in which radiative forcing is stabilised at approximately 6.0 $W.m^{-2}$ after 2100
RCP8.5	Pathway for which radiative forcing reaches greater than 8.5 $W .m^{-2}$ by 2100 and continues to rise for some amount of time

The core of ISIMIP, the different impact models, cover different impact sectors (see the list in Figure 7), e.g. agriculture or forest. Models for different scale simulations are included in ISIMIP, from the local, regional to the global scale. Within ISIMIP there are also sector-specific focus regions as displayed in Figure 8. Simulation runs for these regions help to improve model intercomparison, e.g. between regional water and global models.

Figure 7 also provides a list of objectives of ISIMIP which shape the scenario design for each simulation round, e.g. the simulation protocols may be designed to allow aggregation of impacts across different sectors, analyse cross-sectoral interactions or analyse cross-scale impacts.

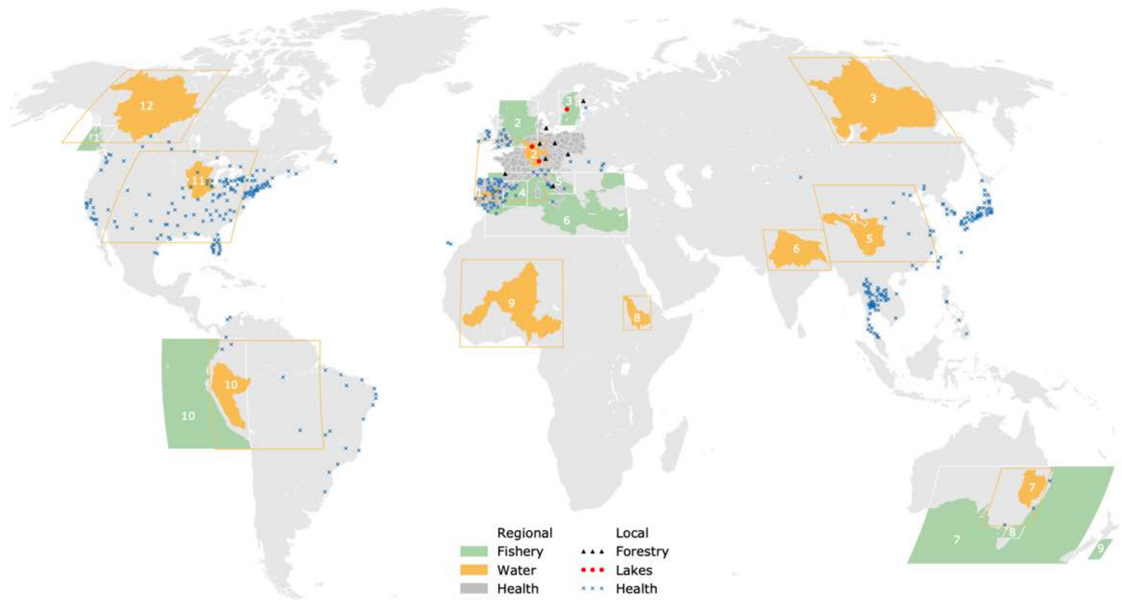
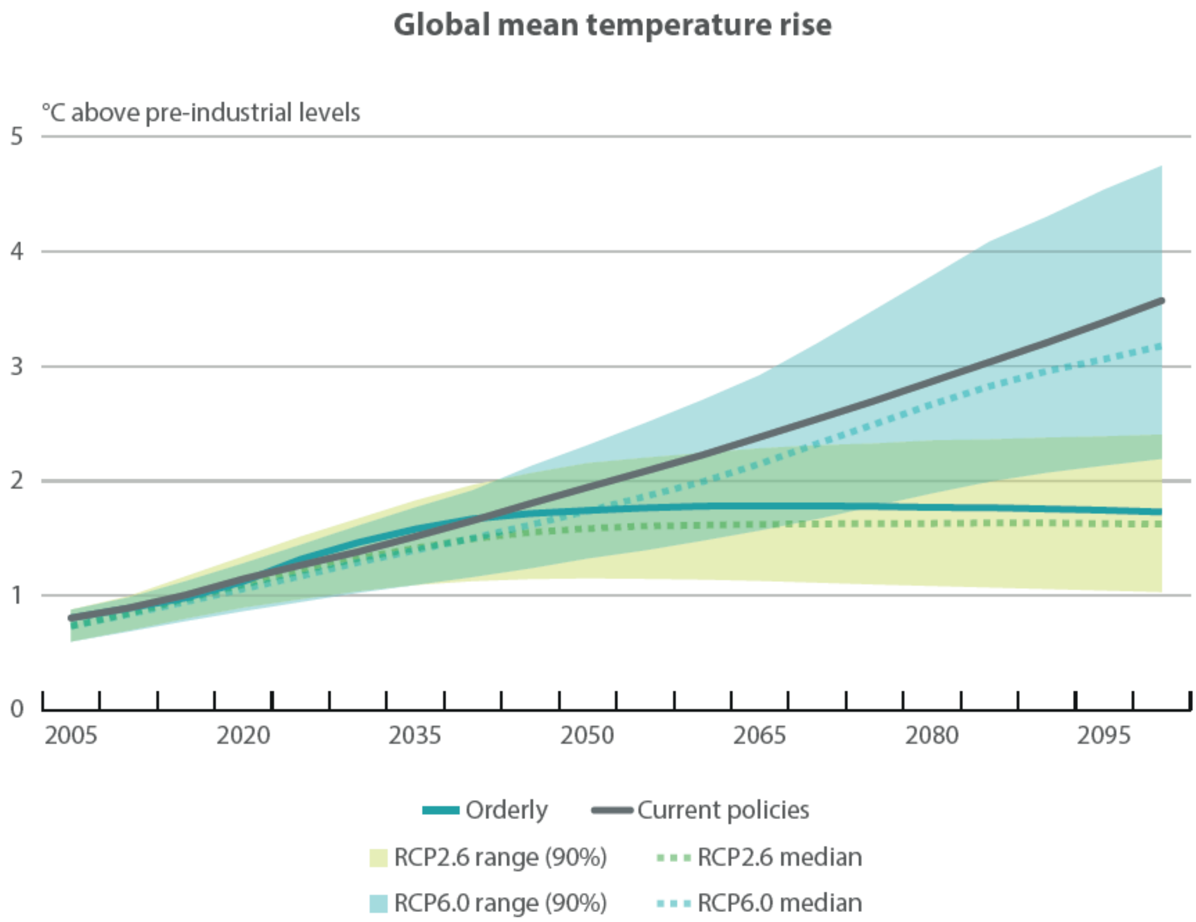


Figure 8 ISIMIP focus regions (Frieler et al., 2017)

4.1.1. ISIMIP and NGFS transition scenarios

The impact models deploy the RCP2.6 and RCP6.0 scenarios commonly used in climate science including the IPCC reports that comprise the range of the transition pathways (see Figure 9). In the context of the NGFS scenarios (see Table 3), the (dis)orderly 1.5° and 2°C scenarios are in the range of the RCP2.6 scenario, whereas the Current policies scenario is close to the RCP6.0 scenario by the end of the century (Note that the RCP scenarios were designed about 10 years ago and do not match well with recent emissions trends: They show lower warming until about mid-century than the transition scenarios of similar long-term warming outcomes).

In Figure 9, for the RCP scenarios, median warming projections (full lines) as well as the 90% uncertainty range for different warming outcomes for the same concentration scenario (based on the MAGICC6 model, see Section 3.1.3) are shown. For the transition scenarios, only the median projection is shown (Note that the warming outcomes under these scenarios are subject to the same uncertainties as the warming outcomes of the RCPs).



Source: IIASA NGFS Scenarios Portal. 90% uncertainty range based on the MAGICC6 model for each Representative Concentration Pathway (RCP).

Figure 9 Overview of global warming trajectories for the RCP scenarios (RCP2.6 and RCP6.0) deployed in the ISIMIP2b impact studies as well as key NGFS transition scenarios

4.1.2. Scenario and model assumptions

ISIMIP is organised into simulations rounds. For each round, a simulation protocol is developed which defines a set of simulation scenarios based on the respective focus topic.

Three simulations rounds have been completed so far (Fast Track, 2a and 2b) and two new simulations rounds (3a and 3b) are currently conducted (https://www.isimip.org/about/#simulation-rounds).

The simulation round 2b of ISIMIP was designed to provide a scientific basis for the IPCC special report in the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. The lowest emission scenario, RCP2.6, was considered to be in line with the 1.5°C of global warming, while RCP6.0 was chosen as a no-mitigation scenario (Frieler et al., 2017).

The projections on socio-economic development are aligned with the SSP scenarios, which have been mentioned earlier (Section 3.1.2). For ISIMIP2b, the designated simulation round for this analysis, only SSP2 is used and therefore, a comparison of the different SSPs is excluded from this documentation.

So far, 80 output datasets have been generated for the ISIMIP2b simulation round.

The simulation scenarios are divided in three groups addressing different research questions.

1. Group 1 was designed to quantify pure climate change effects of the historical warming to pre-industrial reference levels

2. Group 2 was designed to quantify future impacts for the low (RCP2.6) and high (RCP6.0) scenarios without changes in socio-economic conditions (since 2019 also for RCP8.5)

3. Group 3 was designed to quantify future impacts for the low (RCP2.6) and high (RCP6.0) scenarios assuming the "middle-of-the-road" SSP2

The model runs for the three groups are displayed in Figure 10. Group 1 consists of model runs to separate the pure effect of the historical climate change from other human influences. Group 2 consists of model runs to estimate the pure effect of the future climate change assuming fixed year 2005 levels of population, economic development, land use and management (2005soc). The yellow dashed line represents an optional sensitivity run with RCP6.0 climate forcing using statistical downscaling and improved bias-correction (ewembi-isimip3basd). This run, as well as the RCP8.5 run (red line) were introduced in February 2019. Group 3 consists of model runs to quantify the effects of the land use changes, and changes in population, GDP, and management from 2005 onwards associated with RCP6.0 (no mitigation scenario under SSP2) and RCP2.6 (strong mitigation scenario under SSP2). Forcing factors for which no future scenarios exist (e.g. dams/reservoirs) are held constant after 2005.

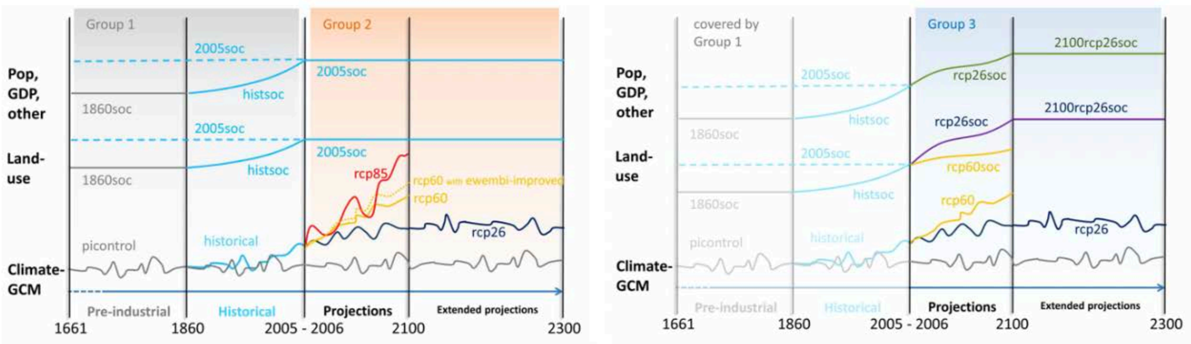


Figure 10 Scenario design for ISIMIP2B (Simulation Protocol, latest version from 19th May 2020)

Climate input data

The data on climate scenario is available from the Coupled Model Intercomparison Project (CMIP5), a standard protocol for coupled atmosphere-ocean general circulation models (https://esgf-node.llnl.gov/projects/cmip5/). Out of this model repository, four Global Circulation Models (GCM) were used to generate the climate-forcing data set for ISIMIP2b: IPSL-CM5A-LR from the Institut Pierre-Simon Laplace (France), (2) GFDL-ESM2M from the NOAA Geophysical Fluid Dynamics Laboratory (USA), (3) MIROC5 from the Japanese Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, and (4) HadGEM2-ES from the Met Office Hadley Centre (UK).

Figure 11 shows a comparison of the different GCM's output on annual global mean near-surface temperature change. The outputs are divided in 4 time periods: pre-industrial from 1661-1869, historical from 1861-2005, future from 2006-2099 and future extended from 2100-2299. The gray lines display annual global mean near-surface temperature without climate change, the black ones display the historical (observed) changes, the yellow and blue lines RCP6.0 and RCP2.6 respectively. The horizontal red and green lines mark the overshoot of the 1.5°C and 2°C scenario and show that those points differ between the models.

GCM selection should be based on the data availability: Data from IPSL-CM5A-LR and GFDL-ESM2M are the first- and second-priority climate input datasets respectively, since these GCMs provide all the monthly ocean data required and since IPSL-CM5A-LR additionally offers an extended RCP2.6 projection (Frieler et al., 2017).

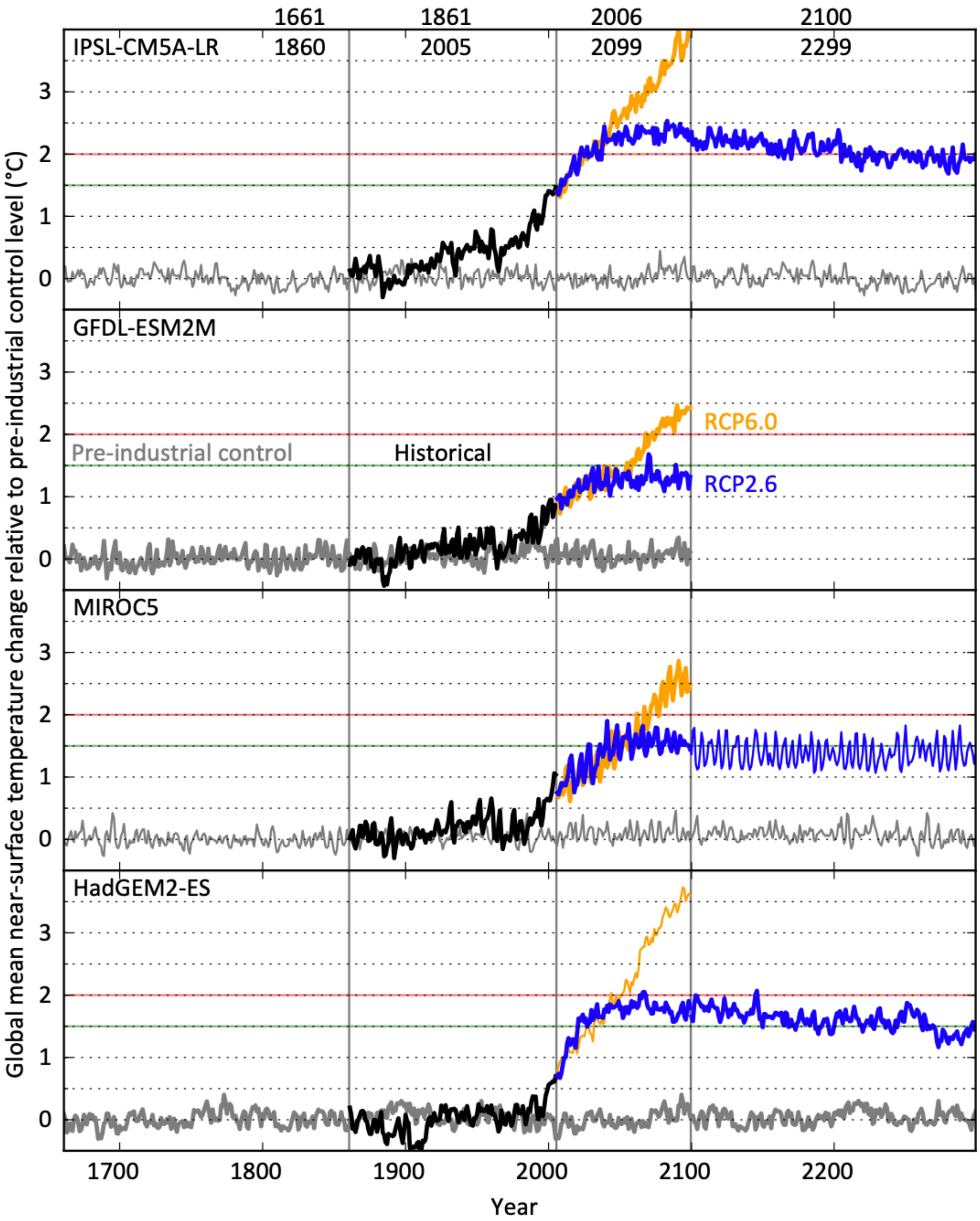


Figure 11 Time series of annual global mean near-surface temperature change relative to pre-industrial levels (1661-1860) with 4 different GCMs (Frieler et al., 2017)

Bias-correction of the climate input data

ISIMIP climate-forcing input data is bias-corrected to adjust the daily anomalies from monthly mean values (see Table 9 in Section 4.1.3).

The correction was done based on biases identified by comparing simulated to observed data from a historical reference period (1979-2013). Here, simulated data from historical CMIP5 runs for 1979-2005 and from RCP8.5 projections for 2006-2013 have been used.

The ISIMIP2b climate input data were corrected using the newly complied reference dataset EWEMBI (E2OBS, WFDEI and ERAI data merged and bias-corrected for ISIMIP). The correction was done independently for each variable, grid cell and month. The bias adjustment was performed on a regular 0.5° EWEMBi grid to which the CMIP5 GCM data were interpolated (Frieler et al., 2017; Lange, 2018).

More detailed information on the methodology can be found in the ISIMIP2b bias-correction fact sheet under www.isimip.org/gettingstarted/isimip2b-bias-correction/.

Non-climatic input data

Input data for ISIMIP impact models may include in addition to climate input data (Table 8):

Table 8 **Non-climatic input data for ISIMIP**

Input type	Comments
Ocean input data	These data are situated on a different grid than regular ISIMIP (1° resolution, and western boundary at 0° meridian)
Land-use patterns	Historical land-use changes from HYDE data, future patterns from MAgPIE
Sea-level rise patterns	Regional variations (glaciers, large-ice sheets) are scaled from their respective gravitational patterns
Population patterns and economic output (GDP)	Annual country-level data based on SSP2 projections (Figure 12)
Other human influences (reservoirs & dams, water abstraction for domestic and industrial uses, irrigation water abstraction, N fertiliser, Nitrogen deposition, fishing intensity, forest management)	Refer to simulation protocol for the newest information

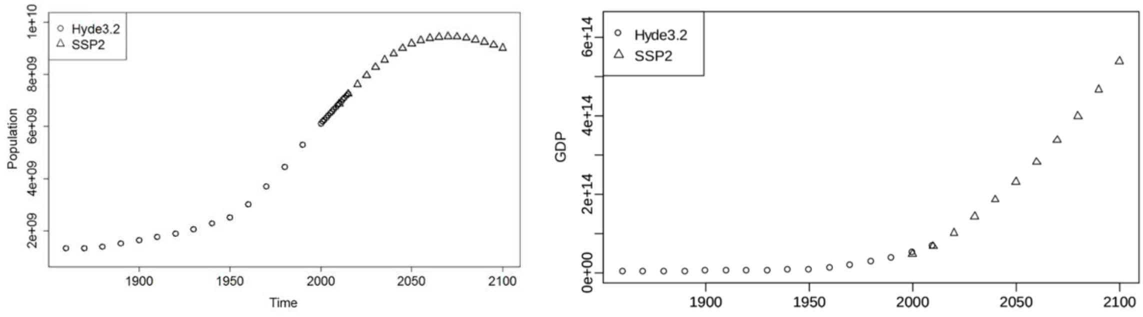


Figure 12 Left panel: Time series of global population for the historical period (dots) and future projections following the SSP2 storyline (triangles) Right panel: Time series of global GDP (Frieler et al., 2017)

4.1.3. ISIMIP climate impact variables

The following tables provides an overview on the key ISIMIP climate input and impact output variables that are of particular interest for NGFS. The information of the variables includes the unit, temporal and spatial resolution, and the respective GCM and impact models used for its computation.

For the climate-forcing data from CMIP5 displayed in Table 9, all variables are available on daily basis on the regular 0.5°x0.5° ISIMIP grid. The bias-correction for the output of the four GCMs mentioned in the previous section is indicated through the ending "-Adjust". Further data, on lakes and the water sector at regional scale, is available on the DKRZ input data repository (see Simulation Protocol).

Table 9 **ISIMIP climate-forcing input variable**

Variable name	Short variable name	Unit	Description
Near-Surface Relative Humidity	hursAdjust	%	Ratio of water vapor in the air to the total amount that could be held at its current temperature (saturation level)
Near-Surface Specific Humidity	hussAdjust	kg kg-1	Ratio of the mass of water vapour to the total mass of the air parcel
Precipitation	prAdjust	kg m-2 s-1	Mass of water (both rainfall and snowfall) per unit area and time
Snowfall Flux	prsnAdjust	kg m-2 s-1	Mass of water (in the form of snow) per unit area and time
Surface Air Pressure	psAdjust	Pa	Pressure of the air at the surface
Sea-level Pressure	pslAdjust	Pa	Pressure of the air at the sea level
Surface Downwelling Longwave Radiation	rldsAdjust	W m-2	Downward radiative longwave flux of energy at the surface
Surface Downwelling Shortwave Radiation	rsdsAdjust	W m-2	Downward radiative shortwave flux of energy at the surface
Near-Surface Wind Speed	sfcWindAdjust	m s-1	Magnitude of air velocity near the surface (10m)

Near-Surface Air Temperature	tasAdjust	K	Temperature of the air near the surface (2m)
Daily Maximum Near-Surface Air Temperature	tasmaxAdjust	K	See above
Daily Minimum Near-Surface Air Temperature	tasminAdjust	K	See above
Sea-Level Rise	total	m	Increase in sea levels relative to the mean of 1861-2005

Table 10 displays a selection of ISIMIP output variables (more than 70 output variables are available for ISIMIP2b). Most of the here listed variables can be used for different impact sector analysis, e.g. water and agriculture sectors, and thus, for different hazards such as fluvial and pluvial floods.

A table with the listed impact models can be found in the Annex. Some of the variables are available from a large number of impact models, e.g. discharge, while for other variables there are few impact models (Note that group 3 outputs are not available for all models, so the actual number of available output can be smaller than indicated in Table 10).

Table 10 **ISIMIP impact variables**

Variable name	Short variable name	Unit	Temporal resolution	Available ISIMIP impact models	Comments
Annual Maximum Thaw Depth	thawdepth	m	annual	4 *(CLM45, LPJmL, ORCHIDEE, ORCHIDEE-DGVM)*	Calculated from daily thaw depth data
Definition: *The thaw depth is the level to which the permafrost soil will normally thaw each year. The layer of soil over the thaw depth (with a temperature above zero degrees Celsius) is called the active layer, while the soil below is called permafrost, which remains frozen for two or more consecutive years. Global warming increase permafrost melting causing the release of carbon dioxide and methane. Permafrost melting is relevant for both acute, e.g. global temperature increases, and chronic impacts of climate change, e.g. landslides caused by erosion of the soil.*					
Snow Depth	snd	m	monthly	5 *(CARAIB, CLM45, ORCHIDEE, ORCHIDEE-DGVM, VEGAS)*	Grid cell mean depth of snowpack
Definition: *The snow depth is the thickness of the snow layer covering the ground. The melting of snow levels favors both acute, e.g. avalanches, and chronic impacts, e.g. sea-level rise.*					
Surface Runoff	qs	$Kg.m^{-2}.s^{-1}$	monthly	12 *(CARAIB, CLM45m, H08, JULES-W1, LBJ-GUESS, LBJmL, MATSIRO, MPI-HM, ORCHIDEE, ORCHIDEE-DGVM, PCR-GLOBWB, WaterGAP2)*	
Definition: *Surface runoff (also called overland flow) describes the flow of water occurring on the surface when excess water, e.g. rainwater, cannot longer be absorbed by the soil because the soil is saturated by water. Changes in surface runoff display chronic changes, e.g. soil erosion, and acute changes, e.g. in flooding.*					

Discharge	dis	$m^3.s^{-1}$	daily	15 (*CLM45, H08, HYPE, JULES-W1, LPJmL, MATSIRO, MPI-HM, ORCHIDEE, ORCHIDEE-DGVM, PCR-GLOBWB, SWIM-NVE, SWIM-PIK, VIC-NVE, WaterGAP2, mHM)*	
Definition: *Discharge (also called streamflow) is the volume of water flowing through a given area. It is an important indicator for chronic changes, e.g. droughts, and acute changes, e.g. in flooding.*					
Monthly Maximum of Daily Discharge	maxdis	$m^3.s^{-1}$	monthly	2 *(CLM45, MPI-HM)*	
Definition: *See above*					
Monthly Minimum of Daily Discharge	mindis	$m^3.s^{-1}$	monthly	See above	
Definition: *See above*					
Temperature of Lake Water	watertemp	K	Daily	2 (*ALBM, CLM45)*	Representative lake associated with grid cell
Definition: *This variable indicates the water temperature at lake surface. Changes in lake temperature are relevant for the ecosystems, e.g. fish population.*					
Total Soil Moisture Content	soilmoist	$Kg.m^{-2}$	Monthly per gridcell	15 *(CARAIB, CLM45m DBH, H08, JULES-W1, LBJ-GUESS, LBJmL, MATSIRO, ORCHIDEE, ORCHIDEE-DGVM, PCR-GLOBWB, SWIM-NVE, SWIM-PIK, VEGAS, VIC-NVE, WaterGAP2)*	Unit = dry matter
Definition: *Soil moisture describes the water storage in the soil which is important for plant and crop growth and soil erosion. Therefore, this variable is an important indicator for agricultural risk, e.g. for droughts.*					
Yields (maize)	yield	$t.ha^{-1}$	per growing season	3 (*GEPIC, LBJmL, PEPIC)*	Unit = dry matter
Definition: *Crop yields are calculated in the unit dry matter per hectar. Here, the outputs are available for four major crops. To account for double harvests within one year, growing season is chosen as temperal resolution. Crop yields outputs can be divided between "constraint irrigation" or rainfed if necessary. Changes in the crop yields caused by either droughts or extreme precipitation/flooding provide important information on food production and food security.*					
Yields (rice)	yield	See above	See above	See above	See above

Definition: *See above*

Yields (soy)	yield	See above	See above	See above	See above
Definition: *See above*					
Yields (wheat)	yield	See above	See above	See above	See above
Definition: *See above*					

Two other datasets have been identified to be useful to fulfil the special requirements on temperature-related health hazards.

For the human health sector, database on temperature-related hazards can be complemented by heat- and cold-related excess data generated by Vicedo-Cabrera et al. (2018). Heat-related health risk are prominent in cities through the urban heat island effect. To analyse these risks it is important to look at the local scale. Based on ISIMIP climate-forcing data, this study provides information on changes in excess mortality (%) for 451 locations (displayed in Figure 13) for four global warming levels (1.5°, 2°, 3° and 4°C). This data is available at https://gitlab.com/climateanalytics/ngfs/-/tree/ISIMIP.

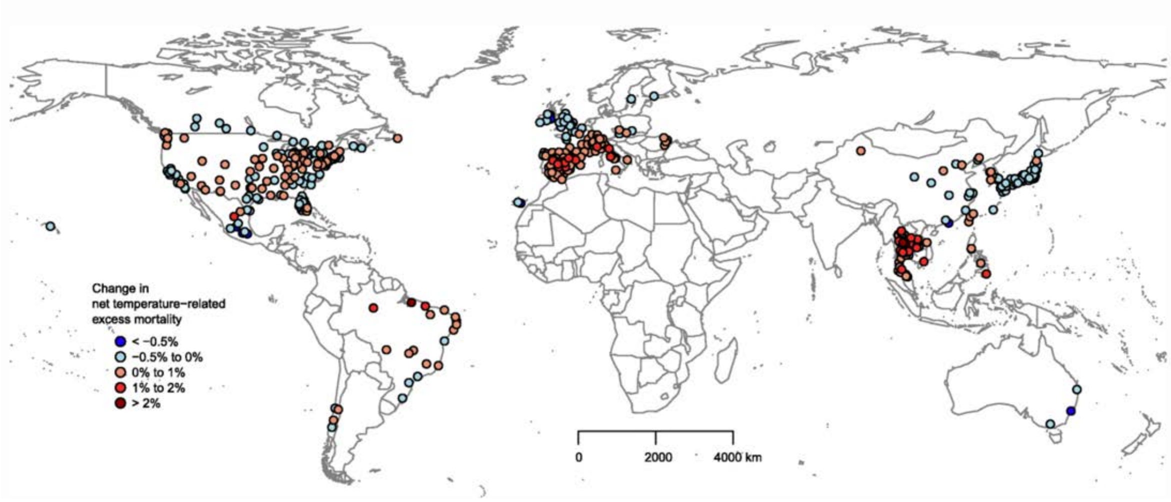


Figure 13 Map showing the geographical distribution of the location-specific total excess mortality change between 1.5 and 2 °C scenarios (Vicedo-Cabrera et al., 2018)

Furthermore, the Heat Wave Magnitude Index daily (HWMId) (Russo et al., 2015) has been identified to complement the ISIMIP database on heat waves. Here, a period of 3 or more days with consecutive days with a maximum temperature above the daily threshold for the reference period 1981-2010 is defined as a heatwave.

HWMId global data is available from CMIP5 models outputs for the three warming levels (1.5°C, 2°C and 3°C) and can be obtained from https://gitlab.com/climateanalytics/ngfs/-/tree/ISIMIP.

4.2. User manual for the ISIMIP climate impact database

ISIMIP data is hosted by the ESGF platform at PIK and can be downloaded from the ISIMIP data archive: https://esg.pik-potsdam.de/search/isimip/. To access ISIMIP data, a new user has to register at ESGF: https://esgf-data.dkrz.de/user/add/?next=/ac/subscribe/ISI-MIP_Unrestricted/.

To access ISIMIP data, a web-interface is provided (Figure 14). Here, the publicly ISIMIP data can be listed and downloaded. The different identifiers of each output data sets are described in the next section. An explanation on the different ways to download ISIMIP data can be found at https://www.isimip.org/outputdata/isimip-data-on-the-esgf-server/.

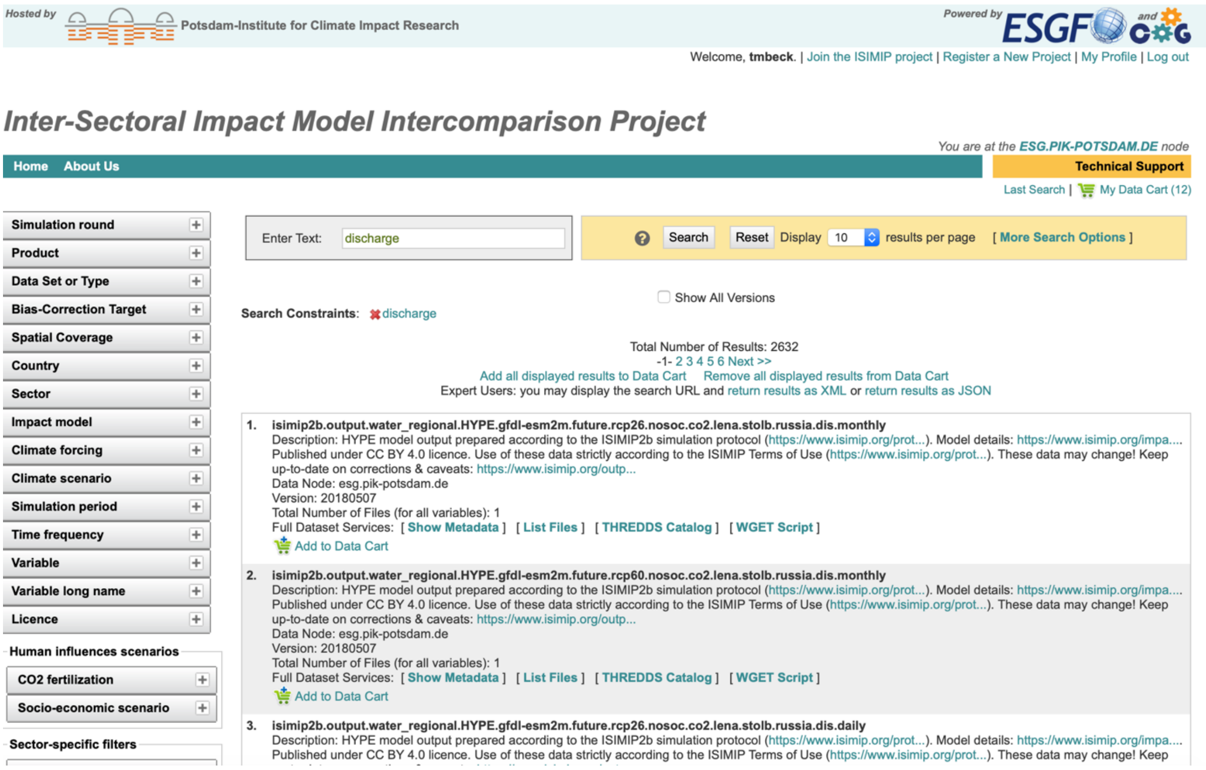


Figure 14 Screenshot of the ISIMIP Interface (https://esg.pik-potsdam.de/search/isimip)

To download larger quantity of datasets at the same time or to further process them with python, a separate readme on the installation steps and tutorial (jupyter notebook) providing guidance on how to access and download ISIMIP data using python can be found at the Climate Analytics gitlab: https://gitlab.com/climateanalytics/ngfs/-/tree/ISIMIP

4.2.1. Data availability and license

Data can be downloaded in the NetCDF format (.nc4), a machine-independent data format that is widely used for array-oriented scientific data. The output data is available on a grid, which ranges from 89.75 to -89.75° latitude, and -179.75 to 179.75° longitude for global models. The regular grid for ISIMIP has a resolution of 0.5°x 0.5° (50km resolution at the equator and then less with increasing latitude)

Most of the ISIMIP data is available for unrestricted use under the Attribution 4.0 International license (CC BY 4.0) license with only two model outputs under the non-commercial (CC BY-NC 4.0) and share alike license (CC BY-SA 4.0). The detailed terms of use can be found under https://www.isimip.org/gettingstarted/terms-of-use/terms-use-isimip-data-during-embargo-period.

4.2.2. Data Identifiers

The latest protocol on ISIMIP2b data can be found under www.isimip.org/protocol/#isimip2b. This protocol describes the simulation scenarios, input data sets and outputs variables necessary to participate in the ISIMIP2b simulation round.

Identifiers for the output data are the name of the impact model, the name of the global circulation model, the use of bias-correction, the climate scenario, the socio-economic scenario, region and timestep (see Table 11). For more information, please refer to the simulation protocol.

Table 11 **Dataset identifier**

Data identifier	Description
<model-name>	Name of the Impact model, e.g. "H08"
<gcm/observations>	Name of the GCM from which climate-forcing input data was used, e.g. "hadgem2-es"
<bias-correction>	Bias correction method, e.g. "ewembi"
<climate-scenario>	RCP scenario, e.g. "rcp26"
<socio-econ-scenario>	Socio-economic scenario, e.g. "2005soc" (constant 2005 socio-economic conditions)
<co2sens-scenarios>_	Standard "co2" (for some sensitivity experiments "2005co2"
<variable>_	See Table 10, e.g. discharge "dis"
<region>_	"Global" or region-specific identifier
<timestep>_	Temporal resolution, e.g. "daily"
<start-year>_	Start year, standard is the second year of a decade
<end-year>	End year, standard first year of the next decade

For global daily data, files cover 10 years starting in the second year of a decade and end in the first year of the next decade. Data on a lower than daily temporal resolution or non-global data are submitted for the entire simulation period.

Glossary

The following table lists a number of key terms and acronyms used within this document, and gives definitions and further information. Some of the definitions are taken from the glossaries of the fourth assessment report and the special report on 1.5 °C of the IPCC (IPCC 2007, 2018b), where much more terms and more extensive explanations can be found (e.g. https://www.ipcc.ch/sr15/chapter/glossary).

Term	Acronym	Definition
Agriculture, Forestry and Other Land Use	AFOLU	The Agriculture, Forestry and Other Land Use is a unique sector since the mitigation potential is derived from both an enhancement of removals of greenhouse gases (GHG), as well as reduction of emissions through management of land and livestock.
Bioenergy		Energy derived from any form of biomass or its metabolic by-products.
Biofuel		A fuel, generally in liquid form, produced from biomass. Biofuels currently include bioethanol from sugarcane or maize, biodiesel from canola or soybeans, and black liquor from the paper-manufacturing process. See also Biomass and Bioenergy.
Biomass		Living or recently dead organic material. See also Bioenergy and Biofuel.
Bioenergy with Carbon Capture and Storage	BECCS	Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere. The integrated assessment models used to develop the NGFS transition scenarios assume that BECCS technologies remove carbon dioxide from the atmosphere. See also Bioenergy and Carbon dioxide capture and storage (CCS).
Carbon Budget		This term refers to three concepts in the literature: (1) an assessment of carbon cycle sources and sinks on a global level, through the synthesis of evidence for fossil fuel and cement emissions, land-use change emissions, ocean and land CO_2 sinks, and the resulting atmospheric CO_2 growth rate. This is referred to as the global carbon budget; (2) the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a reference period, taking into account global surface temperature contributions of other GHGs and climate forcers; (3) the distribution of the carbon budget defined under (2) to the regional,

		national, or sub-national level based on considerations of equity, costs or efficiency.
Carbon dioxide	CO_2	A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1.
Carbon Capture and Storage	CCS	A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon capture and storage.
Carbon Dioxide Removal	CDR	Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.
Carbon price (also emissions price)		The price for avoided or released carbon dioxide (CO_2) or CO_2-equivalent emissions. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic costs of mitigation, carbon prices are used as a proxy to represent the level of effort in mitigation policies.
Global Change Assessment Model	GCAM	GCAM is an integrated tool for exploring the dynamics of the coupled human-Earth system and the response of this system to global changes. http://www.globalchange.umd.edu/gcam
Global climate model (also referred to as general circulation model)	GCM	A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or

		biological processes are explicitly represented, or the level at which empirical parametrisations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions.
Global mean surface temperature	GMST (also GMT)	Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.
Global warming		The estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.
Greenhouse gases	GHG	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Earth System Grid Federation	ESGF	The Earth System Grid Federation (ESGF) Peer-to-Peer (P2P) enterprise system is a collaboration that develops, deploys and maintains software infrastructure for the management, dissemination, and analysis of model output and observational data. ESGF's primary goal is to facilitate advancements in

		Earth System Science. It is an interagency and international effort. https://esgf.llnl.gov
Energy		The amount of work or heat delivered. Energy is classified in a variety of types and becomes useful to human ends when it flows from one place to another or is converted from one type into another. **Primary energy** (also referred to as energy sources) is the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium) that has not undergone any anthropogenic conversion. It is transformed into **secondary energy** by cleaning (natural gas), refining (oil in oil products) or by conversion into electricity or heat. When the secondary energy is delivered at the end-use facilities it is called **final energy** (e.g., electricity at the wall outlet), where it becomes **usable energy** (e.g., light). Daily, the sun supplies large quantities of energy as rainfall, winds, radiation, etc. Some share is stored in biomass or rivers that can be harvested by men. Some share is directly usable such as daylight, ventilation or ambient heat. **Renewable energy** is obtained from the continuing or repetitive currents of energy occurring in the natural environment and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves and geothermal heat, as well as carbon-neutral technologies such as biomass.
Integrated Assessment Model	IAM	Integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land-use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost–benefit

		framework and have been used to estimate the social cost of carbon.
International Institute for Applied Systems Analysis	IIASA	The International Institute for Applied Systems Analysis (IIASA) is an independent, international research institute that conducts policy-oriented research into issues that are too large or complex to be solved by a single country or academic discipline. This includes pressing concerns that affect the future of all of humanity, such as climate change, energy security, population aging, and sustainable development. https://iiasa.ac.at
Inter-Sectoral Impact Model Intercomparison Project	ISIMIP	The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) offers a framework for consistently projecting the impacts of climate change across affected sectors and spatial scales. An international network of climate-impact modellers contribute to a comprehensive and consistent picture of the world under different climate-change scenarios. https://www.isimip.org
Model for the Assessment of Greenhouse Gas Induced Climate Change	MAGICC	Name of simple climate model http://www.magicc.org
Model of Agricultural Production and its Impacts on the Environment	MAgPIE	Land use system component of PIK's IAM framework REMIND-MAgPIE https://www.pik-potsdam.de/research/projects/activities/land-use-modelling/magpie/magpie-2013-model-of-agricultural-production-and-its-impact-on-the-environment
Model for Energy Supply Strategy Alternatives and their General Environmental Impact	MESSAGE	Energy system module of IIASA's IAM framework MESSAGEix-GLOBIOM, used here as short form to refer to the whole model https://message.iiasa.ac.at/projects/global/en/latest
Methane	CH_4	One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol and is the major component of natural gas and associated with all hydrocarbon fuels. Significant emissions occur as a result of animal husbandry and agriculture, and their management represents a major mitigation option

Nationally determined contribution	NDC	A term used under the *United Nations Framework Convention on Climate Change (UNFCCC)* whereby a country that has joined the *Paris Agreement* outlines its plans for reducing its emissions. Some countries' NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience.
Net zero CO_2 emissions		A situation of net zero CO_2 emissions is achieved when, as a result of human activities, the same amount of CO_2 is removed from the atmosphere than is emitted into it. Net CO_2 emissions become negative when more CO_2 is removed from the atmosphere than emitted into it (i.e. net negative CO2 emissions). When multiple greenhouse gases are involved, the quantification of negative emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).
NGFS Scenario Explorer	NGFS SE	The NGFS Scenario Explorer is a web-based user interface for scenario results and historical reference data and is hosted by IIASA data.ene.iiasa.ac.at/ngfs.
Nitrous oxide	N_2O	One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol. The main anthropogenic source of N_2O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.
Pathway		The term is being used with two slightly different meanings (see below), including in this report. The term "Transition pathways" is being used here to refer to the transition scenarios (to clearer differentiate from the term "NGFS scenarios"), although one of them ("Current Policies") is not a pathway in the strict sense of meaning (1). (1) A goal-oriented scenario: The temporal evolution of natural and/or human systems towards a future goal. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures

		to solution-oriented decision-making processes to achieve desirable societal goals (which means the term in this meaning is only applicable to a subset of scenarios, as not all scenarios (e.g. baseline scenarios) are target-focused). Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals and actors across different scales. (2) Trajectory of a specific aspect (or variable(s)) in a scenario, for example the evolution of greenhouse-gas concentrations in the RCPs. This can lead to confusion, e.g. when "RCP 8.5" in form of a synecdoche (pars-pro-toto) is also being used to refer to the underlying baseline scenario, which is not a pathway in the sense of meaning (1).
Potsdam Institute for Climate Impact Research, Member of the Leibniz Association	PIK	A public research institute in Potsdam, Germany www.pik-potsdam.de
Pre-industrial		The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).
Primary energy accounting		Several accounting methods are used in energy analyses that lead to different estimates of primary energy use. Three methods are predominantly used: the *direct equivalent method* used in UN Statistics and IPCC reports, the *physical energy content method* used by the OECD, the IEA and Eurostat and the *substitution method* used by BP and the US EIA. The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy.
Regional Model of Investments and Development	REMIND	Energy system component of PIK's IAM framework REMIND-MAgPIE, used here as short name to refer to the whole model https://www.pik-potsdam.de/research/transformation-pathways/models/remind

Representative Concentration Pathway	RCP	Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2010). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al., 2010). RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding emission scenarios.
Shared Socioeconomic Pathway	SSP	Shared Socio-economic Pathways (SSPs) were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation (Kriegler et al., 2012; O'Neill et al., 2014). Based on five narratives, the SSPs describe alternative socio-economic futures in the absence of climate policy intervention, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil–fueled development (SSP5) and middle-of-the-road development (SSP2) (O'Neill et al., 2017; Riahi, Vuuren, et al., 2017). The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based climate projections provides an integrative frame for climate impact and policy analysis.
Scenario		A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.
Sustainable Development Goals	SDGs	The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development, including ending poverty and hunger; ensuring health and well-being, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and

	partnerships; and taking urgent action on climate change.

Appendix

1. Regional definitions of integrated assessment models

Table A1.1 **Regional definition of the GCAM model**

Model region	NGFS SE identifier	Iso codes
Africa_Eastern	GCAM 5.2|Africa_Eastern	BDI, COM, DJI, ERI, ETH, KEN, MDG, MUS, REU, RWA, SDN, SOM, UGA
Africa_Northern	GCAM 5.2|Africa_Northern	DZA, EGY, ESH, LBY, MAR, TUN
Africa_Southern	GCAM 5.2|Africa_Southern	AGO, BWA, LSO, MOZ, MWI, NAM, SWZ, TZA, ZMB, ZWE
Africa_Western	GCAM 5.2|Africa_Western	BEN, BFA, CAF, CIV, CMR, COD, COG, CPV, GAB, GHA, GIN, GMB, GNB, GNQ, LBR, MLI, MRT, NER, NGA, SEN, SLE, STP, TCD, TGO
Argentina	GCAM 5.2|Argentina	ARG
Australia_NZ	GCAM 5.2|Australia_NZ	AUS, NZL
Brazil	GCAM 5.2|Brazil	BRA
Canada	GCAM 5.2|Canada	CAN
Central America and Caribbean	GCAM 5.2|Central America and Caribbean	ABW, AIA, ANT, ATG, BHS, BLZ, BMU, BRB, CRI, CUB, CYM, DMA, DOM, GLP, GRD, GTM, HND, HTI, JAM, KNA, LCA, MSR, MTQ, NIC, PAN, SLV, TTO, VCT
Central Asia	GCAM 5.2|Central Asia	ARM, AZE, GEO, KAZ, KGZ, MNG, TJK, TKM, UZB
China	GCAM 5.2|China	CHN
Colombia	GCAM 5.2|Colombia	COL
EU-12	GCAM 5.2|EU-12	BGR, CYP, CZE, EST, HUN, LTU, LVA, MLT, POL, ROM, SVK, SVN
EU-15	GCAM 5.2|EU-15	AND, AUT, BEL, CHI, DEU, DNK, ESP, FIN, FLK, FRA, FRO, GBR, GIB, GRC, GRL, IMN, IRL, ITA, LUX, MCO, NLD, PRT, SHN, SMR, SPM, SWE, TCA, VAT, VGB, WLF
Europe_Eastern	GCAM 5.2|Europe_Eastern	BLR, MDA, UKR

Europe_Non_EU	GCAM 5.2|Europe_Non_EU	ALB, BIH, HRV, MKD, MNE, SCG, SRB, TUR, YUG
European Free Trade Association	GCAM 5.2|European Free Trade Association	CHE, ISL, LIE, NOR, SJM
India	GCAM 5.2|India	IND
Indonesia	GCAM 5.2|Indonesia	IDN
Japan	GCAM 5.2|Japan	JPN
Mexico	GCAM 5.2|Mexico	MEX
Middle East	GCAM 5.2|Middle East	ARE, BHR, IRN, IRQ, ISR, JOR, KWT, LBN, OMN, PSE, QAT, SAU, SYR, YEM
Pakistan	GCAM 5.2|Pakistan	PAK
Russia	GCAM 5.2|Russia	RUS
South Africa	GCAM 5.2|South Africa	ZAF
South America_Northern	GCAM 5.2|South America_Northern	GUF, GUY, SUR, VEN
South America_Southern	GCAM 5.2|South America_Southern	BOL, CHL, ECU, PER, PRY, URY
South Asia	GCAM 5.2|South Asia	AFG, BGD, BTN, LKA, MDV, NPL
South Korea	GCAM 5.2|South Korea	KOR
Southeast Asia	GCAM 5.2|Southeast Asia	ASM, BRN, CCK, COK, CXR, FJI, FSM, GUM, KHM, KIR, LAO, MHL, MMR, MNP, MYS, MYT, NCL, NFK, NIU, NRU, PCI, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, SYC, THA, TKL, TLS, TON, TUV, VNM, VUT, WSM
Tawain	GCAM 5.2|Tawain	TWN
USA	GCAM 5.2|USA	PRI, USA, VIR

Table A1.2 **Regional definition of the MESSAGEix-GLOBIOM model**

Model region	Name	NGFS SE identifier	Iso codes
CPA	Centrally planned Asia	MESSAGEix-GLOBIOM 1.0|R11_CPA	CHN, HKG, KHM, LAO, MNG, PRK, VNM
PAS	Other Pacific Asia	MESSAGEix-GLOBIOM 1.0| R11_PAS	IDN, KOR, ASM, BRN, CCK, COK, CXR, FJI, FSM, GUM, KHM, KIR, LAO, MHL, MMR, MNP, MYS, MYT, NCL, NFK, NIU, NRU, PCI, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, SYC, THA, TKL, TLS, TON, TUV, VNM, VUT, WSM, TWN
SAS	South Asia	MESSAGEix-GLOBIOM 1.0| R11_SAS	AFG, BGD, BTN, IND, LKA, MDV, NPL, PAK
EEU	Eastern Europe	MESSAGEix-GLOBIOM 1.0| R11_EEU	BGR, CYP, CZE, EST, HUN, LTU, LVA, MLT, POL, ROU, SVK, SVN, ALB, BIH, HRV, MKD, MNE, SCG, SRB, TUR, YUG
WEU	Western Europe	MESSAGEix-GLOBIOM 1.0| R11_WEU	AND, AUT, BEL, CHI, DEU, DNK, ESP, FIN, FLK, FRA, FRO, GBR, GIB, GRC, GRL, IMN, IRL, ITA, LUX, MCO, NLD, PRT, SHN, SMR, SPM, SWE, TCA, VAT, VGB, WLF, CHE, ISL, LIE, NOR, SJM
FSU	Former Soviet Union	MESSAGEix-GLOBIOM 1.0| R11_FSU	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, UZB
LAM	Latin America and the Caribbean	MESSAGEix-GLOBIOM 1.0| R11_LAM	ABW, AIA, ARG, ATG, BHS, BLZ, BMU, BOL, BRA, BRB, CHL, COL, CRI, CUB, CYM, DMA, DOM, ECU, FLK, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA, LCA, MEX, MSR, MTQ, NIC, PAN, PER, PRY, SLV, SUR, TCA, TTO, URY, VCT, VEN, VGB, VIR
MEA	Middle-East and North Africa	MESSAGEix-GLOBIOM 1.0| R11_MEA	DZA, EGY, ESH, LBY, MAR, TUN, ARE, BHR, IRN, IRQ, ISR, JOR, KWT, LBN, OMN, PSE, QAT, SAU, SYR, YEM
NAM	North America	MESSAGEix-GLOBIOM 1.0| R11_NAM	PRI, USA, VIR, CAN
PAO	Pacific OECD	MESSAGEix-GLOBIOM 1.0| R11_PAO	AUS, NZL, JPN
SSA	Sub-Saharan Africa	MESSAGEix-GLOBIOM 1.0| R11_AFR	AGO, BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, COM, CPV,

			DJI, ERI, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LBR, LSO, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, REU, RWA, SEN, SHN, SLE, SOM, STP, SWZ, SYC, TCD, TGO, TZA, UGA, ZAF, ZMB, ZWE

Table A1.3 **Regional definition of the REMIND-MAgPIE model**

Model region	Name	NGFS SE identifier	Iso codes
China	China, Hong Kong and Macau	REMIND-MAgPIE 1.7-3.0|CHN	CHN, HKG, MAC
India	India	REMIND-MAgPIE 1.7-3.0|IND	IND
Japan	Japan	REMIND-MAgPIE 1.7-3.0|JPN	JPN
Russia	Russian Federation	REMIND-MAgPIE 1.7-3.0|RUS	RUS
USA	United States of America	REMIND-MAgPIE 1.7-3.0|USA	USA, PRI, VIR
OAS	Other Asian Countries	REMIND-MAgPIE 1.7-3.0|OAS	AFG, ASM, BGD, BRN, BTN, CCK, COK, CXR, FJI, FSM, GUM, IDN, KHM, KIR, KOR, LAO, LKA, MDV, MHL, MMR, MNG, MNP, MYS, NCL, NFK, NIU, NPL, PAK, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, THA, TKL, TLS, TON, TUV, TWN, VNM, VUT, WLF, WSM
EUR	European Union (former EU-28 until 31 January 2020)	REMIND-MAgPIE 1.7-3.0|EUR	AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, FRO, GBR, GIB, GRC, GRL, HUN, IMN, IRL, ITA, JEY, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, SWE
LAM	Latin America and the Caribbean	REMIND-MAgPIE 1.7-3.0|LAM	ABW, AIA, ARG, ATG, BHS, BLZ, BMU, BOL, BRA, BRB, CHL, COL, CRI, CUB, CYM, DMA, DOM, ECU, FLK, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA, LCA, MEX, MSR, MTQ, NIC, PAN, PER, PRY, SLV, SUR, TCA, TTO, URY, VCT, VEN, VGB, VIR

MEA	Middle-East, North Africa and Central Asia	REMIND-MAgPIE 1.7-3.0|MEA	ARE, ARM, AZE, BHR, DZA, EGY, ESH, GEO, IRN, IRQ, ISR, JOR, KAZ, KGZ, KWT, LBN, LBY, MAR, OMN, PSE, QAT, SAU, SYR, TJK, TKM, TUN, UZB, YEM
SSA	Sub-Saharan Africa without South Africa	REMIND-MAgPIE 1.7-3.0|AFR	BDI, COM, DJI, ERI, ETH, KEN, MDG, MUS, REU, RWA, SDN, SOM, SSD, UGA, AGO, BWA, LSO, MOZ, MWI, NAM, SWZ, TZA, ZMB, ZWE, BEN, BFA, CAF, CIV, CMR, COD, COG, CPV, GAB, GHA, GIN, GMB, GNB, GNQ, LBR, MLI, MRT, NER, NGA, SEN, SLE, STP, TCD, TGO
ROW	Rest of the World	REMIND-MAgPIE 1.7-3.0|ROW	ALB, AND, AUS, BIH, BLR, CAN, CHE, GGY, HRV, ISL, LIE, MCO, MDA, MKD, MNE, NOR, NRU, NZL, SJM, SMR, SPM, SRB, TUR, UKR, VAT, ZAF

2. ISIMIP Impact Models

All available ISIMIP impact models are listed on https://www.isimip.org/impactmodels/. Table A2.1 provides an overview of those which are potentially relevant for the NGFS project:

Table A2.1 **List of ISIMIP Impact Models**

Model Name	Model full name	Sectors	Region
ALBM	Arctic Lake Biogeochemistry Model	Lakes (global), Lakes (local)	Global/local
CARAIB	CARbon Assimilation In the Biosphere	Biomes, Forests	Global/regional
CLM4.5	Community Land Model	Biomes, Permafrost, Water (global), Agriculture, Lakes (global)	Global
DBH	Distributed biosphere hydrological model	Water (global)	Global, regional
GEPIC	GIS-based Environmental Policy Integrated Climate (EPIC) model	Agriculture	global
H08	Hydrological Model	Water (global)	global
HYPE	Hydrological Predictions for the Environment) water quality model	Water (regional)	regional
JULES-W1	Joint UK Land Environment Simulator	Water (global)	global
LPJ-GUESS	Lund-Potsdam-Jena	Biomes, Agriculture, Forests	Global/regional
LPJmL	Lund-Potsdam-Jena managed Land	Water (global), Biomes, Permafrost, Agriculture	Global/regional
MATSIRO	Minimal Advanced Treatments of Surface Interaction and Run Off	Water (global)	global
MPI-HM	Max Planck Institute – Hydrological Model	Water (global)	global

ORCHIDEE	*Organising Carbon and Hydrology In Dynamic Ecosystems*	Water (global), Biomes, Permafrost	global
ORCHIDEE-DGVM	*Organising Carbon and Hydrology In Dynamic Ecosystems* - Dynamic Global Vegetation Model	Water (global), Biomes, Permafrost	global
PCR-GLOBWB	PCRaster Global Water Balance	Water (global)	global
PEPIC	Python-based Environmental Policy Integrated Climate (EPIC) model	Agriculture	global
SWIM-NVE	Soil and Water Integrated Model – Norwegian Water Resources and Energy	Water (regional)	regional
SWIM-PIK	Soil and Water Integrated Model – Potsdam Institute	Water (regional)	regional
VEGAS	VEgetation-Global-Atmosphere-Soil	Biomes	global
VIC-NVE	Variable Infiltration Capacity model	Water (regional)	regional
WaterGAP2	Water Global Assessment and Prognosis	Water (global)	global

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