Tracing the impact of consumption on water stress via international trade and virtual flows

Comparing SSP1 and SSP3 consumption and trade patterns using an integration of the MAGNET CGE model and LPJmL gridded hydrology and crop model.

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Introduction

Sustainable management of water resources requires an understanding of the dynamics driving the demand for water. Similarly, shifting to sustainable consumption requires an understanding of resource demands of the products consumed but also the resource demands of the inputs for those consumed products. The concept of virtual flows, an accounting of the resources used in the production of the inputs used in the final commodity consumed including intermediate inputs and international trade, is a useful tool for understanding the environmental impacts of current patterns of consumption (Philippidis et al., 2021). The concept of virtual flows has often been applied to assess the impact of consumption patterns on global water resources with concepts like the water footprint gaining wide prominence in recent years.

Water supply, however, has a very strong spatial and temporal component where water can be abundant in certain times and places and very scarce in others, therefore a simple accounting of the total water used in the creation of the inputs of a final product is often not enough for a sustainability assessment of the use of scarce water resources. Further, for policy makers and water managers it is important to understand the consumption patterns driving demand for water in their specific river basin. In addition, as water supply projects such as dams or pipelines are long term lumpy investments, it is important to have an understanding of how these demands for water and water intensive products might change over time.

Water demand, driven by global consumption of water intensive products depends on many socio-economic factors such as population trends, income, consumption preferences (diets), agricultural competitiveness and trade relationships. Various combinations of how these factors might change over time are incorporated into the Shared Socio-Economic Pathway (SSP) narratives (O'Neill et al 2017).

In addition, there is uncertainty regarding the impact of climate change on water stressed regions from changes in temperatures and precipitation patterns, affecting both the supply of water locally and the direct demand for water from agricultural activities (van Vuuren et al., 2011).

With the aim of improving both the sustainability assessment of consumption patterns as well as the ability for policy makers and water managers to anticipate future demand for local water resources this study integrates two global models – the GTAP based Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer et al. 2014) and the Lund–Potsdam–Jena managed Land (LPJmL) (Schaphoff et al., 2018) by means of the MAGNETGrid (Diogo et al., 2020) crop allocation model to explore the impacts of e.g., European consumption food and agricultural products on water stress in water scarce regions. We explore the possible futures by implementing and comparing the current consumption to projected consumption in 2050 in the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios using this integrated model combination.

Methods

In this section the models used are briefly described as well as the method of collaboration between them

MAGNET

MAGNET is a multi-regional multi-sector recursive dynamic equilibrium model built on neo-classical microeconomic theory (Woltjer et al 2014). The core of MAGNET is the GTAP v7 (Corong et al 2017) and the GTAPv11C database, base year 2017 (Aguiar et al 2022) and the extension of MAGNET is mainly in the domain of agriculture and the bioeconomy (Woltjer et al 2014, Van Meijl et al 2018). Key features of MAGNET relevant for this study are endogenous land markets, capturing the dynamics between agricultural land supplied and real land prices including the total potential suitable land available for agriculture (Dixon et al 2016, van Meijl et al 2006) and segmented factors markets in agricultural and non-agricultural labor and capital.

MAGNET scenario results are generated as the model, after implementing consecutive shocks on e.g. population and GDP, finds a new equilibrium in the global economy by adjusting prices for commodities and factors (labor, capital, land). Producers adjust their input use in response to changes in input prices to maximize profits, where the producers are operating under conditions of zero profit. Representative households respond to changes in income from factor sales and to fluctuations in commodity prices by maximizing their utility within their income constraint. Bilateral trade flows between all regions are modelled, with regional sourcing of imports based on the Armington assumption, allowing for two-way trade flows.

At the core, MAGNET results are multi-regional input-output tables that are update through time through external shocks and subsequent stepwise equilibrium solutions. Thus, through a so-called 'Leontief inverse' approach a footprint analysis can be based on the MAGNET production, intermediate demand, trade, and consumption data, tracing e.g., European consumption to demand pressures on water stressed regions where European consumption is sourced directly or indirectly from.

By capturing the bilateral trade flows of goods and services between all regions of the world, the MAGNET model can link the consumption patterns in one region to production systems in other parts of the world. Linking MAGNET's global agricultural and land-use change economics with LPJmL's detailed representation of hydrology and climate impacts on crop yields, we can provide an integrated assessment of climate change, global consumption and patterns of global trade on water stressed regions.

LPJmL

The Lund-Potsdam-Jena managed Land (LPJmL) model captures the daily interaction between the hydrological and carbon cycles and can be used for the simulation of water availability, agricultural water demand and vegetation growth (Schaphoff et al., 2018). This makes it a suitable tool to study the interactions between water availability and food production. The models output is on a resolution of 0.5 degree grid cells on a global scale.

LPJmL simulates the daily water balance at sub-grid scale. Water enters the grid cell through precipitation or irrigation and is first diverted into direct surface runoff and infiltration into the soil. Subsequently, the infiltrated water percolates through 5 soil layers of variable thickness, or enters the river system as subsurface runoff when soil water content exceeds saturation. In addition, water leaves the soil by evaporation from the upper 20 cm soil layer, or via transpiration by natural vegetation or crops. Water that percolates to the groundwater eventually contributes to baseflow. The generated runoff and baseflow enters the river system, assuming a constant flow velocity of 1 m/s.

Irrigation occurs in the growing period of irrigated crops. Crop-specific daily irrigation demand is calculated as the minimum amount of water needed to fill the upper soil to field capacity and the amount needed to fulfil the atmospheric demand. Subsequently, the withdrawal demand is calculated by accounting for losses during conveyance, distribution, and application of water, depending on the type of irrigation system installed (surface, sprinkler or drip) and the soil type of the irrigated cell (see below, section 'irrigation efficiency'). Water for irrigation is withdrawn from surface water first. This is the water available in the river (so including river water from upstream) and natural lakes of the cell where the irrigated cropland is located, or a neighboring cell with higher water availability. If an artificial reservoir with irrigation supply purpose is in reach of the irrigated fields, water can also be withdrawn from those reservoirs. If the irrigation withdrawal cannot be fulfilled by the available surface water, water is withdrawn from groundwater, leading to overexploitation and depletion when withdrawal exceeds recharge.

Rainfed and irrigated crop growth is simulated based on daily assimilation of carbon in four pools: leaves, stems, roots and harvestable storage organs. The amount of carbon allocated to those pools depends on crop phenology and is adjusted in case of water stress for the plants. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al. 2007).

MAGNETGrid

The key linkage between the MAGNET and LPJml models is the model MAGNETGrid. MAGNETGrid is a model framework that simulates the spatial patterns of agricultural land use resulting from economic decisions on the use of land. It does so by combining future scenario-based projections on the supply, demand, prices and production costs of different agricultural commodities (as simulated by the MAGNET model) with grid-based projections on the biophysical suitability (as simulated by LPJmL for agricultural production). Hence, by carrying out a spatial-economic optimization of land returns, MAGNETGrid allows the user to project and visualize future agricultural land-use change patterns that emerge from climatic and socio-economic developments under a set of conditions that are specified in scenarios (Diogo et al., 2020).

The resulting changes to agricultural land areas are used as inputs to LPJmL to estimate the actual amount of water demands in the projected years future years (time interval of 10 years – 2030, 2040 and 2050). This step requires some post processing tasks on the projected land use maps, such as: disaggregating MAGNET-GTAP crops into LPJmL crop definitions; split the crop areas between rainfed and irrigated (base year share will be applied to the projected maps as no future projections on land share of rainfed and irrigation is available); convert MAGNETGrid land (physical) area output into harvested area, which is the relevant information to LPJmL estimating water demands. This is shown graphically in Figure 1.

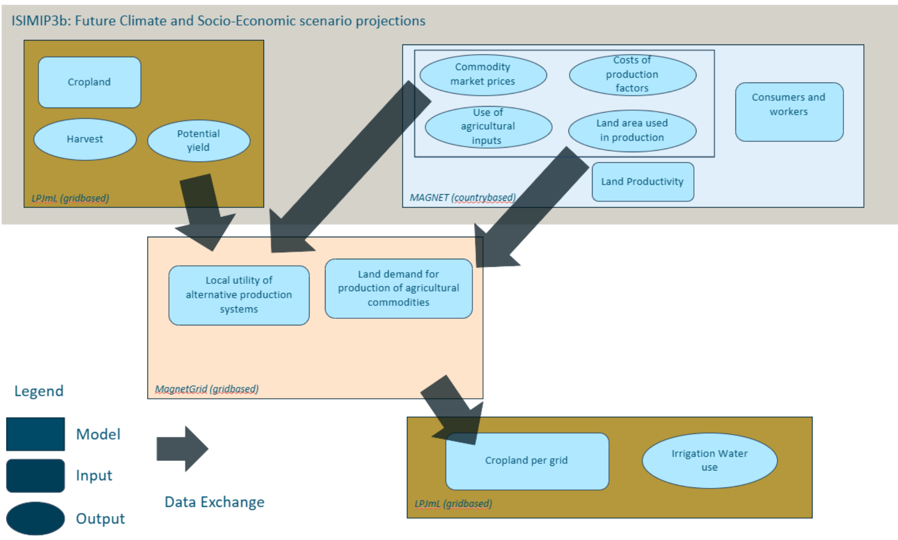

Figure 1: MAGNET - MAGNETGrid – LPJmL linkage: The macro-economic model MAGNET provides land demand changes and production information on crop/region level to the MAGNETGrid model which is then downscaled to the grid level and used to update cropland allocation in LPJmL.

Scenarios

The main framework used for the scenario setup is that of the well know combinations of shared socio-economic pathways (SSPs) and representative concentration pathways (RCPs). The SSPs describe a set of diverging future socio-economic developments, whereas the RCPs describe a range of GHG emissions pathways quantified in terms of the resulting radiative forcing by 2100.

SSP Socio-economic drivers

The main exogenous drivers of MAGNET are based on shared socioeconomic pathway (SSP) projections, including population, technological change, and land productivity. Technological change is calibrated the GDP growth of the SSP projections. These scenarios implicitly capture the impact of new technologies, such as new food (technologies) or agricultural technologies, within the SSP narratives. In SSP2, technological trends do not deviate significantly from historical trends, SSP1 represents a more sustainable path with high technological change towards lower material and reduced resource and energy consumption, while in SSP3 technological change is falling (O'Neill et al 2017, Riahi et al 2017). The recently updated SSPv3.2 database was used for the GDP and Population projections, whereas various other inputs (see Table 1) are prepared by the IMAGE modelling team.

Table 1: Main drivers in SSPs implemented in MAGNET.

	SSP1 Sustainability	SSP2 Middle of the Road	SSP3 Fragmentation
Population (billion) (2050/2100)	8.6/7.0	9.2/9.1	9.9/12.6
GDP(thousand 2017 US$ per capita) (2050/2100)	26/59	21/43	15/16
Globalization of trade	Highly globalized – abolishment of tarrifs by 2050	Moderately globalized – Current tarrifs	Less globalized – 10% import tax on agricultural goods by 2050.
Animal product consumption	Reduced preference for animal products	Current preference for animal products	High preference for animal products
Land-use change regulation	Strict regulation – 30% of terrestrial area protected.	Moderate regulation – Current levels of protected area.	Little regulation – only "strictly protected" area.
Agricultural productivity	High yield improvement	Moderate yield improvement - following largely the projections by FAOs agricultural outlook	Low yield improvement

ISIMIP Climate Drivers

The Climate data that serves as input for LPJmL are taken from ISIMIP3b. The climate variables from ISIMIP3b used by LPJmL include temperature, precipitation and solar radiation (Müller and Robertson, 2014). The data used from ISIMIP3b has spatial resolution of 0.5°x0.5°. Climate datasets have temporal resolution of daily. ISIMIP3b includes data from 5 global climate models (GCMs) MRI-ESM2-0, IPSL-CM6A-LR, MPI-ESM1-2-HR, UKESM1-0-LL, GFDL-ESM4 form Coupled Model Intercomparison Project (CMIP6) which are bias-adjusted, downscaled, and daily, global at 0.5° resolution. ISIMIP3b does not have SSP2, so we use SSP1-RCP26 and SSP3-RCP70, which will be the two main scenarios investigated.

Preliminary Results

Figure 2 and Figure 3 show the level of water stress per river basin from the LPJmL model, based purely on the changing climate signal without the crop land allocation changes from MAGNETGrid. Towards 2050 in the Climate Scenario RCP7.0, there are no basins that decrease in water stress. In Afghanistan, Iran, Mexico and China some river basins are becoming high water stressed basins instead of moderate. In Spain and India there are river basins that become sever water stressed.

Water stress is determined by the ratio of total water withdrawal to water availability. Water availability the amount of water that is available if there would not be any extraction. Withdrawal is the consumption permanently removed from the surface water together with the return flows. As these return can be potentially used again the water stress indicator may overestimate the water stress in a region. Four different levels of water stress are defined:

1. No stress: WS < 20%
2. Moderate stress: WS = 20% - 40%
3. High stress: WS = 40% - 70%
4. Extreme stress: WS > 70%

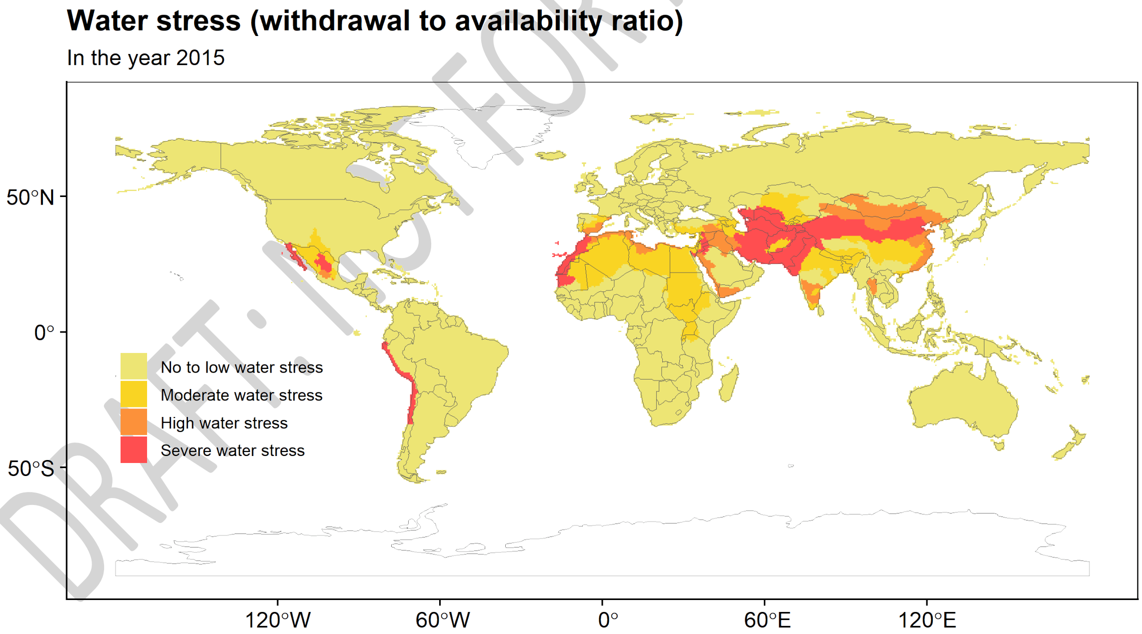

Figure 2: Results from the LPJmL model Water Stress in 2015

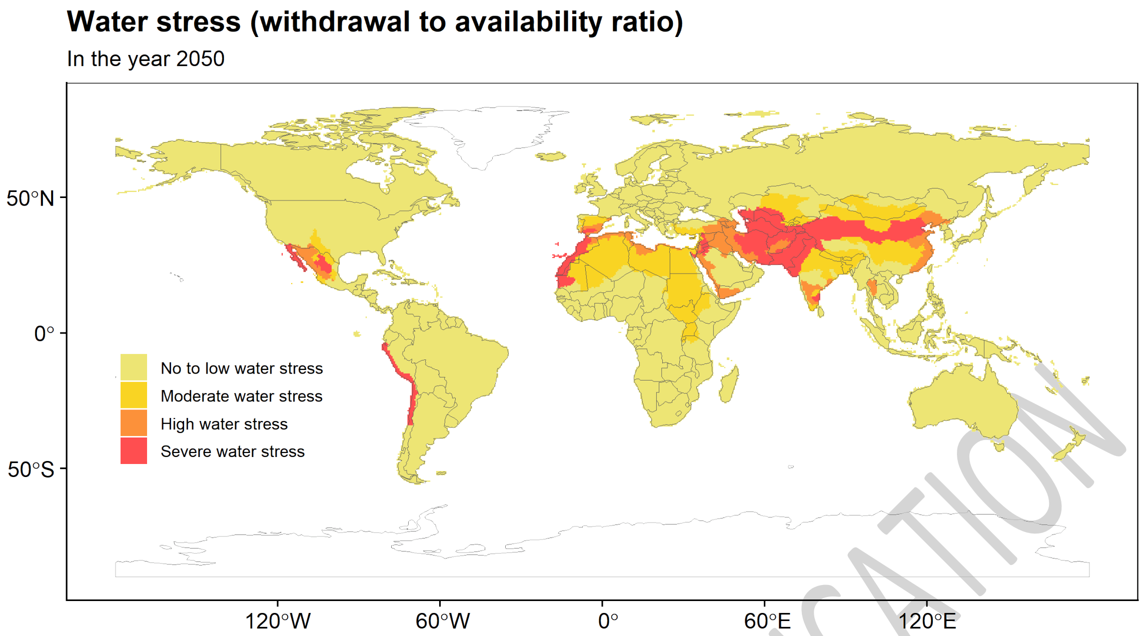

Figure 3: Results from the LPJmL model Water Stress in 2050 based purely on the climate signal RCP7.0, without land allocation changes from MAGNETGrid.

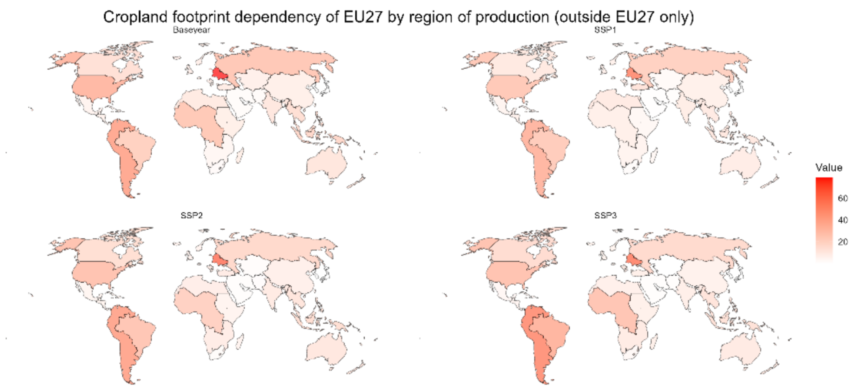

Figure 4: Global Cropland Footprint of Consumption in the European Union (excluding land used in the EU). Results from the MAGNET model in 2050 from SSP1-3

Figure 4 shows the Global Cropland Footprint of Consumption in the European Union (excluding land used in the EU) from the MAGNET model results in 2050 for the Socio-Economic Pathways 1-3. These results will further be expanded with an analysis including MAGNETGrid which links the crops at the national level from the MAGNET model to the grid-cell level of the specific river basins experiencing water stress as shown in Figure 2 and Figure 3.

References

Aguiar, A., Narayanan, B., & McDougall, R. (2022). GTAP Database Version 11. Purdue University. https://www.gtap.agecon.purdue.edu/databases/v11/index.aspx

Bondeau, A., et al. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology, 13(3), 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x

Corong, E., et al. (2017). The Standard GTAP Model, Version 7. Journal of Global Economic Analysis, 2(1), 1–119. https://doi.org/10.21642/JGEA.020101AF

Diogo, V., Hennen, W., Verma, M., Oudendag, D., & Kuiper, M. (2020). MagnetGrid : Model description and user guide. https://doi.org/10.18174/512146

Müller, C., & Robertson, R. D. (2014). Projecting future crop productivity for global economic modeling. *Agricultural Economics*, *45*(1), 37-50.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Philippidis, G., et al. (2021). Eating your greens: a global sustainability assessment. Resources, Conservation and Recycling. Volume 168, May 2021, 105460. https://doi.org/10.1016/j.resconrec.2021.105460

Schaphoff, S., et al. (2018). LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. Geoscientific Model Development, 11, 1343–1375. https://doi.org/10.5194/gmd-11-1343-2018

van Meijl, H., et al. (2018). Comparing impacts of climate change and mitigation on global agriculture by 2050. Environmental Research Letters, 13, 064021. https://doi.org/10.1088/1748-9326/aabdc4

van Vuuren, D.P., Edmonds, J., Kainuma, M. *et al.* The representative concentration pathways: an overview. *Climatic Change* **109**, 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

Woltjer, G., et al. (2014). *The MAGNET model: Module description*. No. 14-57. LEI, 2014.

Annex: Demonstration of MAGNETGrid land allocation changes for a single region

Figure 5 shows the spatio-temporal distribution of croplands in the SSP3 scenario as a result of MAGNETGrid, based on the initial inputs from the LPJmL model and the national level production changes resulting from global demand coming from the MAGNET model.

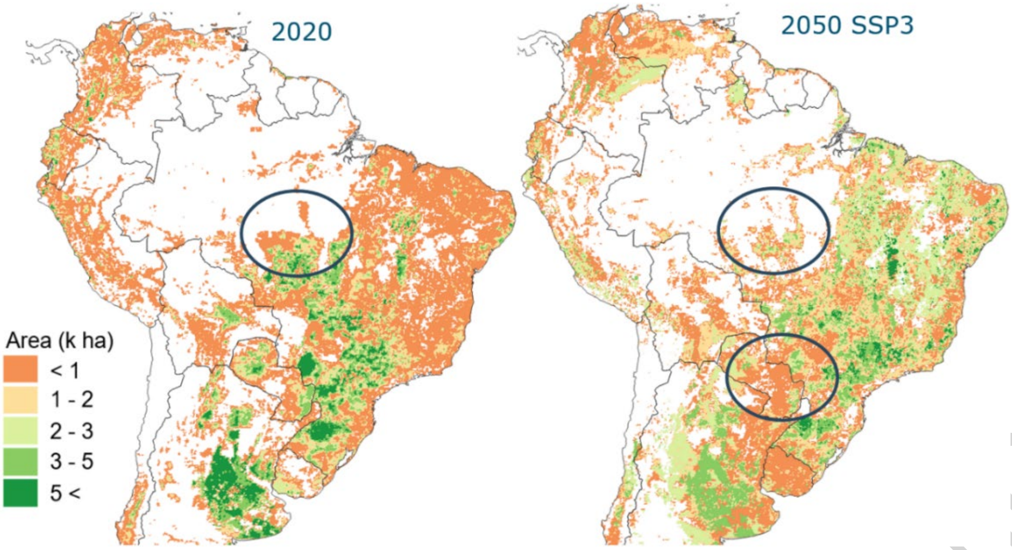

Figure 5: Initial results agricultural land use modelling showing the Spatio-temporal cropland distribution in South America between 2020 and 2050 in the SSP3 scenario.

These changes in cropping areas will then be incorporated into LPJmL to estimate the actual amount of water demand in the projected years future years (time interval of 10 years – 2030, 2040 and 2050).