Document information and consolidated data available according to specific Nexus dimensions from Modelling, Repository and Inter-Comparison projects

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Project

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Abstract

This Deliverable aims at providing a wide overview of the biophysical and socio-economic data that could be made available to develop the integrated complexity science tools that will be used to support the development of policies to manage resources effectively in each case study. The Deliverable gives an initial overview of the origin of the data, their purpose within the NEXOGENESIS project, the model used, the sectors covered, the RCP and SSP scenarios discussed, and the spatial and temporal scale at which this quantitative information can be provided.

Keywords

RCP, SSP, WEF nexus, Coherency, Modelling, Socio-Economic, Biophysical, Climate, Hydrology, Agriculture, Water Demand, Ecosystem Functions

Abbreviation/Acronyms

AGMIP	Agricultural Model Intercomparision and Improvement Project
CGE	Computable general equilibrium
CMIP	Coupled Model Intercomparison Project
GDP	Gross Domestic Product
GHGs	GreenHouse Gases
GTAP	Global Trade Analysis Project
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
RCP	Representative Concentration Pathway
SDM	System Dynamic Model
SLNAE	Self-Learning Nexus Assessment Engine
SSP	Shared Socioeconomic Pathways
WEFE	Water-Energy-Food-Ecosystem

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Executive Summary

The deliverable D2.1 identifies and present a portfolio of biophysical and socio-economic macro data/general trends that can be made available across all project case studies under uniform methodology, assumptions and modelling, in line with a set of selected IPCC scenarios, as combination of shared socioeconomic pathway (SSP) and representative concentration pathway (RCP) scenarios. This Deliverable gives an overview of the origin of the available data to support the integrated complexity science tools, their purpose within the NEXOGENESIS project, the model used, the sectors covered, and the spatial and temporal scale at which this quantitative information can be provided. To characterize physical, environmental trends between current and future conditions consolidated data available according to specific WEFE nexus dimensions from repository data and InterComparison projects (ISI-MIP, COPERNICUS, AgMIP, etc.) and outputs from ad-hoc modelling implementation have been documented and described in the deliverable.

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1 Introduction

1.1 Project summary

Water, Energy, Food, and Ecosystems are interconnected and part of a complex system referred to as the Water-Energy-Food-Ecosystem (WEFE) nexus. The assessment of the interactions between these components through the nexus approach is crucial to enhance synergies and minimize trade-offs between sectors, thus to inform decision makers with feasible strategies to accelerate sustainable and inclusive socio-economic development. The Nexogenesis (NXG) project aims at improving policies related to water, energy, food and ecosystems and contribute to the operationalization of the WEFE nexus approach by developing and validating three main solutions: i) the self-learning nexus assessment engine (SLNAE) that exploits artificial intelligence to provide a series of possible actions that maximise nexus performance; ii) a WEFE Nexus Footprint, i.e., a composite indicator that will contribute to monitor sustainability of resource management; iii) policy packages developed per each case study for streamlining water-related policy into the nexus which include the impact of external drivers such as the climate and the socio-economic system. The project aims at developing a coherent, consistent and replicable framework - co-created and validated by local experts and stakeholders - that will support out-scaling of the project`s outcomes to wider regions.

1.2 Case studies

NEXOGENESIS (NXG) will develop and apply a coherent and consistent framework in five case studies characterised by a large variety of nexus policy issues.

The project case studies are located in different geographical areas (Figure 1) and each of them address different challenges:

- Nestos River Basin (BG-EL): ecologically significant delta, hydropower, water diplomacy up-/downstream countries;

- Lielupe River Basin (LT-LV): increased fertiliser use, pollutant runoff, hydropower impacts, water diplomacy issues;

- Lower Danube Basin (SRB-BG-RO): iron gates hydropower, significant (80%) wetland loss, agriculture;

- Adige River Basin (IT): ecosystem services support, equitable resource distribution, lack of trust/collaboration, peculiar governance regime due to cultural and historical reasons;

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- Inkomoti-Usuthu Water Management Area (ZA-SZ-MZ): strategic management of water sources, three-nation, complex water diplomacy issues

Fig 1. Case studies geographical location.

The case studies represent: (i) diverse spatial, social, cultural, and development situations; (ii) strong WEFE nexus relations, with the potential for disruption from policy implementation; (iii) allow assessment of how water-related policy can be streamlined into the nexus; and (iv) project outcomes are potentially transferable to other regions.

1.3 Bio-Physical human modelling in NXG

The NXG WP2 aims at providing a portfolio of consolidated future biophysical and socio-economic data trends for each case study to characterize climatic, hydrological, environmental, and socio-economic variables, in line with a set of selected IPCC scenarios, as combination of shared socioeconomic pathway (SSP) and representative concentration pathway (RCP) scenarios. The framework of macro data/general trends has been structured, listing significant available variables that can be generated under uniform methodology, assumptions and modelling across all case studies. The inventory list is formulated and about to be presented to describe potential support for SDM development for the different case studies.

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2 Climate / Biophysical projections and trends

2.1 Data Sources

A general screening of potentially available climate and biophysical data, with listing produced and made available for the case studies and the entire consortium on the Surfdrive, i.e., the project platform identified for files sharing (Annex 1). Several main sources of climate and biophysical have been screened so far:

- Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)
- The COordinated Regional climate Downscaling EXperiment (CORDEX)
- Hydrology-related climate impact indicators Copernicus C3S
- Simulation of Evapotranspiration of Applied Water - GIS (SIMETAW-GIS)
- Global Biodiversity (GLOBIO) model for policy support

ISIMIP. The Coupled Model Intercomparison Project (CMIP5) in combination with the ISIMIP products has been suggested to provide relevant and harmonized modelling outputs for different sectors (Climate, Water, Agriculture, Forest, Biomes, terrestrial biodiversity, etc.) following common standard protocol and underlying climate forcing/scenarios. Thus, the ISIMIP data provides a consistent framework for cross-sectoral, cross-scale modelling of the impacts of climate change. The key goal of the ISIMIP is to contribute to the comprehensive (cross-sectoral) understanding of the impacts of politically and scientifically-relevant climate-change scenarios. The ISIMIP is organised in "simulation rounds" and the one that has been selected so far for achieving the purpose of the NXG project is the simulation round 2b, that is directly linked to specific sectors. ISIMIP2b considers impacts on different sectors at the global and regional scales: water, fisheries and marine ecosystems, energy supply and demand, forests, biomes, agriculture, agro-economics, terrestrial biodiversity, permafrost, coastal systems, health and lakes.

The focus topic for ISIMIP2b is to provide robust information about the impacts at different levels of global warming and related emission pathways (i.e. RCPs), as required for the elaboration of results for IPCC Reporting.
Each simulation round covers specific sectors namely: global and regional water, fisheries and marine ecosystems, energy supply and demand, regional forests, global biomes, and agriculture, agro-economic modelling, terrestrial biodiversity, permafrost, coastal systems, health, lakes,

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and fire. The sectors screened so far are the climate, water, agriculture, terrestrial biodiversity, biomes, and permafrost sector (Annex 1).

All the climate and biophysical data ISIMIP data proposed for the development of the System Dynamics Models (SDMs) within the NXG project are bias corrected and are available at global scale with a spatial resolution of 0.5°x0.5°. The frequency of the available climate and biophysical data ranges from daily to monthly to 30-yr mean temporal resolution depending on the variable. Data are available for the historical (1860-2005) and future (2006-2100) time period and under one or more climate scenarios i.e., RCP 2.6, RCP 4.5, RCP 6, RCP 8.5.

Hydrological and land modelling tools (e.g. WaterGAP, LPJmL, CLM45, ORCHIDEE) consolidated within ISIMIP2b, will allow the estimation of supply and demand from different nexus sectors under future climate. Furthermore, new versions (v3a and v3b) of ISIMIP modelling projections are foreseen in the upcoming future (starting from 2023), based on the latest CMIP6 projections.

The **COordinated Regional climate Downscaling EXperiment (CORDEX)**, implemented to improve downscaling of regional climate simulations and climate change scenarios to resolutions variable between 0.11, 0.22 and 0.44 degrees, according to different domains and projections. There are a total of fourteen official CORDEX domains, building on a common experimental framework. In particular, the entire EURO-CORDEX domain, shown in Figure 2, covers the four European NXG Case Studies with the same and homogeneous climate downscaled simulation run outputs. These have the highest resolution at 0.11-0.22 degrees (about 10-25km), with downscaling products based on CMIP5 program, therefore not the latest generation of global climate models (CMIP6). A subset of the Euro-CORDEX simulations have been bias-adjusted by a few different methods, and mostly available for mean/max/min temperature and precipitation. Downscaled simulation for the Euro-CORDEX domain from CMIP6 family simulations run are expected to roll out at the beginning of 2023.

Figure 2: The EURO-CORDEX domain

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Other simulations are available from other CORDEX domains, worldwide, including the AFRICA-CORDEX domain, which would cover the NXG South-African case study with climate variables at resolution variable between 0.22 and 0.44 degrees. Clearly, simulations from this domain are independent and distinct from those developed from EURO-CORDEX.

Copernicus C3S. Hydrology-related climate impact indicators from 1970 to 2100 derived from bias adjusted European climate projections, based on hydrological impact modelling, forced by bias adjusted EURO-CORDEX regional climate simulations. The dataset provides both daily mean river discharge, and a set of climate impact indicators of water quantity and quality.

The Copernicus biophysical data proposed to the NXG case studies so far are able to cover the water sector especially in terms of water quality (e.g., phosphorus and nitrogen concentration in the basin). The data are bias corrected and are available at European level at catchment scale and on a 5x5 km resolution. The hydrological model (E-Hype), the climate forcing (e.g., EC-Earth, HadGEM2-ES) and the regional climate models (e.g., RACMO22E, CCLM4-8-17) have been identified for each variable proposed.
The Copernicus data are available as mean values, but also monthly time-series upon request, over the 30-yrs period of time, i.e., 1971-2000, 2011-2040, 2041-2070, 2071-2100. Data are available as yearly and/or monthly temporal resolution.

GLOBIO: GLOBIO calculates indexes of biodiversity, expressed by the mean species abundance (MSA) indicator, average population/level across a range of species or species groups, as a function to different stressors including land use, road disturbance, fragmentation, nitrogen deposition and climate change. The core of the model consists of quantitative pressure-impact relationships established based on extensive terrestrial biodiversity databases. The model can be used as a static assessment of how far below a pristine state the current environment is or to estimate how a change in any of the stressors would lead to a stress in biodiversity or ecosystem integrity, as indicated by MSA. GLOBIO thus combines pressure–impact relationships with data on past, present or future pressure levels, resulting in maps of MSA values and variation due to each pressure. These maps are then combined to obtain overall MSA values.

The GLOBIO (v4) model has been implemented with global maps of drivers providing information about biodiversity for the NXG case study (e.g. Mean Species Abundance, MSA). Data are available at global level with a spatial resolution of 300x300 m and the values of the variables selected so far range from 0 to 1 indicating local biodiversity intactness relative to a pristine reference situation. Data are available for different climate scenarios (i.e. RCP 2.6, RCP 6, and RCP 8.5) and for a period of time that ranges from 2015 to 2050. Further refining of these analyses can be implemented for case studies using refined and more specific regional data in combination with observation of species abundance.

SIMETAW-GIS: The SIMETAW-GIS (Simulation of Evapotranspiration of Applied Water-GIS) model (Masia et al., 2021) was implemented using GIS libraries available in R

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programming language to allow spatially distributed applications. The model is able to estimate atmosphere-soil-water-crop interactions at different temporal and spatial scales. The model can accommodate data from different sources; the scenarios (e.g., RCPs/SSPs) and the spatial and temporal scales (e.g., regional, national, global) of the model outputs depend on the input data used to run the model simulations. SIMETAW_GIS is used to estimate the daily reference, well-watered crop and actual evapotranspiration (ETo, ETc, ETa), the evapotranspiration of applied water (ETaw), the irrigation schedule (e.g., irrigation dates and number of irritations), the crop growth and the yield reduction for 69 crops managed in both rainfed irrigated conditions. The spatial platform couples and automates interactions using extensive climate and environmental geospatial datasets and allows for different agronomic practices to process the soil water balance for multiple years and pixels across regional and continental scales. The tool has good potential in estimating climate change impact on crop water needs at regional scale and can be used to support policy decisions and strategies targeted to sustainable integrated resource management.

2.2 NEXUS Sectors (Models and Variables)

The climate and biophysical variables screened so far from the ISIMIP 2b database are able to cover the climate, water, agriculture, terrestrial biodiversity, biomes, and permafrost sectors (see details in Annex 1). The SIMETAW_GIS model complement the biophysical variable for agricultural and water sector provided by the ISIMIP 2b. Regarding the water sector quantitative information about water quality are provided by the Copernicus C3S database. Information about biodiversity are available both from the ISIMIP 2b database and the GLOBIO model.

2.2.1 Climate

Climate scenarios projections are representations of various possible future states of the climate system, based on numerical model simulations. These models describe the complex processes and interactions affecting the climate system, but also use information about anthropogenic climate forcing. Different factors of anthropogenic activity like socio-economic, technological, demographic and environmental development are characterized in climate models, such as changes in GHG concentrations, land use, etc.

ISIMIP 2b.

Bias corrected data are based on simulations of five GCMs (see Tab 1) from CMIP5 archive.

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Table 1: GCMs from which ISI-MIP data were produced for round 2b

Acronym	Origin
HadGEM2-ES	Met Office Hadley Centre (UK) and Instituto Nacional de Pesquisas Espaciais (BR)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace (FR)
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (U Tokyo), and National Institute for Environmental Studies (JP)
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory (US)
NorESM1-M	Norwegian Climate Centre (NO)

They consist of historical model runs for the years 1950–2005 and scenarios each for the years 2006–2099. From each model, four scenario based on the Representative Concentration Pathway (RCP) emission scenarios (Moss et al. 2010, van Vuuren et al. 2011, Meinshausen et al. 2011) are available: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Thus, there are 20 different ISI-MIP climate driving projection scenarios, for a combination of 5 climate models and 4 emission scenarios. A model ensemble with a high number of endmembers ensures better coverage of model uncertainty and allows for quantile and other statistical analyses. The selected five models cover a broad response space defined by global temperature (figure 3, adapted by Portman et al., 2013)

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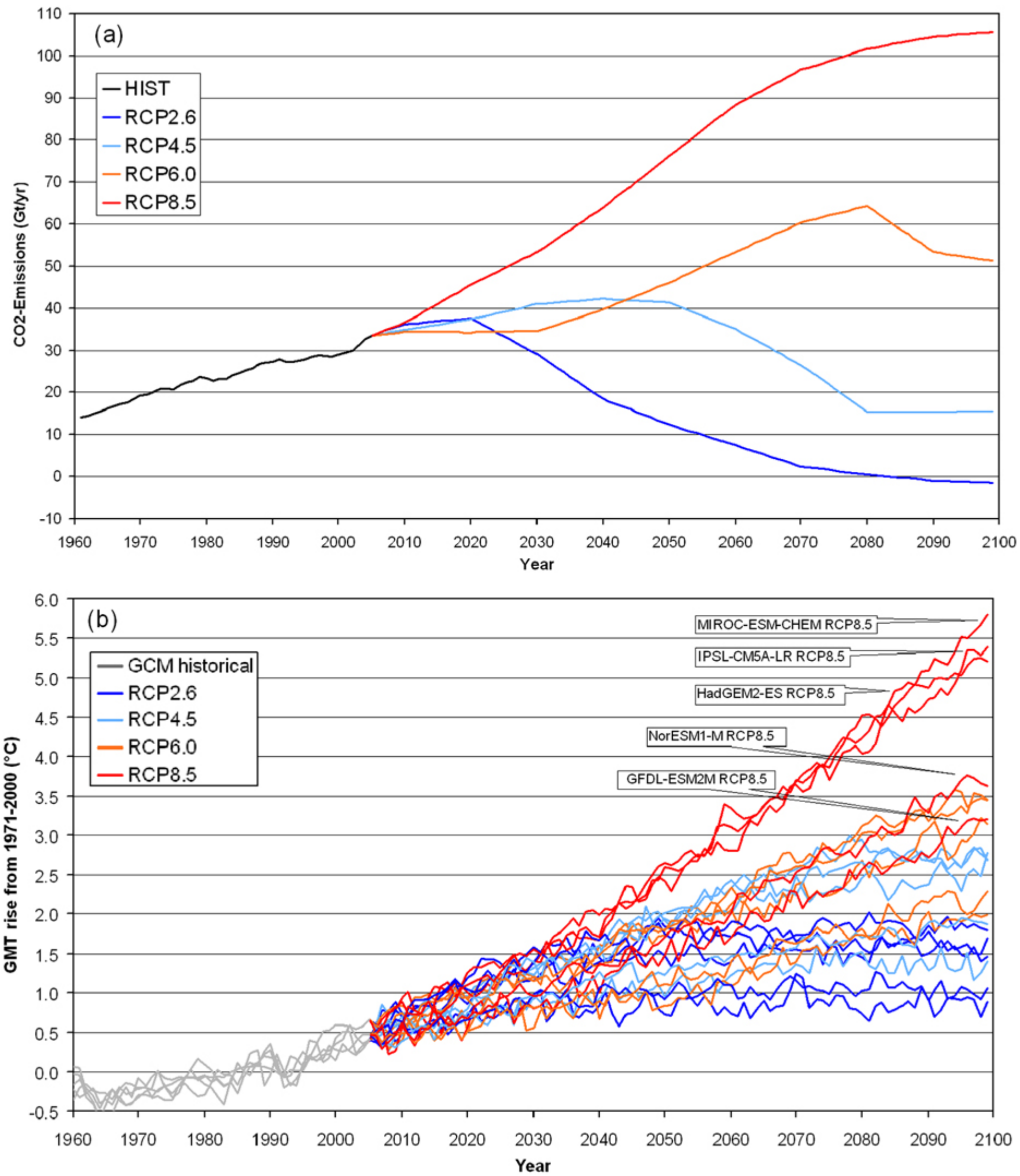

Figure 3. *CO_2-emissions from anthropogenic and natural sources(a), global mean temperature (GMT) as a function of time compared to 1971–2000 average (b), for historical periods until 2005, and starting in 2006 for RCPs 2.6, 4.5, 6.0, and 8.5, for five different GCMs, respectively (*Portman et al., 2013).

The climate trajectories of the RCPs do not substantially diverge before the middle of the 21st century, therefore it is advisable that the most remarkable and expected differences for assessments are inferred following the second half of the century.

The applied bias correction method preserves the long-term trends of the variables. In a first step, only the monthly variability and mean are corrected using a constant offset or multiplicative correction factor that corrects for long-term differences between the simulated and observed monthly mean data in the historical period. Then the daily variability of the simulated data is modified about their monthly means to match the observed daily variability.

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An implicit downscaling was implemented to the finer resolution of a 0.5° using the WATCH Forcing Data (WFD, Weedon et al. 2011) as observation-based reference data. The variable selected so far from the ISIMP database for the development of the NXG complexity science are:

Total Precipitation (short_name *pr*) Total precipitation is expressed as kg m-2 s-1 or mm day-1 and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Average Temperature (short_name *tas*) Near-Surface Air average Temperature is expressed as K° or C° and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Maximum Temperature (short_name *tasmax*) Near-Surface Air Maximum Temperature is expressed as K° or C° and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Minimum Temperature (short_name *tasmin*) Near-Surface Air Minimum Temperature is expressed as K° or C° and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Snowfall (short_name *prsn*) Total snowfall is expressed as kg m-2 s-1 or mm day-1 and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Relative Humidity (short_name *rhs*) Near-Surface Average Relative Humidity is expressed as % and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Shortwave Radiation (short_name *rsds*) Surface Downwelling or Incoming Shortwave Radiation is expressed as W m-2 and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Longwave Radiation (short_name *rsds*) Surface Downwelling or Incoming Longwave Radiation is expressed as W m-2 and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Wind Speed (short_name *wind*) near surface wind speed (m s-1) is expressed as m s-1 and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Atmospheric pressure (short_name *ps*) Surface Air Pressure is expressed as Pa and is available at daily or monthly temporal resolution under RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

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CORDEX

CORDEX simulations have been performed for Europe (EURO-CORDEX) for two different horizontal resolutions:

● 0.44 degree (EUR-44, ~50 km)
● 0.11 degree (EUR-11, ~12.5km)

A subset of the Euro-CORDEX simulations (both EUR-11 and EUR-44) have been bias-adjusted by a few different methods, and available for mean/maximum and minimum temperature and precipitation. The downscaling exercise in the CORED project implement specific dynamic downscaling though Regional Climate Modelling, which implies more reliable downscaling at higher resolution. However, such dynamic modelling is often highly demanding in terms of computing time with fewer projections available associated to bias correction limited only to few variables (i.e. mean/maximum and minimum temperature and precipitation). Later implementation of Euro-CORDEX simulations from CMIP6 archive may be available only from 2023 onward.

2.2.2 Agriculture

In the NXG project, the agricultural sector is covered by two data sources, i.e., the ISIMP2b database and the SIMETAW_GIS model

ISIMIP 2b

The ISIMIP database provides modelling output of agricultural production in terms of crops cultivated for both food and energy purposes at global scale. Four impact-model participate in the ISIMIP simulation round 2b for this sector: CLM4.5, *Community Land Model;* GEPIC, *GIS-based EPIC model;* LPJmL, *Lund-Potsdam-Jena managed Land;* PEPIC. *Python-based Environmental Policy Integrated Climate (EPIC) model* (model details at https://www.isimip.org/impactmodels/).

CLM4.5. *Community Land Model is the "land model for the Community Earth System Model (CESM). It examines the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. The central theme is that terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, are important determinants of climate. Model components consist of: biogeophysics, hydrologic cycle, biogeochemistry and dynamic vegetation. The land surface is represented by 5 primary sub-grid land cover types (glacier, lake, wetland, urban, vegetated) in each grid cell. The vegetated portion of a grid cell is further divided into patches of plant functional types, each with its own leaf and stem area index and canopy height. Each subgrid land cover type and PFT patch is a separate column for energy and water calculations. The current version of the Community Land Model is CLM4.5. Simulations for ISIMIP2b were conducted with CLM4.5, and include an interactive Carbon and Nitrogen cycle with the crop model. ISIMIP2a simulations were conducted either with CLM4.0 (global water) or CLM4.5post (agriculture, at 2° resolution)".*
https://www.isimip.org/impactmodels/details/198/.

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LPJmL. *Lund-Potsdam-Jena managed Land was developed "from LPJ, a Dynamic Global Vegetation Model (DGVM), which was designed to simulate the global terrestrial carbon cycle and the response of carbon and vegetation patterns under climate change. As carbon and water cycles are intimately linked, it was quickly extended to also simulate the terrestrial water cycle…The model LPJmL ("Lund-Potsdam-Jena managed Land") is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. Using a combination of plant physiological relations, generalized empirically established functions and plant trait parameters, it simulates processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, runoff, evapotranspiration, irrigation and vegetation structure.*

LPJmL. is currently the only DGVM that has dynamic land use fully incorporated at the global scale and also simulates the production of woody and herbaceous short-rotation bioenergy plantations and the terrestrial hydrology. It differs from other models in the wider field by computing carbon, nitrogen and water flows explicitly: most other macro-hydrological models lack the important vegetation structural and physiological responses that influence the water cycle, while most other vegetation models lack the advanced consistent water balance of LPJmL, or are not global in scale."
https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml

PEPIC. *Python-based Environmental Policy Integrated Climate (EPIC) model is developed in Python and is based on the EPIC model. PEPIC was initially developed "to evaluate the impacts of soil erosion on soil productivity. EPIC can be used to simulate a large number of soil-water-climate-management processes, for example, weather, hydrology, erosion, pesticide, nutrient, plant growth, tillage, soil temperature, and environmental control. EPIC simulates crop growth at a daily step based on the concept of energy-biomass conversion. Daily potential biomass increase is the product of intercepted solar radiation and a crop-specific biomass-energy ratio. Several crop growth stresses (water, nutrient, temperature, aeration, and salinity) are considered to reduce the potential biomass to actual biomass. The crop grain yield is estimated by the product of the harvest index and actual biomass accumulation".* https://www.nature.com/articles/s41597-019-0023-8

GEPIC. *GIS-based EPIC model was developed "to simulate spatial and temporal dynamics of the major processes (e.g. crop growth, hydrological cycle, nutrient cycle, carbon cycle, erosion, climate change impact) of the soil-crop-atmosphere-management system. GEPIC is a GIS-based agroecosytem model integrating a bio-physical EPIC model (Environmental Policy Integrated Climate) with a Geographic Information System (GIS). The GEPIC model can be used to simulate the spatial and temporal dynamics of the major processes of the soil–crop–atmosphere-management system. The first version of the GEPIC model was developed between 2004 and 2005 to serve for a Swiss National Science Foundation funded project "Water Scarcity – Its Measurement and Implications for Virtual Water Import". The model was developed to quantify crop yield and crop water use on a global scale with a spatial resolution of 30 arc-minutes (around 50 km by 50 km nearby the equator). Since the GEPIC model can potentially use all functions of EPIC, it has later been used to simulate impacts of climate change on crop production, green and blue water use assessments, effects of biofuel production on land and water resources, soil and water erosion etc.". https://www.eawag.ch/fileadmin/Domain1/Abteilungen/siam/software/modawec/gepic_user_manual.pdf* .

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Crop modelling simulations are available, according to the above mentioned models, following forcing driven by different ISIMIP 2B bias corrected climate model inputs (i.e. GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5). Within the ISIMIP2b, the models above mentioned generate quantitative information for 12 crops i.e., Cassava, Field Pea, Ground Nuts, Maize, Millet, Rapeseed, Rice, Soy, Sugar Beet, Sugarcane, Sun Flower, Wheat considering managed in both rainfed (noirr) and in full irrigated conditions (firr).

The agricultural model simulations selected so far do either or not consider future CO_2 fertilization changes; provided data can then consistently consider CO_2 concentration in the atmosphere fixed to 2005, i.e., 378.81 ppm, or transient levels following RCPs scenarios (i.e., climate and CO2 scenario: 2005-CO_2). Keep in mind that this alternative scenario is to check the direct effect of CO2 fertilization on crop physiology. Changes in management up to 2005 are considered also for the socio-economic scenario (i.e., human influence & land-use scenarios in terms of variation of land use, water abstraction, nitrogen deposition and fertilizer input; human influence and land use scenario: 2005CO_2, CO_2). Data are delivered yearly per growing season with a resolution of 0.5°x 0.5°. The variable selected so far from the ISIMP database for the development of the NXG complexity science are:

Irrigation Water Withdrawal. The irrigation water withdrawal is expressed in mm of water per growing season. The data refers to irrigation water withdrawn in case of optimal irrigation, in addition to rainfall. The model simulations are under the assumption that there are no losses in water distribution and conveyance and that there is unlimited water supply. The data are available for the historical climate and future under RCP 2.6 and RCP 6.0 climate scenarios.

Actual evapotranspiration. The actual evapotranspiration is expressed in mm of water consumed by the crop per growing season. This is seen as the portion of all water (including rain) that is evapotranspired. The data are available for the historical climate and future under RCP 2.6 and RCP 6.0 climate scenarios.

Nitrogen application rate. The total nitrogen application rate is expressed as kg ha^{-1} per growing season. The data are available for the historical climate and future under RCP 2.6 and RCP 6.0 climate scenarios.

Planting and maturity dates. Both the planting and the maturity day are expressed as Julian day, i.e., day of the year. The data are available for the historical climate and future under RCP 2.6 and RCP 6.0 climate scenarios.

Crop Yield. The crop yield is expressed in dry matter as tons ha^{-1} per growing season. The crop model simulations have a global spatial coverage under the assumption that the crops are cultivated everywhere. The data are available for the historical (1860-2005) and future (2006-2100) climate. RCP 2.6, RCP 6.0, and RCP 8.5 are used to represent the future climate change scenarios.

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SIMETAW-GIS

SIMETAW-GIS model provides daily quantitative information for more than 60 irrigated and rainfed crops. The temporal and the spatial scale and the RCPs depend on the input data used to run the model simulations.

Crop evapotranspiration. The crop evapotranspiration (Etc) is expressed in mm and refers to the amount of water consumed by a specific crop cultivated in well-water conditions and more in general in optimal agronomic conditions. The crop evapotranspiration is the product of the ETo and a crop coefficient (Kc) which depends on the crop and its physiology, its age, the absorbed light, the stage of the growing season, and the soil humidity. In SIMETAW-GIS model the ends of the growth periods are estimated as a percentage of the length of the season (Snyder et al. 2012) . This approach differs from the one proposed by the FAO where the ending points of the growing season are identified by estimating the number of the days in each step of the growth periods. Being often unknown to the crop growers the information about the number of days within growth periods, the application of the percentages might be an advantage.
The model allows the adjustment of the Kc during the midseason as a function of the local climate by using the ETo as an input following Guerra et al. (2015) equation.

Actual evapotranspiration. The actual evapotranspiration (Eta) is the crop water consumption under no-standard conditions. The Eta is obtained as the product between the Etc and a stress coefficient (Ks) which depends on the soil water conditions (Ks = 1, no-water deficit; Ks <1, water deficit).

Crop yield reduction. The crop yield decrease is expressed as percentage and it defines the reduction in crop yield when crop stress is caused by a soil water shortage. This variable expresses the relation between yield and evapotranspiration. In SIMETAW-GIS the yield losses are computed following Steduto et al. (2009), thus taking into account the crop evapotranspiration (i.e., water amount consumed by a specific crop in well-watered conditions), the actual evapotranspiration (i.e., crop evapotranspiration in case of water deficit), and the yield response factor.

2.2.3 Water

In the NXG project, the water sector is covered by three data sources. The quantitative information about the water quantity in the selected river basin is provided by the ISIMP database and the SIMETAW_GIS model. Copernicus C3S and ISIMP 2b include quantitative information about water quality.

ISIMIP 2b.

The water model simulations selected so far from the ISIMIP2b, considers changes in land use and other human influences up to 2005, with options to include future projections. Historical and future bias corrected data can be available daily and/or monthly with a resolution of 0.5°x 0.5°. Different climate scenarios can be available, i.e., historical, RCP2.6, RCP 6.0, and

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RCP8.5. All the variables selected so far, can consider the effect on vegetation of CO_2 fertilization and their future increasing availability. The socio-economic scenario can be available considering the historical period varying historical land use, nitrogen deposition and fertilizer input (1861-2005; histsoc); the 2005 as fixed year and the related values of land use (2005soc), nitrogen deposition and fertilizer input; the future period varying land use, water abstraction, nitrogen deposition and fertilizer input according to SSP2 and RCP2.6 and SSP2 and RCP6.0 (2006-2099; RCP26soc and RCP60soc). In the latter, for dams and reservoirs, 2005 is used as a fixed year. In one of the socio-economic scenarios also no direct human influences on the water cycle is considered (nosoc). In the ISIMIP 2b water sector, the "human influences" is considered as the human interference directly with the hydrological fluxes of the water cycle for the purposes of e.g., irrigation and domestic water use, manufacturing and livestock production, water management.

The impact-models that participate in the ISIMIP simulations round 2b for the water variables selected so far for the NXG project are eight: CLM45, H08, JULES-W1, LPJmL, MATSIRO, ORCHIDEE, PCR-GLOBWB, WaterGAP2.

CLM45. *"The Community Land Model is the land model for the Community Earth System Model (CESM). It examines the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. The central theme is that terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, are important determinants of climate. Model components consist of: biogeophysics, hydrologic cycle, biogeochemistry and dynamic vegetation. The land surface is represented by 5 primary sub-grid land cover types (glacier, lake, wetland, urban, vegetated) in each grid cell. The vegetated portion of a grid cell is further divided into patches of plant functional types, each with its own leaf and stem area index and canopy height. Each subgrid land cover type and PFT patch is a separate column for energy and water calculations."* https://www.isimip.org/impactmodels

H8. **"***H08 is a grid-cell based global hydrological model. It consists of six sub-models, namely land surface hydrology, river routing, reservoir operation, crop growth, environmental flow, and water abstraction. The formulations of sub-models are described in detail in Hanasaki et al. (2008a,b, 2010). In the standard simulation settings, H08 spatially covers the whole globe at a resolution of 0.5° in order to assess geographical heterogeneity of hydrology and water use. Simulation period is typically for several decades and the calculation interval is a day. The six sub-models exchange water fluxes and updates water storage at each calculation interval with the complete closure of water balance (the error is less than 0.01% of the total input precipitation). These characteristics enable us to explicitly simulate the major interaction between natural water cycle and major human activities of the globe. Source code and the manuals of H08 is open to the public, available at http://h08.nies.go.jp. In addition, a simple groundwater scheme was added to the land surface hydrology sub-model. It enabled us to estimate water abstraction from six major water sources, namely, streamflow regulated by global reservoirs (i.e. reservoirs regulating the flow of main channel of the world major rivers), aqueduct water transfer, local reservoirs, seawater desalination, renewable groundwater, and non-renewable groundwater."* https://www.isimip.org/impactmodels/details/52/

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JULES W1. *The Joint UK Land Environment Simulator (JULES) is a land surface model where "W1" stands for water-related simulations run within the ISMIP framework. Jules W1, former Jules_TUC (Joint UK Land Environment Simulator) is a land surface and atmosphere model that allows simulations of water, carbon, and energy fluxes. Further details of JULES in the Biome section.*

LPJmL. "The model LPJmL ("Lund-Potsdam-Jena managed Land") is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. Using a combination of plant physiological relations, generalized empirically established functions and plant trait parameters, it simulates processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, runoff, evapotranspiration, irrigation and vegetation structure.The LPJmL model simulates potential natural vegetation, represented by 9 plant-funtional types (PFTs), as well as agriculture, represented by 12 crop-functional types (CFTs) and managed grasslands, and biomass for bioenergy plantations represented by 3 biomass-functional types (BFTs). The composition of natural vegetation is determined dynamically. BFTs, CFTs and managed grasslands are grown on prescribed areas with a distinction between irrigated and rainfed agriculture."

https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml

https://www.isimip.org/impactmodels/details/81/.

MATSIRO. *"The Minimal Advanced Treatments of Surface Integration and RunOff (MATSIRO) model is developed to represent all major hydrologic processes governing water and energy exchanges between land and atmosphere in a physically based way." (Koirala et al., 2010)*

ORCHIDEE. *The ORganizing Carbon and Hydrology In Dynamic Ecosystems Environment (ORCHIDEE), renamed in 2019 as ORCHIDEE-DGVM, "is the land surface model of the IPSL (Institut Pierre Simon Laplace) Earth System Model. Hence, by conception, the ORCHIDEE model can be run coupled to a global circulation model. In a coupled set-up, the atmospheric conditions affect the land surface and the land surface, in turn, affects the atmospheric conditions. Coupled land-atmosphere models thus offer the possibility to quantify both the climate effects of changes in the land surface and the effects of climate change on the land surface. However, when a study focuses on changes in the land surface rather than on the interaction with climate, ORCHIDEE can be run off line as a stand-alone land surface model. The stand-alone configuration receives the atmospheric conditions such as temperature, humidity and wind, to mention a few, from the so-called 'forcing files'. Unlike the coupled set-up, which needs to run at the global scale (but with the possibility of a regional zoom), the stand alone configuration can cover any area ranging from the global domain to a single grid point."*

https://orchidee.ipsl.fr/about-orchidee/

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PCR. GLOBWB.*"The global hydrological model PCR-GLOBWB simulates for each grid cell (0.5 degree globally over the land) and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers (infiltration, percolation, and capillary rise) and between the top layer and the atmosphere (rainfall, evapotranspiration, and snow melt). The model also calculates canopy interception and snow storage. Water use for agriculture, industry and households is dynamically linked to hydrological simulation at a daily time step. The simulated local direct runoff, interflow, and baseflow are routed along the river network that is also linked to water allocation and reservoir operation scheme."* https://www.isimip.org/impactmodels/details/104/

WaterGAP**.** *"WaterGAP is a global hydrological model that quantifies human use of groundwater and surface water as well as water flows and water storage and thus water resources on all land areas of the Earth. Since 1996, it has served to assess water resources and water stress both historically and in the future, in particular under climate change. It has improved our understanding of continental water storage variations, with a focus on overexploitation and depletion of water resources. In this paper, we describe the most recent model version WaterGAP 2.2d, including the water use models, the linking model that computes net abstractions from groundwater and surface water and the WaterGAP Global Hydrology Model (WGHM)."* (Müller Schmied et., 2020). The GRanD Global Reservoir and Dam database (http://www.gwsp.org/products/grand-database.html) has been used to define reservoirs location and capacities, under simulation, the Global Lakes and Wetlands Database were used to characterize natural water bodies.

The variables selected so far from the ISIMIP 2b database for covering the water sector and subsequently developing the NXG complexity science are:

Total Runoff. The Total runoff is expressed in kg m-2 s-1 and is the sum of surface and subsurface runoff. Data are available at both daily and monthly scale.

Surface runoff. The surface runoff is expressed in kg m-2 s-1 and it is the water that leaves top soil layer (the surface layer). Data are available at both daily and monthly scale.

Subsurface runoff. The subsurface runoff is expressed in kg m-2 s-1 and it is the sum of water that flows out from the subsurface layer/s and includes the groundwater layer when present. It equals the groundwater runoff in case of a groundwater layer below only one soil layer. Data are available at both daily and monthly resolution.

Groundwater recharge. The groundwater recharge is expressed and it is water that percolates through the soil layer/s into the groundwater layer. Data are available at monthly resolution.

Groundwater runoff. The groundwater runoff is expressed in kg m-2 s-1 and it is the water that leaves the groundwater layer. Data are available at monthly resolution.

Discharge. The discharge is expressed in m3 s-1. Data are available at both daily and monthly resolution.

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Monthly maximum and minimum of daily discharge. The monthly minimum of daily discharge is expressed as m3 s-1. Data are available at monthly resolution.

Total Evapotranspiration. The total evapotranspiration is expressed as kg m-2 s-1 and it is the sum of evaporation, transpiration, sublimation, interception losses. Data are available at monthly resolution.

*Potential Evaporation***.** The potential evaporation is expressed as kg m-2 s-1. As for the total evapotranspiration, but with all the resistances set to zero, except the aerodynamic one. Data are available at monthly resolution.

Total Soil Moisture Content. The total soil moisture content is expressed in kg m-2 and it is equal to the soil water storage. Data are available at monthly resolution.

Total Soil Moisture Content Available for Evapotranspiration. The total Soil Moisture Content Available for Evapotranspiration is expressed in kg m-2 and it is the total simulated soil moisture available for evapotranspiration. Data are available at monthly resolution.

Total water storage. The total water storage is expressed in kg m-2 and it is the water storage in all compartments (monthly mean). Data are available at monthly resolution.

Groundwater storage. The groundwater storage is expressed in kg m-2 the water storage in the groundwater layer (monthly mean). Data are available at monthly resolution.

Lake storage. The lake storage is expressed in kg m-2 and it is the water storage in lakes (monthly mean) - except for reservoirs. Data are available at monthly resolution.

Wetland storage. The wetland storage is expressed in kg m-2 and it is water storage in wetlands (monthly mean). Data are available at monthly resolution.

Reservoir storage. The reservoir storage is the water storage in reservoirs (monthly mean). Data are available at monthly resolution.

River storage. The river storage is the water storage in rivers (monthly mean). Data are available at monthly resolution.

Copernicus C3S.

The quantitative information about water quality is available at catchment level from the Copernicus C3S database for the European domain from 1970 to 2100. Data are provided daily and as 30 year annual and monthly means. The variables selected so far from the C3S database for the development of the NXG complexity science are based on the E-HYPE model. E-HYPE model is "*based on the continuous process-based hydrological model HYPE (HYdrological Predictions for the Environment; Lindström et al. 2010), which simulates components of the catchment water cycle and water quality. The model is semi-distributed, in which a river basin may be subdivided into multiple subcatchments, which are further subdivided into hydrological*

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response units (HRUs) based on soil type and land use classes. It has conceptual routines for the major hydrological surface and subsurface processes (e.g., snow/ice accumulation and melting, evapotranspiration, surface and macropore flow, soil moisture, runoff generation, groundwater fluctuation, routing through rivers and lakes), land management , (irrigation, abstractions), and nutrient turnover (diffuse and point source releases, solid-matter and dissolved sub-surface pools, plant uptake, riverine transport) that are controlled by a number of parameters that are often linked to physiography to account for spatial variability and estimated through calibration."
https://datastore.copernicus-climate.eu/documents/sis-hydrology-derived/C3S_D424.SMHI.3.1c_HydrologicalModelsSpecification_v1-1.pdf

From such hydrological model runs, variables selected so far for the NXG project are:

Total Nitrogen concentration in catchments. The total nitrogen (N) concentration in catchment is expressed in mg L^{-1}. The Nitrogen concentration is computed as the mass of N divided by the volume of water. The indicator is calculated as the annual or monthly mean values of total N concentration, from a catchment averaged over a period of 30 year, while for the future periods, it is computed as a relative change against the reference (1971-2000) period.

Total Nitrogen load in catchments. Total N load in catchments is expressed in kg year-1 or kg month-1 for reference period. N load is the product of river discharge volume and the N concentrations. The indicator is calculated as the annual or monthly mean values of total N load from a catchment averaged over a period of 30 year, while for the future periods, it is computed as a relative change against the reference (1971-2000) period.

Total Phosphorus concentration in catchments. The total *Phosphorus* (P) concentration in catchment is expressed in mg L^{-1}. The P concentration is computed as the mass of P divided by the volume of water. The indicator is calculated as the annual or monthly mean values of total P concentration, from a catchment averaged over a period of 30 year, while for the future periods, it is computed as a relative change against the reference (1971-2000) period.

Total Phosphorus load in catchments. Total P load in catchments is expressed in kg year-1 or kg month-1 for reference period. P load is the product of river discharge volume and P concentrations. The indicator is calculated as the annual or monthly mean values of total P load from a catchment averaged over a period of 30 year, while for the future periods, it is computed as a relative change against the reference (1971-2000) period.

Water temperature in catchments. Water temperature in catchments is expressed in °C and it refers to the simulated water temperature in a specific catchment. The indicator is computed as the mean annual values of water temperature for a period of 30 years, while for the future periods, it is computed as an absolute change against the reference (1971-2000) period.

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SIMETAW-GIS

SIMETAW-GIS model provides daily quantitative information for more than 60 irrigated and rainfed crops. The temporal and the spatial scale and the RCPs depend on the input data used to run the model simulations.

Reference evapotranspiration. The reference evapotranspiration (ETo) is expressed in mm and refers to the evaporative request of the atmosphere for a hypothetical crop. ETo is only affected by meteorological variables, thus crop and soil characteristics are not considered. The ETo refers to a virtual well water crop entirely covering the soil, with a height of 12 cm, albedo of 0.23, and surface resistance fixed to 70 s m-1. In SIMETAW_GIS model, it is estimated by applying the Hargreaves-Samani (ETo_HS, Hargreaves and Samani, 1985) equation or the standardized FAO-56 Penman-Monteith reference evapotranspiration equation for short canopies (ETo_PM, Allen et al., 1998, 2005, 2006) depending on data availability. In the ETo_PM computation, SIMETAW_GIS allows the adjustment of the canopy resistance allowing the assessment of the effect of CO_2 concentration changes in the atmosphere following the equation proposed by Snyder et al (2011). This adjustment allows the estimation of future climate change impact on crop water requirements.

Net irrigation application. The net irrigation application (NA) is the amount of water that is applied for each irrigation event. It is considered as the water amount necessary to refill the soil to field capacity. In the model, this variable is computed in two different ways according to the step of the crop growing season. During the crop initial growth, so when only the 10% of the soil is cover by the crop, the net application depends on the mean Eto during the initial period, the coefficient of the bare soil, and the number of water applications scheduled during this specific period of time. From the beginning of the mid-season onward, thus from the effective full crop cover, the net water application takes into account the characteristics of the irrigation system, the water management, and the runoff.

Evapotranspiration of applied water. The evapotranspiration of applied water (ETaw) is expressed in mm and it is the sum of the net irrigation applications. ET_{aw} is an estimation of the total amount of water applied by irrigation that contributes to the crop evapotranspiration during a crop growing season. ETaw does not include water from other sources (e.g., in-season effective rainfall, seepage from levees or water from water tables, and preseason stored soil water)

Irrigation scheduling. SIMETAW_GIS provides the irrigation scheduling in terms of number of irrigation events, irrigation dates, and amount of water to apply (see NA description). The number of irrigation (Ni) is estimated considering the evapotranspiration of applied water and the management of allowable depletion, i.e., the amount of water that may be depleted between irrigation events without incurring in deficit of water.

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2.2.4 Ecosystems/Biomes

The biomes sector is covered by the ISIMIP 2b database. The impact models involved in this sector are six: CARAIB, CLM45, JULES, LPJ-GUESS, LPJmL, ORCHIDEE, ORCHIDEE-DGVM

CARAIB. *"CARAIB (CARbon Assimilation In the Biosphere) dynamic vegetation model is a process-based model which calculates carbon and water fluxes between the atmosphere and the terrestrial biosphere. It simulates the major processes of the plant development (establishment, growth, decease) as well as their geographic distributions (Plant Functional Types or species) in response to climate change. Its various modules describe respectively (i) soil hydrology, (ii) photosynthesis/stomatal regulation, (iii) carbon allocation and plant growth, (iv) litter/soil carbon dynamics, (v) vegetation cover dynamics, (vi) seed dispersal, and (vii) fire disturbance. Originally dedicated to natural plant types, CARAIB includes now the representation of agricultural plants, crops and meadows."*

https://www.isimip.org/impactmodels/

LPJ-GUESS. *"The Dynamic Land Ecosystem Model (DLEM) was developed to meet critical needs for understanding and predicting the large-scale patterns and processes of terrestrial ecosystems and continental margins, and complex interactions among climate, ecosystem and human in the context of multifactor global change. The DLEM couples major biophysical, biogeochemical, vegetation dynamical and land use processes, and works at multiple scales in time step ranging from daily to yearly and spatial resolution from meters to kilometers, from region to globe. The DLEM is characterized by the following features: 1) multiple factors driven; 2) fully-coupled cycles of carbon, nitrogen and water; 3) concurrently simulation of major greenhouse gases (CO2, CH4, N2O, & H2O); 4) dynamically tracking changes in land cover/use and vegetation distribution."* (Hanqin et al., 2010)

JULES. "*The Land Environment Simulation (JULES) System is a demonstrably world class land environment simulation system, underpinned by excellent science, to deliver measurable socio-economic benefits. The JULES system is a unique tool that integrates a full suite of land-based processes, rigorously based on observations and theoretical science from a diverse community of scientists. The JULES system is a critical component of current UK-led coupled weather and climate prediction systems, and is also a powerful stand-alone tool, used to address science questions with societal impact. It is a process-based prediction system that can be used over a variety of spatio-temporal dimensions, with multiple configurations. The JULES system comprises a numerical modelling suite consisting of code, scientific configurations, documentation, driving and ancillary data, but also tools and data for evaluation and benchmarking. The JULES system plays a significant cross-cutting role increasing the scientific understanding within the following themes; Hydrology (, Ecosystem Services & Agriculture (ES&A), Urban (U) and Cryosphere (C). The science brings the following socio-economic benefits."* https://jules.jchmr.org/sites/default/files/JULES_vision.pdf

LPJ-GUESS. *"LPJ-GUESS is a process-based dynamic vegetation-terrestrial ecosystem model designed for regional or global studies. Models of this kind are commonly known as dynamic*

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global vegetation models (DGVMs). Given data on regional climate conditions and atmospheric carbon dioxide concentrations, it can predict structural, compositional and functional properties of the native ecosystems of major climate zones of the Earth.Outputs include vegetation composition and cover in terms of major species or plant functional types (PFTs), biomass and soil organic matter carbon pools, leaf area index (LAI), net primary production (NPP), net ecosystem carbon balance, carbon emissions from wildfires, biogenic volatile organic compounds (BVOCs), evapotranspiration, runoff, and nitrogen pools and fluxes. The latest version (4.1) includes further outputs and functionalities such as methane emissions, soil nitrogen chemistry, permafrost dynamics, and a new wildfire model." https://web.nateko.lu.se/lpj-guess/

Details about CLM45, LPJmL, and ORCHIDEE in the Water session.

The biome model simulations selected so far from the ISIMIP 2b database can be available for different climate scenarios, i.e. historical, RCP2.6, RCP 6.0, and RCP8.5. All the variables selected so far, can consider the effect on vegetation of CO2 fertilization and their future increasing availability. The socio-economic scenario can be available considering land use, nitrogen deposition, and fertilizer input constant to pre-industrial value (1661-1860; 1860soc); the historical period varying historical land use, nitrogen deposition and fertilizer input (1861-2005; histsoc); the 2005 as fixed year and the related values of land use (2005soc), nitrogen deposition and fertilizer input; the future period varying land use, water abstraction, nitrogen deposition and fertilizer input according to SSP2 and RCP2.6 and SSP2 and RCP6.0 (2006-2099; RCP26soc and RCP60soc). These SSPs scenarios are available for all the variable selected so far except for the Carbon Mass in Above Ground and below Vegetation Biomass. Bias corrected data with a resolution of 0.5°x 0.5° are delivered for the historical (1860-2005) and the future period (2006-2100). The variable selected so far from the ISIMIP 2b database for covering the Biomes sector and subsequently developing the NXG complexity science are:

Carbon Mass in Vegetation. The Carbon Mass in Vegetation is expressed in kg m^{-2} and is available at an annual resolution for the historical and future, under RCP 2.6, RCP6.0 climate, and RCP8.5. This variable is also relevant for the permafrost sector.

Carbon Mass in Above and Below Ground Vegetation Biomass. Carbon Mass in Above and Below Ground Vegetation Biomass is expressed in kg m^{-2} and is available at an annual resolution for the historical and future period, under RCP2.6 and RCP6.0 climate scenarios.

Carbon Mass Flux out of Atmosphere due to Gross Primary Production on Land. The Carbon Mass Flux out of Atmosphere due to Gross Primary Production on Land is expressed in kg m-2 s-1 and is available at an annual and monthly resolution for the historical and future period, under RCP2.6, RCP6.0, and RCP8.5 climate scenarios. This variable is also relevant for the permafrost sector. This variable is also relevant for the permafrost sector.

Carbon Mass Flux into Atmosphere due to Autotrophic (Plant) Respiration on Land ***(2033).*** Carbon Mass Flux into Atmosphere due to Autotrophic (Plant) Respiration on Land (2033) is expressed in kg m-2 s-1 and is available at an annual and monthly resolution for the historical and future period, under RCP2.6, RCP6.0, and RCP8.5 climate scenarios. This variable is also relevant for the permafrost sector.

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Carbon Mass Flux out of Atmosphere due to Net Primary Production on Land. The Carbon Mass Flux out of Atmosphere due to Net Primary Production on Land is expressed in kg m-2 s-1 and is available at an annual and monthly resolution for the historical and future period, under RCP2.6, RCP6.0, and RCP8.5 climate scenarios. This variable is also relevant for the permafrost sector.

Carbon Mass Flux into Atmosphere due to Heterotrophic Respiration on Land. Carbon Mass Flux into Atmosphere due to Heterotrophic Respiration on Land is expressed in kg m-2 s-1 and is available at monthly resolution for the historical and future period, under RCP2.6, RCP6.0, and RCP8.5 climate scenarios. This variable is also relevant for the permafrost sector.

Plant Functional Type Grid Fraction. Plant Functional Type Grid Fraction is expressed as a percentage and is available at annual resolution for the historical and future period, under RCP2.6, RCP6.0, and RCP8.5 climate scenarios. This variable is also relevant for the permafrost sector.

Transpiration. Transpiration is expressed in kg m-2 s-1 and is available at daily and monthly resolution for the historical and future period, under RCP2.6, RCP6.0, and RCP8.5 climate scenarios.

2.2.5 Biodiversity

Different model types have been used to simulate different aspects of biodiversity, such as correlative species distribution models, macroecological species richness models, process-based biodiversity models, and others. In particular, with the aim to build more comprehensive biodiversity metrics, and their variation due to environmental factors, Species Distribution Models are used to identify the potential niche of single species and/or groups and its relation to environmental factors. These factors more often include climate variables, widely used to predict a species' probability of occurrence under present and future climatic conditions. By overlapping modelled distribution functions for multiple species, as metrics of biodiversity/species richness, summed probability of occurrence or Mean Species Abundance (a proxy of species richness) has been defined by few model attempts.

ISIMIP 2b.

The BioScen1.5-MEM-GAM models are macroecological models of terrestrial vertebrate richness (amphibians, birds, mammals) using Generalized Additive Models as model algorithm. BioScen1.5-MEM-GAM are statistical models, which were calibrated using a 30-year average (1980-2009) from ISIMIP2 observed climate input data set and species richness maps derived from the International Union for Conservation of Nature (2011) and BirdLife International (2014) range maps of 15496 terrestrial vertebrate species (2964 amphibians, 8493 birds and 4039 mammals). Explanatory variables are limited to climate factors, thus excluding effect of other environmental factors (e.g. land use, topography, etc.). Outputs consist of 30-year means of aggregated summed probabilities of occurrence for different endemic or threatened animal

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groups (i.e. amphibian, terrestrial birds, mammals). The output variables available then include:

- *Species richness per cell of amphibian species*
- *Species richness per cell of terrestrial bird species*
- *Species richness per cell of terrestrial mammal species*
- *Summed probability of occurrence per cell of endemic amphibian species*
- *Summed probability of occurrence per cell of endemic terrestrial bird species*
- *Summed probability of occurrence per cell of endemic terrestrial mammal species*
- *Summed probability of occurrence per cell of threatened amphibian species*
- *Summed probability of occurrence per cell of threatened terrestrial bird species*
- *Summed probability of occurrence per cell of threatened terrestrial mammal species*

GLOBIO 4.

GLOBIO model (https://www.globio.info/what-is-globio) quantifies biodiversity intactness (using MSA-mean species abundance as an indicator), as a function of human pressures. Depending on the model used (terrestrial or aquatic) the human pressures accounted for are:

Terrestrial- “Land use”, “road disturbance”, “fragmentation”, “hunting”, “nitrogen deposition” and “climate change”.

Aquatic- “Land use”, “flow alteration”, “eutrophication” and “water temperature”.

As Nexogenesis is developed around generating water-related policies, the GLOBIO-aquatic approach is a better fit for the project as it accounts for the spatial interlinkages created by water bodies (Janse et al. 2016). To do this it uses an aggregated impact of the relevant drivers across a waterbody (i.e. instead of using “local land use” changes as a predictor, in a river it takes into account all of the aggregated land use changes upstream that will influence it).

Mean species abundance (MSA) is a local indicator of biodiversity intactness. It ranges from 0-1 where 1 means that biodiversity is locally fully intact, while 0 means the disappearance of all native species locally. It is calculated based on the abundance of individual species in a reference undisturbed situation vs the abundance of species under a driver of change.

Globio model presents a total of 9 drivers affecting biodiversity intactness (6 for terrestrial, 4 for aquatic). From this drivers “Land Use” impacts biodiversity the most, followed by climate change and contamination (atmospheric nitrogen deposition for terrestrial and eutrophication

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for aquatic), while the other drivers seem to have a minor impact in comparison (Janse et al 2015; Schipper et al 2020). Future predictions agree on an increase on the land needed to produce food (Popp et al, 2017), which will lead to an increase on the impact of land use change on biodiversity at global and local scales.

Data from six taxonomic groups is used in the terrestrial model (mammals, birds, reptiles, amphibians, terrestrial invertebrates and vascular plants) and seven for the aquatic model (plants, mosses, fishes, amphibians, macro-invertebrates, birds, mammals) that also accounts for algal blooms. The MSAs from each taxonomic group are combined together in order to establish cause-effect relationships (for certain drivers certain taxonomic groups are excluded as they are assumed to not be significantly affected).

The GLOBIO database already provides global maps of local terrestrial biodiversity intactness, as represented by the mean species abundance (MSA) indicator, at a 10 arcsecond spatial resolution, roughly 300m at the equator. Following variables are available from the GLOBIO 4 database for covering the biodiversity component and subsequently developing the NXG complexity science:

Mean species abundance (MSA) overall

Mean species abundance (MSA) plants

Mean species abundance (MSA) birds and mammals

N.B: **Further site-specific analyses of MSA can be expanded and refined with local specific data on biodiversity metrics and environmental drivers with an open-source framework available from GLOBIO using open-source software. The model is using Python as a scripting language to run various biodiversity pressure-response modules**

Implementation of the GLOBIO model, and its components can be compiled to follow a conceptual framework of stressors on biodiversity metrics based on literature (Brauman et al., 2007; Grizzeti et al., 2016) and the different indications (miroboard, surfdrive) shared within the project. The framework elaborates links to explicit variables across the nexus sectors that have been listed in this deliverable.

2.3 Purpose of data

In NXG, both data collection and generation are of crucial importance because they are linked to all the objectives and the activities run within the project. Data are at the base of the qualitative and quantitative analysis of the case study, i.e. development of conceptual mapping, casual loop diagram, and system dynamic models for the case studies. In addition, the data provided will be essential to in depth understanding of the interlinkages between the nexus components and the policy effects through Key Performance Indicators (KPI) and the development of a self-learning nexus assessment engine tool aimed at optimising the generation of policies.

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3 Socio-economic models

3.1 Data sources

The primary data source for the CGE models used in this project is the GTAP global Social Accounting Matrix, currently at version 10, with version 11 expected soon. This data is complemented by various other sources, like regional statistics provided by Eurostat, allowing a disaggregation of some macroeconomic data at NUTS2 regional level.

For the construction of scenarios, the main source is the quantitative repository available at IIASA, defining the SSP scenarios in terms of projected GDP, and various demographic characteristics, like population structure by age, educational attainment, sex, urbanization. These scenarios are currently under revision, and a conference is being organised in 2022 (to which we aim to participate) will discuss the necessary adjustments and extensions.

As national accounts are the main data sources over which macroeconomic models are based, the typical output of model runs will be in terms of national aggregates. However, results will be processed inside or outside the models, to achieve a finer spatial disaggregation. Most macroeconomic variables will be provided at NUTS2 regional scale.

Interactions with the MAGNET model, which includes a module (MagnetGrid, Diogo et al., 2020) for downscaling national level projections to grid cell resolution (the unit of reference in bio-physical models), will allow us to provide information at this scale, especially for land economic related variables (e.g. agricultural land use, land prices, land opportunity costs). A major downside to be jointly solved with biophysical modelling in WP2 is the spatial-grid resolution of the downscaling. As MAGNET is global model, its downscaling component also make use of global land data input (i.e. MapSpam cropland maps and IIASA Global AgroEcological Zones; You et al., 2014, Fischer et al., 2018), which might be too coarse for the case studies at river basin level. On the other hand, MagnetGrid is also flexible as it can be easily adapted to new/finer land data input, which shall be sourced from the biophysical modelling in WP2 (e.g. LPJML, Schaphoff et al., 2018). In this regard, MagnetGrid has the ability to integrate biophysical and socio-economic models in WP2.

In any case, the results will be adapted to the dimension of case studies in the project. To give a simple example, if one case encompasses an area situated in two different regions, economic variables will be estimated as weighted averages of the gross results obtained from the models.

3.2 The GTAP Global Social Accounting Matrix

A Social Accounting Matrix is a data framework, which shows the circulation of income and market transactions among agents of an economic system. It is the primary information source

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for the calibration of model parameters in Computable General Equilibrium Models, and others macroeconomic models, relying on official economic national accounts.

The GTAP Data Base is a consistent representation of the world economy for a pre-determined reference year. Underlying the data base there are several data sources, including among others: national input-output (I-O) tables, trade, macroeconomic, energy and protection data. The underlying input-output tables are heterogeneous in sources, methodology, base years, and sectoral detail, thus for achieving consistency, substantial efforts are made to make the disparate sources comparable. For these reasons, the objective of the GTAP Data Base is not to provide I-O tables, but to facilitate the operation of economic simulation models ensuring users a consistent set of economic facts.

The central ingredient in GTAP's success has been the global data base. It combines detailed bilateral trade, transport and protection data characterizing economic linkages among regions, together with individual country input-output (I-O) data bases which account for inter-sectoral linkages within regions.

Construction and maintenance of this data base adheres to the following principles:

- Public Availability. The data base is made available to anyone requesting it, at a modest fee. This prevents needless duplication of effort in creating this public good.
- Regular Updates. The current release is the tenth (GTAP 10 Data Base) since 1993. (The average life span of a release is about three years.)
- Broad Participation. The network of GTAP users represents an excellent resource for extension of the data base. Another benefit from broad participation is the extensive scrutiny to which the data base is subjected. Those who identify areas for improvement or extension of the data base are free to make this available to GTAP staff, in order to have it considered for incorporation into the next release of the data base.
- Comparative Advantage. By making the data base publicly available and offering to incorporate improvements provided by members of the network, each individual is able to work to his/her own comparative advantage, while capitalizing on the contributions of others.
- Documentation and Replicability. One requirement for new contributions to the GTAP Data Base is that the sources and procedures used to create them be provided along with the data.
- Quality Assurance. As the GTAP Data Base has become more widely used and the policy analyses based on this platform have become more influential, the demands for improved quality control have also increased. Over the past decade, this has emerged as the top priority of consortium members and the Center has therefore devoted increasing resources and attention to this issue.

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3.4 The Shared Socio-Economic Pathways

Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies.

The scenarios are:

- SSP1: Sustainability (Taking the Green Road)
- SSP2: Middle of the Road
- SSP3: Regional Rivalry (A Rocky Road)
- SSP4: Inequality (A Road divided)
- SSP5: Fossil-fueled Development (Taking the Highway)

They have been used to help produce the IPCC Sixth Assessment Report on climate change, published on 9 August 2021.

The SSPs provide narratives describing alternative socio-economic developments. These storylines are a qualitative description of logic relating elements of the narratives to each other. In terms of quantitative elements, they provide data accompanying the scenarios on national population, urbanization, and GDP (per capita). The SSPs can be combined with various Integrated Assessment Models (IAMs), to explore possible future pathways both with regards to socioeconomic and climate pathways.

Two SSPs have been selected for use in NEXOGENESIS, to steer CGE models, and to produce detailed information for the case studies:

SSP2: Middle of the road

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall, the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP4: Inequality (A Road Divided)

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both

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across and within countries. Over time, a gap widens between an internationally connectedsociety that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

A data repository is maintained at IIASA, where the narratives above are quantified and expressed as numerical data, employable in CGE and other integrated assessment models. The SSP quantifications build upon the collaborative effort between the IAV and IAM community. The narratives describe the main characteristics of the SSP future development pathways and served as the starting point for the identification of internally consistent assumptions for the quantification of SSP elements. A range of different modeling tools were used to develop quantifications of these storylines, including factors like population, economic development, land use and energy use.

For each SSP a single population and urbanization scenario, developed by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR), is provided. For GDP, three alternative interpretations of the SSPs by the teams from the Organization for Economic Co-operation and Development (OECD), the International Institute for Applied Systems Analysis (IIASA) and the Potsdam Institute for Climate Impact Research (PIK) have been developed. The GDP projections are based on harmonized assumptions for the interpretation of the SSP storylines in terms of the main drivers of economic growth. They differ however with respect to the employed methodology and outcomes. In case users can only use one interpretation of the SSPs, for each SSP a single 'illustrative' case has been selected.

3.5 NUTS2 Sub-National Economic Data

CGE models are rooted on national economic accounts. To get a finer geographical detail, however, some regional data are available, which allows some downscaling in the results. The main source is statistics from EUROSTAT (https://ec.europa.eu/eurostat/web/national-accounts/data).

Regional accounts are a regional specification of the corresponding accounts of the national economy. Regional accounts provide a regional breakdown for major aggregates, such as gross value added (GVA) and household income.

Overall, regional accounts use the same concepts as national accounts. However, due to conceptual and measurement limitations at regional level, regional accounts are not calculated

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for the expenditure approach as industry detail is more limited. Sector accounts are only calculated for the household sector.

Regional data are classified according to the 'Nomenclature of territorial units for statistics' (NUTS), all variables are available broken down by NUTS 2 and a sub-set is available by NUTS 3, and according to the 'Statistical Classification of Economic Activities in the European Community' (NACE) by 10 economic activities.

Data cover in general the reference period from 2000 to the actual calendar year minus 2 years (t-2) for total GVA, GDP and employment and minus 3 years (t-3) for other variables.

4 Data coherency

4.1 Scenarios

A framework of macro data/general trends will be generated under uniform methodology, assumptions and modelling across all case studies. Climatic, environmental, and socio-economic conditions are expressed in quantitative terms for each case study to characterize climatic, environmental, and socio-economic variables, in line with a combination of selected IPCC future scenarios (SSP and RCP).

Representative Concentration Pathways (RCPs) include time series of emissions and concentrations of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as trends representing dynamics of land use/land cover. Each RCP provides a possible scenario, the trajectory over time extending up to 2100, defining specific radiative forcing characteristics. Several RCPs are produced and introduced from published literature, and were used in Fifth and Sixth IPCC Assessment as a basis for the climate predictions and projections, each categorized by the peak radiative forcing in 2100, thus:

- RCP2.6 peaks at approximately 3 W m^{-2} before 2100 and then declines;
- RCP4.5 and RCP6.0 represent intermediate stabilisation pathways in which radiative forcing is stabilised at 4.5 W m^{-2} and 6.0 W m^{-2} after 2100;
- RCP 7.0 and RCP 8.5 high pathway for which radiative forcing reaches greater than 7 or 8.5 W m^{-2} by 2100 and continues to rise for some amount of time.

Shared socio-economic pathways (SSP) is a collection of pathways describing alternative socio-economic future development.

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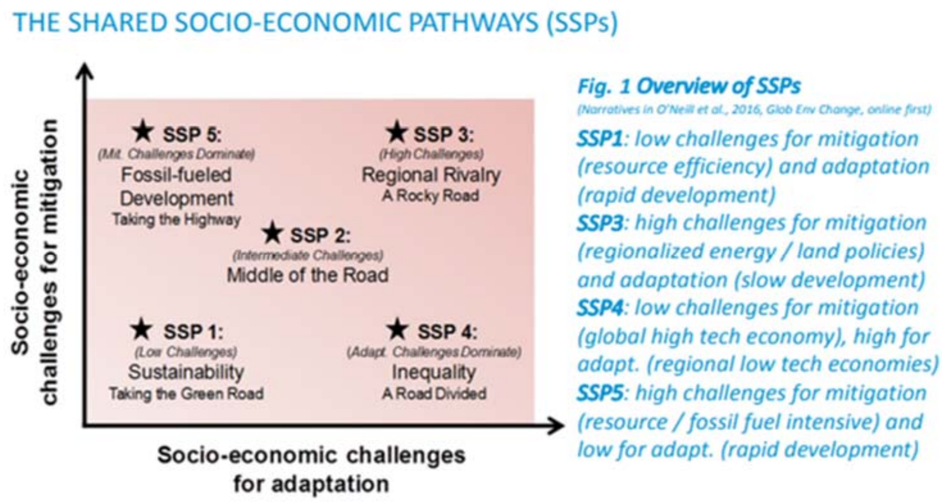

The combination of Representative Concentration Pathway (RCP) climate projections and SSP socio-economic scenarios should provide an integrated framework useful to combine climate impact and policy analysis

Under the assumption of plausible range of future scenarios as boundary condition for SDM development and policy analyses for NEXOGENESIS case studies, two combinations are currently being proposed and considered:

- one at **low end SSP2** (middle of the road) with **RCP2.6** (strong mitigation efforts to keep raising temperatures below 2 °C by the end of century), and;
- at higher end **SSP4** (inequality – a road divided) together with **RCP8.5** to rather follow historical patterns or business as usual.

4.2 Naming convention and Data Type format

All the climate and biophysical data that will be collected will follow a specific ontology, i.e., naming convention to represent nexus components and variables. The data come with the description, the unit, and an already established long and short name provided by the specific data source (e.g., ISIMIP, C3S) which will be used to identify the specific variable. The use of the naming convention within the NXG project will be crucial to be able to avoid mistakes and/or misinterpretations of the variables that will be used in the development of the complexity science model for case studies.

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5 Conclusions and contribution to other project activities

The main aim of this deliverable, and in general for task 2.1, was to provide knowledge base for project activities and facilitate the use and implementation of macro trends from modelling projections to characterize thematic factors across the WEFE Nexus and relevant for project case studies. The document and support information consolidated with this deliverable in task 2.1, provided valuable help shaping in task 2.2 and task 2.3 an inventory list of climate, biophysical and socio economic modelling sources and relevant key variables to indicate the potential support for development of activities for the different case studies. In fact, the documents describing availability of modelling outputs, together with several interactions with case study responsible, developers and stakeholders, refined the list of desiderata and relevant available variable which could be streamlined to the different project activities. That would effectively help 1) characterizing pertinent nexus interlinkages relevant to the different case studies and stakeholders during the development of System Dynamic Model (SDM) in WP3; 2) support stakeholder's perception of knowledge and basic data characterizing biophysical-human nexus aspects and assess stakeholder preferences for data in WP5; 3) support data knowledge for elaboration of feasible and optimal solutions to be integrated in complexity science model(s) for each Case Study at conceptual stage in WP3.

It is also worthwhile to stress the importance of deriving and defining data that are structured and harmonized across case studies to facilitate an effective and comparable implementation of each case study-specific designed solution. This is provided given modelling assessments of plausible macroeconomic conditions and bio-physical forcing due to standardized global changes that follow similar scenarios and climate drivers. Furthermore, the consolidated modelling data available according to specific Nexus dimensions was linked and made available to support the development and feasibility (given the available quantitative information) of policy representation to promote effective resource management under complexity science tools for the different case studies. Last, we can anticipate that although already quite extensive, the variables indicated and consolidated in the data inventory list may increase during the project lifetime, while some new data requests may come to light and newer modelling activities accomplished.

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