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GoNEXUS
Tools and solutions for governing the nexus

Deliverable D3.1: Global and continental scale WEFE model improvement

WP3

Version 3.0, May 2023

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Deliverable D3.1: Global and continental scale WEFE model improvement

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Abstract: This deliverable describes the setup of the individual thematic models at global and continental scales. It also describes the improvements and changes made to the individual thematic models that together define the different components of the WEFE nexus at global and continental scales, including water (PCR-GLOBWB, LISFLOOD-EPIC), energy (PRIMES, PROMETHEUS), agri-food (CAPRI, LISFLOOD-EPIC), and ecosystems (GLOBIO). Improvements and changes aim to set up the models for additional scales and to make the models suitable for including the WEFE interactions. The target audiences are the GoNEXUS partners, in particular those working on large-scale WEFE modelling, scientists working on large scale WEFE modelling, and EU bodies currently using these models (Directorate-General of Agriculture and Rural Development, Climate Action, Energy, and Environment). It will be used in Task 3.2.

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Version History

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V1.0	31/03/2023	Maria Blanco (UPM), Imen Arfa (UPM); Alessia De Vita (E3M); Berny Bisselink (JRC); Kristina Govorukha (E3M); Aafke Schipper (PBL)	Draft sent to internal review by UU and UPV. Revised by: Manuel Pulido (UPV) Desamparados Martinez Domingo (UPV) Marc Bierkens (UU)
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1 Introduction

The thematic models (water, energy, food, ecosystem) to be used for the global and continental assessments of the WEFE nexus in GoNEXUS are operational. They are currently employed for research and policymaking, including some of the models used on a regular basis by the European Commission[1] - as well as other international institutions such as the Organisation for Economic Co-operation and Development (OECD) or the World Bank - for impact assessments and the analysis of policy options. The model set includes operational climate-water, climate-energy, biodiversity, and food-water models. Each of those models considers the interdependencies of only a few components of the WEFE nexus and no single one takes into account all components of the nexus together with climate change.

GoNEXUS will model the WEFE nexus at the global level integrating the assessments provided by the water model PCR-GLOBWB, the energy model PROMETHEUS, the agri-food model CAPRI, the biodiversity model GLOBIO, and the economic model GEM-E3. These models will provide simulations of the future trajectories of the WEFE nexus at the global level and assess the worldwide performance of the solutions defined through the Nexus Dialogues.

At the continental scale (Europe), GoNEXUS will assess the WEFE nexus using the integrated water resource and crop model LISFLOOD-EPIC, the energy model PRIMES, the agri-food model CAPRI (global but with higher resolution for the EU), and the biodiversity model GLOBIO. These models will provide simulations of future trajectories of the WEFE nexus for the EU and assess the impacts of the nexus solutions identified. Boundary conditions for continental models will come from linked global models (e.g., PROMETHEUS will provide boundary conditions for PRIMES, and GEM-E3 will provide boundary conditions for PRIMES and CAPRI) and from the outcomes of the global scenarios for the same model (e.g., boundary conditions for the continental runs of CAPRI and GLOBIO will be provided by the global runs of the same models for the associated global scenarios). GoNEXUS will update and improve these models to provide more precise WEFE assessments. The improvement and combination of these models will allow to assess large-scale WEFE synergies and trade-offs, estimate impacts of global and continental WEFE policies and solutions (WP7), and serve as boundary conditions for river basin WEFE models (WP4).

The structure of this document is as follows: chapter 2 shows an overview of the models that will be used in GoNEXUS, including examples of previous model applications. In chapter 3, planned improvements of the different models are described. Furthermore, this chapter shows how the global and continental models have been adapted to simulate the Tier 1 scenarios. Chapter 4 describes how the linkages between global and continental models will be implemented, as well as the preparation of the second round of the simulations (Tier 2).

2 Overview of the models

2.1 PCR-GLOBWB2

2.1.1 Main features and description of the model

PCR-GLOBWB 2 is a grid-based global hydrology and water resources model developed at Utrecht University. The computational grid has a 5 arc-minute resolution (~10 km at the equator) and covers

[1] https://web.jrc.ec.europa.eu/policy-model-inventory/

all continents except Greenland and Antarctica. Time steps for hydrology and water use are one-day, while the internal time stepping for hydrodynamic river routing is variable. For each grid cell and each time step, PCR-GLOBWB 2 simulates moisture storage as well as the water exchange between the soil, atmosphere and underlying groundwater reservoir. The exchange with the atmosphere comprises precipitation, evaporation from open water, snow and soils and plant transpiration, while the model also simulates snow accumulation, snowmelt, and glacier melt. PCR-GLOBWB simulates runoff partitioned into surface runoff, interflow, and groundwater recharge as well as routing of water over the terrain. Runoff generated by snow and glacier melt, surface runoff, interflow, and groundwater is routed across the river network to the ocean or endorheic lakes and wetlands using the kinematic wave approximation. This approximation to the full equations describing river flow assumes that the energy loss of the flood wave is the same as the slope of the riverbed. It is also possible to include floodplain inundation and to simulate surface-water temperature. PCR-GLOBWB 2 includes over 6000 manmade reservoirs from the GranD database that are progressively introduced in time and a reservoir operation scheme dependent on each reservoir's purpose. Human water use is fully integrated with the hydrological model. Thus, at each time step: 1) water demand is estimated for irrigation, livestock, industry, and households; 2) these demands are translated into actual withdrawals from groundwater and surface water (rivers, lakes, and reservoirs) subject to the availability of these resources and maximum groundwater pumping capacity in place; and 3) consumptive water use and return flows are calculated per sector. As an option PCR-GLOBWB 2 can be partially or fully coupled to a 2-layer global groundwater model based on MODFLOW and to the hydrodynamic model codes DFLOW-FM, CaMaFlood and LISFLOOD-FP.

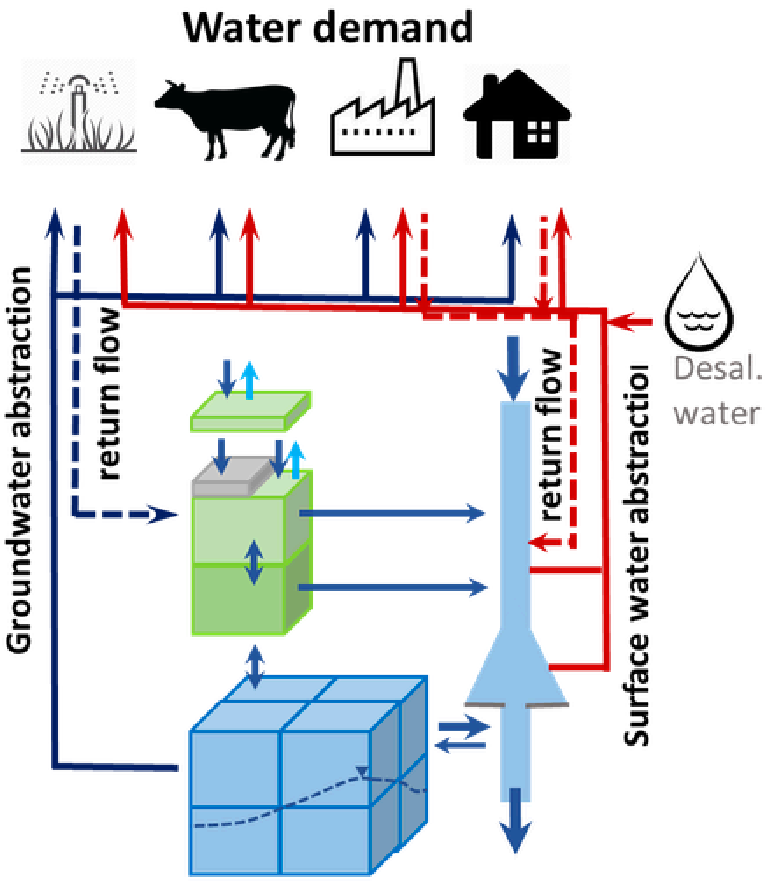


Figure 1.Schematic of PCR-GLOBWB 2 cell with its functionality

2.1.2 Recent model applications

Some highlights of the application of PCR-GLOBWB over the past 5 years:

- PCR-GLOBWB 2 was used to supply input for the new WRI Aqueduct Water Risk Atlas and the Aqueduct Floods website (https://www.wri.org/aqueduct)
- PCR-GLOBWB 2 was fully coupled with a global groundwater model to assess the impacts of groundwater withdrawal on exceeding the environmental flow limits worldwide (De Graaf et al., 2019).
- The outputs from large-ensemble (2000-year) simulations from a global climate model (EC-EARTH) were used as input to PCR-GLOBWB to assess extreme discharge frequency distributions worldwide (Van Der Wiel et al., 2019)
- Using the temperature module of PCR-GLOBWB 2 the impact of global warming on 11,500 freshwater fish species was analysed (Barbarossa et al., 2021).
- PCR-GLOBWB was forced with climate projections from CMPI6 for 3 RCP scenarios to assess the developments in land storage on future regional sea levels (Karabil et al., 2021).
- PCR-GLOBWB 2 is one of the water models used in the ISI-MIP 3 multi-sectoral model intercomparison project, part of the Copernicus Ulysses seasonal forecasting consortium and used in scoping studies by PBL, World Bank, National Geographic, and Greenpeace (see www.globalhydrology.nl for specifics).
- PCR-GLOBWB 2 has recently been used to estimate the global water gap per sector and total as part of the National geographic World Water map project: https://worldwatermap.nationalgeographic.org/

2.2 LISFLOOD-EPIC

2.2.1 Main features and description of the model

The LISFLOOD model is a hydrological rainfall-runoff model (De Roo et al., 2000; Van der Knijff et al., 2010; Burek et al., 2013; Bisselink et al., 2018) capable of simulating the hydrological processes that occur in a catchment (Fig. 2). LISFLOOD has been developed by the floods group of the Natural Hazards Project of the Joint Research Centre (JRC) of the European Commission. The specific development objective was to produce a tool that can be used in large and transboundary catchments for a variety of applications, including: flood forecasting, and assessing the effects of river regulation measures, and land-use and climate change.

Recently, LISFLOOD has been coupled with crop growth processes from the EPIC model (Williams et al., 1989; Williams, 1995; Sharpley and Williams, 1990) and a newly developed irrigation module (Gelati et al., 2020). The resulting integrated model (LISFLOOD-EPIC) simulates the interactions between catchment hydrology, crop growth, irrigation, and water abstraction and allocation at the daily time scale.

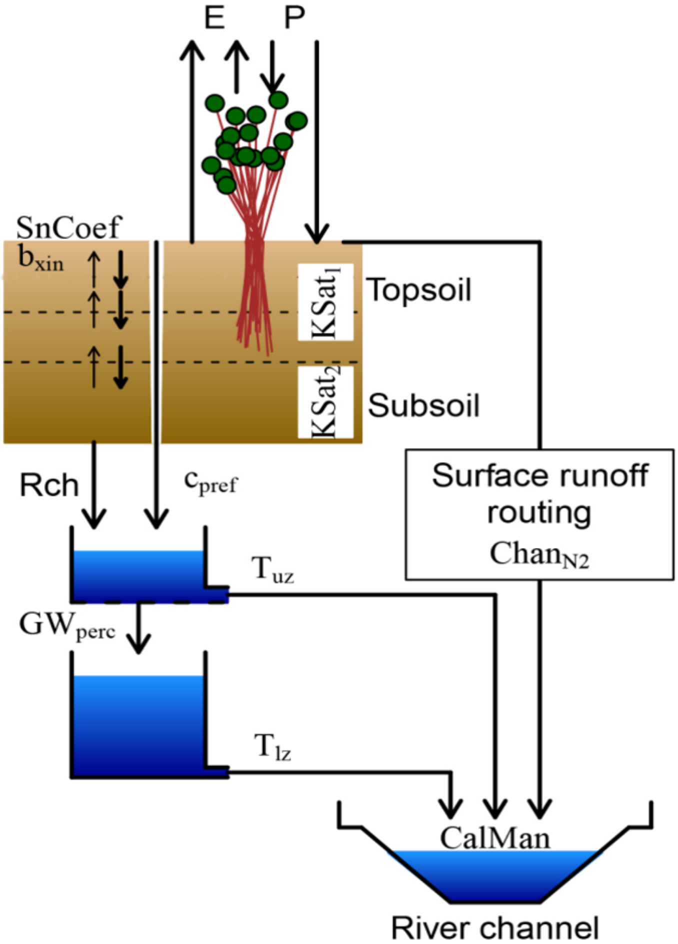


Figure 2. Structure of the LISFLOOD model, showing the main processes simulated in each model

Processes simulated for each grid cell include snowmelt, soil freezing, surface runoff, infiltration into the soil, preferential flow path, redistribution of soil moisture within the three-layer soil profile, drainage of water to the groundwater system, groundwater storage, and groundwater base flow. Runoff produced for every grid cell is routed through the river network, using a double kinematic wave approach, one for the main channel, and one for the floodplain. Lakes, reservoirs and retention areas or polders are simulated by giving their location, size, and in- and outflow boundary conditions and steering parameters. Discharges are calibrated and validated on a regular basis from approximately 1500 gauging stations.

Although LISFLOOD-EPIC is a regular grid-based model with a constant spatial grid (5000 m (whole Europe) and 0.1° (global)) more detailed sub-grid land use classes are used to simulate the main hydrological processes. The model distinguishes for each grid the fraction of open water, urban sealed area, forest area, paddy rice irrigated area, crop irrigation area, and other land uses. Specific hydrological processes (evapotranspiration, infiltration, etc.) are then calculated in a different way for these land use classes. Moreover, sub-gridded elevation information is used to establish detailed altitude zones, which are important for snow accumulation and melting processes, and to correct for surface temperature.

Water abstractions in LISFLOOD-EPIC consist of five components, from which the irrigation water demand is estimated dynamically and crop-specific with the coupled EPIC module.

The other four sectorial components are used as data requirements. These are (manufacturing) industrial water demand, water demand for energy and cooling, livestock water demand, and domestic water demand. The model abstracts the water that is demanded from either surface or groundwater sources. These may include lakes, reservoirs, rivers, and groundwater aquifers, depending on local information available on sources of water. The model takes a local Eflow (environmental flow) threshold into account – which may be user-defined – below which abstraction of water is stopped and flagged as 'shortage'.

LISFLOOD-EPIC produces a number of outputs, such as daily river discharge, soil moisture conditions, groundwater amounts, and water in lakes and reservoirs. In addition, an ensemble of water resource indicators is produced, such as flood and low flow extremes, water scarcity days, Eflow breachings, water availability per capita, and the water exploitation index (WEI+). With the new EPIC module, LISFLOOD-EPIC can simulate, amongst others, changes in crop yield.

2.2.2 Recent model applications

LISFLOOD has been used for several European Commission's Impact Assessments and is used for global (GLOFAS) and European (EFAS (https://www/efas.eu) operational flood forecasting and drought prediction (EDO) systems under the Copernicus Emergency Services programme.

Some other recent applications:

- LISFLOOD-EPIC was used to assess the WEFE NEXUS in the Mediterranean (De Roo et al., 2021).
- LISFLOOD-EPIC was used to assess the sustainability of groundwater irrigation in Spain (Gelati et al., 2020).
- LISFLOOD have been successfully applied in future drought projections (Cammalleri et al., 2020).
- LISFLOOD was used to assess the impact of climate change, land use and water demand change on European water resources for several global warming levels (Bisselink et al, 2018, Bisselink et al., 2020).

2.3 CAPRI

2.3.1 Main features and description of the model

CAPRI (Common Agricultural Policy Regional Impact Model)	
Model type:	**Global agro-economic model**
Purpose:	**Policy impact assessment of EU policies**
Spatial coverage:	**Global**
Spatial resolution:	**National and regional within the EU**
Temporal scale:	**Until 2050 in flexible time steps**
Website:	**http://www.capri-model.org**

CAPRI is a global spatial partial equilibrium model for the agricultural sector developed for ex-ante impact assessment of agricultural, environmental and trade policies with a focus on the European Union. It is a comparative static model solved by sequential iteration between supply and market modules (for a detailed description see Britz and Witzke, 2014):

- **The supply module** consists of independent regional agricultural non-linear programming models for EU-28, Norway, Turkey, and Western Balkans. Supply models depict farming decisions in detail at subnational level (NUTS 2 level or farm type level) by means of a mathematical programming approach, which captures a wide range of interactions between production activities and the environment. CAPRI-Spat downscales regional results to a grid of

1x1 Km based on statistical distribution (Leip et al., 2008; Britz et al., 2011). In addition, the model is also able to compute results at the farm level to capture diversity in farming specialisation and economic size. The CAPRI farm type layer (CAPRI-FT) is especially suitable to simulate farm-specific policy instruments (Gocht and Britz, 2011).

- **The market module** is a static, deterministic, partial, spatial model with global coverage, depicting about 60 commodities (primary and secondary agricultural products) and 40 trade blocks. It simulates supply, demand, and price changes in global markets considering bilateral trade flows, following the Armington assumption (Armington, 1969), as well as trade policies. Demand and supply quantities are endogenous and driven by behavioural functions depending on endogenous prices. Prices in different regions are linked via a price transmission function, whereas prices in different markets in any one region are linked via cross-price terms in the behavioural functions. The parameters of behavioural functions are derived from elasticities obtained from studies and other modelling systems and calibrated to projected quantities and prices in the simulation year. Trade policy instruments cover tariff rate quotes (TRQs), intervention stock changes and subsidised exports.

CAPRI is based upon a complete and consistent database that coherently integrates information from different official data sources (e.g. EUROSTAT, FAOSTAT). Simulation results cover crop areas, herd sizes, production, consumption, trade, income indicators and environmental indicators Nitrogen-Phosphorus- Potassium (NPK) balances, greenhouse gas emissions, water use).

Agricultural GHG emissions are calculated in CAPRI according to the Intergovernmental Panel on Climate Change (IPCC) guidelines. For EU regions, emissions per activity are computed endogenously in the supply module based on activity yields and the through nutrient flow, which considers feeding and fertilisation activities. The emissions per activity are computed as the sum of different activity items multiplied by an emission factor. CAPRI normally applies IPCC Tier 2 methods to calculate GHG emissions, which consider detailed country-specific information on technology and livestock characteristics. Nevertheless, a Tier 1 approach is applied for activities where there is a lack of information, which is the direct calculation by multiplying activity level with emission factor. For non-EU regions, emissions are estimated per product for marketable agricultural commodities using emissions factors of EU countries as a prior, production data from FAOSTAT, and total emissions for non-EU countries from the Emissions Database for Global Atmospheric Research (EDGAR) database (Pérez Dominguez, 2006; Leip et al., 2010; Pérez Dominguez et al., 2012).

The model has been upgraded with the introduction of endogenous GHG emissions mitigation technologies (Van Doorslaer et al., 2015; Pérez Dominguez et al., 2016). Costs of mitigation efforts enter into the total cost function that is split into costs related to mitigation efforts and other costs. Mitigation technologies can reduce emissions according to a factor that depends on the mitigation share and a reduction factor per emission type and activity when a certain mitigation option is fully adopted. The mitigation potential of these technologies is based on the marginal abatement cost curve (MAC), which relates the reduction in emissions in CO2 equivalents with the cost of reduction per tonne of CO2 equivalents. The model optimises the cost of achieving a certain level of CO2 equivalents reduction for each NUT2 region. The model allows for simultaneous use of different mitigation options to reduce emissions. Mitigation options included in CAPRI are based on the Greenhouse gas - Air pollution INteractions and Synergies (GAINS) database (for more detail, see Pérez Dominguez et al., 2016).

CAPRI represents global **biofuel markets** considering endogenous supply, demand and trade flows for biofuels and biofuel feedstocks (Blanco et al., 2013). The biofuel module builds on an ex-post database that includes all market balance positions for biofuels and biofuel feedstock in each EU Member State and non-European region. Behavioural functions for biofuel supply and feedstock demand as well as fuel and biofuel demand and global biofuel trade are specified and calibrated. The reference scenarios draw on trend estimates based on the database and external expert knowledge.

The CAPRI baseline depicts the projected agricultural situation up to 2050 under a status quo policy setting (Himics et al., 2013). The baseline builds on the medium-term outlook for EU agricultural markets and income (EC 2018b) for mid-term projections and other sources for long-term projections (e.g., GLOBIOM, IMPACT). The baseline represents in detail the CAP 2014-2020, both direct payments instruments (i.e., basic payment scheme, coupled payments, green payment, capping and convergence) and rural development measures (i.e., agri-environmental measures, less favoured area payment, Natura 2000). In terms of agricultural trade policies, the baseline considers the commitments under the Uruguay Round Agreement on Agriculture regarding market access and subsidies.

CAPRI water version for the European programming models:

Given the interdependencies between agriculture, water and climate change, a **water module** has been developed in the CAPRI model to expand the analysis of agricultural policies to cover water related issues.

Since 2012, under a series of JRC projects, water considerations have been included in the **supply module of CAPRI**, meaning crop and livestock water use are modelled for the supply regions in CAPRI (NUTS 2 regions of the EU, UK, Norway, Turkey and Western Balkans).

Following a study to explore the feasibility of introducing water into CAPRI (Blanco et al, 2012), Blanco et. al. (2015) extended the CAPRI model with a water module – consisting of an irrigation sub-module and a water use sub-module – and applied the CAPRI-Water version to simulate and assess the potential impact of climate change and water availability on agricultural production. A major limitation of this initial development was the lack of homogeneous and accurate data at regional level within the EU for some of the important variables used in the model (rainfed/irrigated crop areas, rainfed/irrigated crop yields, irrigation water use by crop, irrigation cost, irrigation efficiency, irrigation water availability per region, etc.).

In a further development of the water module, the water database was improved or expanded in order to enhance the performance of the CAPRI water module and the consistency between regional figures and different levels of aggregation (Blanco et al. 2018). Also, the water module was expanded to cover crop-water linkages in rainfed agriculture. Test scenarios regarding less precipitation as well as less water availability for irrigation were simulated to illustrate the behavior of the upgraded water module.

The latest development of the water module accounts for competition between agricultural and non-agricultural water use and allows to differentiate irrigation water use by source (surface water, groundwater, desalinated water and reused water). Furthermore, the current CAPRI-Water version is fully compatible with an updated CAPRI model version.

Summarising, the current CAPRI water module integrates detailed water considerations in the **supply module** of CAPRI. Compared to the standard CAPRI version, in CAPRI-Water the following modifications are included:

- Land is separated as irrigable (equipped for irrigation) and non-irrigable (non-equipped for irrigation). Irrigable land can, in turn, be rainfed (only receives water input from precipitation) and irrigated (receives water input from precipitation and irrigation).
- Crop production activities are split into rainfed and irrigated variants. Input-output coefficients are estimated for both irrigated and rainfed crop variants.
- Water for irrigated/rainfed crop variants is included as a production factor by considering crop-specific water requirements, irrigation/rainfed shares, irrigated to rainfed yield ratio, and irrigation efficiency at regional level.
- Livestock water use includes both daily drinking and service water requirements.

- Domestic and industrial water use relate are computed as a water use intensity ratio times the main driver for water consumption in the sector. The main driving forces of water use are population in the domestic sector and industrial production in the industrial sector.
- Water use balances at the regional level are included to account for competition between agricultural and non-agricultural water use. As rules of water allocation usually give priority to domestic and livestock uses compared to irrigation, irrigation water availability is constraint.
- Baseline calibration incorporates trends on irrigated area shares, irrigation efficiency, water prices, water use and water availability. Change in water abstraction for non-agricultural sectors is driven by changes in population and GDP and, therefore, depends on the socioeconomic trajectory. Trends in freshwater availability depend on the climate scenario while trends in availability of desalinated water and reclaimed wastewater depend on the socioeconomic scenario.

CAPRI water version for the non-European programming models:
The current CAPRI water module for non-European regions is not well detailed and it is being improved.

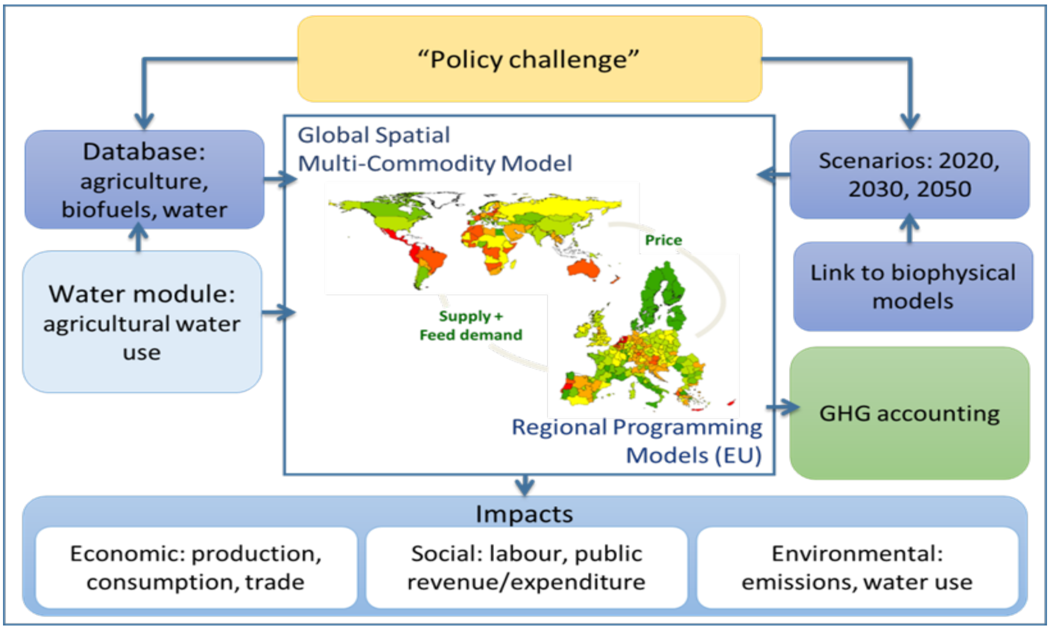


Figure 3. CAPRI modelling system.

2.3.2 Recent model applications

Recent applications of the model include:

- Assessment of the potential impact of climate change in EU agriculture. This enables analyzing regional changes in production within the EU while considering market feedback, as well as the role of trade in counterbalancing uneven effects of climate change across the world (Blanco et al., 2017, Pérez-Dominguez and Fellmann, 2018).
- CAPRI-Water has been applied to assess impacts of climate change on EU agriculture when considering changes in irrigation water availability (Blanco et al., 2015), and water pricing options (Blanco et al., 2019). The module not only enables the analysis of changes in water availability for irrigation, but also the effects of changes in precipitation in rainfed and irrigated agriculture (Blanco et al., 2018),
- Assess the potential of treated water as an alternative water source (Hristov et al., 2019), or the effects of increased irrigation efficiency (Martinez et al., 2019).

- CAPRI-Water applied to several case studies to assess nexus-compliant policies and interventions (https://www.sim4nexus.eu/).
- CAPRI provides the agricultural outlook, in particular on livestock and fertiliser use. Further, it projects how changes in biofuel demand may affect the agricultural sector. Cross-checks are undertaken ex-ante and ex-post to ensure consistency with GLOBIOM on overlapping variables, for the crop sector in particular (EU reference scenario 2020: Energy, transport and GHG emissions: trends to 2050).
- The detailed nutrient flow in CAPRI has been exploited to estimate nitrogen budgets for agriculture in Europe (Leip et al., 2011), to measure nitrogen footprint of food products in the EU (Leip et al. 2014), and to assess the impacts of European livestock production (Leip et al., 2015).
- The CAPRI water module has been applied to assess water pricing scenarios, as well as the impact of climate change on yields and water availability for agriculture (Blanco et al. 2015). The module not only enables the analysis of changes in water availability for irrigation, but also the effects of changes in precipitation in rainfed and irrigated agriculture (Blanco et al., 2018).
- CAPRI has been used to assess if treated water available for agriculture has the potential to reduce freshwater abstraction and, consequently, water stress (Hristov et al., 2021).
- A number of simulations with CAPRI-Water were undertaken to feed the system dynamics model (González-Rosell et al., 2020).
- Assess the impact of EU biofuel targets on agricultural markets and land use (Blanco et al., 2010). The combination of CAPRI and GTAP enabled the analysis of the impact of EU biofuel policies on global markets and EU environmental quality (Britz and Hertel, 2011).
- Support impact analyses regarding agriculture, sustainable management of natural resources, food chains, the bio-based and circular economy, climate change and SDGs in general (https://www.suprema-project.eu)

2.4 PRIMES

2.4.1 Main features and description of the model

PRIMES (Price-Induced Market Equilibrium System) is a large-scale applied energy system model that provides detailed projections of energy demand, supply, prices, and investment, covering the entire European energy system including emissions. The distinctive feature of PRIMES is the combination of behavioural modelling (following a micro-economic foundation) with engineering aspects, covering all energy sectors and markets.

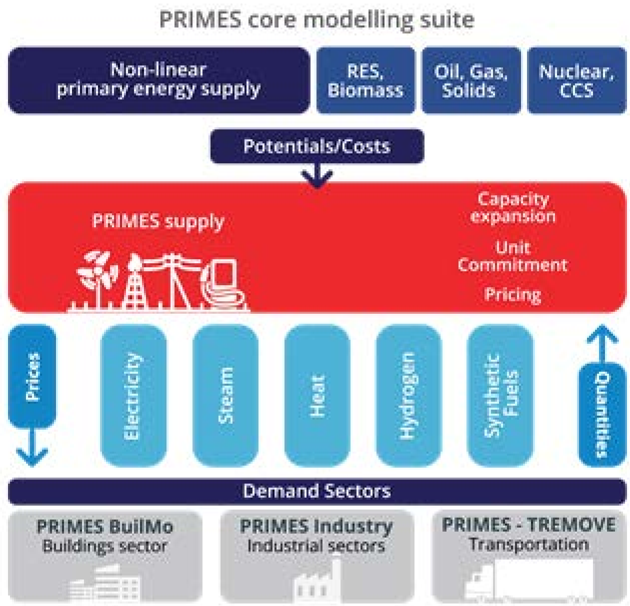


Figure 4. PRIMES modelling system.

The model has a detailed representation of policy instruments related to energy markets and climate, including market drivers, standards, and targets by sector or overall (over the entire system). It handles multiple policy objectives, such as GHG emission reductions, energy efficiency and renewable energy targets, and also provides a pan-European simulation of internal markets for electricity and gas. Cross-border electricity and gas trade and physical flows are accounted with a stylized representation of distribution and transport infrastructure, taking into account transmission/distribution losses and costs. PRIMES offers the possibility of handling market distortions, barriers to rational decisions, behaviours, as well as and market coordination issues and includes a complete accounting of costs (CAPEX and OPEX) and investment expenditure on infrastructure needs. PRIMES is designed to analyse complex interactions within the energy system in a multiple agent– multiple markets framework.

Decisions by agents are formulated based on a microeconomic foundation (utility maximization, cost minimization and market equilibrium) embedding engineering constraints, behavioural elements and an explicit representation of technologies and vintages and optionally perfect or imperfect foresight for the modelling of investments in all sectors. This implies that PRIMES can be seen as an agent-based model. The sectors are introduced in modules that have representative agents participating in the markets and attributed to ten industrial, transport, residential, services and agricultural sectors. At the level of each sector and its sub-sectors and uses, the model calculates the respective energy uses consumption as a function of economic activity. The agents' choice of technology, fuels, energy saving possibilities is subject to constraints on field availability and prices, taxes, as well as behavioural response to policies and limited information.

PRIMES is well-placed to simulate medium and long-term transformations of the energy system (rather than short-term ones) and includes non-linear formulation of potentials by type (resources, sites, acceptability etc.) and technology learning. The PRIMES model covers the EU27+UK as well as 10 non-EU countries including the EFTA countries Norway, Switzerland and Iceland.

2.4.2 Recent model applications

- **EU reference scenario 2020: Energy, transport and GHG emissions: trends to 2050.** The purpose of this publication is to present the "EU Reference Scenario 2020" (European Commission 2021a) which updates the previous version published in 2016. The Reference Scenario projects the impact of macro-economic, fuel price and technology trends and policies on the evolution of the EU energy system, on transport, and on their greenhouse gas (GHG) emissions. The projections concern the 27 EU Member States individually and altogether. The Reference Scenario also includes GHG emission trends not related to energy. In essence, the Reference Scenario is an informed, internally consistent, and policy relevant projection on the future developments of the EU energy system, transport system and greenhouse gas GHG emissions that acts as a benchmark for new policy initiatives. It reflects policies and market trends used by policymakers as baseline for the design of policies that can bridge the gap between where EU energy and climate policy stands today and where it aims to be in the medium- and long-term, notably in 2030 and 2050.
- Fit for 55 scenarios: An assessment of the Fit for 55 legislative packages, stepping up Europe's 2030 climate ambition in reducing greenhouse gas emissions to at least 55% below 1990 levels. PRIMES model covers the core elements of energy sector, energy efficiency measures, renewable targets and CO_2 emissions projections (European Commission, 2021b).
- REPowerEU scenario: achieving the reduction of dependence on Russian fossil fuels. PRIMES model is used to analyse challenges and opportunities in the energy sector, as the expansion of renewables, hydrogen, wider implementation of energy efficiency measures, and gas infrastructure bottlenecks (Liquefied Natural Gas (LNG, pipelines) (European Commission 2022). **INNOPATHS:** Innovation pathways, strategies and policies for the Low-Carbon Transition in Europe (https://innopaths.eu/, Rodrigues et al. 2021)
- **NAVIGATE:** Next generation of AdVanced InteGrated Assessment modelling to support climaTE policy-making (https://www.navigate-h2020.eu/)
- **DEEDS:** Dialogue on European Decarbonisation Strategies (European Commission, Directorate-General for Research and Innovation 2018)

2.5 GEM-E3

2.5.1 Main features and description of the model

The GEM-E3 model is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its interaction with the environment and the energy system. It is an empirical, large-scale model, written entirely in structural form. GEM-E3 allows for a consistent comparative analysis of policy scenarios since it ensures that in all scenarios, the economic system remains in general equilibrium. In addition, it incorporates micro-economic mechanisms and institutional features within a consistent macro-economic framework and avoids the representation of behaviour in reduced form. Particularly valuable are the insights the model provides regarding the distributional aspects of long-term structural adjustments. The GEM-E3 model is extensively used as a tool for policy analysis and impact assessment.

The model is modularly built allowing the user to select among several alternative closure options and market institutional regimes depending on the issue under study. It supports defining several alternative regimes and closure rules without having to re-specify or re-calibrate the model. The most important of these options are presented below:

- Capital mobility across sectors and/or countries
- Flexible or fixed current account (with respect to the foreign sector)

- Flexible or fixed labour supply
- Market for pollution permits national/international, environmental constraints
- Fixed or flexible public deficit
- Perfect competition or Nash-Cournot competition assumptions for market competition regimes

The GEM-E3 model includes projections of full Input-Output tables by country/region, national accounts, employment, balance of payments, public finance and revenues, household consumption, energy use and supply, GHG emissions and atmospheric pollutants.

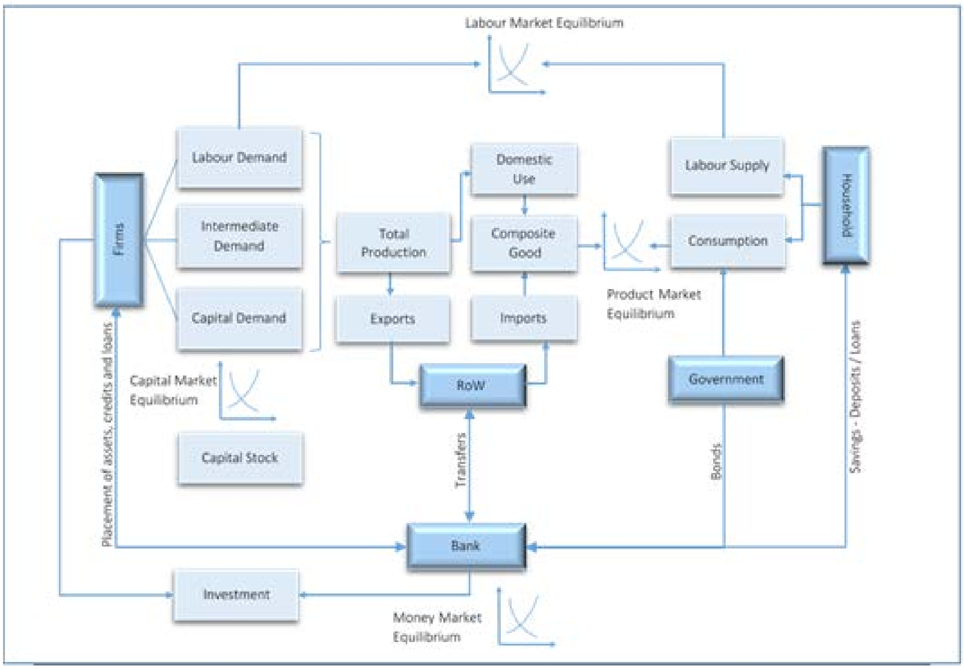


Figure 5.GEM-E3 modelling system.

The GEM-E3 model simultaneously represents 38 regions and 31 sectors linked through endogenous bilateral trade flows. The model features perfect competition market regimes, discrete representation of power-producing technologies, semi-endogenous learning by doing effects, equilibrium unemployment, option to introduce energy efficiency standards, formulates emission permits for GHG and atmospheric pollutants.

Its scope is general in two terms: it includes all simultaneously interrelated markets and represents the system at the appropriate level with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of agent's behaviour. It formulates separately the supply or demand behaviour of the economic agents which are considered to optimize individually their objective while market derived prices guarantee global equilibrium, allowing the consistent evaluation of distributional effects of policies. It considers explicitly the market clearing mechanism and the related price formation in the energy, environment and economy markets: prices are computed by the model as a result of supply and demand interactions in the markets and different market clearing mechanisms, in addition to perfect competition, are allowed. The model formulates production technologies in an endogenous manner allowing for price-driven derivation of all intermediate consumption and the services from capital and labour. In the electricity sector a bottom-up approach is adopted for the representation of the different power producing technologies. For the demand side the model formulates consumer behaviour and distinguishes between durable (equipment) and consumable goods and services.

The model is dynamic, recursive over time, and driven by the accumulation of capital and equipment. Technology progress is explicitly represented in the production function, either exogenous or endogenous, depending on R&D expenditure by private and public sectors and considering spill-over effects. Moreover, it is based on the myopic expectations of the participant agents.

2.5.2 Recent model applications

- **ENGAGE:** ENGAGE engages with stakeholders in co-producing a new generation of global and national decarbonisation pathways using (among others) PRIMES and GEM-E3 models of E3M. The new pathways will integrate cutting-edge insights from social science to reflect multidimensional feasibility of decarbonisation (Drouet L., et al., 2021). The pathways will analyse the timing of net-zero emissions to meet the Paris target and reduce the reliance on controversial negative emissions technologies. EC- H2020 2019-2023 (GA No 821471, http://www.engage-climate.org/).
- **Study on the Macroeconomics of the Energy Union:** The objective was to improve the understanding of the interactions between the macro-economy, the energy – and more broadly low-carbon economy – sector and the EU, national and other relevant subnational policies. The study started from existing models, tools and methods available, and developed them in an open and transparent way to address the macro-economic implications of energy policies. Key developments regard technology diffusion and R&D learning, production factor capacity constraints and representation of the financial sector.
- **"Models for the analysis of international interactions of the EU ETS (Modelle zur Analyse internationaler Wechselwirkungen des EU ETS)":** The study has the following tasks, i) Evaluate the impact on EU and Germany industrial competitiveness of alternative energy and climate policies, ii) Evaluate measures to offsets potential negative impact on competitiveness, iii) Assess the effect of global CO_2 prices in model-based climate protection scenarios up to 2100, iv) Assess different climate protection scenarios up to 2030, taking into account CO_2 price differences and carbon leakage.
- **Trade & Climate Change Quantitative Assessment of the Best Policy Tools to Achieve Climate Neutrality and Competitiveness:** The study analyses the effect of the introduction of the Carbon Border Adjustment Mechanism (CBAM) on the EU trade and potential competitiveness gaps. It focused on the assessment of CBAM to achieve EU carbon emissions reduction target and reduce carbon leakage (Afep, 2021). GEM-E3 model methodological and analytical framework allowed to quantify changes in the international trade and investment flows, the overall balance of carbon emissions and carbon emission avoidance.

2.6 PROMETHEUS

2.6.1 Main features and description of the model

The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system. PROMETHEUS is a fully fledged energy demand and supply simulation model aiming at addressing energy system analysis, energy price projections, power generation planning and climate change mitigation policies.

PROMETHEUS contains relations and/or exogenous variables for all the main quantities, which are of interest in the context of general energy systems analysis. These include demographic and economic activity indicators, primary and final energy consumption by main fuel, fuel resources and prices, CO_2

emissions, greenhouse gas concentrations and technology dynamics (for power generation, road transport, hydrogen production and industrial and residential end-use technologies).
PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (like Renewable energy sources (RES), electric vehicles, Carbon capture and storage (CCS), and energy efficiency) and policy instruments. The latter include both market-based instruments such as cap and trade systems with differential application per region and sector specific policies and measures focusing on specific carbon emitting activities.

Key characteristics of the model, that are particularly pertinent for performing the analysis of the implications of alternative climate abatement scenarios, include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements (increased uptake of a new technology in one part of the world leads to improvements through learning by experience which eventually benefits the energy systems in other parts of the World). PROMETHEUS is designed to provide medium- and long-term energy system projections and system restructuring up to 2050, both in the demand and the supply sides. The model produces quantitative analytical results in the form of detailed energy balances in the period 2015 to 2050 annually. The model can support impact assessment of specific energy and environment policies and measures, applied at regional and global level, including price signals, such as taxation, subsidies, technology, and energy efficiency promoting policies, RES supporting policies, environmental policies and technology standards.

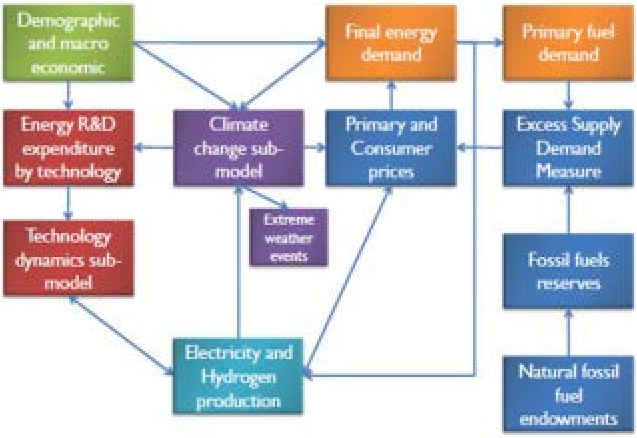


Figure 6. PROMETHEUS modelling system.

PROMETHEUS is a world model and identifies ten countries/regions.

Region code	**Countries included in PROMETHEUS region**
EU15+NO+SW	The old EU-15 member states, plus Norway and Switzerland
New Member States	The New EU Member States that joined the EU after 2000
North America	The USA and Canada
OECD	Western Pacific Japan, South Korea, Australia and New Zealand
China	China and Hong-Kong
India	India
FSU	The former Soviet Union excluding the Baltic Republics
ENA	The Middle East and North Africa region
Emerging Economies	All other countries that had more than 3.000 $2005 PPP per capita in 2005
RESTW	All other countries. Essentially this region contains the poorer economies mostly in Africa and Asia.

2.6.2 Recent model applications

PROMETHEUS has been used to provide scenarios focusing on international fossil fuel prices (Capros et al., 2016), stochastic energy system analysis (Fragkos et al., 2015), carbon price diagnostics (Harmsen et al., 2021), the impacts of specific mitigation options like Carbon Capture and Storage -CCS- (Fragkos, 2021), Nationally Determined Contributions and low-emission strategies in major emitters (Fragkos and Kouvaritakis, 2018), energy system transformation to 1.5ºC (Fragkos, 2020, Marcucci et al., 2019) and, recently, for assessing the emission and energy system impacts of bottom-up energy and climate policies at national and global level (Van Soest et al., 2021) and COVID-19 and green recovery plans (Rochedo et al., 2021). The model has been recently applied in various research projects to analyse the systemic transformations required towards meeting ambitious climate change mitigation goals and to analyse the implications of supply-side policies banning the extraction of fossil fuels (Andreoni et al., 2021). In particular, it has been used in a variety of H2020 research projects exploring decarbonisation pathways (INNOPATHS, ADVANCE, AMPERE) and in projects supporting DG CLIMA in climate policy assessment (COMMIT). Currently, the PROMETHEUS model is heavily used in several H2020 projects exploring pathways and strategies to net zero at national and global level, including NAVIGATE, WHY, NDC-ASPECTS, ECEMF and CAMPAIGNers.

2.7 GLOBIO

2.7.1 Main features and description of the model

The GLOBIO model framework is designed to quantify human impacts on biodiversity and ecosystems worldwide as well as the effectiveness of large-scale policy options for conserving biodiversity and ecosystems (www.globio.info). The framework includes various components representing different and complementary aspects of biodiversity and ecosystems (Figure 7). There are two model components that assess human impacts on local biodiversity intactness, quantified by the mean species abundance (MSA) metric: one for terrestrial systems (GLOBIO) and one for freshwater systems (GLOBIO-Aquatic). The GLOBIO-Species model quantifies the distribution - and if data allows also abundance – of individual vertebrate species as a function of multiple human pressures. Currently the GLOBIO-Species model includes terrestrial mammals and freshwater fish species. Finally, the GLOBIO-ES model component quantifies a selection of provisioning, regulating and cultural ecosystem services, including for example pollination and clean water provisioning.

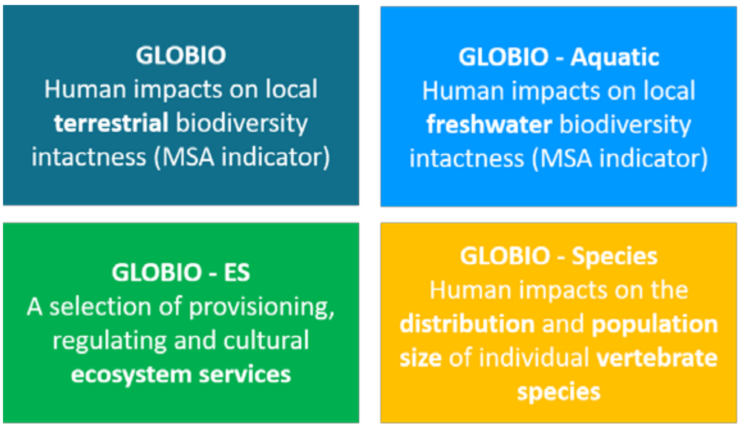


Figure 7.Overview of the components in the GLOBIO modelling framework

GLOBIO

GLOBIO quantifies local terrestrial biodiversity intactness, expressed as the mean species abundance (MSA) indicator, as a function of five major human pressures: climate change, atmospheric nitrogen deposition, land use, roads, and overhunting. The core of the model consists of quantitative, meta-analytical pressure-impact relationships that have been established based on extensive terrestrial biodiversity databases. GLOBIO combines the pressure–impact relationships with data and maps on past, present or future pressure levels, resulting in maps with MSA values corresponding with each pressure. These maps are then combined to obtain overall MSA values (i.e., across all pressures). MSA values can be aggregated to larger (user-defined) regions. In addition, the contributions of the different pressures to the losses in MSA can be quantified.

GLOBIO-Aquatic

GLOBIO-Aquatic quantifies freshwater biodiversity intactness, expressed as the mean species abundance (MSA) indicator, as a function of various key human pressures on freshwater systems. GLOBIO-Aquatic currently includes the following pressures: land use, streamflow alteration (due to dams and climate change), and eutrophication (nitrogen and phosphorous inputs from agricultural and urban sources). Pressure-impact relationships are quantified based on literature review and meta-analyses. GLOBIO-Aquatic covers different freshwater systems: flowing water (rivers, streams), lakes and wetlands. Losses in MSA are calculated per freshwater system type, using specific pressure-impact relationships and pressure input data retrieved from various sources, including the IMAGE model, the Global Nutrient Model and global hydrological models (e.g., PCR-GLOBWB or LPJmL). GLOBIO-Aquatic follows a catchment approach: impacts on a certain water body depend on the land use and/or the accumulated nutrients aggregated over the upstream part of the corresponding catchment. After calculating the MSA per freshwater type per grid cell, the MSA values can be aggregated across different freshwater types and/or to larger (user-defined) regions.

GLOBIO-Species

GLOBIO-Species is designed to assess the impacts of human pressures on individual vertebrate species. For terrestrial mammals, the model currently includes the impacts of climate change (via range contraction), land use (via habitat loss and fragmentation) and infrastructure (via changes in abundance in the proximity of the roads). For freshwater fish species, the model currently accounts for the impacts of climate change and habitat fragmentation by dams and barriers. The impacts of climate change are calculated based on changes in species distribution due to alterations in streamflow and water temperature. Fragmentation is quantified based on an index representing the degree to which the geographic range of a species is connected (0-100%). Input data required to calculate the impacts of climate change and dams include spatially explicit weekly streamflow and water temperature data (from PCR-GLOBWB and DynWat) and georeferenced data on current and future dams.

GLOBIO-ES

GLOBIO–ES is a global model for assessing the current state and possible future trends of various ecosystem services (ES), i.e., the benefits that people obtain from nature. The model currently includes a selection of provisioning, regulating and cultural ecosystem services, including pollination, climate change mitigation and the support of nature to people's mental and physical health through the experience of nature. ES are modelled according to a supply-demand approach, quantifying the extent to which the supply of a given ES meets a corresponding societal demand.

2.7.2 Recent model applications

Recent GLOBIO model applications include the following:

- GLOBIO was used to evaluate the biodiversity consequences of three Shared Socioeconomic Pathways (SSPs) coupled with three Representative Concentration Pathways (SSPs), as part of the first global assessment of the IPBES (Schipper et al., 2020).
- GLOBIO was used to evaluate the extent to which ambitious nature conservation scenarios would lead to improvements in biodiversity, as part of the 'bending the curve' project (Leclère et al., 2020).
- GLOBIO, GLOBIO-Aquatic, GLOBIO-Species and GLOBIO-ES were used to evaluate the benefits and potential trade-offs of ambitious global biodiversity conservation strategies as part of the fifth Global Biodiversity Outlook (Kok et al., 2020)
- GLOBIO-Aquatic was used to project freshwater biodiversity intactness to 2050 based on a business-as-usual scenario as part of the Future Water Challenges project (https://themasites.pbl.nl/future-water-challenges/)
- GLOBIO-Species was used to quantify the impacts of both current and planned future large dams on the range connectivity of freshwater fish species globally (Barbarossa et al., 2020)
- GLOBIO-Species was used to evaluate the benefits of limiting global warming for the distribution and diversity of freshwater fish species (Barbarossa et al., 2021)

3 Adaptation and improvement of the global and continental models to simulate GoNEXUS scenarios

Before being applied to run GoNEXUS scenarios, the global and continental models have been adapted to better represent the interaction between the WEFE nexus components. Also, the baseline scenario has been defined for each model, according to the work done in WP2 (covering the climate, socioeconomic, land use and policy domains).

3.1 Improvement of the global and continental models to simulate GoNEXUS scenarios

The global and continental models are being improved in the framework of GoNEXUS. The improvements and changes are made to the individual thematic models that together define the different components of the WEFE nexus at global and continental scales, including water (PCR-GLOBWB, LISFLOOD-EPIC), energy (PRIMES, PROMETHEUS), agri-food (CAPRI, LISFLOOD-EPIC), and ecosystems (GLOBIO). Improvements and changes aim to set up the models for additional scales and to make the models suitable for including the WEFE interactions (see Table 1). In the table, green ticks mean that the improvement is done and the red one means ongoing improvement.

PCR-GLOBWB	LISFLOOD-EPIC	CAPRI	PROMETHEUS RI	PRIMES	GEM-E3	GLOBIO
	√ Addition of a	√ Update and improvemen	√ inclusion of water	√ Improved thermal and	√ Further integratio	Inclusion of the

√ Add crop model (WOFOST) √ Split industrial water use into manufacturing and thermo-electric use √ Thermal pollution by thermo(nuclear) power plants included	module on water temperature is ongoing. √ Better integration of the crop growth model EPIC	t of the water database at global and EU level	constraints for the power sector by region under different scenario conditions	nuclear power plants database.	n of the effects of the nexus, with improvements of the representation of agriculture and land use	combined effects on fish species distributions and diversity of: √ Dam building √ Water temperature √ Streamflow change
		√ Improvement of interlinkages between agricultural water use and environmental quality	√ Verification of biomass demand/potential under different scenario conditions	√ Improvements to include water constraint for thermal and nuclear power plants		
				√ Verification and improvements of biomass linkage with CAPRI		

Table 1. Summary of model improvements

3.1.1 PCR-GLOBWB

PCR-GLOBWB2 simulates hydrology, water management, rainfed and irrigation water use and productivity, hydropower, and temperature-based cooling water potential at 0.1° (~10 km) globally. The main ongoing improvements in the framework of GoNEXUS are:

- Separation of industrial water use into manufacturing and energy cooling water (finished);
- Consideration of thermal pollution by thermal (nuclear) power plants (finished);
- Coupling with crop growth model WOFOST (under way).

3.1.2 LISFLOOD-EPIC

The grid-based LISFLOOD-EPIC model simulates hydrological processes, water management, and irrigated and rainfed crop yield at spatial resolutions from 5km (Europe) and 0.1° (global).
The main ongoing improvements in the framework of GoNEXUS are:

- Addition of a module on water temperature to assess temperature effects of energy plants, industries and treated wastewater, as well as further improvements on the energy-hydropower module.
- Better integration with the crop growth model EPIC to dynamically simulate hydrology, crop growth and irrigation, accounting for water abstractions for household, livestock, industry and

energy sectors at a daily time step and every grid-cell defined in the model domain (finished). LISFLOOD-EPIC is now able to simulate future scenarios.

3.1.3 CAPRI

CAPRI (UPM) simulates food supply, demand and trade flows, producer and consumer prices, agricultural yield and input use (including water and energy) and environmental indicators (nutrient balances, GHG emissions) both globally (at the country or country group level) and at regional level within the EU. It is widely used for assessing EU policies (Common Agricultural Policy, climate and environmental policy).
The main ongoing improvements are:

- Improvement of the water module to cover all global regions (both EU and non-EU regions);
- Update and improvement of the water database at global and EU level;
- Improvement of interlinkages between agricultural water use and environmental quality.

3.1.4 PRIMES

PRIMES (E3M) simulate energy supply and demand, CO_2 emissions, investment in demand and supply, energy technology penetration and prices and costs for the European energy system and markets on a country-by-country basis and across Europe for the entire energy system. The model is being regularly used to create the "Reference outlook for EU energy, transport and GHG emission trends to 2050", and as basis for many impact assessments in the field of energy and climate policy including the EU Long-Term Strategy.
The main ongoing improvements in the framework of GoNEXUS are:

- Improvements under way to include water constraints for thermal and nuclear power plants;
- Verification and improvement of water constraints;
- Verification and improvements of biomass linkage (ongoing).

3.1.5 GEM-E3

GEM-E3 (E3M) is a global advanced computable general equilibrium model with 55 individual production sectors and detailed representation of the energy sector. EU member states are represented individually. The model is widely used for impact assessments for the European Commission and as a global IAM model.
The main ongoing improvements are:

- Improvements of the water/land use including agriculture elements for employment.

3.1.6 PROMETHEUS

PROMETHEUS (E3M) provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices, and investment to the future covering the global energy system. PROMETHEUS is a fully fledged energy demand and supply simulation model aiming at addressing energy system analysis, energy price projections, and power generation planning and climate change mitigation policies.
The main ongoing improvements in the framework of GoNEXUS are:

- Verification/inclusion of water constraints for the power sector by region under different scenario conditions;
- Verification of biomass demand/potential under different scenario conditions.

3.1.7 GLOBIO

GLOBIO is a global assessment model designed to quantify global human impacts on biodiversity and ecosystems and the effectiveness of large-scale policy options for conserving biodiversity and ecosystem services.
The main ongoing improvements in GoNEXUS are:

- Quantifying the effects of dams on the global distributions of freshwater fish species.
- Quantifying the combined effects of dams and climate change (via alterations in water temperature and streamflow) on the distributions of freshwater fish species.

In addition, we have performed a systematic literature review in order to obtain data from experimental nutrient addition experiments for quantifying eutrophication impacts on freshwater fish species, but we found too little data to establish response relationships.

3.2 Tier 1 scenarios: First round of simulation runs

Simulation scenarios are being defined in WP2, covering the climate, socioeconomic, land use and policy domains. The climate change scenarios defined and analysed are obtained from the Coupled Model Intercomparison Project (CMIP). The global and continental scales refer to CMIP Phase 6 (CMIP6). CMIP6 scenarios include two activities: The Scenario MIP (standard resolution) and the ISIMIP3b (Inter-Sectoral Impact Model Intercomparison Project, high resolution data). From the combinations between RCPs and SSP and according to deliverable 2.1, GoNEXUS has selected the SSP1-1.9 and SSP1-2.6 (related to achieving the goal of not surpassing 1.5 and 2 degrees of global warming as indicated in the Paris Agreement), SSP3-7.0 (business as usual scenario considering the ongoing energy transition) and SSP5-8.5 (worst case scenario). A first scenario run (Tier1) will be established based on common inputs from WP2 (e.g. demographics, GDP, land use change, etc.) in order to have a homogeneous set-up for all the global WEFE models. After this first scenario run with common inputs (tier 1), the outputs required for the exchanges as established shared on the common dataserver.The Tier 1 scenario runs for the following models have been completed: 3 out 7 (PCR-GLOBWB, GLOBIO, PRIMES) of the baseline scenario runs are uploaded to the YODA and 4 out of 7 (GEM-E3, PROMETHEUS, CAPRI, LISFOOD-EPIC) runs are completed and will soon be uploaded. These will be used as input for creating model linkages for Tier 2 scenario runs and policy scenario runs and be used as boundary conditions for regional case studies. Global and continental models have been adapted to simulate the Tier 1 scenarios.

3.2.1 PCR-GLOBWB

Bias-corrected (using WFDE5; Cucchi et al., 2020) historical climate scenarios (1979-2005) and future projections (2006-2100) under joint climate socioeconomic scenarios (SSP1-2.6, SSP3-7.0 and SSP5-8.5) have been used as input to PCR-GLOBWB 2. For each SSP-RCP combination, inputs from 5 GCMs have been used (following the ISI-MIP 2b protocol). These runs have produced the Tier 1 output which is available for use by other models. These outputs consist of all the hydrological states and fluxes calculated by PCR-GLOBWB, including sectoral water use, globally at 5 arc-minutes and at monthly time steps.

PCR-GLOBWB Tier 1 runs available on Yoda. Global 5 arcminutes monthly output for observed climate (control: WFDE5 forcing 1979-2019) and 1961-2099 for the following CMIP6 scenarios: SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5, with 5 climate runs per scenario (following ISI-MIP3) (see Figure 8 for a graphical summary).

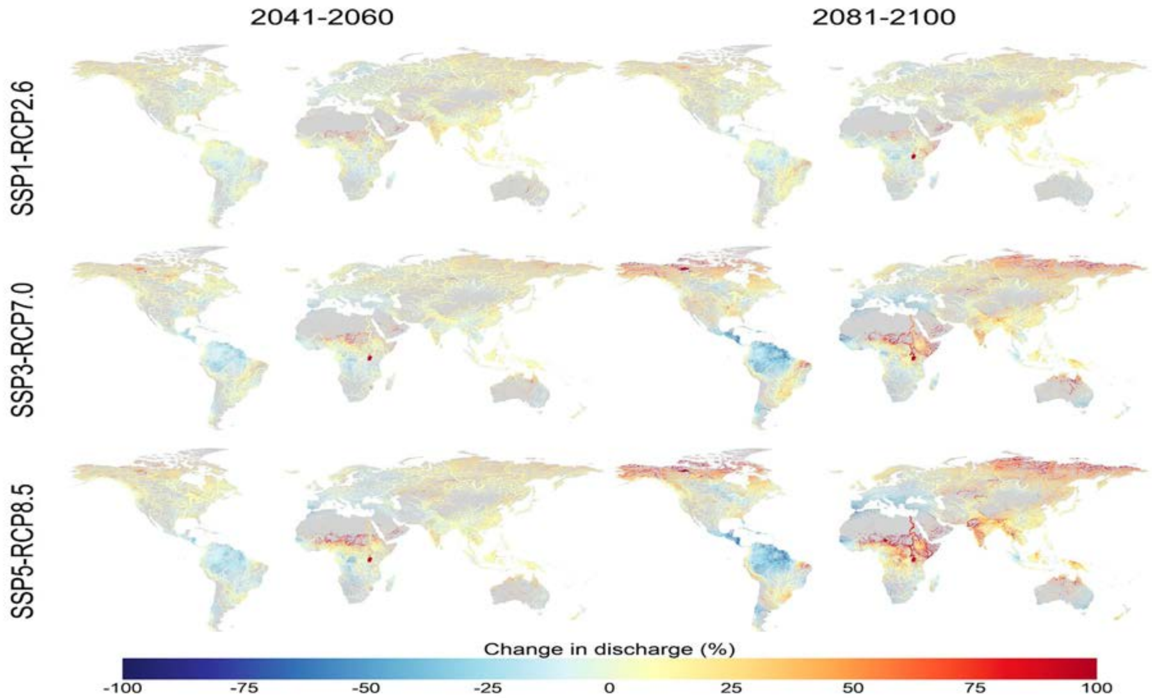


Figure 8. Percentage change in discharge for 2041-2060 and 2081-2100 under combined climate and socio-economic scenarios, relative to a historical reference period (2005 – 2020)

3.2.2 LISFLOOD-EPIC

Historical climate scenarios (1981-2010) and future projections (2011-2100) from 11 EURO-CORDEX climate projections under the RCP4.5 and RCP8.5 emissions scenarios were used to drive the LISFLOOD hydrological model at a daily scale including socio-economic projections (population, water demand for several sectors). The future projections of land use in Europe are derived from the LUISA modelling platform (Jacobs-Crisioni et al., 2017). LUISA translates socio-economic trends and policy scenarios into processes of territorial development. The output of these simulations are fully available for Tier1 (without EPIC irrigation module – no yield projections). Apart from the climate scenarios, the output of a control run with observed climate (1990-2018) is available as well.

3.2.3 CAPRI

Data on climate socioeconomic scenarios (SSP1-1.9, SSP1-2.6, SSP3-7.0 and SSP5-8.5) has been processed at national level for all global regions and aggregated at the spatial scale in CAPRI for non-EU regions. Regarding climate change effects on the agri-food sector, the CAPRI model does not use climate data for each RDP directly but uses changes in crop productivity and water for each RCP coming from biophysical models. Climate change scenarios have been defined in CAPRI as follows:

- Socioeconomic data (changes in GDP and global population) enters the CAPRI model as exogenous parameters.
- Changes in crop yields due to climate change come from EPIC
- Changes in water availability and water demand by sector come from CWAT

Scenarios have been run for 2030, 2040 and 2050. Figure 9 presents some results on irrigated area and irrigation water use in the EU.

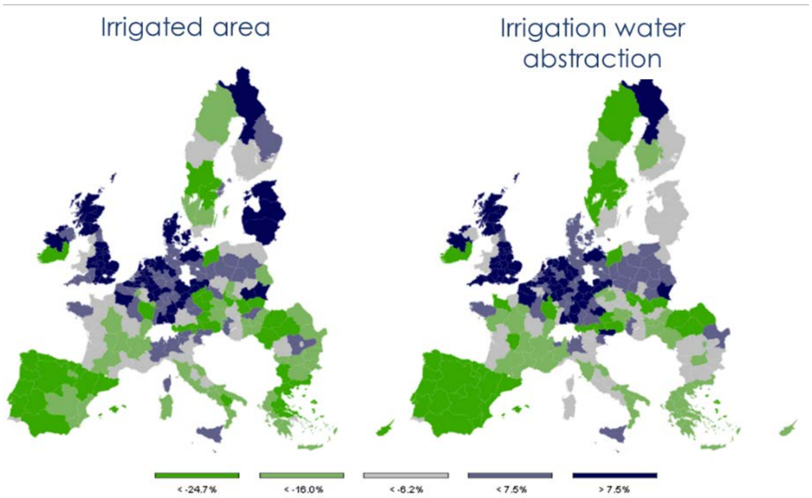


Figure 9. Change in irrigated area and irrigation water abstraction under RCP8.5 in 2050 (% relative to no climate change scenario)

3.2.4 PROMETHEUS

Socioeconomic scenarios provide key climate variables and socioeconomic assumptions (land use, GDP, water availability) under different climate change scenarios (SSP1-1.9, SSP1-2.6, SSP3-7.0 and SSP5-8.5) on regional and European scale. An impact from climate variables can be included indirectly via the link with sector specific and biophysical models that provide demographic and economic activity indicators, and changes in primary and final energy consumption.

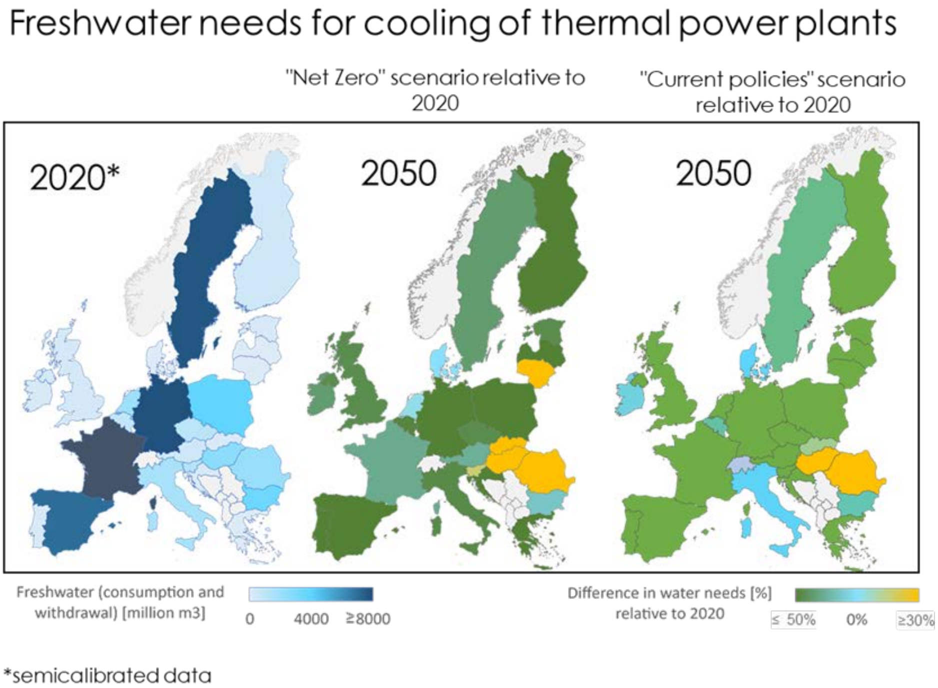
3.2.5 PRIMES

Key indicators have been analysed on national and European level based on the available socio-economic and climate projections. The analysis was focused on the effects on water needs of thermal and nuclear power plants for historic time and future time periods, as well as on the potential of biomass for energy sector.
To identify cooling needs for thermal power plants, we enhanced the model's representation of the power generation fleet. We identified locations, key technical features such as cooling method classification and water usage type (freshwater or seawater). Furthermore, we developed a more intricate model for the precise estimation of water consumption and withdrawal. Our initial comparison of water consumption and withdrawal for cooling requirements with relevant literature demonstrates a high degree of consistency.

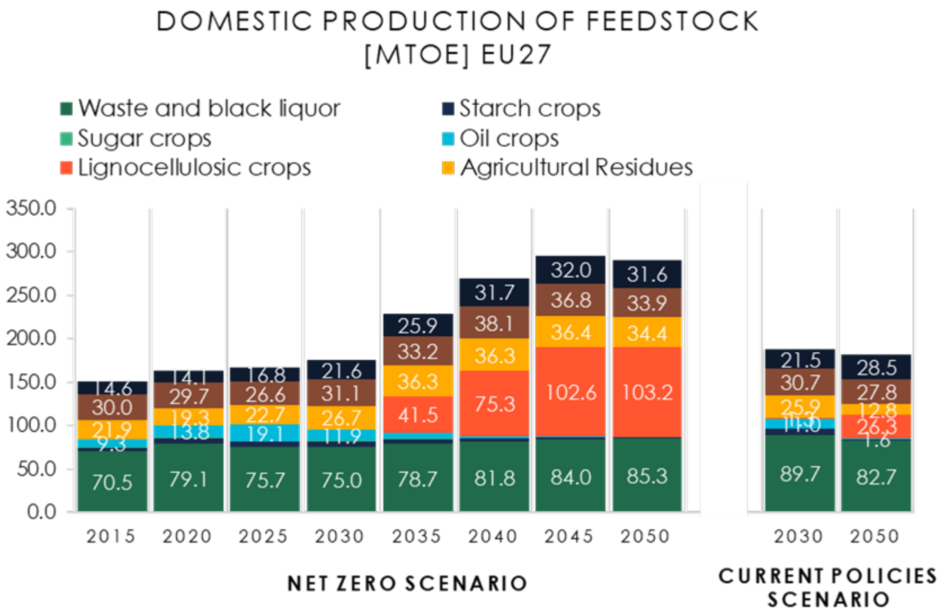
Although most climate parameters provided by the global climate models cannot be directly integrated into our analysis, their impacts are accounted for by using the IAM model outputs, such as changes in energy crop potential due to climate, socioeconomic, and land use changes. PRIMES Net Zero scenario includes recent projections for key global energy commodity prices and the latest EU's climate policies (Fit for-55 legislative package) aimed to reduce net greenhouse gas emissions and achieve climate neutrality by 2050. The Current Policies scenario reflects the current-policy baseline, taking into account currently implemented policies and socio-economic assumptions including the effects of COVID-19. Tier 1 scenarios are completed and uploaded to YODA, covering the following aspects:

Energy: primary energy by source, final energy uses in sectors; prices by sector and fuel; water consumption and withdrawal for cooling of thermal power plants (see figure 10a).

Biomass: domestic production of feedstock per type, imports, cultivated land area, commodity prices (see figure 10b).


Freshwater needs for cooling of thermal power plants
"Net Zero" scenario relative to 2020
"Current policies" scenario relative to 2020
2020*
2050
2050
Freshwater (consumption and withdrawal) [million m3]
0
4000
≥8000
Difference in water needs [%] relative to 2020
≤ 50%
0%
≥30%
*semicalibrated data

(a)


DOMESTIC PRODUCTION OF FEEDSTOCK [MTOE] EU27
Waste and black liquor
Starch crops
Sugar crops
Oil crops
Lignocellulosic crops
Agricultural Residues
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
2015
2020
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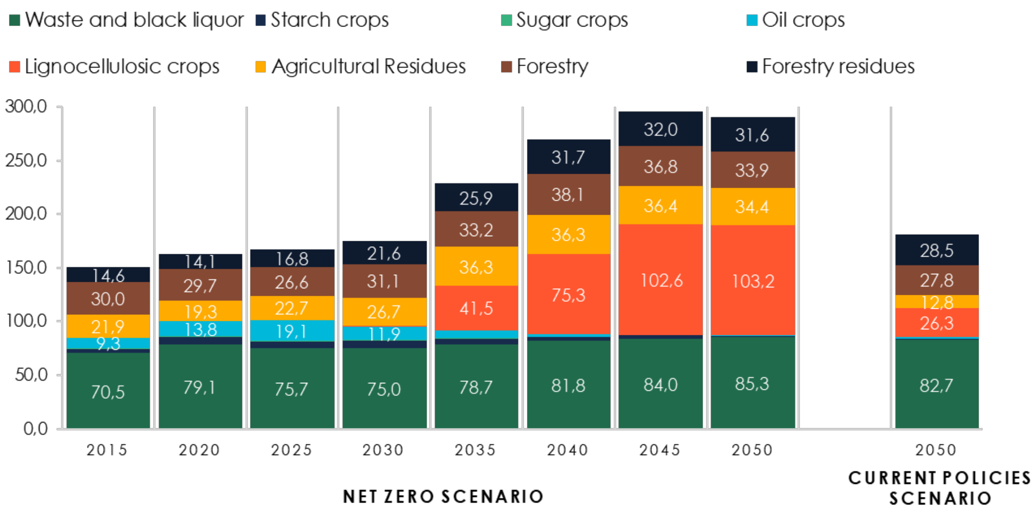
NET ZERO SCENARIO
2030
2050
CURRENT POLICIES SCENARIO



(b)

Figure 10. (a) Freshwater needs for cooling of thermal power plants, (b) EU domestic porduction of feedstock (MTOE)

3.2.6 GEM-E3

Climate socioeconomic scenarios were analysed to identify key challenges for regional, for European, and global economic activities (provided by GEM-E3) driven by changes in water availability and land use as a result of climate change. GEM-E3 model cannot directly use climate data, but can include changes in biomass potential, crop yields and agricultural commodity flows and energy projections from other models to simulate effects on economic activity and employment. The Tier 1 scenarios are complete.

3.2.7 GLOBIO

For Tier 1, future projections of freshwater fish species distributions are obtained based on projections of weekly streamflow and weekly water temperature for three SSP-RCP combinations (SSP1-2.6, SSP3-6.0 and SSP5-8.5) obtained with PCR-GLOBWB 2.0 (Bosmans et al. 2022). The updated GLOBIO-Species model was applied to assess the impacts of climate change (via alterations in streamflow and water temperature) and hydropower dams (via habitat fragmentation) on the distributions of freshwater fish species according to the Tier 1 scenarios. Tier 1 scenarios are uploaded to the Yoda server, covering the following aspects:

- The proportion of geographic range threatened (%) per lotic fish species in relation to each pressure variable (dams (current and future), changes in river flow (Q-min; Qmax; number of zero-flow weeks) and changes in water temperature (T-min and Tmax)) per GCM (gfdl, hadgem, ipsl, miroc, noresm), scenario (hist and rcp2p6, rcp4p5, rcp6p0, rcp8p5), and target year (2030, 2050) (see Figures 11 and 12 for a graphical summary).
- The Potentially Affected Fraction (PAF) of lotic fish species in each 5 arcminute grid cell in relation to each pressure variable (dams (current and future), changes in river flow (Q-min; Qmax; number of zero-flow weeks) and changes in water temperature (T-min and Tmax)), per GCM (gfdl, hadgem, ipsl, miroc, noresm), scenario (hist and rcp2p6, rcp4p5, rcp6p0, rcp8p5), and target year (2030, 2050) (see Figure 13 for a graphical summary).

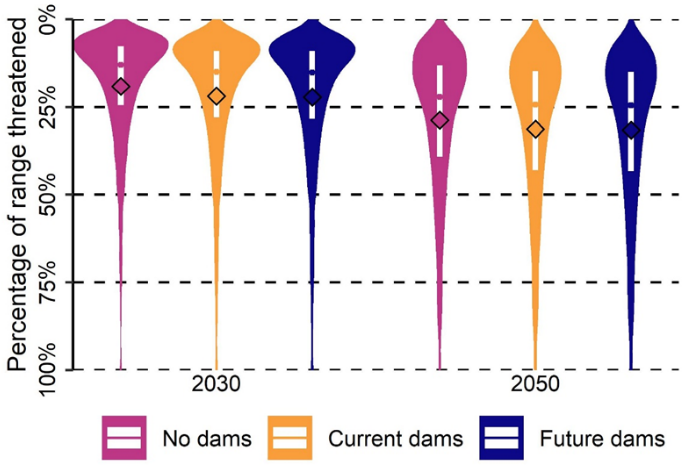


Figure 11. Proportion of geographic range threatened in 2030 and 2050. The violin plots show the proportion of geographic range threatened by future climate extremes for 10,143 freshwater fish species, different target years and multiple dams situations. For each species and target year, the mean across the different scenarios (GCM–RCP combinations) is calculated. Within each violin, the white boxes show the interquartile range as well as the median, while diamonds represent the mean. See Fig. 12 for differences among GCMs and RCPs.

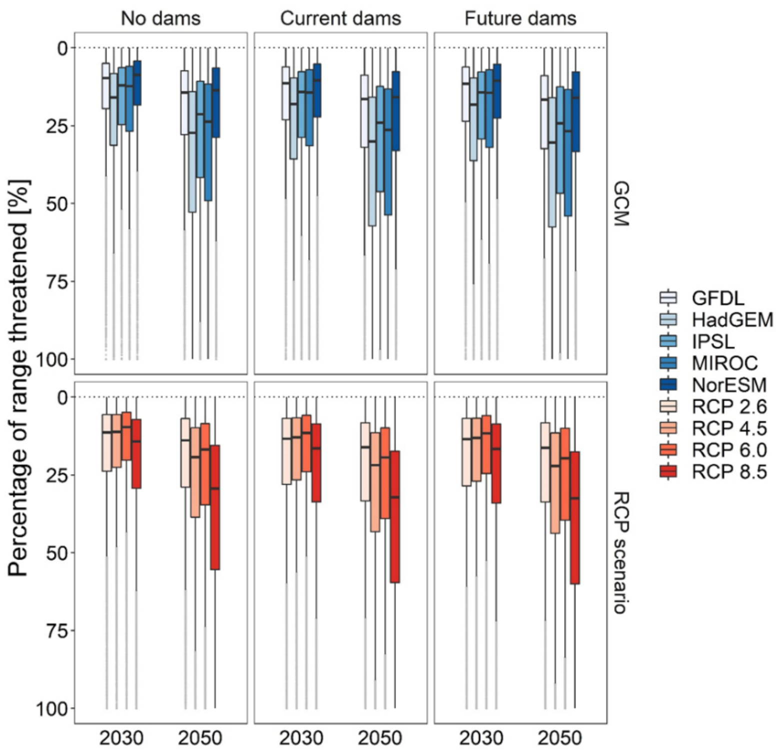


Figure 12. Output variability stemming from the different inputs of Global Climate Models and Representative Concentration Pathway scenarios.

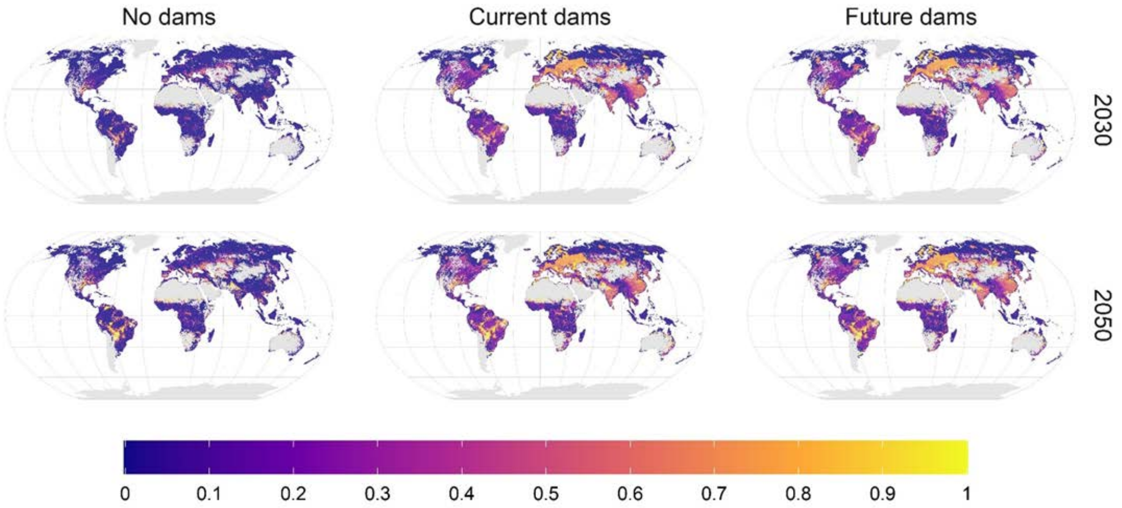


Figure 13. Spatial patterns of climate change threat, expressed as the potentially affected fraction of freshwater fish species, for different dam situations

4 Next steps

4.1 Model linkages for improved WEFE nexus assessment

Besides the improvements foreseen in individual models of the WEFE and the development of new models at the river basin scale, GoNEXUS will improve the representation of the WEFE by a set of multi-scale and multi-model WEFE interlinkages (see Figure 14).

These linkages will be materialised through a data server created by GoNEXUS using the Open-source Project for a Network Data Access Protocol (OPeNDAP) modular data server Hyrax, freely available on a GitHub repository. This server will be used to store the scenario data to be used by the Model Toolbox, as well as the models' results necessary to interlink them and build the evidence.

First of all, an input harmonisation strategy will be implemented to unify the variables, units and formats used by all models. Afterwards, a communication system between the models and the data server will be established: each model downloads the scenario datasets required, as well as the data on the interlinked variables from the rest of the models; and will upload the results of the runs performed with the downloaded data. Downloads and uploads will be performed automatically (using Python, R or MatLab scripts) or manually. The communication system will be implemented sequentially: in a first stage the models will have no new linkages, getting all the inputs from the scenario datasets; in a second stage we will implement the linkages between global and continental models, using the results of the first stage for the interlinked model variables as inputs instead of the scenario data; and in the third stage the models will implement all the linkages, using the results of the second stage for the interlinked model variables as inputs instead of the scenario data.

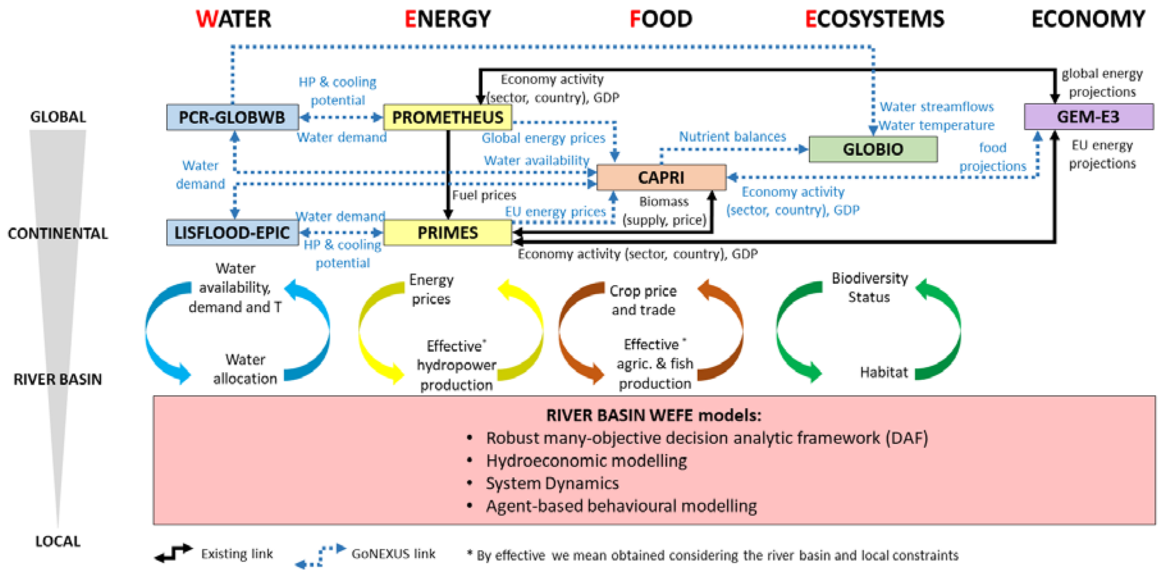


Figure 14. GoNEXUS' Model Toolbox and model interlinkages

Hereafter, the existing linkages (between GEM-E3 and PRIMES, GEM-E3 and PROMETHEUS, and CAPRI and PRIMES) will be complemented by the following (Table 2):

- PCR-GLOBWB will provide hydropower and cooling potential to PROMETHEUS, water availability to CAPRI global runs, and streamflow and water temperature to GLOBIO.
- LISFLOOD-EPIC will provide hydropower and cooling potential to PRIMES, water availability to CAPRI continental runs, and crop yield anomalies to CAPRI as well.
- PROMETHEUS will provide water demand for energy to PCR-GLOBWB, and energy prices to CAPRI global runs.
- PRIMES will provide water demand for energy to LISFLOOD-EPIC, and energy prices to CAPRI continental runs.
- CAPRI global runs will provide agricultural water demand to PCR-GLOBWB, and food projections to GEM-E3.
- CAPRI continental runs will provide agricultural water demand to LISFLOOD-EPIC, and food projections to GEM-E3.

Model links	PCR-GLOBWB/ LISFLOOD-EPIC	CAPRI	PRIMES	GEM-E3	PROMETHEUS	GLOBIO
PCR-GLOBWB/ LISFLOOD-EPIC		Crop water requirements and effective precipitation, Water balances (availability by source and use by sector), Irrigation efficiency	Discharge		Discharge Surface water temperature	Dam locations, Discharge, Surface water temperature
CAPRI	Agricultural water demand (based on agricultural needs) (annual)		Potential for energy crops, in particular implications for higher	Agricultural commodity trade flows	Food projections	

Model links	PCR-GLOBWB/ LISFLOOD-EPIC	CAPRI	PRIMES	GEM-E3	PROMETHEUS	GLOBIO
			Ligno-cellulosic crops; land and water needs from bio-energy demand			
PRIMES	Energy demand by sector Energy mix Energy crops need Hydropower needs	EU energy prices Share of biofuels in total transportation fuel use Energy demand by sector Energy mix Energy crops need Energy efficiency		EU energy projections		
GEM-E3			EU economic activity		Global economic activity	
PROMETHEUS	Energy demand by sector Energy mix Energy crops need Hydropower needs	Global energy prices		Energy cropping needs Energy prices, demand and production		

Table 2. Model interlinkages for improved WEFE nexus assessment

4.2 Tier 2 scenarios: Second round of simulation runs

After this first scenario run with common inputs (Tier 1), a second scenario run (Tier 2) will then be simulated based on common inputs from WP2 but also using the model linkages. The models will use the necessary outputs (Tier 1) from other models taken from the dataserver as inputs leading to a consistent scenario set-up which will serve as baseline scenario.

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