Food-Energy-Water (Energy-Water-Land) Systems

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PLCY-798K
Integrated Human-Earth System Modeling and Policy Assessment

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Today’s Topics

- **Motivation**
- **Nexus interactions in IAMs**
- **Common Interconnections we model:**
    - Socioeconomics Drivers
    - Energy-Water Nexus
    - Water-Land-Food Nexus
    - Climate Impacts on Energy, Water, Land Nexus
- **Example Case Studies**

Motivation

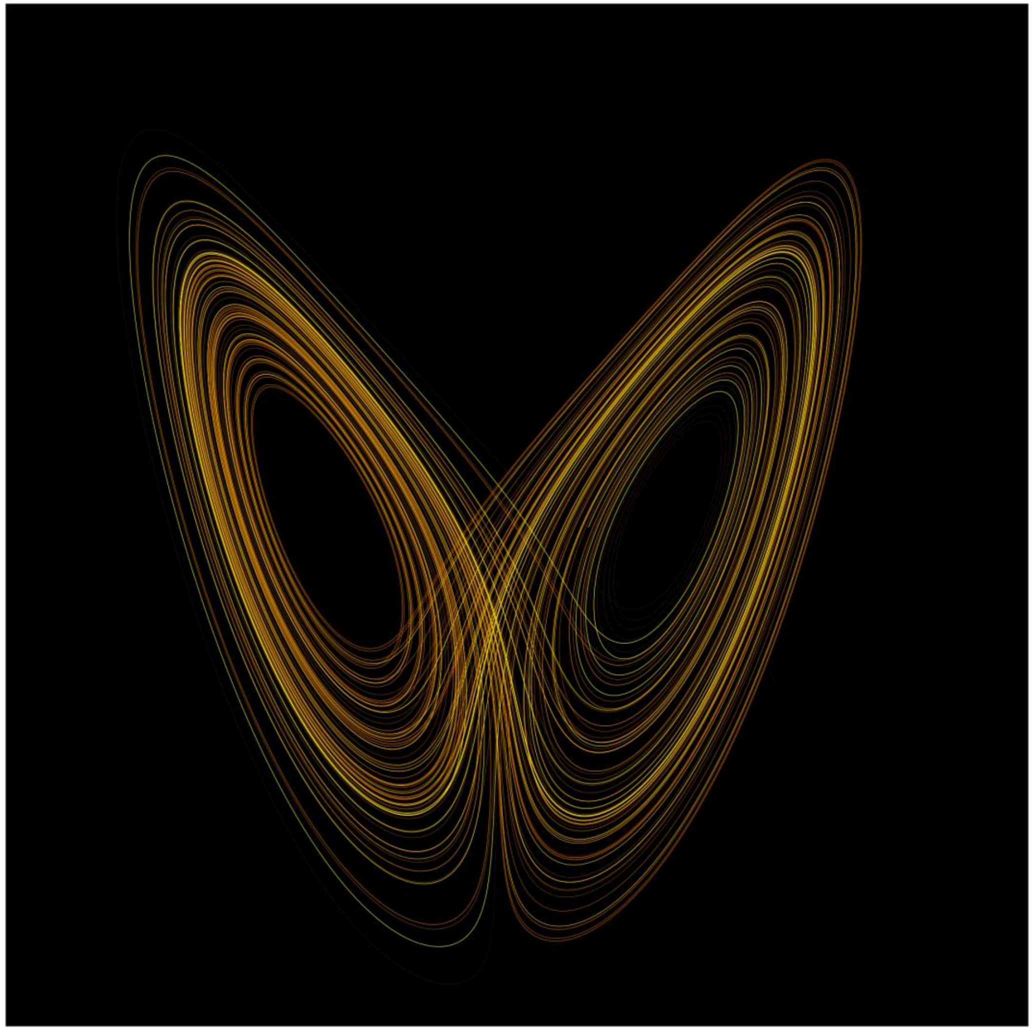
Motivation – Everything is connected

1960s - Edward Lorenz, Meteorology professor MIT (Chaos Theory)

Running a computer program to test various weather simulations and he (Lorenz) discovered that rounding off one variable from **.506127 to .506 dramatically changed** the two months of weather predictions in his simulation.

"The 'innumerable' interconnections of nature, Lorenz noted, mean a butterfly's flap could cause a tornado — or, for all we know, could prevent one. Similarly, should we make even a tiny alteration to nature, 'we shall never know what would have happened if we had not disturbed it,' since subsequent changes are too complex and entangled to restore a previous state."

Peter Dizikes - Boston Globe - 2008

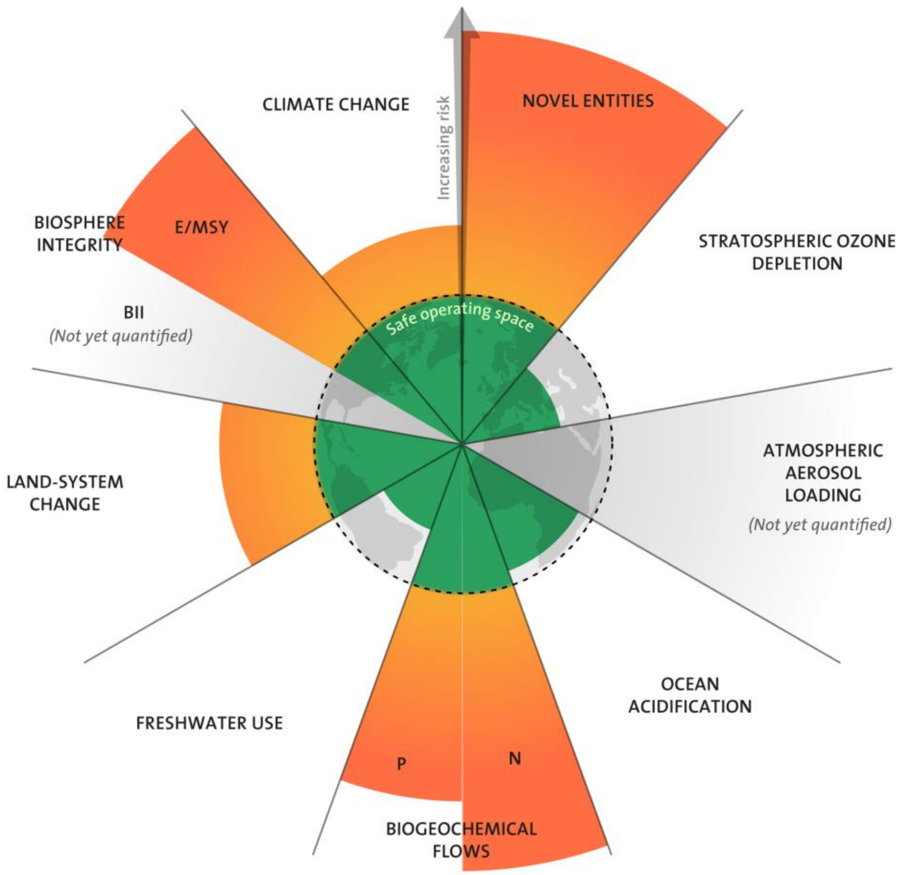


Butterfly Effect – Lorenz Attractor simulation

https://science.howstuffworks.com/math-concepts/butterfly-effect.htm

Motivation – Limits & Tipping Points

Planetary Boundaries



Stockholm Resilience Centre, based on analysis in Persson et al 2022 and Steffen et al 2015
https://www.stockholmresilience.org/research/planetary-boundaries.html

Tipping Points

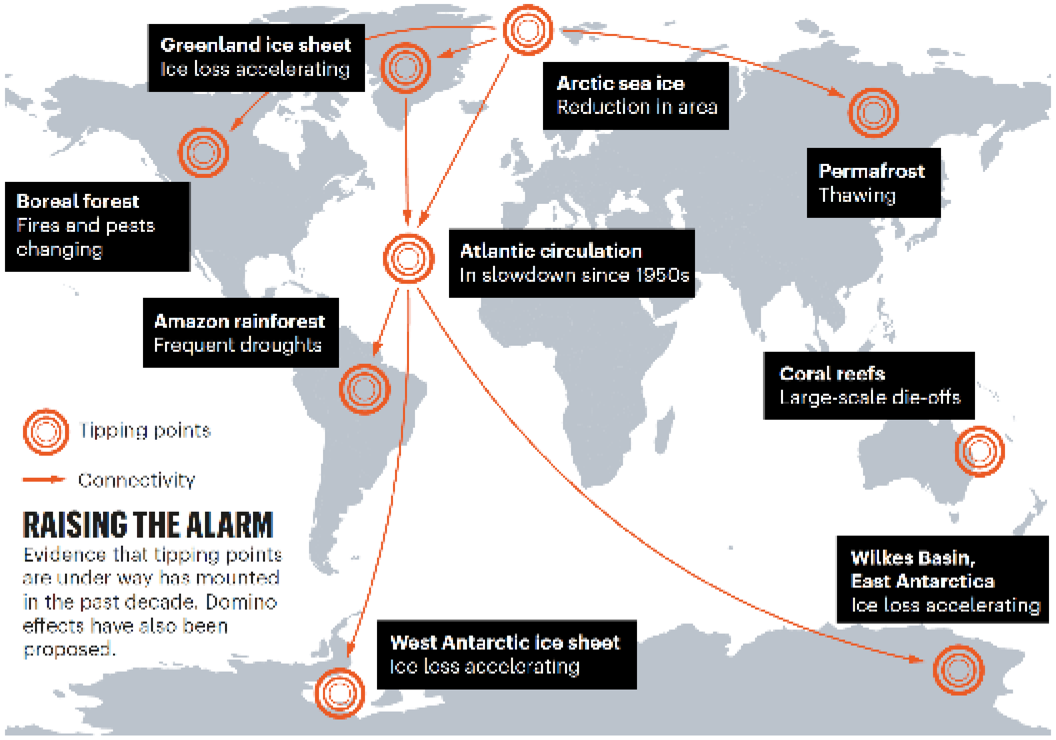
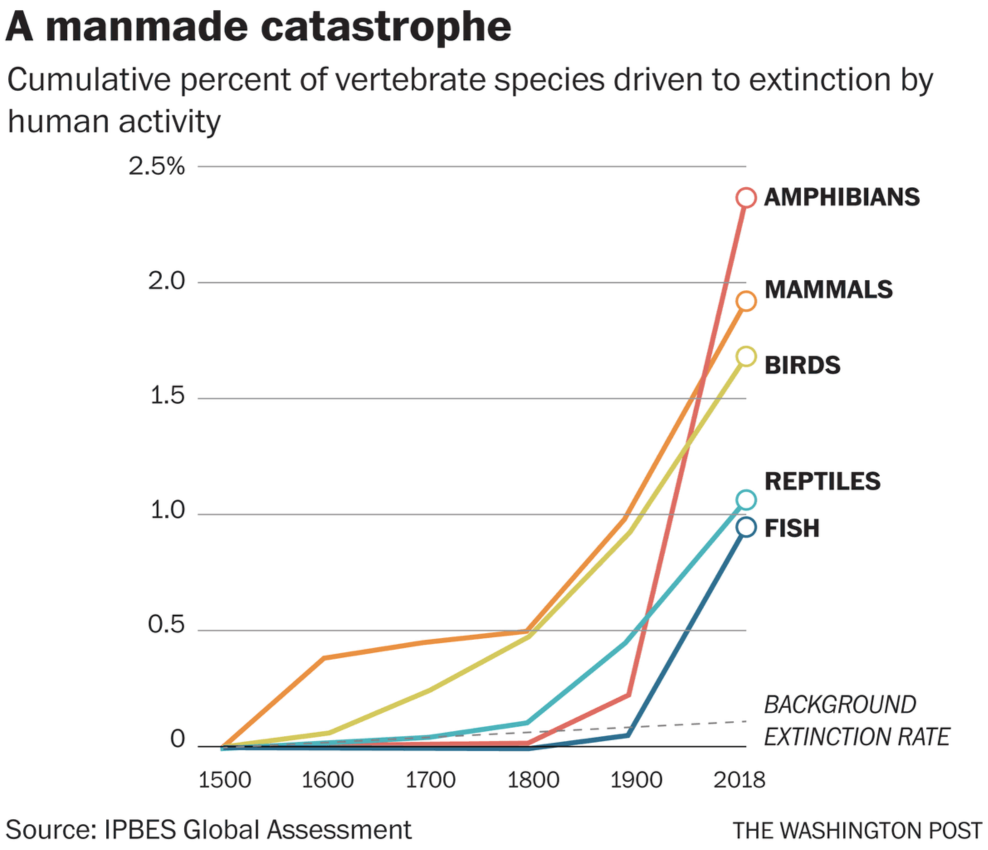


Figure 1. Climate tipping elements that could cross this century due to human activities (from [Lenton et. al., 2019, Nature](#))

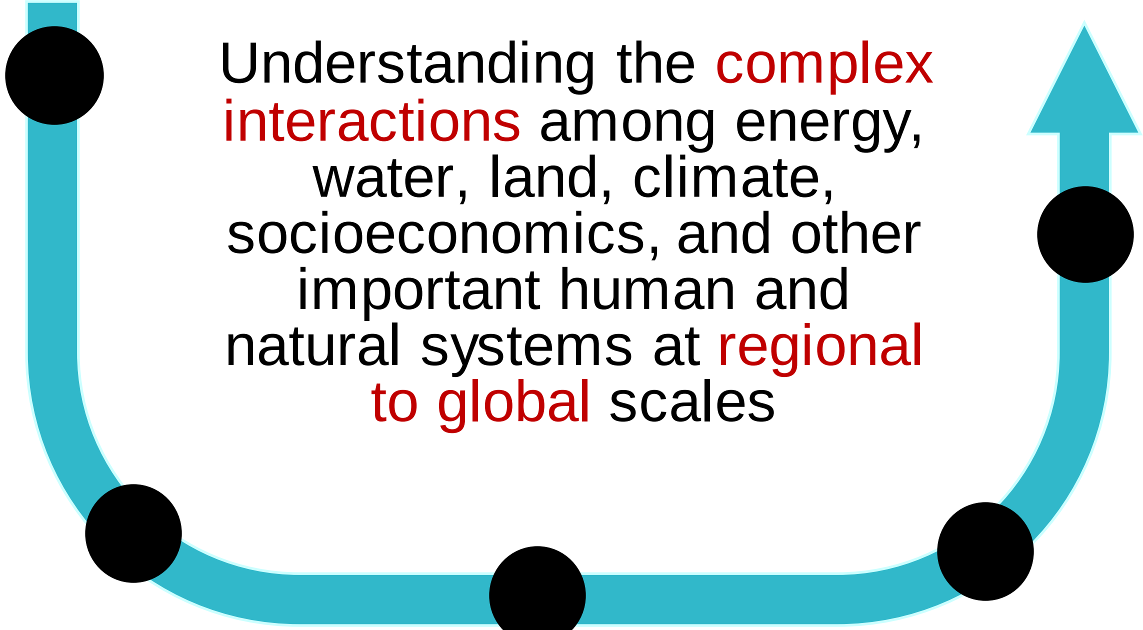
Motivation – Collapse of Systems



https://phys.org/news/2019-04-earth-major-mass-extinctions.html

https://www.washingtonpost.com/business/2019/08/16/scientists-decry-ignorance-rolling-back-species-protections-midst-mass-extinction/

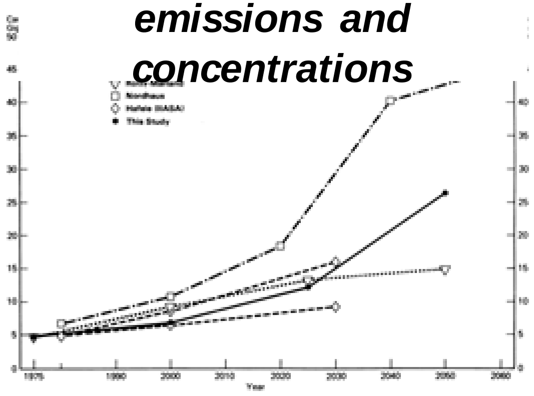
The Evolution of GCAM Research



Understanding the complex interactions among energy, water, land, climate, socioeconomics, and other important human and natural systems at regional to global scales

<u>1980s</u>

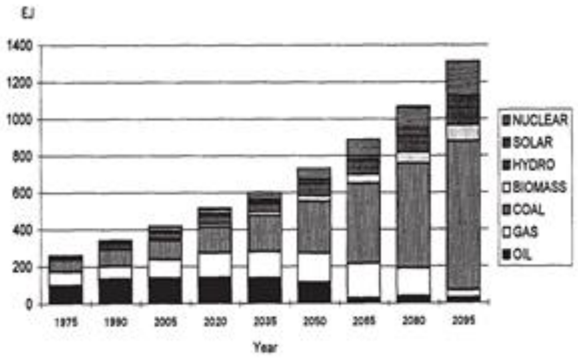
Projections of emissions and concentrations



Edmonds and Reilly (1983). *The Energy Journal.*

<u>1990s</u>

Energy and

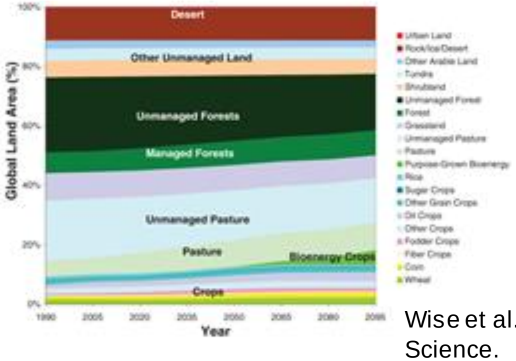


Edmonds et al. (1995). Energy Policy.

ENERGY-ECONOMY-CLIMATE

<u>2000s</u>

Land use system

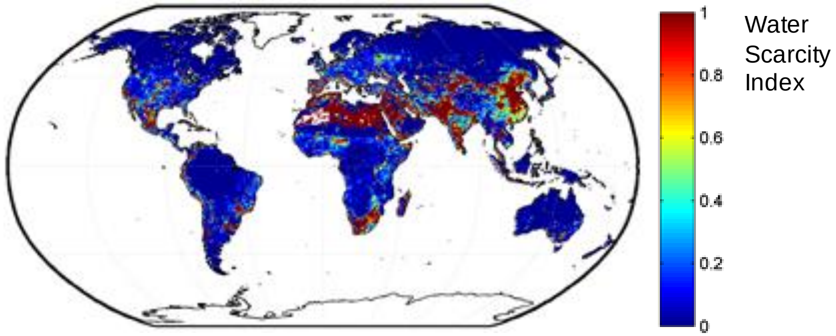


Wise et al. (2009). Science.

ENERGY-ECONOMY-LAND-CLIMATE

<u>2010s</u>

Water system

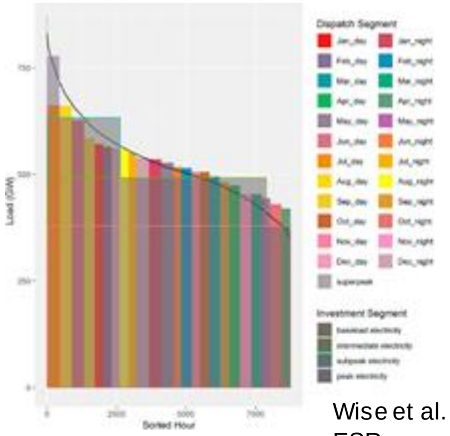


Hejazi et al. (2014). HESS.

ENERGY-ECONOMY-LAND-WATER-CLIMATE

<u>2015–Present</u>

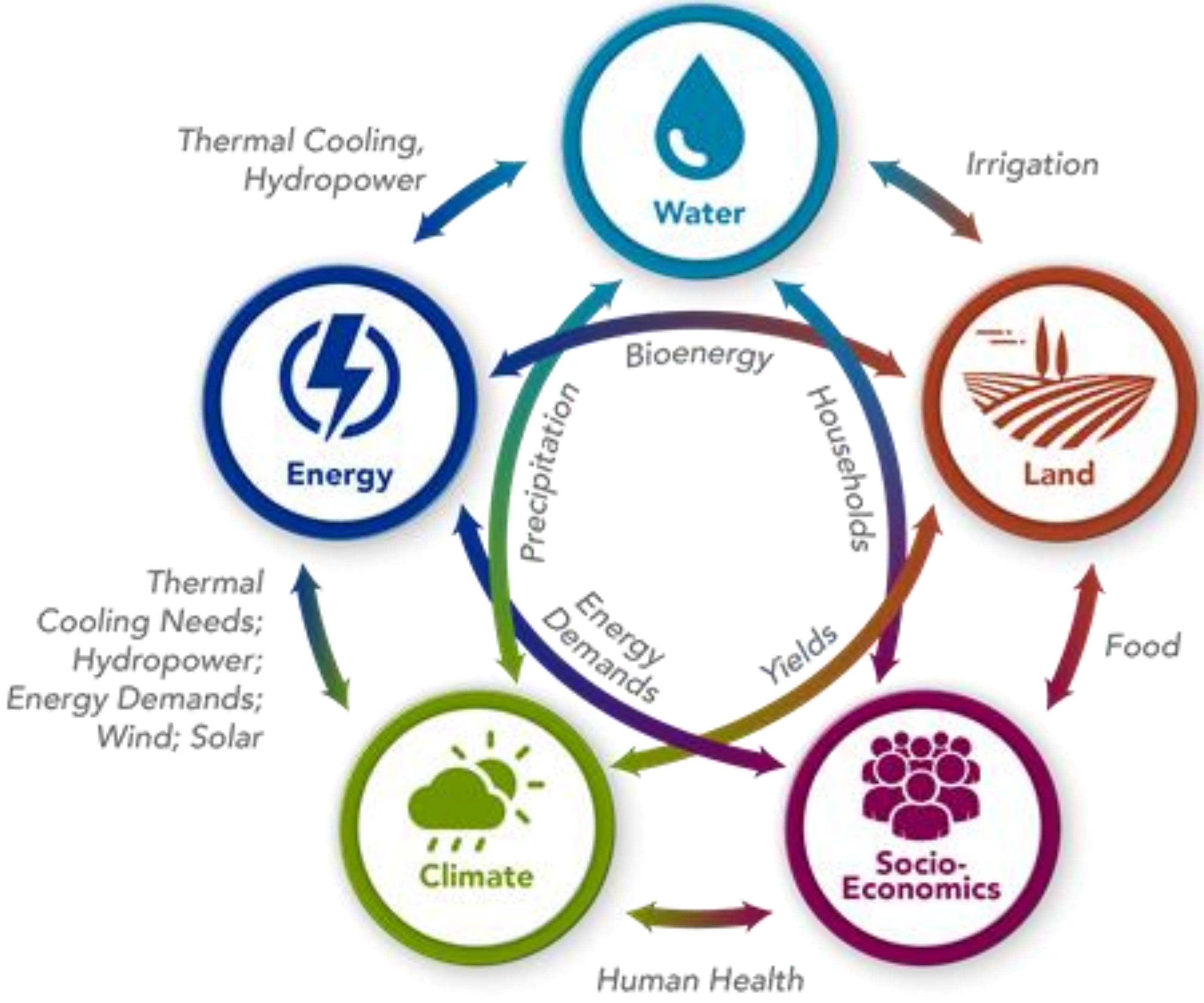
Integrating impacts



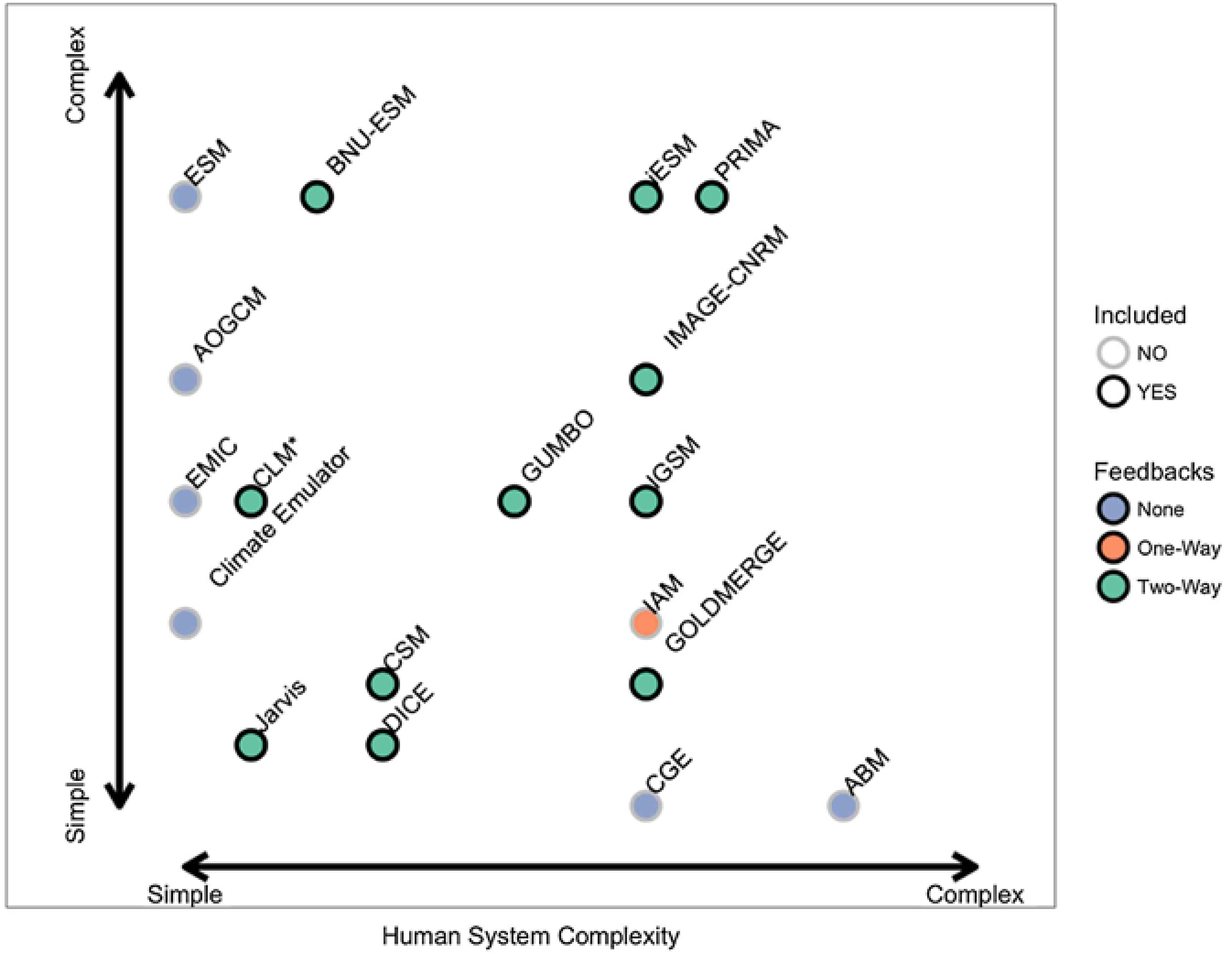
Wise et al. (2019). ESR.

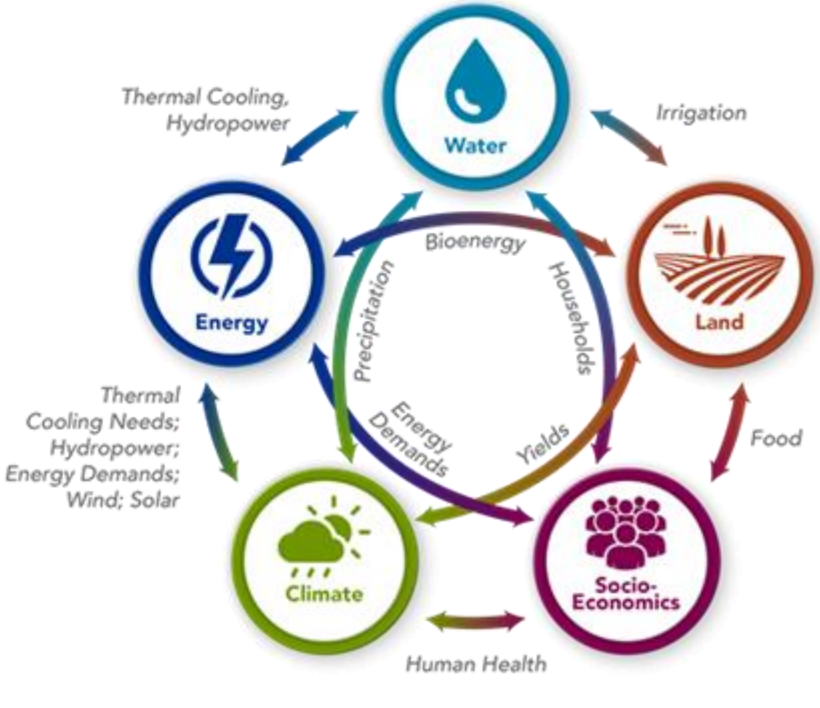
Nexus interactions in IAMs

What important "nexus" interactions exist in reality? Do they all appear in IAMs?



IAMs do not typically account for two-way feedbacks. Instead, we feed climate impacts on water supply one-way.

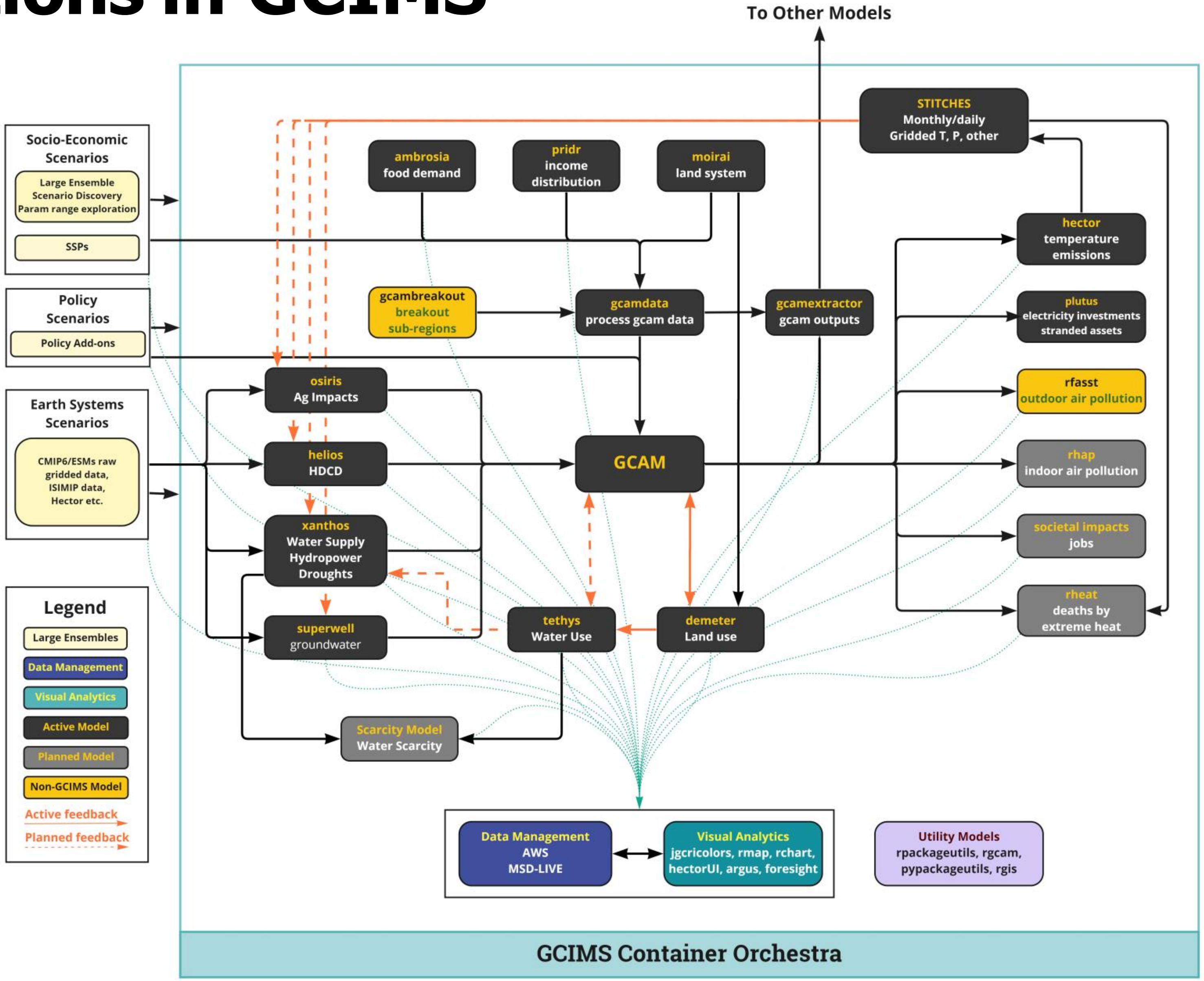




Calvin and Bond Lamberty (2018), *ERL*

IAM Interconnections in GCIMS

- Several endogenous GCAM feedbacks
- Several one-way feedbacks with exogenous models
- Time-step by time-step feedback under development



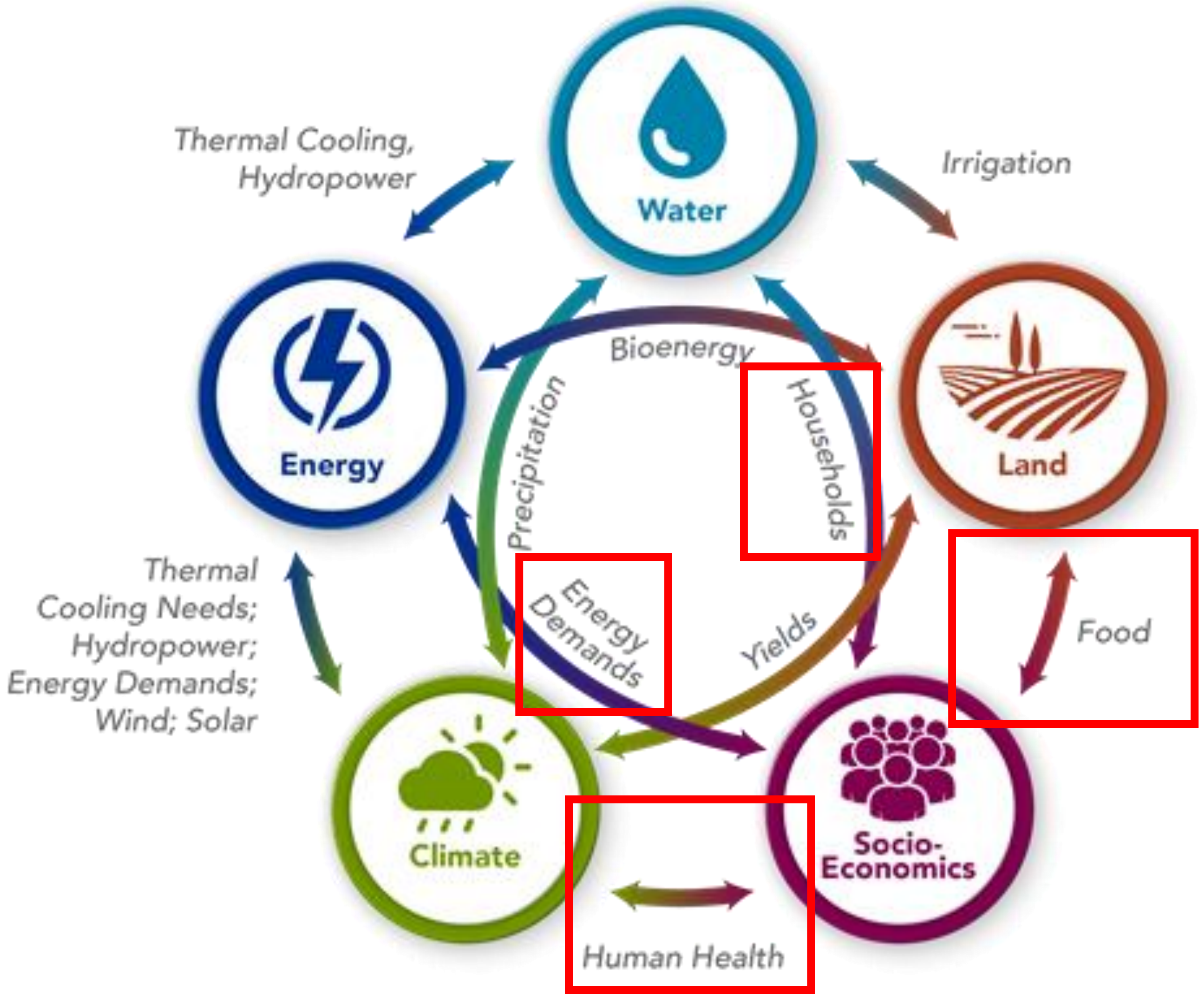
https://jgcri.github.io/gcims_integration/software.html

Common Interconnections we model:

Socioeconomics

Socioeconomic Nexus

How will socioeconomics interact with other factors? **IAMs have traditionally been weak on representing these feedbacks.**



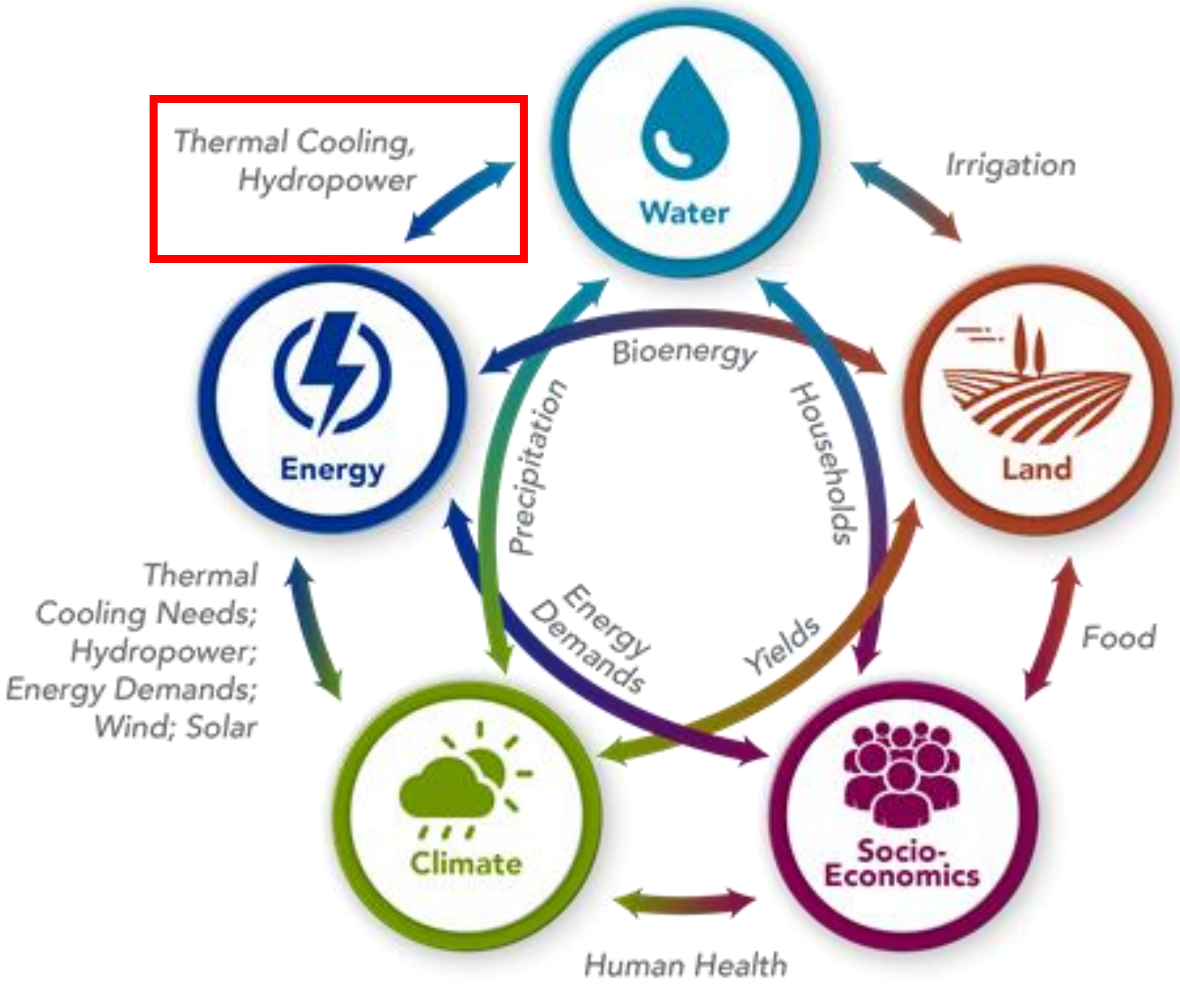
- Exogenous drivers (GDP, Pop) of demand and consumption
- Feedback on health, mortality, diets, behaviour, migration, heating and cooling

Common Interconnections we model:

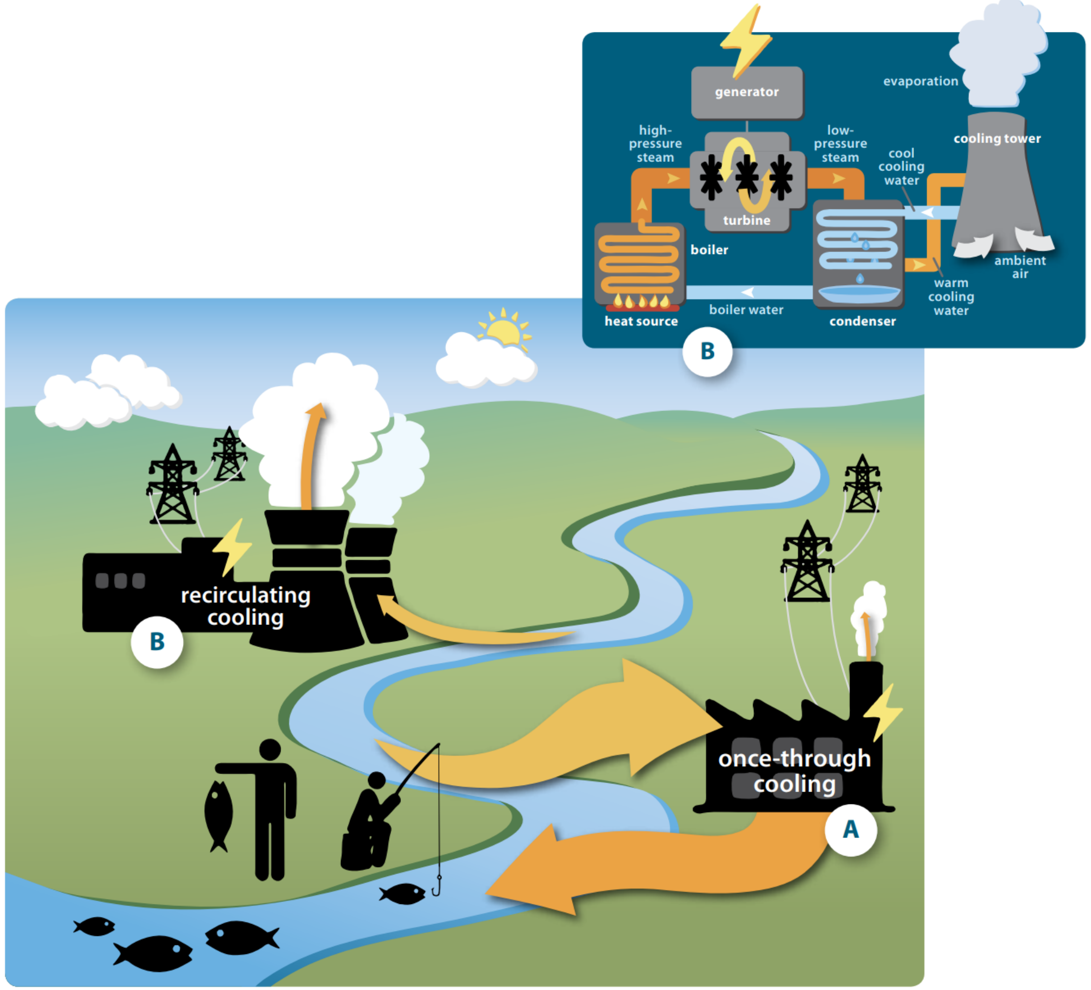
Energy – Water nexus

Energy-Water Nexus

How much energy is used for water, and vice versa?



Thermoelectric power plants require cooling



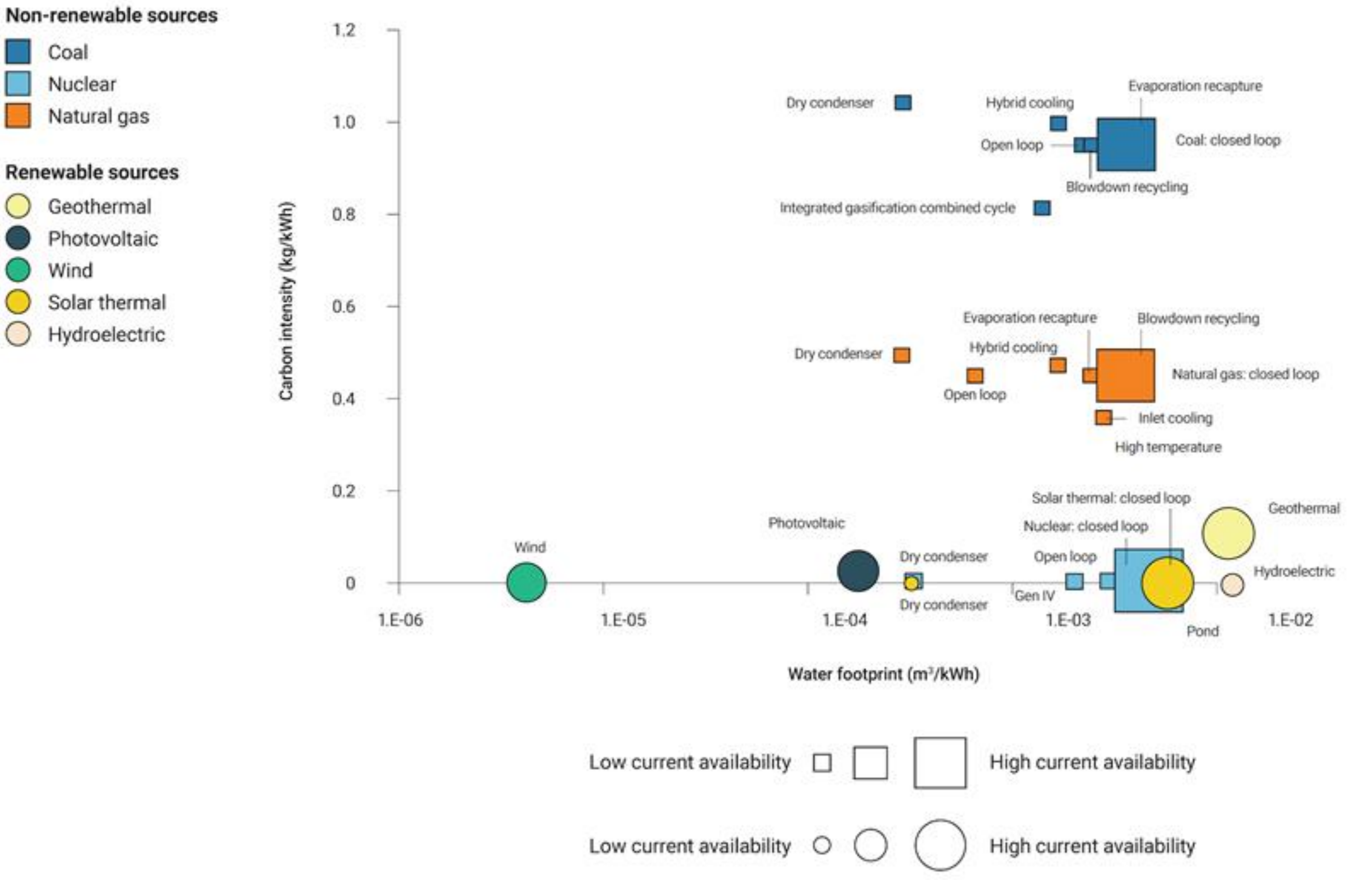
Source: Averyt et al. (2011)

- Once-through cooling technology requires a lot of water “withdrawal”, with some “consumption”
- Recirculating cooling technology requires much less water “withdrawal”, but high “consumption”

Water for Energy

- Some renewables, like wind and solar, have low carbon intensity and low water footprints
- Gas and coal have similar water footprints, but gas has lower carbon intensity

Figure 7.4 Indicative water footprint and carbon intensity of energy production, by source



Source: Adapted from World Bank (2016a, fig. 3.1, p. 30). © World Bank, openknowledge.worldbank.org/handle/10986/23665, licensed under: CC BY 3.0 IGO.

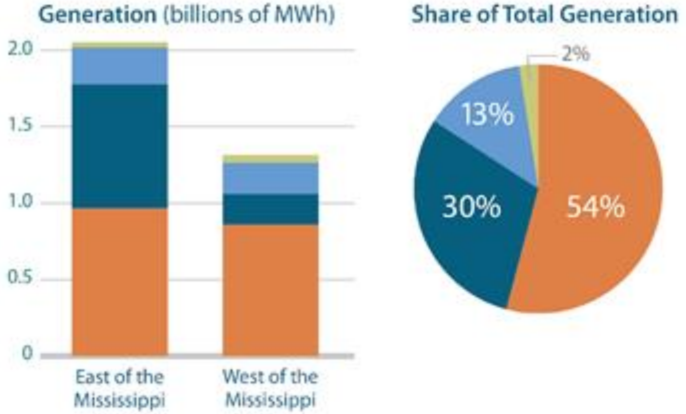
Dramatic Differences Between Eastern and Western U.S.

Source: Averyt et al. (2011)

FIGURE 3. Power Plant Water Withdrawals: East versus West

Water withdrawals in 2008 were much higher east than west of the Mississippi. That is because plants with once-through cooling—which withdraw huge volumes of water—produced a much larger share of electricity in the eastern half of the country, and because overall electricity production was also higher east of the Mississippi. Plants with once-through cooling were located chiefly along the coasts, on the shores of the Great Lakes, and on large rivers and reservoirs.

Note: Based on median NREL values for the use of both freshwater and seawater. Cooling ponds may operate as once-through systems, recirculating systems, or a combination of the two.



Water for Energy

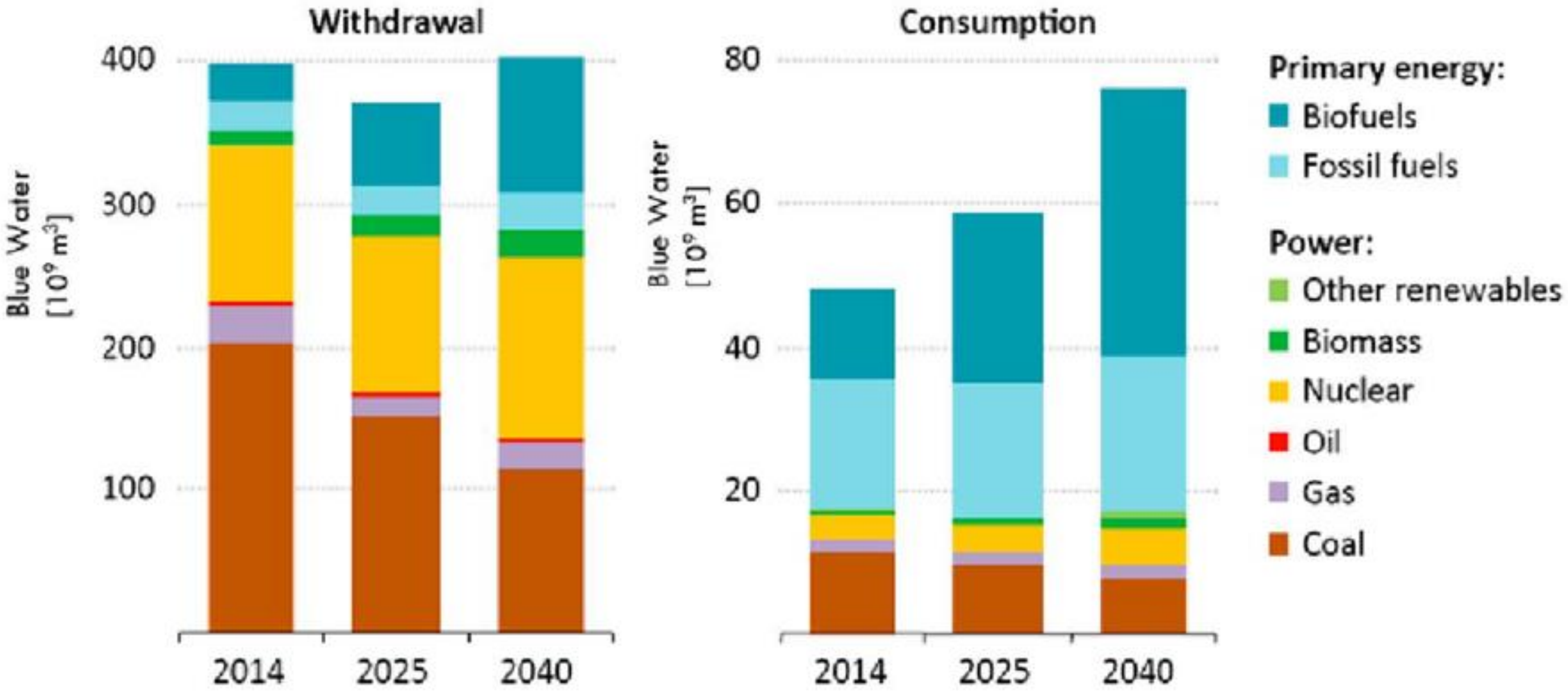
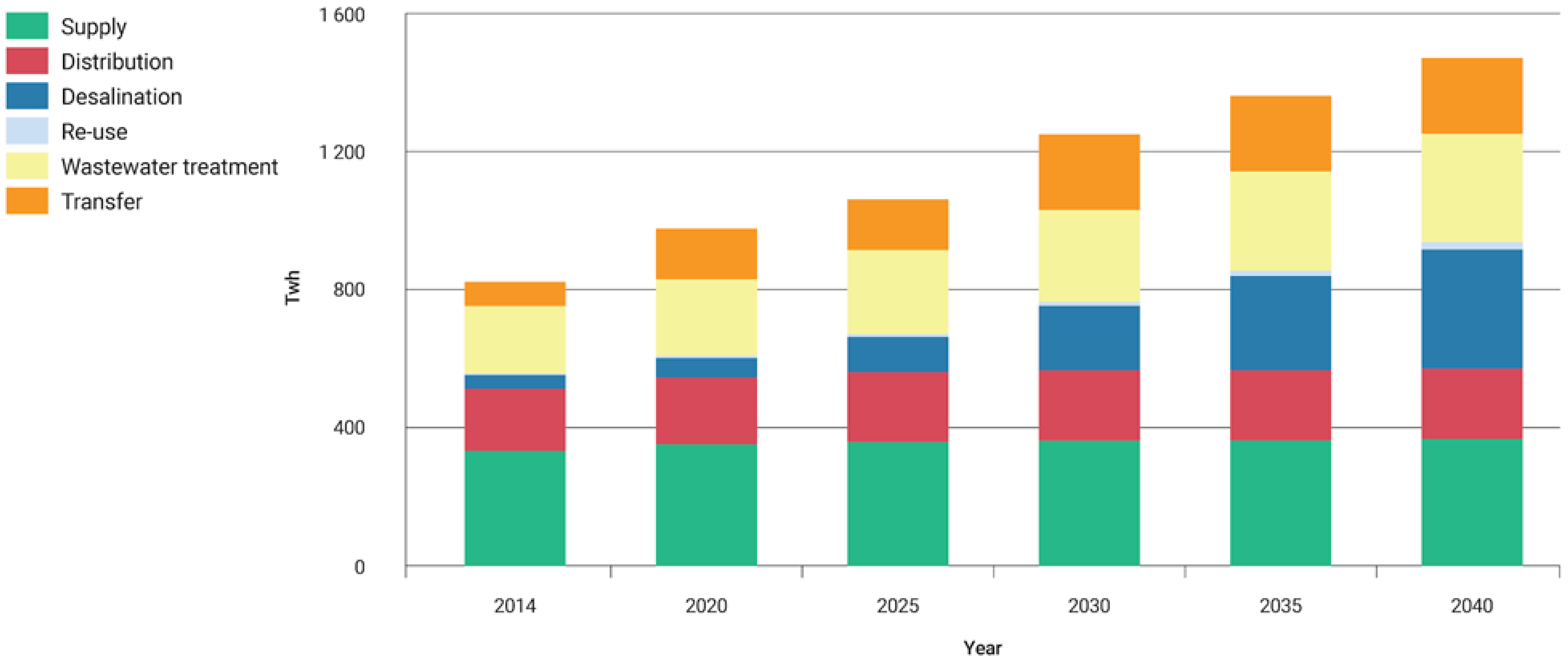


Figure 12. Water withdrawals and consumption for energy production (date source: International Energy Agency, 2016).

D'Odorico et al. (2018), *Geophysical Research Letters*

Energy for Water

Figure 3.2 Electricity consumption in the water sector by process, 2014–2040



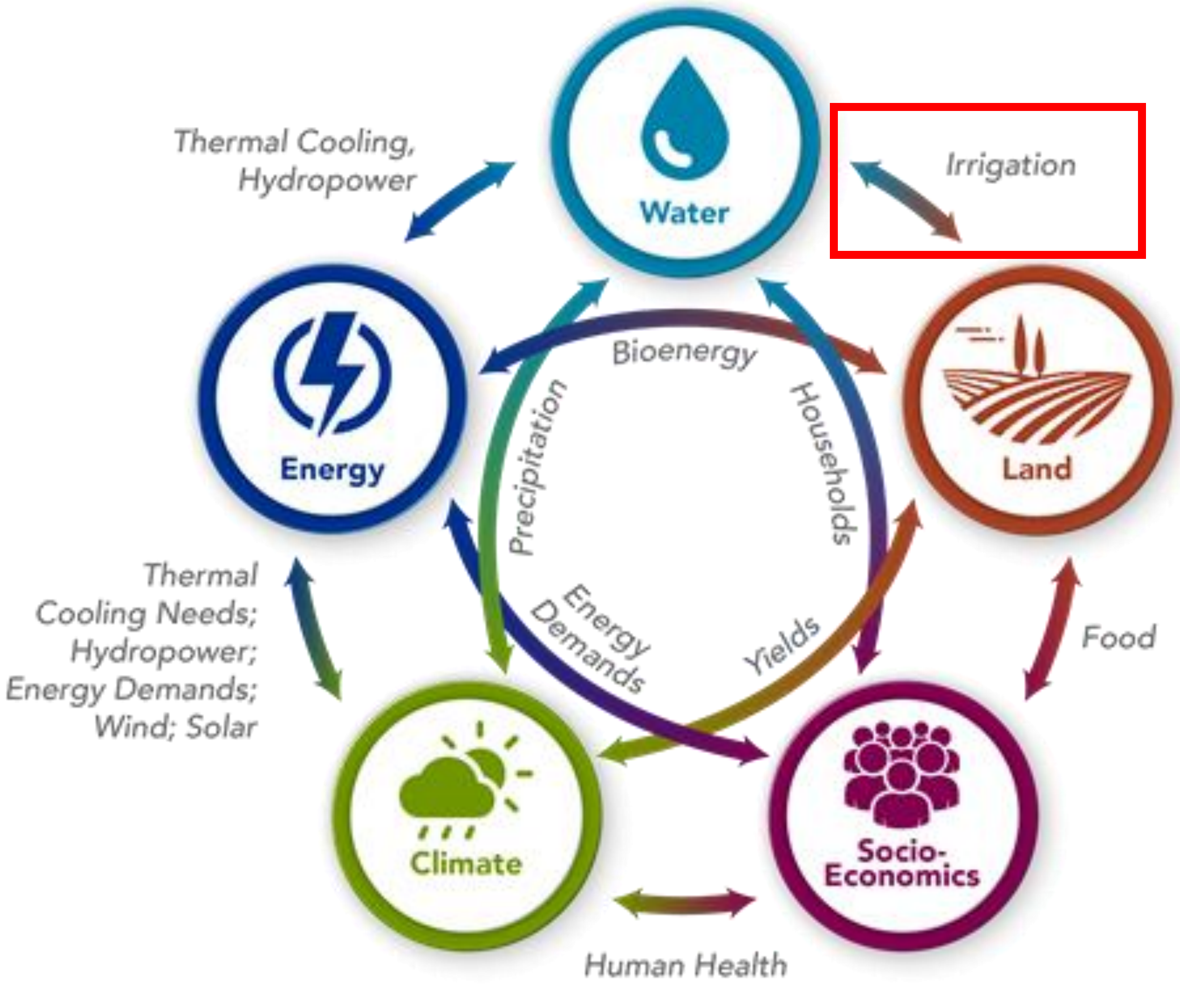
Source: IEA (2018).

Common Interconnections we model:

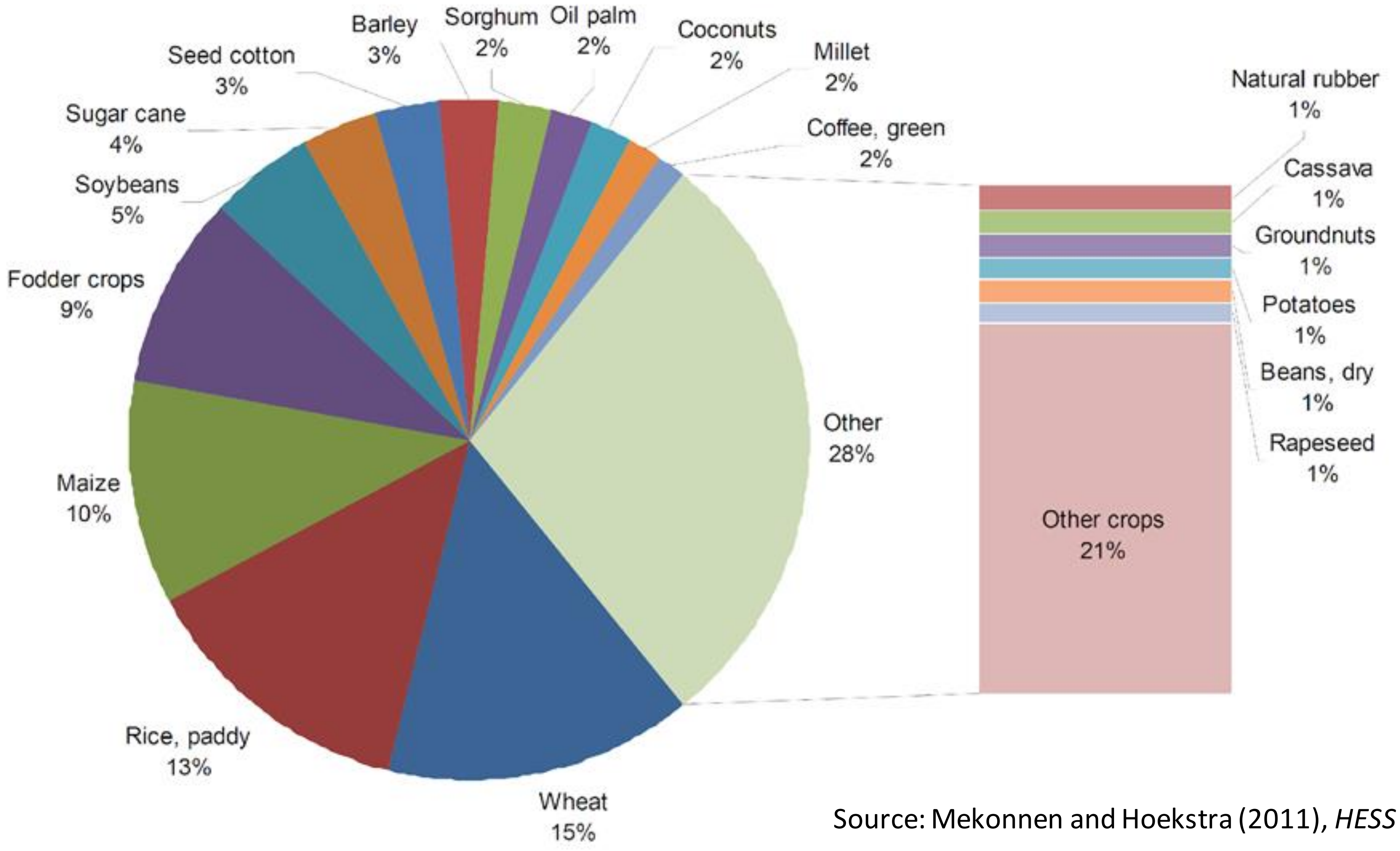
Water – Land – Food Nexus

Water-Land-Food Nexus

How much water is used to produce crops and food from land?



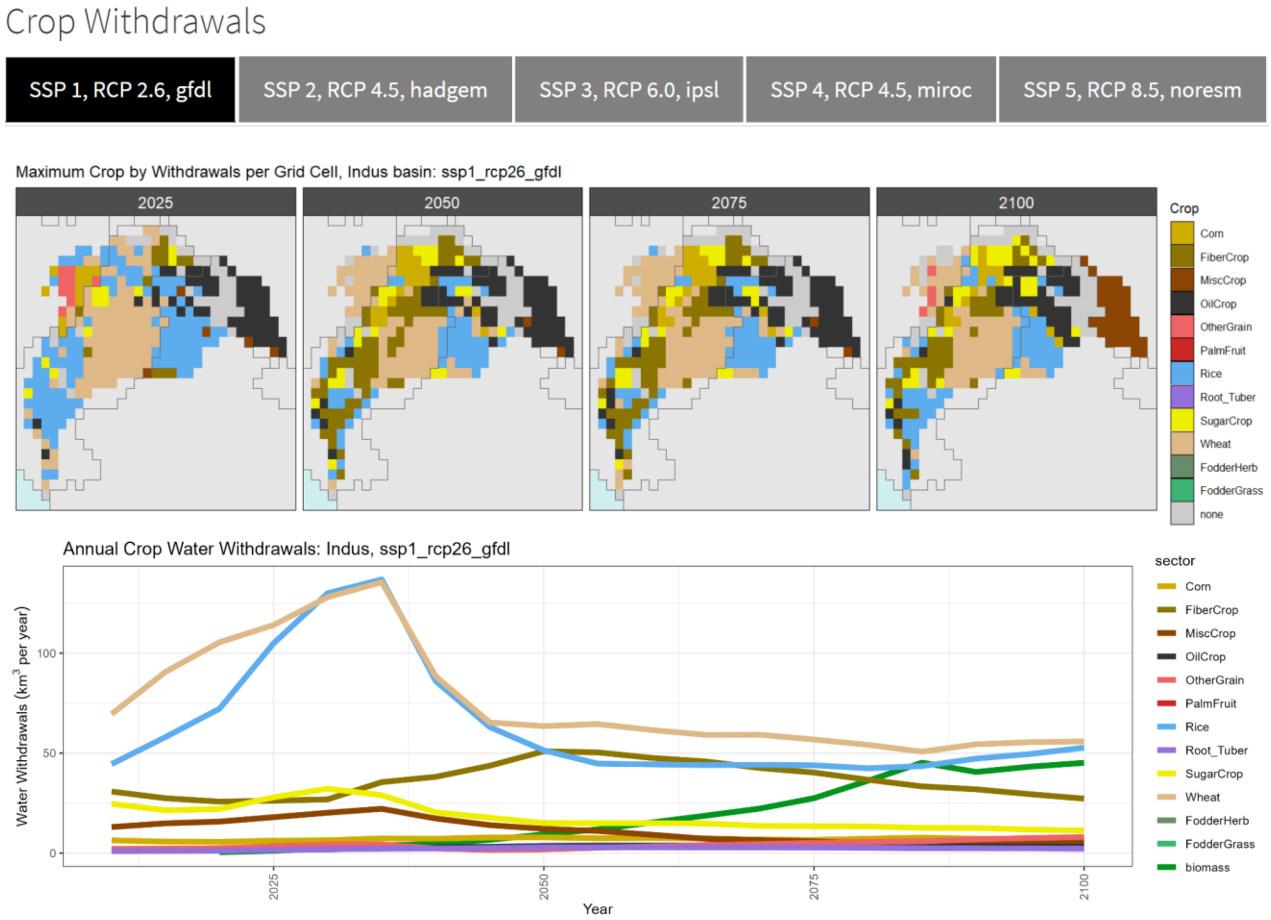
Share of total global water usage by crop



Source: Mekonnen and Hoekstra (2011), *HESS*

Fig. 1. Contribution of different crops to the total water footprint of crop production. Period: 1996–2005.

Gridded Water withdrawals and consumption



https://jgcri.github.io/khan-etal_2022_tethysSSPRCP/index.html

Water & Carbon Implications of Food

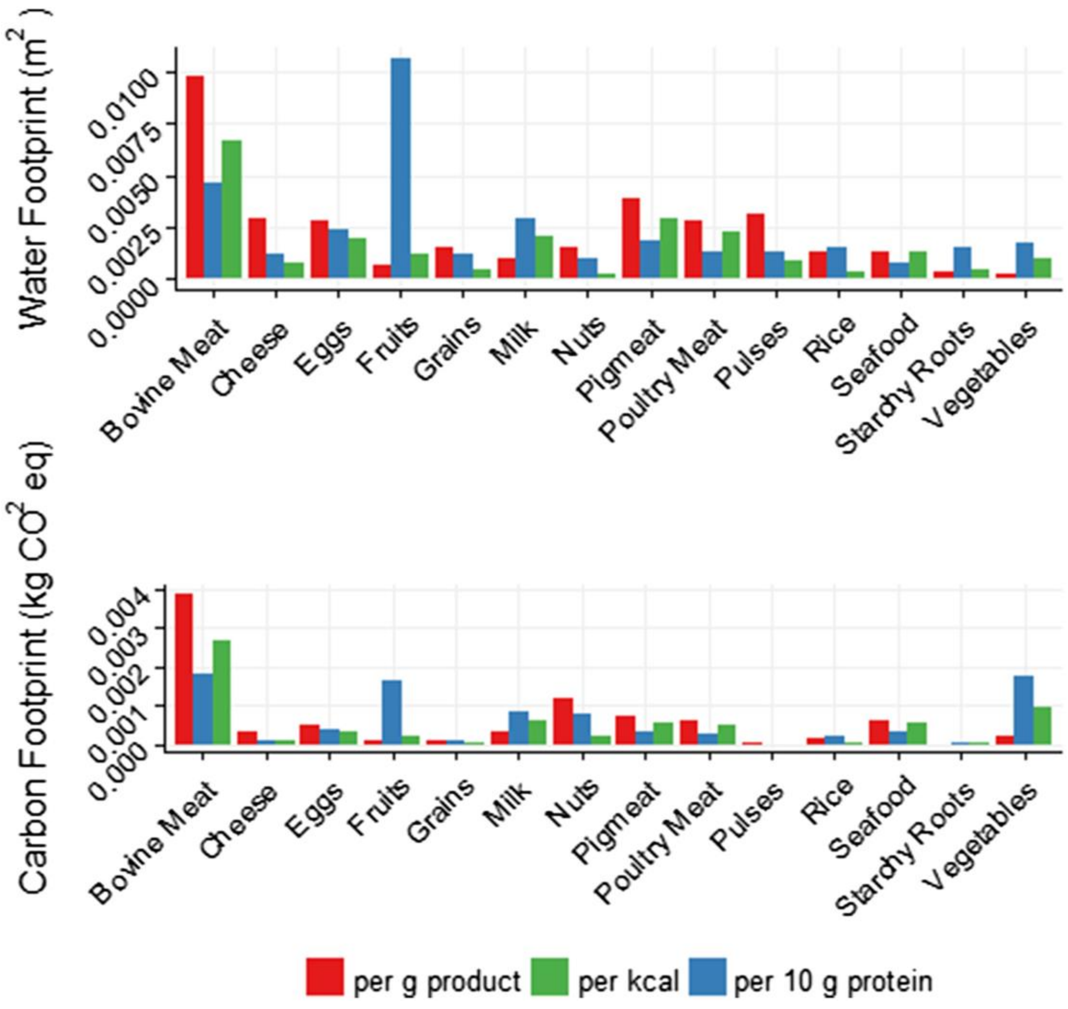


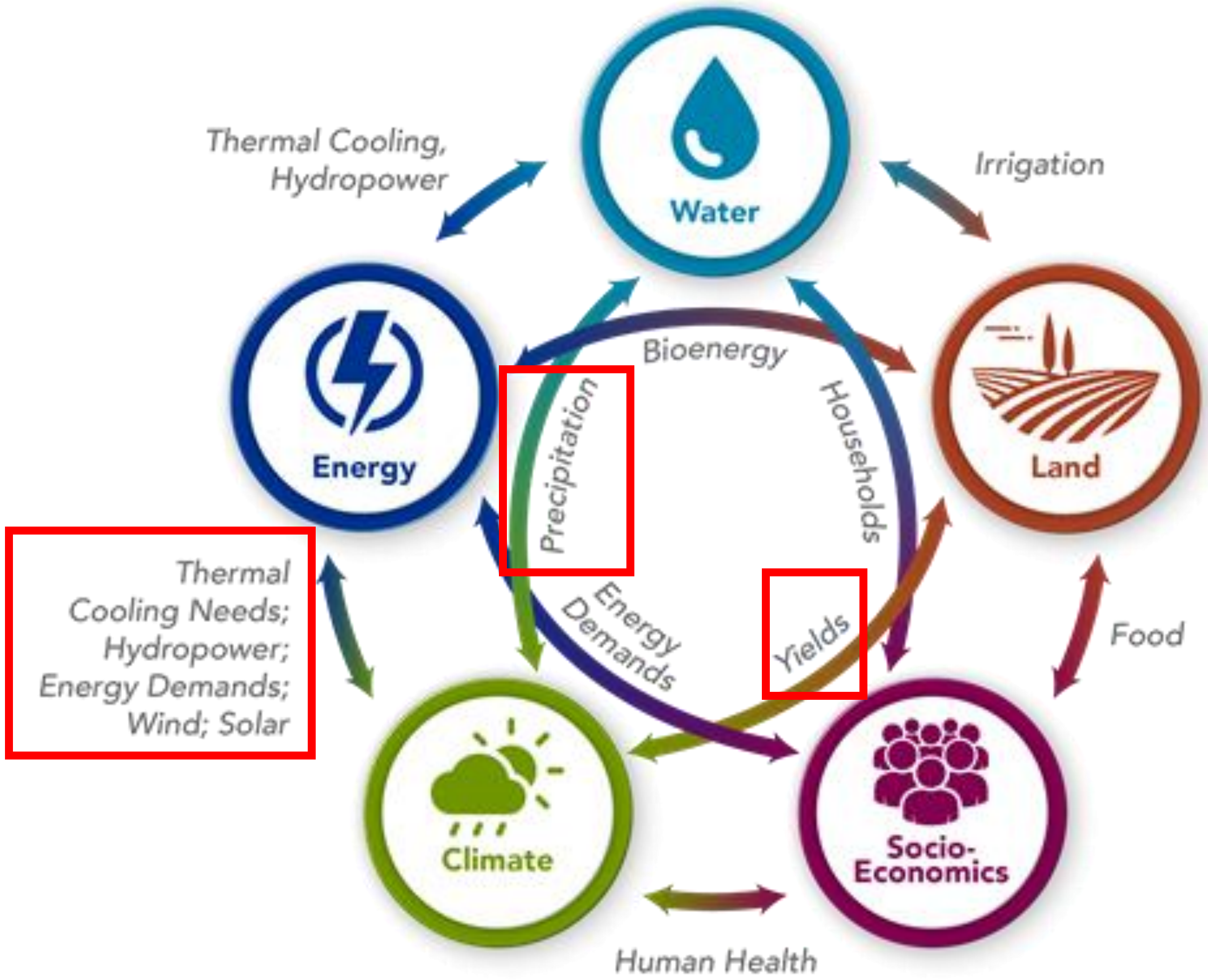
Figure 2B: The water and carbon footprints of food products (based on Gephart, Davis, et al., 2016). (Source: d'Odorico et al. (2018), *Geophysical Research Letters)*

Common Interconnections we model:

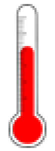
Climate Impacts on Energy, Water, Land Nexus

Climate-Energy,Water,Land Nexus

Energy and land usage impact climate change, that water is a constraint on energy and land development. But how does climate in turn impact energy, water, and land systems?



Climate Change Impacts Across Multiple Sectors

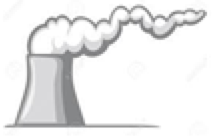


Energy Demand → Increases in electricity demand, decreases in natural gas demand

+

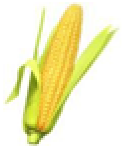
Hydropower → Changes in production of hydropower

+



Thermal Power → Decreases in thermal power production

+

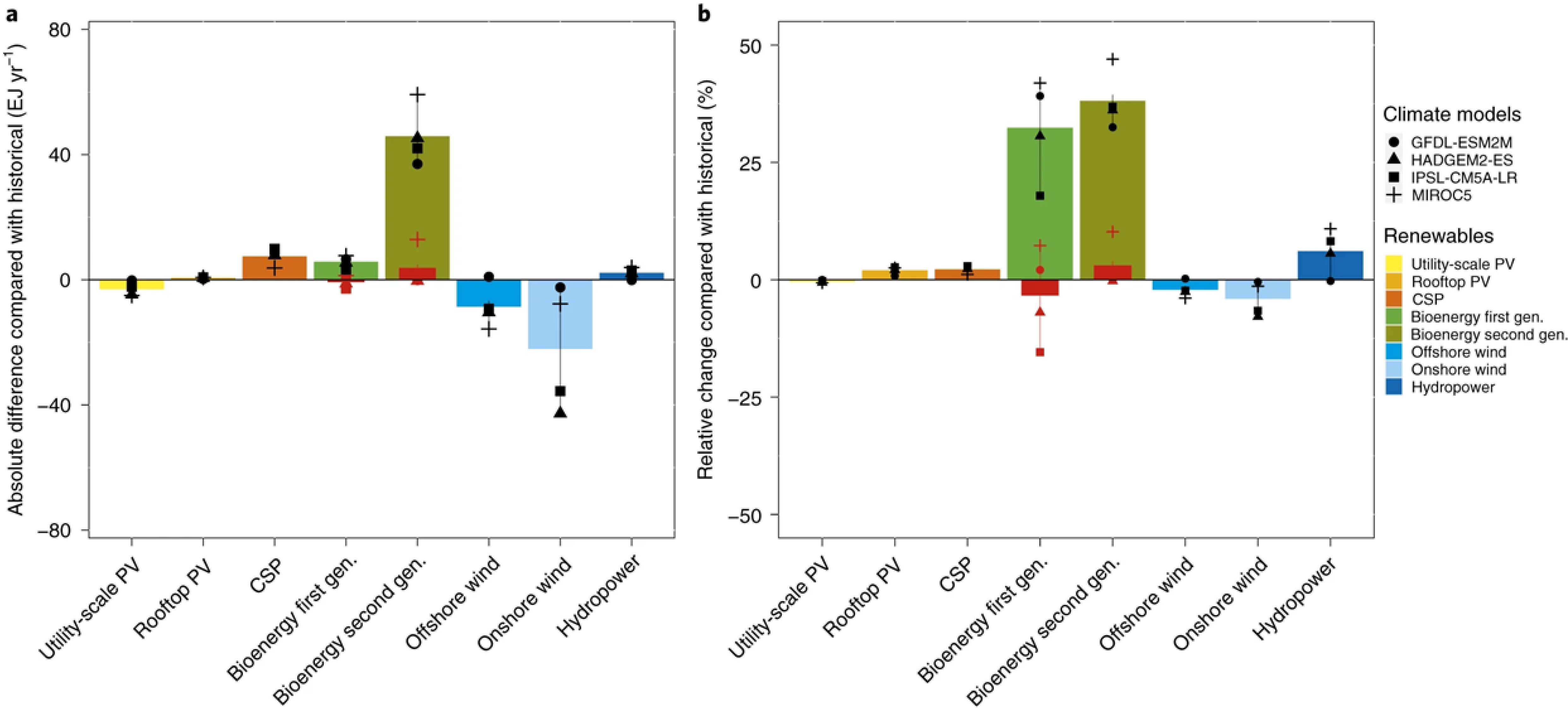


Agriculture → Changes in productivity of land, bioenergy supply, crop production, carbon sequestration

+

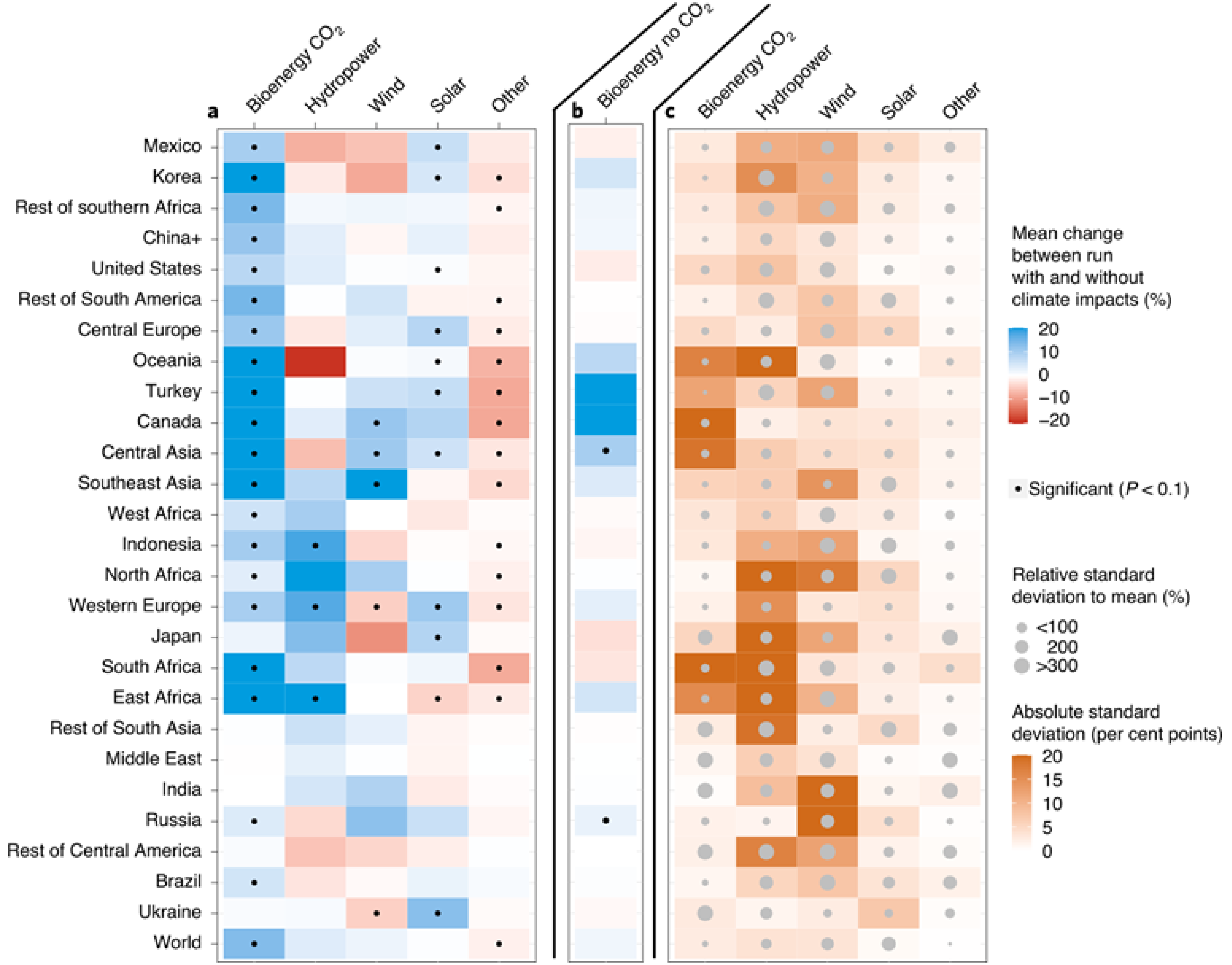
Water Supply → Changes in water availability (globally and regionally)

Climate Change Impacts on Renewable Energy Supply



Source: Gernaat et al. (2021), *Nature Climate Change*

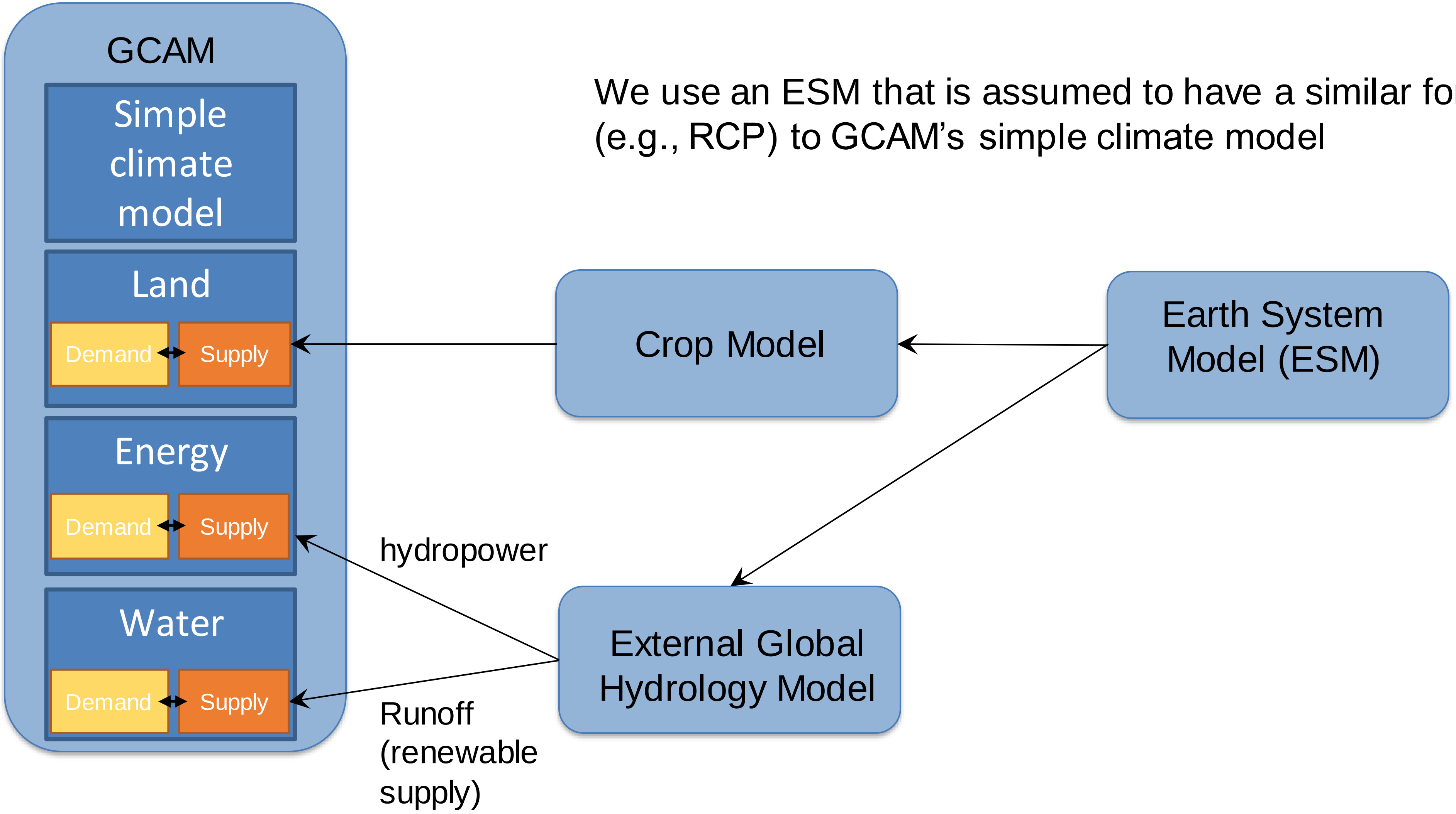
Climate Change Impacts on Renewable Energy Supply



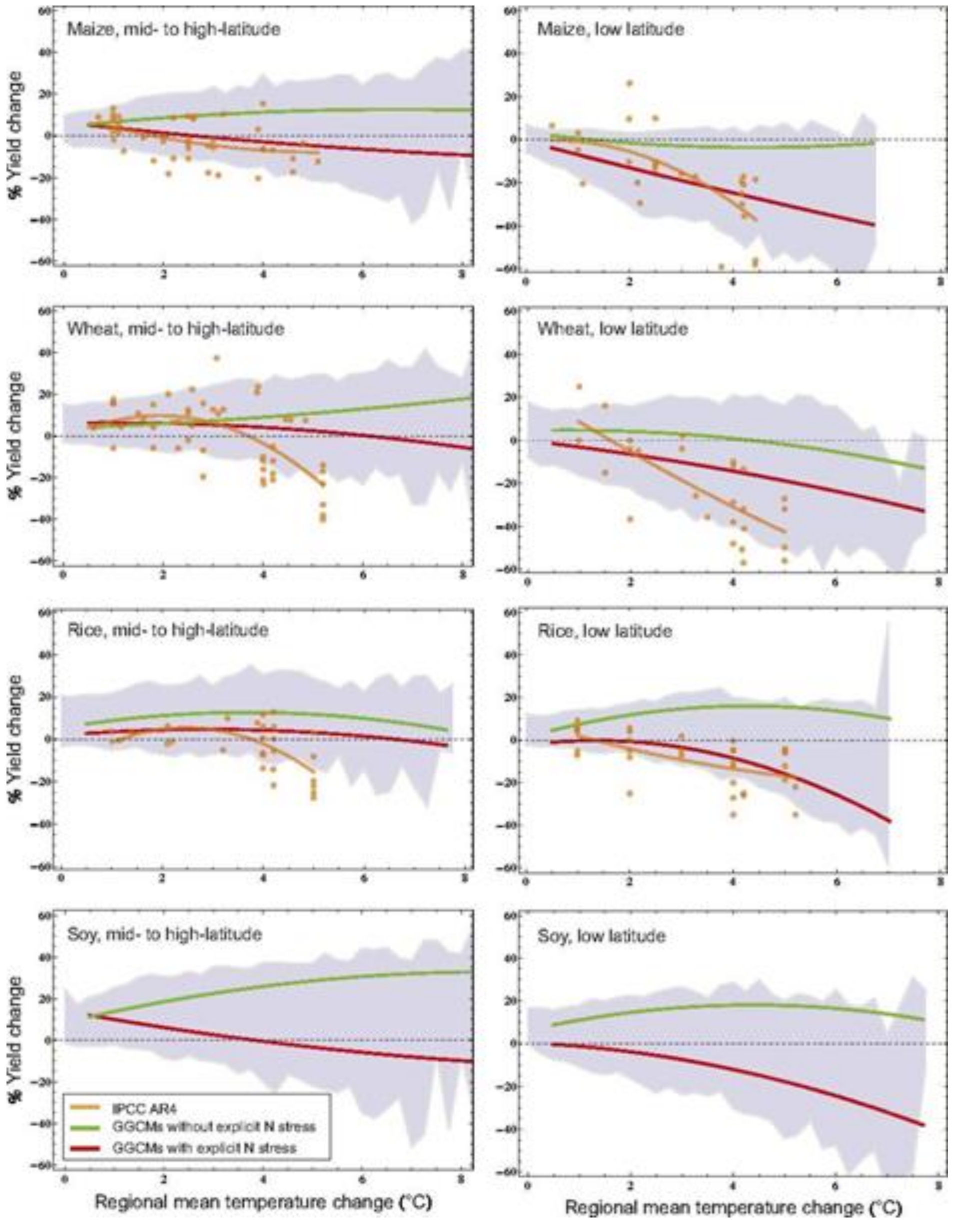
https://www.nature.com/articles/s41558-020-00949-9

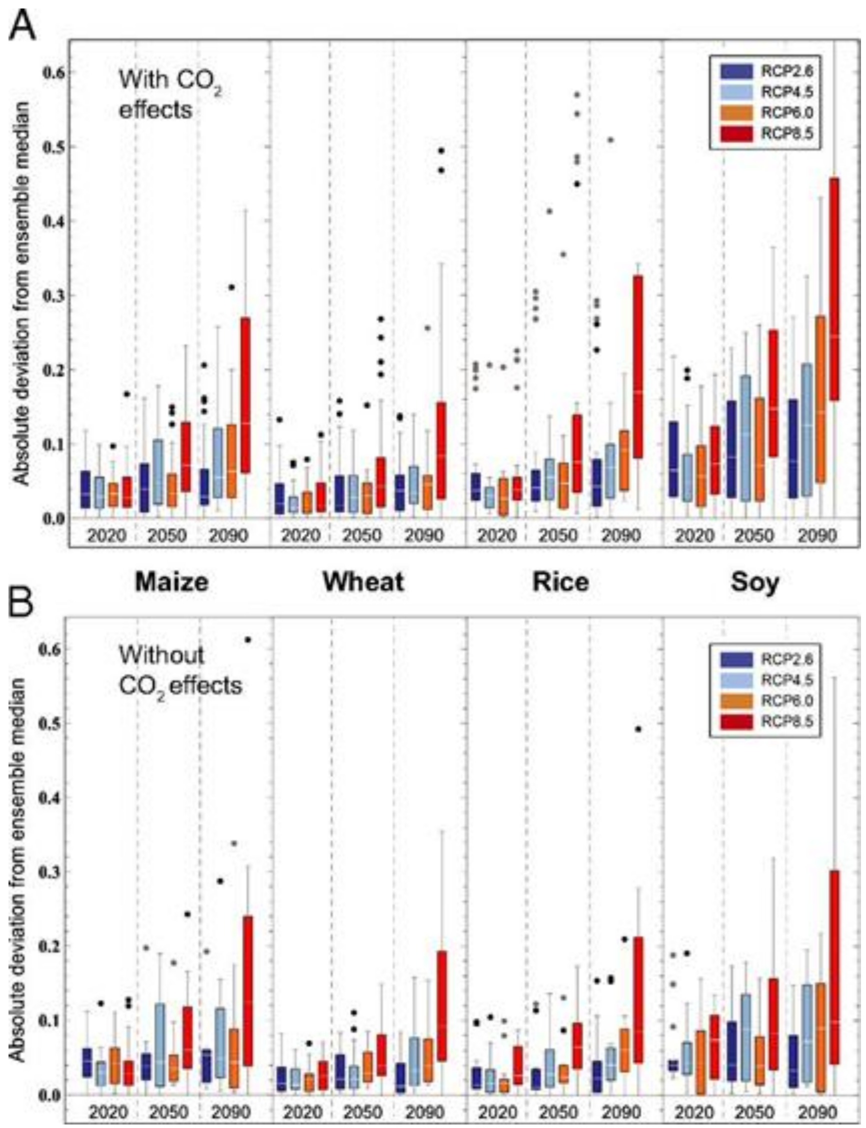
The approach we take in GCAM for climate impacts (e.g., for water supply and hydropower)

We use an ESM that is assumed to have a similar forcing (e.g., RCP) to GCAM's simple climate model



Climate Impacts on Agricultural Yields





Source: Rosenzweig et al. (2014), *PNAS*

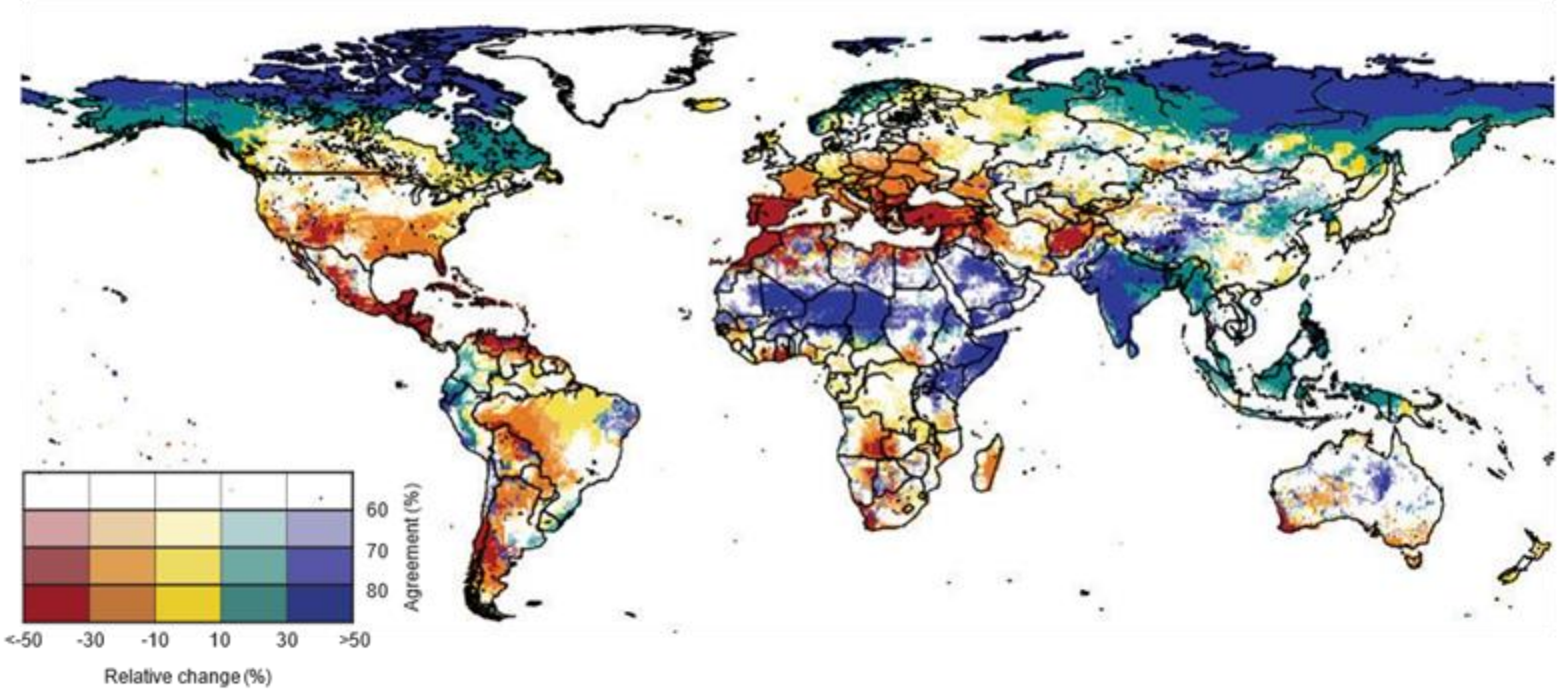
How will Climate Change Impact Water Supply?

- An accelerated water cycle will increase rainfall and thus renewable freshwater flux. But there will be winners and losers. Some regions will see more and some less water on average.

- There is huge uncertainty—Earth System Models (ESMs) only agree for about 1/3 of land area.

- This is a big challenge for IAMs, because they have not been built to consider extreme events

Figure 8 Climate change scenario trends in water availability

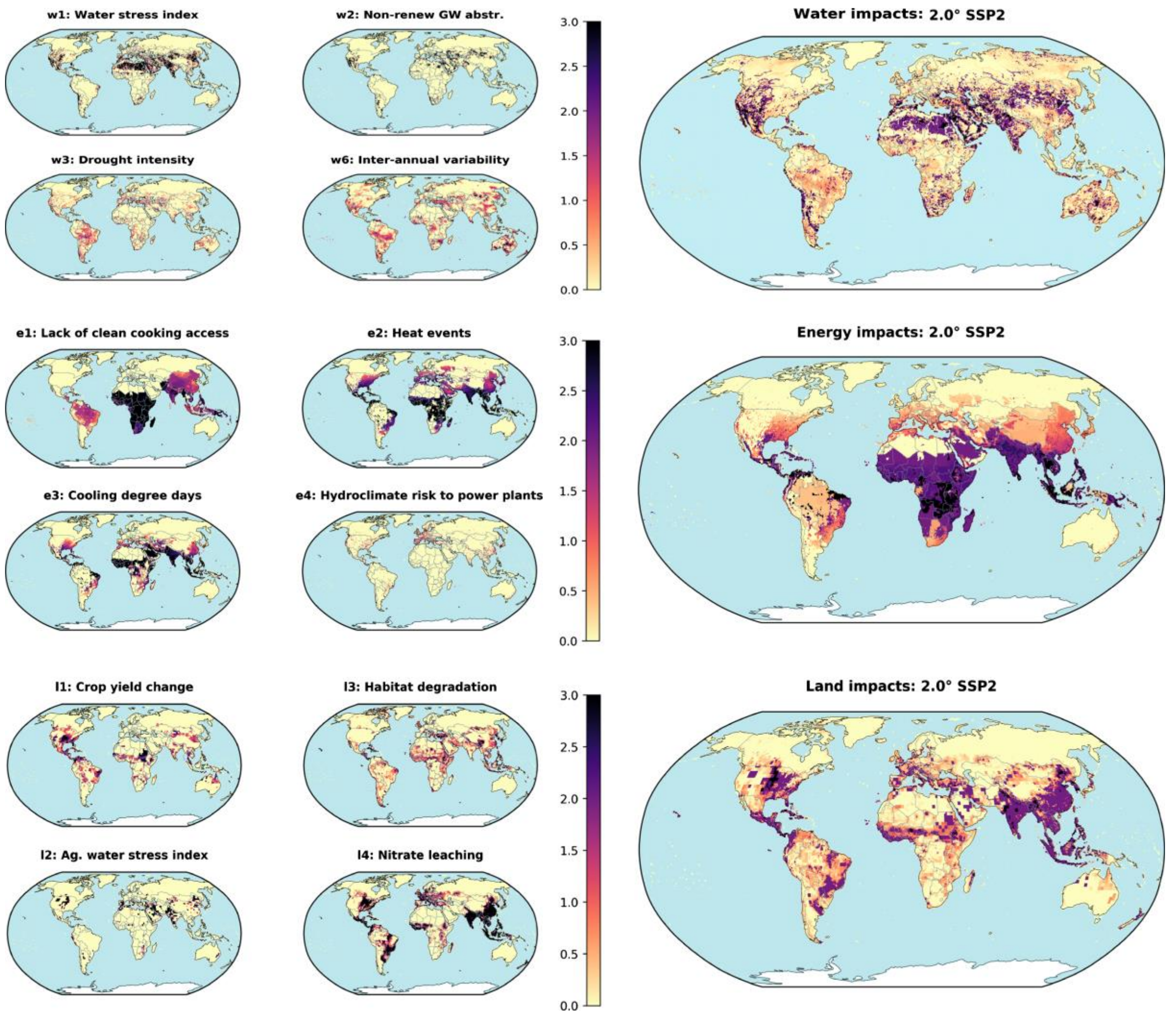


Note: This figure depicts the relative change in annual discharge at 2°C temperature increase compared with present day, under RCP8.5.

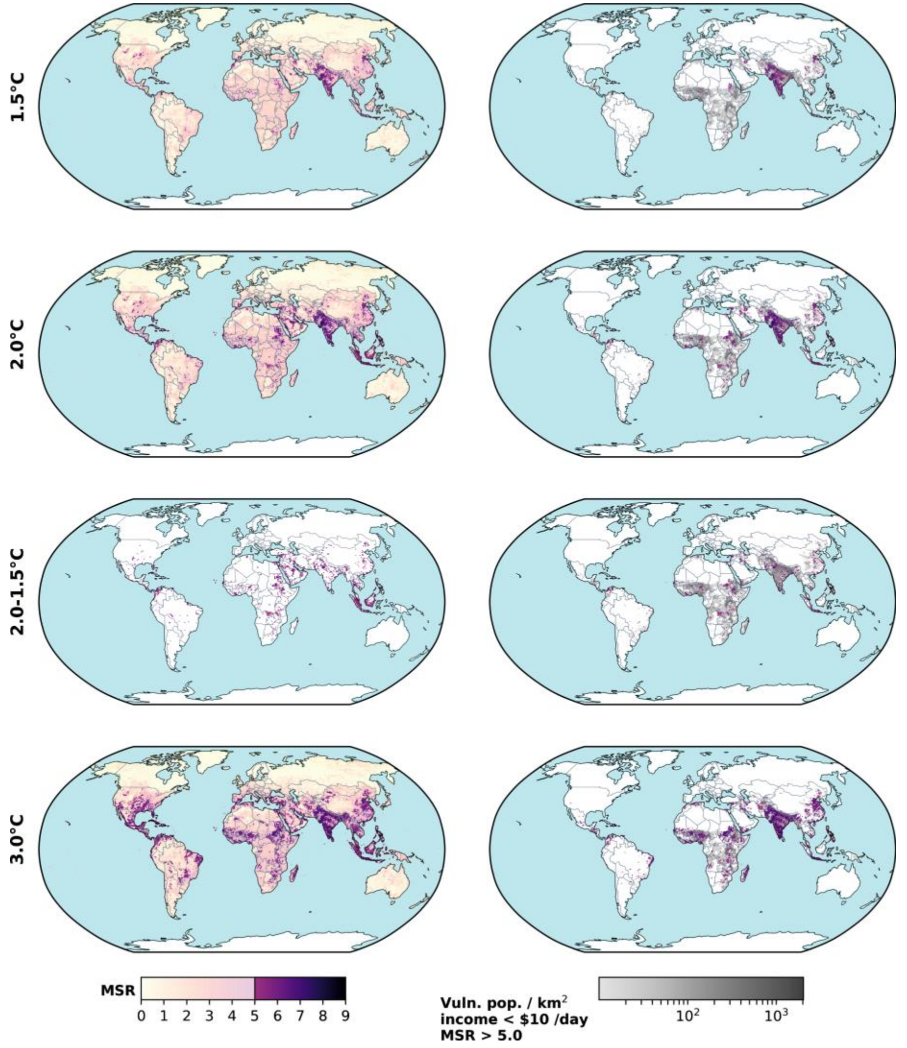
Source: Schewe et al. (2014, fig. 1, p. 3246). The Attribution Share-Alike 3.0 IGO (CC BY-SA 3.0 IGO) licence does not apply to this figure.

Vulnerability to Climate Impacts

Impact Risks



Vulnerable Populations



Byers et al. 2018 (ERL) https://iopscience.iop.org/article/10.1088/1748-9326/aabf45/meta

Summary

Summary

- IAMs consider energy, water, land, socioeconomics, and climate in a single, consistent economic framework

- IAMs do not include all possible nexus interactions, but they have evolved to include many important interactions

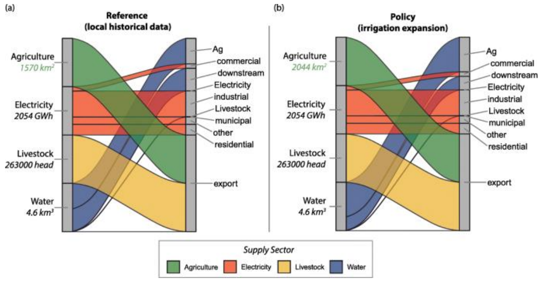
- GCAM accounts for climate feedbacks with water, energy, and land via one-way input files, rather than two-way feedbacks (for now)

- Carefully consider a given IAMs internal dynamics in crafting research questions

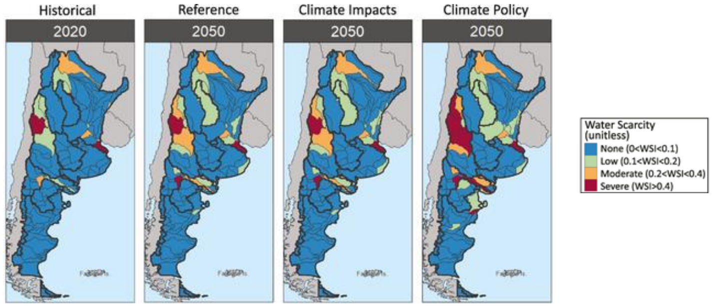
Example Case Studies

Some Nexus Case-study Papers

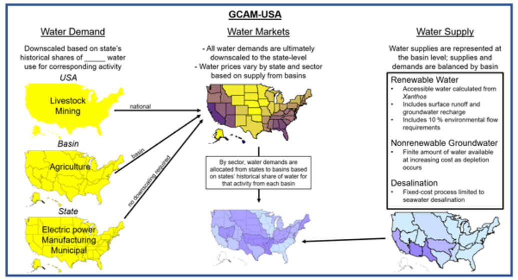
- Integrated energy-water-land nexus planning in the Colorado River Basin (Argentina) – (Wild et al. 2021)



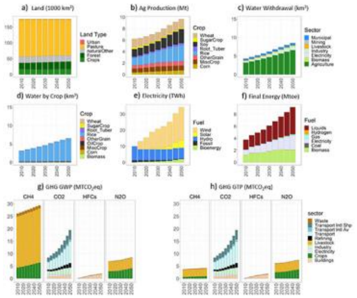
- The Implications of Global Change for the Co-Evolution of Argentina's Integrated Energy-Water-Land Systems – (Wild et al. 2021)



- GCAM-USA v5.3_water_dispatch: integrated modeling of subnational US energy, water, and land systems within a global framework – (Binsted et al. 2022)



- Integrated energy-water-land nexus planning to guide national policy: an example from Uruguay – (Khan et al. 2020)



Exploring Energy-Water-Land Nexus in Latin America

Exploring approaches to enhance energy-water-land nexus planning via pilot projects in Colombia, Uruguay, and Argentina with local collaborators.

Argentina

Instituto Nacional del Agua

COIRCO

COREBE
Comisión Regional del Río Bermejo

Wild et al. (in review), *Earth's Future*
Wild et al. (in revision), *Reg. Env. Change*

Colombia

Universidad de los Andes Colombia

Universidad del Rosario

GOBIERNO DE COLOMBIA

DNP Departamento Nacional de Planeación

Wild et al. (in preparation), *Environmental Research Letters*

Uruguay

UNIVERSIDAD DE LA REPÚBLICA URUGUAY

PRESIDENCIA
REPÚBLICA ORIENTAL DEL URUGUAY

Khan et al. (2020), *Environmental Research Letters*

Integrated energy-water-land nexus planning to guide national policy: an example from Uruguay

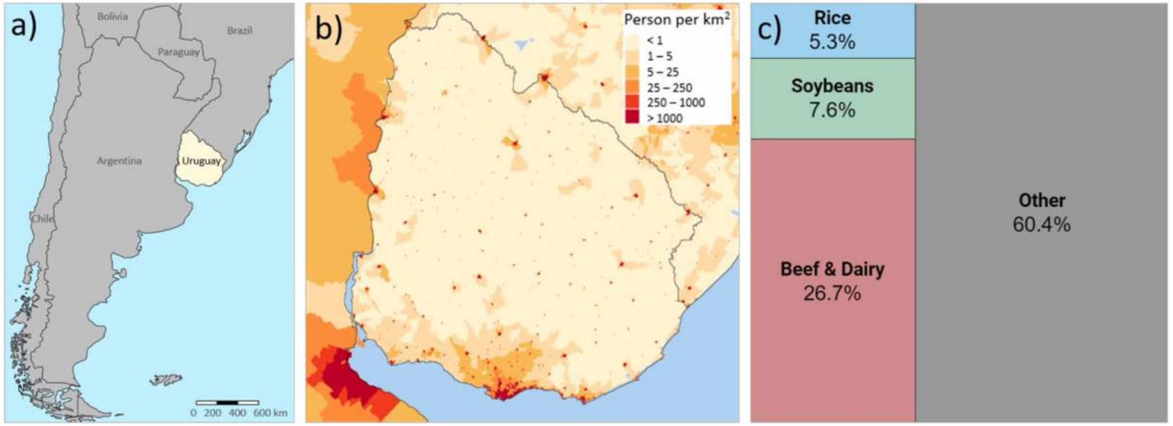


Figure 1. (a) Location of Uruguay in Latin America, (b) Population density in Uruguay in 2015 [46], and (c) Percentage of Uruguay's total export revenue in 2017 by selected sectors (Data from [5]).

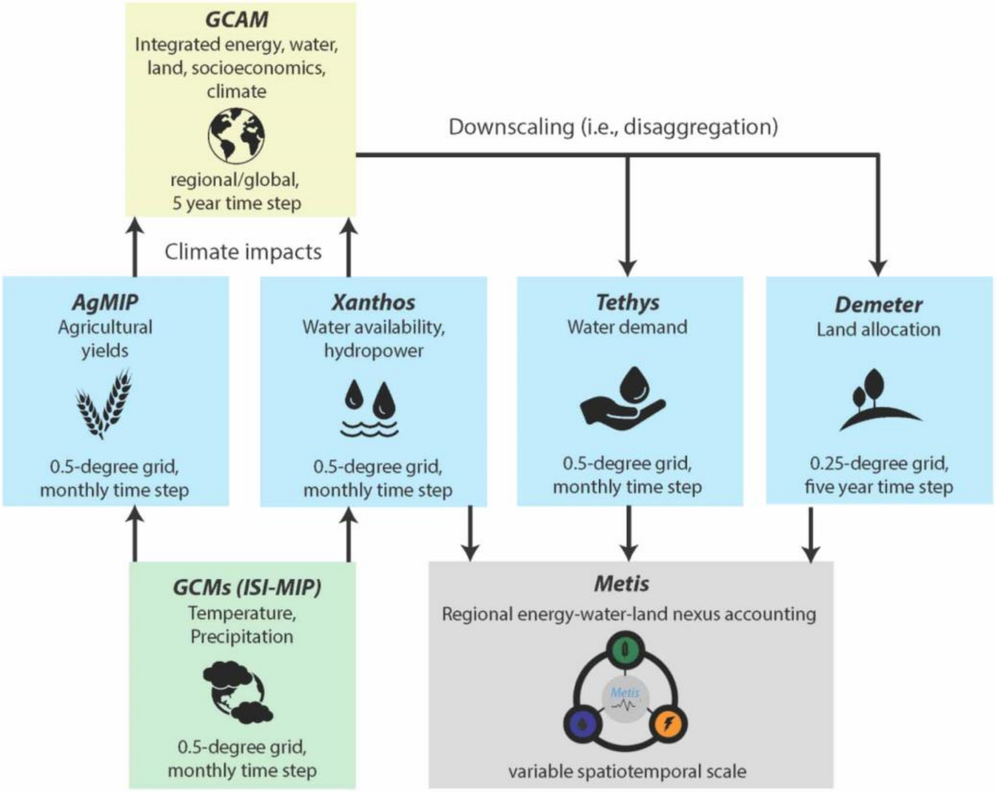


Figure 2. Modeling framework used to analyze energy-water-land dynamics at relevant spatiotemporal scales in Uruguay.

https://iopscience.iop.org/article/10.1088/1748-9326/ab9389

Uruguay Nexus Case Study: Scenarios

Table 1. Summary of scenarios used in study.

Scenario	Description
Reference	Uses an agreed upon set of assumptions for key drivers such as population and GDP growth in Uruguay. For the rest of the world, the scenario is roughly consistent with the Shared Socioeconomic Pathway 2 (SSP2). The SSP2 scenario represents costs, prices, elasticities and preferences in a "middle-of-the-road" narrative in which social, economic, and technological trends do not shift markedly from historical patterns [64–66]. The Climate and policy scenarios below employ the same basic socioeconomic assumptions built into the Reference scenario
Climate	•Evaluates the impacts of climate change on three key parameters: hydro-electric power production, agricultural yields, and water availability (i.e. runoff) for five bias-corrected Global Climate Models (GCMs) from the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) [67] and four Representative Concentration Pathways (RCP) [68]. This range of models and climate forcing scenarios are used to explore uncertainty surrounding future climate conditions. From among this range of Climate scenarios, we selected one to be used in the Climate scenario, which consists of the GFDL GCM run with the RCP8.5 climate forcing trajectory. This results in the following outcomes, which are fed into GCAM:Hydropower increases by 20% by 2050 from the Reference scenario •Runoff increases by 3% by 2050 from the Reference scenario •Irrigated Soy yield increases by about 4% by 2050 from the Reference scenario within Uruguay, though significant changes also take place in global markets •Irrigated Rice yield fluctuates between ± 4% by 2050 from the Reference scenario within Uruguay, though significant changes also take place in global markets
Beef	•Increases the productivity by weight of beef production, and decreases the CH_4 and N_2O emissions intensity of beef production in line with the National Adaptation Plan for Agriculture (NAP-Ag) [8, 69] and the Nationally Determined Contributions (NDCs) of emissions outlined in Uruguay's commitment as part of the Paris Agreement [70].Increase production (kg beef/kg feed) by 40% by 2030 relative to 2015 values, then hold this production efficiency constant through 2050 •Decrease emission intensity (emissions/kg) of CH_4 by 40% by 2030 relative to 1990 values, then hold this production efficiency constant through 2050 •Decrease emission intensity (emissions/kg) of N_2O by 40% by 2030 relative to 1990 values, then this production efficiency hold constant through 2050
Soy	•Increases irrigated area of soybean crops to gain higher yields in line with the National Plan to Improve Irrigated Agriculture [71, 72].Increases share of irrigated soybean area as compared to rainfed soybean area, so that irrigated soybean area is 600% of the 2015 values in 2030. Shares of irrigated vs rainfed soybean area are then held constant through 2050
Rice	•Improves the yield of rice based on recommended best-practices from Uruguay's Ministry of Agriculture to close the national rice yield gap [73, 74].Adjusts annual rice yield growth to increase yields (tons/ha) by 20% by 2030 relative to 2015 values, and then maintain reference growth in yields through 2050

Uruguay Nexus Case Study: Reference

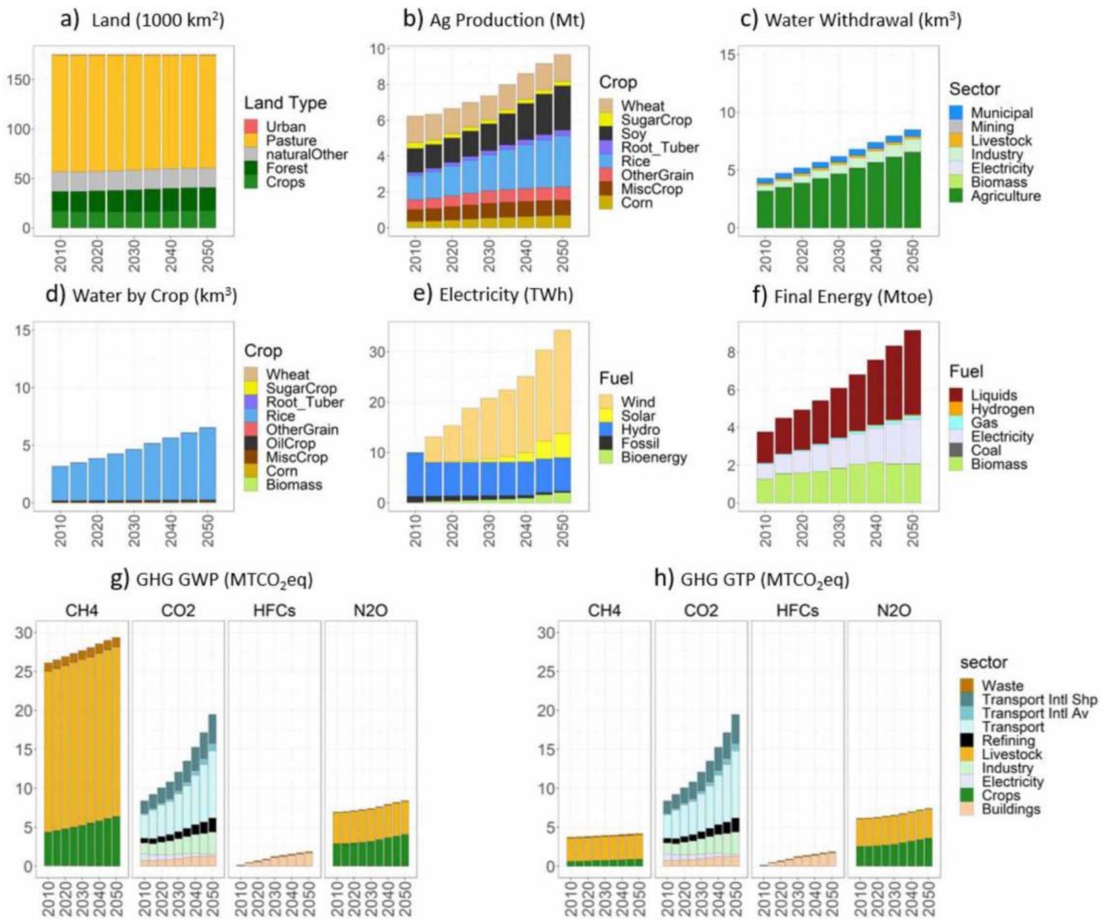


Figure 3. Nexus overview of the Reference scenario. (a) Land-use (1000 km^2) (b) Agricultural Production (Mt) (c) Water withdrawals (km^3) (d) Water use by Crop (km^3) (e) Electricity generation (TWh) (f) Final Energy (Mtoe) (g) GHG emissions GWP (MTCO$_2$eq) by gas and sector (h) GHG emissions GTP (MTCO$_2$eq) by gas and sector (HFCs = Hydrofluorocarbons).

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Uruguay Nexus Case Study: Impacts

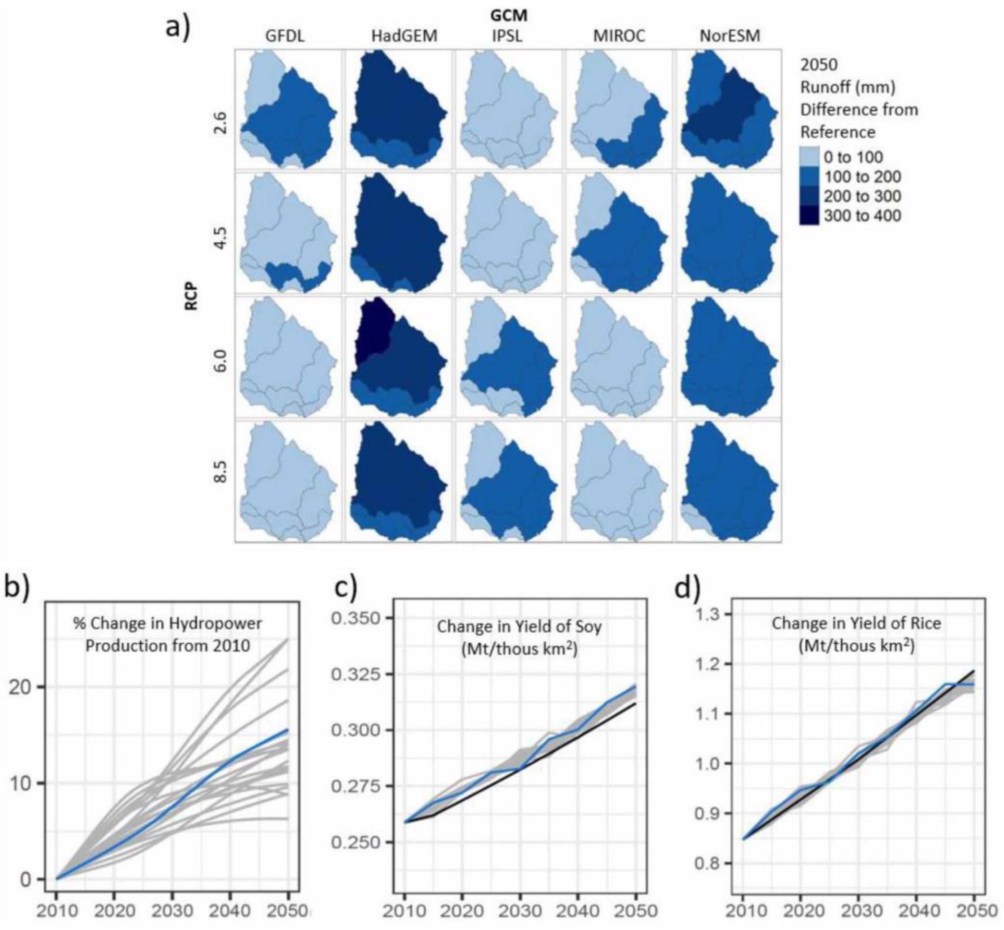

Figure 5. Climate scenario inputs. Projected changes for combinations of five different GCMs and four RCPs for (a) absolute difference between 2050 and reference runoff (mm) (b) % change in hydropower (c) change in yield of soy (Million tons per thousand square kilometers) (d) change in yield of rice (Million tons per thousand square kilometers). For illustration: black lines correspond to the Reference scenario, blue lines correspond to the chosen climate scenario for this study (GFDL_RCP8p5), while the grey lines show all other GCM/RCP combinations. Note: 1 Mt/thous km^2 = 10 ton/hectare.

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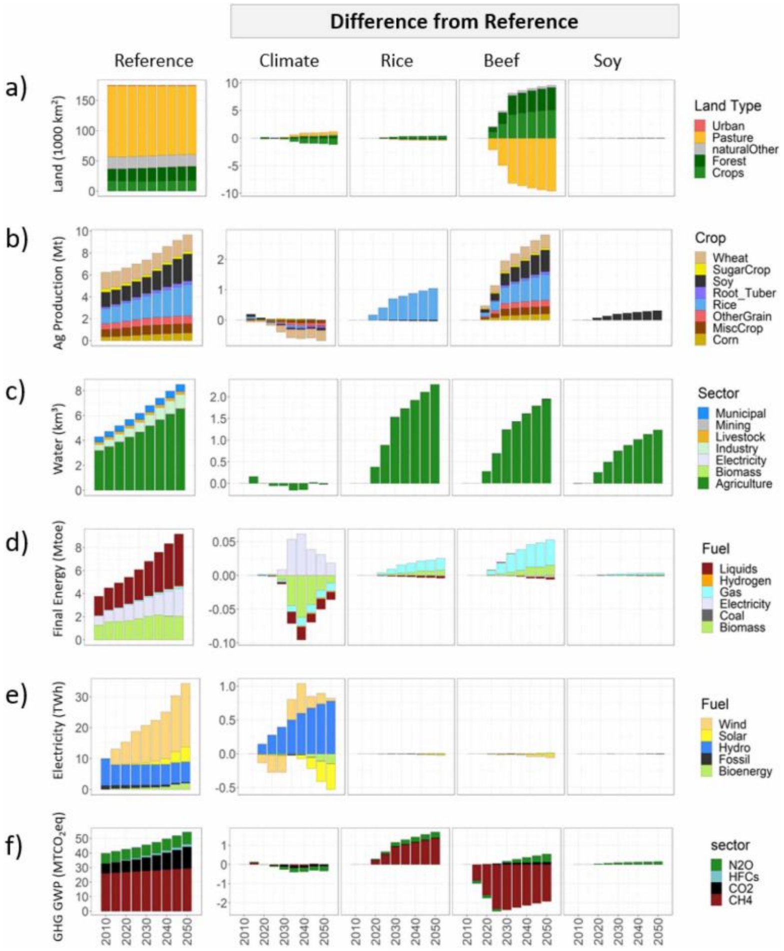
Uruguay Nexus Case Study: Nexus Analysis



- **Nexus insight 1:** Improving beef production efficiency and emissions intensity could indirectly impact land, crops, and water.
- **Nexus Insight 2:** Increased emissions from rice yields could offset decreased emissions from enhancing beef production efficiency and emissions intensity.
- **Nexus insight 3:** Soy irrigation expansion policy is the least disruptive to EWL systems.
- **Nexus insight 4:** The human dimension of change may exceed climate change with respect to EWL nexus impacts.

Figure 7. Nexus comparison across scenarios. First column shows sub-sector details for the Reference scenario, and the second through fifth columns show the differences between the Reference scenario and the Climate, Rice, Beef, and Soy scenarios, respectively. (a) Land allocation (1000 km^2), (b) Agricultural Production (Mt), (c) Water withdrawals (km^3), (d) Final energy (Mtoe), (e) Electricity (TWh), and (f) GHG emissions GWP ($MTCO_2eq$).

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