Gridded Economic Responses to Environmental and Climate Changes

Analyze SIMPLE-G Results in Jupyter Notebook and R

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Abstract

This manuscript provides a step-by-step guide to analyzing the outputs of the SIMPLE-G model using Jupyter Notebook and R. The SIMPLE-G model is a gridded economic model for what-if analysis of the impacts of climate change, environmental changes, and conservation policies on agriculture, land use, and the global economy at a high spatial resolution (grid cells ranging from 250 meters to 25 kilometers. Jupyter Notebook provides a powerful reproducible environment for visualizing, analyzing, and summarizing the model's results, enabling in-depth comparison and sensitivity analyses.

Useful Resources

- SIMPLE-G Book: https://doi.org/10.1007/978-3-031-68054-0
- SIMPLE-G Webpage: https://www.gtap.agecon.purdue.edu/simple-g/
- SIMPLE-G Short Course: https://mygeohub.org/courses/sustainability_shortcourse_2024
- SIMPLE-G YouTube Videos: https://tinyurl.com/SIMPLE-G-Book
- SIMPLE-G Web Application: https://mygeohub.org/resources/simpleus
- SIMPLE-G Experiments: Groundwater Conservation Scenarios
    - Output: https://mygeohub.org/resources/1706/supportingdocs
    - Notebook: Gridded Economic Analysis of Groundwater Conservation Scenarios
    - Model Code and Data:
- SIMPLE-G Experiments: Future Projections: Global Drivers of Local Water Stress
    - Output:
    - Notebook: Global Drivers of Local Water Stress
    - Model Code and Data
- SIMPLE-G Experiments: Adaptations to A Compound Pandemic-Weather Stress Event
    - Output:
    - Notebook:
    - Model Code and Data:

Note:
The figures in this handout are generated from different versions of the model and might be different from the Jupyter Notebook.

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Introduction

SIMPLE-G, the Simplified International Model of agricultural Prices, Land use, and the Environment- Gridded, is a multi-scale high-resolution economic model that considers economic decisions and their market implications in evaluating the impacts of changes in environment on land and water use (Figure 1).

Figure 1. Economic decisions are important for accurate evaluation of the impacts of policies and environmental changes on land and water use.

Economic analysis at the grid cell level

When evaluating the impacts of climate and global changes on environmental resources, economic decisions play an important role. Ignoring market-mediated responses may lead to overestimation or underestimation of the impacts and biased policy recommendations. This manuscript illustrates two examples focusing on environmental footprints and groundwater conservation scenarios.

The SIMPLE-G model includes the decisions on agricultural production and input use at each grid cell considering specific economic and biophysical features of each location. Figure 2 can help illustrate possible changes in farmers' decisions in response to groundwater restrictions. With restrictions on groundwater withdrawals at each grid cell:

1. Surface water withdrawal may increase if available depending on relative costs.
2. Irrigation technology may improve to increase efficiency.
3. Farmers may seek improved use of all resources through better management.
4. They may apply more fertilizer to partially compensate production loss, depending on relative yield response to water and fertilizer.
5. Overall irrigation production may decline as the production costs are less competitive.
6. Farmers may convert land to rainfed depending on land rents.
7. And rainfed production may increase depending on production costs.

In this figure, τ and σ are economic behavioral parameters in SIMPLE-G model.

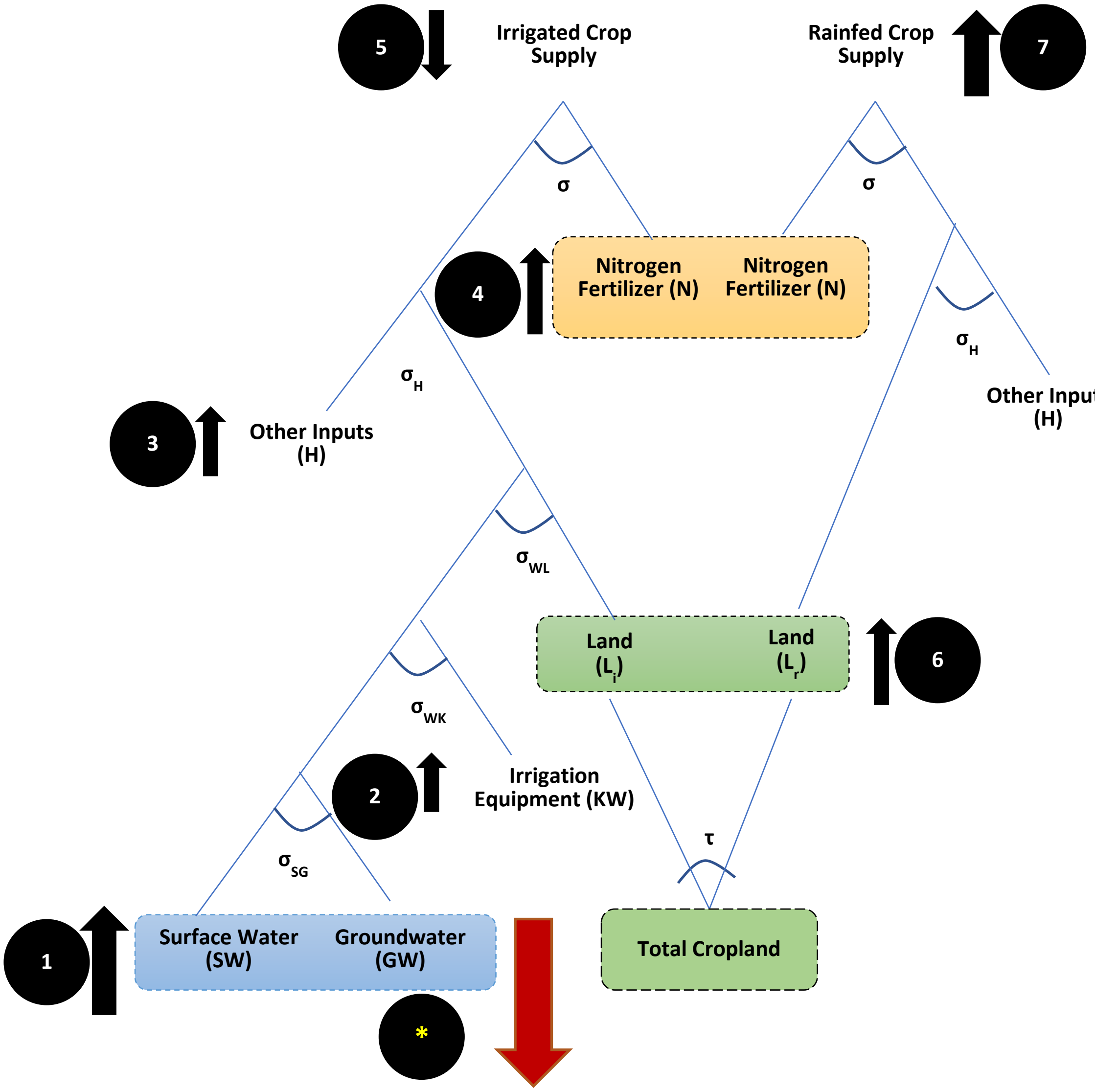

Figure 2. Economic decisions in response to lower groundwater availability or restrictions.

SIMPLE-G Outputs

Variables and Notations

The SIMPLE-G model reports a variety of key variables related to agriculture, water resources, and land use at the grid cells, region, and global scales. These include irrigation groundwater and surface water withdrawals, cropland harvested area, aggregate crop production, nitrogen fertilizer application, and farmworker employment. Below is the list of notations used for geospatial variables reported for each grid cell:

- QCROP: Quantity index of crops produced per year (total value of crops / corn price index)
- QLAND: Cropland harvested area per year (1000 ha)
- QNITRO: Quantity of N fertilizer application per year (1000 kg)
- QWATGRD: Volume of groundwater withdrawals per year (1000 m3)
- QWATSRF: Volume of surface water withdrawals per year (1000 m3)
- QWEQPT: Quantity index of irrigation equipment and technology (index)
- QLABOR: Index of labor input (index)
- LON: Longitude
- LAT: Latitude
- GID: SIMPLE-G grid ID

Each quantity variable has an associated price variable. The equilibrium price and quantity for each agricultural input or output is determined in local, regional, or global markets.

Temporal resolution

SIMPLE-G model outputs show the state of agricultural economic system between two points of time. Depending on parameter calibration it can be interpreted as short run (1-2 years) or long-run (3-7 years). Note that this framework is most appropriate for what-if analysis and projecting the impacts of scenarios. Unless otherwise noted, the model shows the change in the long-run.

Spatial resolution

The economic variables are simulated at high spatial resolution with grid cells ranging from 250 meters to 25 kilometers. For the current exercise, the US model is at 5 arc min (~8 km) and the global model at 15 arc-min (~25 km).

The coordinates are reported as LON and LAT, there are two versions of coordinates and the user needs to verify to choose the right approach:

- LON/LAT: lon/lat WGS 84
- LON/LAT: x 120: multiplied by 120

Files and format

SIMPLE-G is solved in GEMPACK, a general-purpose modeling system widely used in economics. When SIMPLE-G is run through GEMPACK, it generates three primary output files:

- HAR file: This file contains the historical data used in the model, including variables like GDP, population, and agricultural production. It serves as a baseline for comparison with the model's results.
- SL4 file: This file stores the solution to the model's equations. It includes the simulated values of various economic variables under different policy scenarios or shocks.

- TXT Outputs: To facilitate analysis and visualization, the SIMPLE-G model may also generate additional output files in TXT format. These TXT files contain gridded data that can be mapped to visualize spatial patterns. The exact contents of the TXT files may vary depending on the specific configuration of the SIMPLE-G model and the desired outputs.

For this exercise, the SIMPLE-G model outputs are organized into text files that follow a specific naming convention. For example, files starting with 'simpleg_old_' contain pre-simulation values, while files starting with 'simpleg_new_' contain post-simulation values. The suffix 'pct' indicates percentage changes in variables. Additionally, files ending in '_i' represent variables related to irrigated agriculture, '_r' for rainfed agriculture, and '_t' for both irrigated and rainfed agriculture.

- simpleg_old_* = pre-simulation values
- simpleg_new_* = post-simulation values
- simpleg_pct_*= percentage change in variables
- simpleg_*_i = variables for irrigated agriculture
- simpleg_*_r = variables for rainfed agriculture
- simpleg_*_t = variables for irrigated and rainfed agriculture

Parameter Space: Realization

The concept of “realization” from climate science can be adapted to economic models (like SIMPLE-G). In economics, a realization can refer to a single simulation or run of an economic model with a specific set of initial conditions and parameters. This approach can help in understanding the variability and uncertainty in economic projections, similar to how it is used in climate science.

- Income Elasticity of Demand. Measures how the quantity demanded of a good may respond to a change in consumers’ income.
- Substitution Elasticity. Measures the ease with which one factor of production (like labor and capital or land and water) can be substituted for another in response to changes in their relative prices.
- Supply Elasticity: Measures how much the quantity supplied of a good may respond to a change in its market price.

Parameter space for:	**wnt1**	**wnt2**	**wnt3**	**wnt4**	**wnt5**
Land Supply Elasticity: ELAND				x2	
Water and irrigation technology substitutability: ESUB_WK	0.5	2.5	2.5	2.5	.5
Spatial crop substitutability (spillover): ESUB_MKT	2	2	10	10	10
Groundwater and surface water substitutability: ESUB_SG	2.5	.5	.5	.5	.5

About Computation and Visualization Tools

Figure 3 shows some of the tools available for execution of the model and analyzing the results. While model computation is mainly done in GEMPACK, data preparation and visualization can be done in other environments like R and Python.

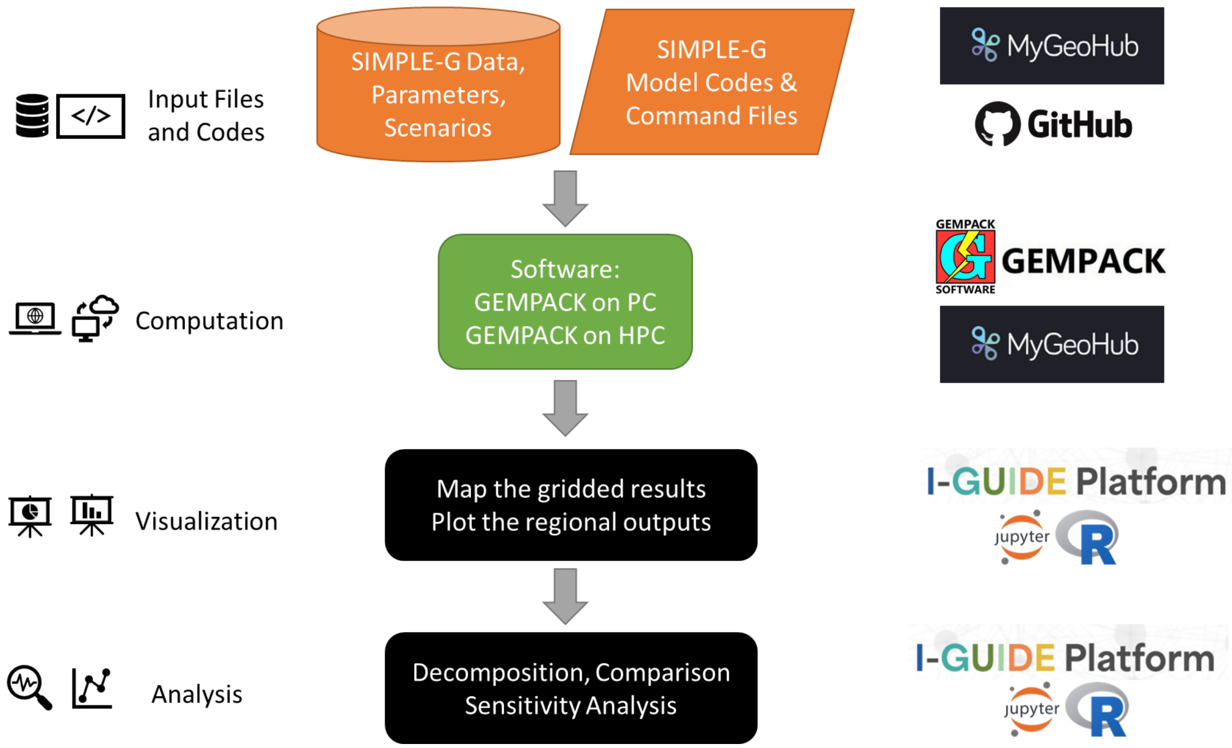

Figure 3. Tools and software environments for running SIMPLE-G model and viewing the results.

Model Codes and Database

The model codes and datasets of various versions of SIMPLE-G are publicly available on MyGeoHub. The model code and equations are stored in a TAB file; while command files and closures for each scenario are in CMF files; the data and parameters are in HAR files; for use in Windows machines an EXE file is provided that can be used with GEMPACK. For a list of different models and closures look at the SIMPLE-G webpage:
https://www.gtap.agecon.purdue.edu/simple-g/

For more details look at the SIMPLE-G Book and published papers available on SIMPLE-G Webpage: https://www.gtap.agecon.purdue.edu/simple-g/

GEMPACK (Offline and Online)

The model is solved in GEMPACK. Installing it on desktop computers for offline use will require a license that can be obtained from WWW. Note that a free trial option is also available.

Purdue University and the Centre of Policy Studies (CoPS) have provided complementary access to cloud computation of SIMPLE-G without license requirement. To use this application, you need to have an account on MyGeoHub. To access the online tools, look at:

Jungha Woo; Uris Lantz C Baldos; Lan Zhao; Carol Song; Jaewoo Shin (2020), "SIMPLE-G US Web Application," https://mygeohub.org/resources/simpleus.

Gaurav Sachdev; Jungha Woo; Lan Zhao (2023), "SIMPLE-G US Jupyter Notebook," https://mygeohub.org/resources/simplegus. (DOI: 10.21981/5C2H-P780).

Pre-Solved Scenarios

The solution time for different scenarios vary from less than one minute to above one hour. For educational purposes of short workshops, it is recommended to use the pre-solved scenarios related to SIMPLE-G model outputs for published papers available on SIMPLE-G Webpage: https://www.gtap.agecon.purdue.edu/simple-g/

Visualization R and Jupyter Notebook

This guide employs R and Jupyter Notebook for the visualization of SIMPLE-G results. R's comprehensive data handling capabilities facilitate the efficient processing of generated TXT files and the execution of custom visualization scripts. Jupyter Notebook provides an interactive platform that is well-suited for educational purposes, allowing users to explore and interpret results in a dynamic and engaging manner.

Example 1: Market-Mediated Spillovers

Research question: What are the economic impacts of global conservation policies?

Research objectives:

- **Compare Crop Production Before and After Conservation Policy:** Create map plots to visualize changes in crop production.
- **Identify Factors Affecting Crop Production:** Consider factors like policy, surface water, irrigation technology, land conversion.
- **Explore Market Adjustments:** Analyze how markets have responded to changes in crop production.

Step 1: Open Jupyter Notebook

The Notebooks for this exercise are stored on GitHub and are available for use on I-GUIDE Platform. Go to https://platform.i-guide.io/notebooks and look for: SIMPLE-G-Global-Water: Global Groundwater Conservation Scenarios

Step 2: Import Required Libraries

To visualize the outputs generated by SIMPLE-G, we employ a combination of popular data visualization packages in R: plotly, ggplot2, raster, and terra. These tools provide useful features for creating informative and visually appealing representations of the model's results. Note that they are substitutable. While these packages offer different options for visualization, users may choose according to their preferences.

Step 3: Get the Model Outputs

Users can get the pre-solved model outputs as a ZIP file for each scenario from MyGeoHub:

- Market Mediated Spillovers

After getting the files, inspect the content of the output archive:

- Download
- Unzip to "in" folder
- Look at the files
- Remove the comment from text files
- View the content of text files

Step 4: Plot the Policy

Take the "in/simpleg_water_00_**pct_**t.txt" file and use one of the visualization packages to plot the percentage change in groundwater withdrawals (QWATGRD) due to policy restrictions.

- Use LON and LAT for coordinates
- Double-check the format of LON and LAT

Figure 4 shows the groundwater withdrawals after policy illustrating the hotspots in the US, China, and India, and Middle East.

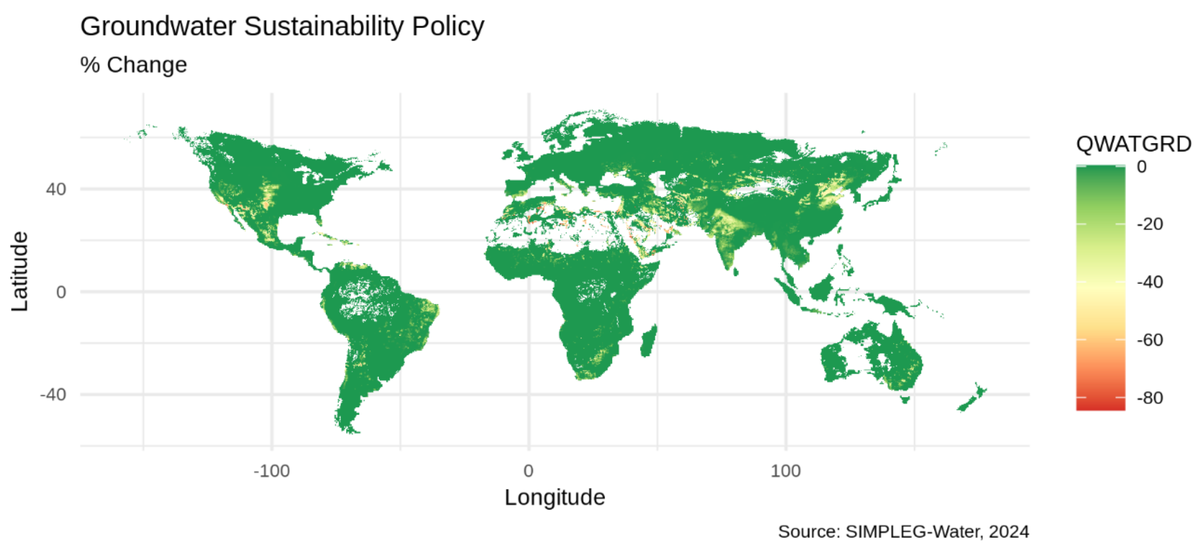

Figure 4. The percentage change in global groundwater withdrawals due to restrictions.

Step 5: Global Crop Production

Using the same file, "in/simpleg_water_00_pct_t.txt", plot the percentage change in agricultural production due to policy restrictions. Figure 5 shows the change in crop production after policy. As expected, it shows the hotspots in the US, China, and India, and Middle East. However, the range of impacts are limited to around -8%. While the reduction in groundwater was up to -80%.

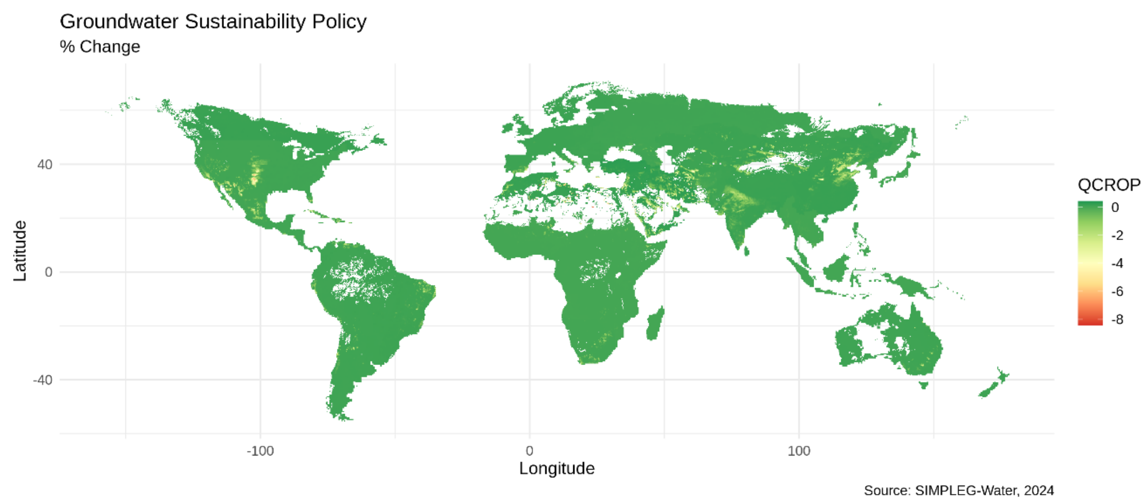

Figure 5. The percentage change in global crop production due to conservation policy.

Step 6: Focus and Compare QCROP and QWATGRD

For a better comparison let's focus on the US and truncate to -25%. Figure 6 clearly shows that the reduction in production is much smaller than reduction in groundwater.

Why?

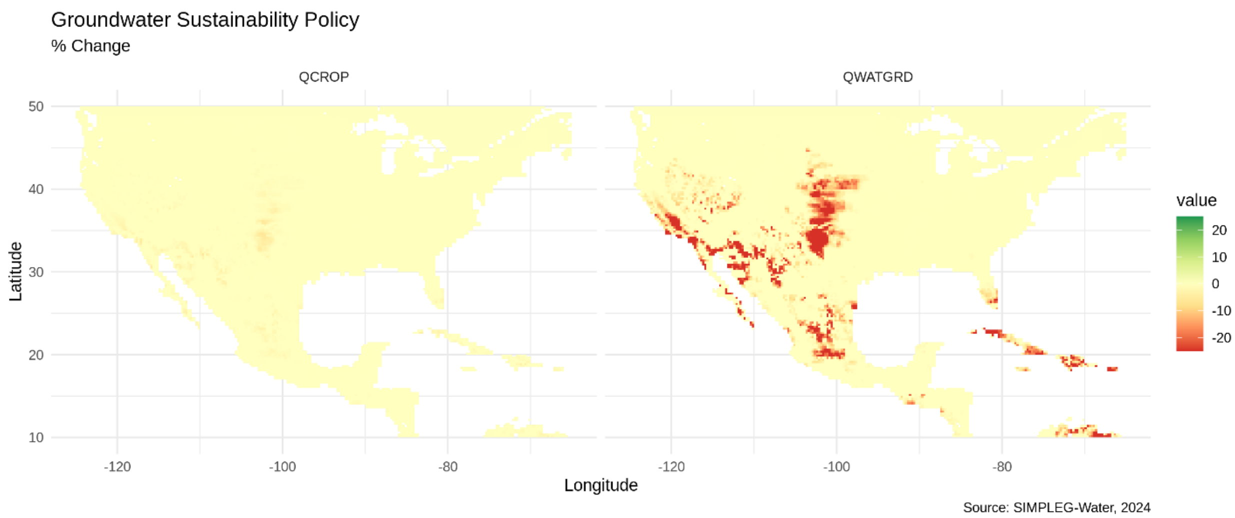

Figure 6. The percentage change in US-MEX crop production and groundwater withdrawals due to policy.

Step 7: Compare QWATSRF and QWATGRD

As shown in figure 2, farmers may substitute groundwater and switch to surface water resources depending on the economic costs and benefits. Figure 7 shows the increase in surface water as estimated in this version. Note that this is % change, depending on the base the volumes can be equivalent.

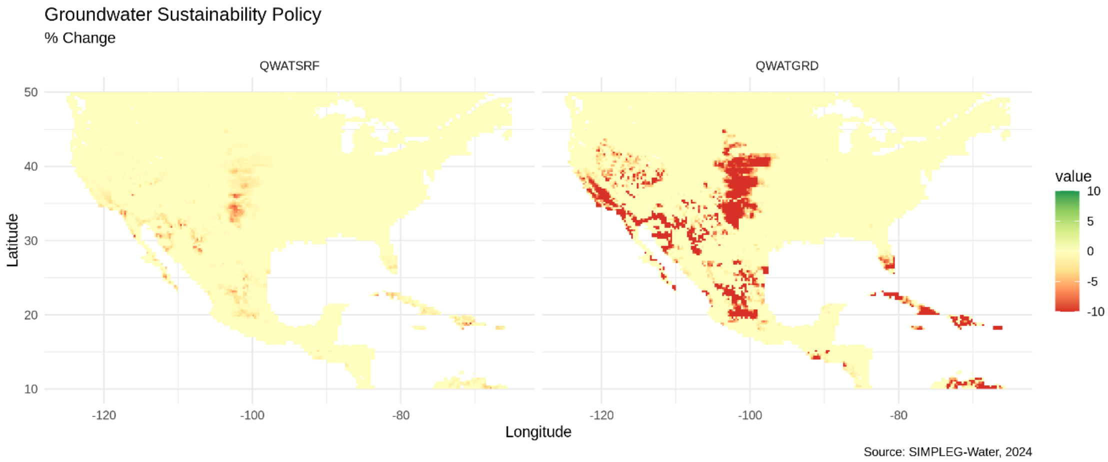

Figure 7. The percentage change in US-MEX irrigation surface water and groundwater withdrawals due to conservation policy.

Step 8: Compare QLAND_IRR and QLAND_RFD

As shown in figure 2, farmers may convert rainfed and irrigated land. Figures 7 and 9 show the changes in irrigated and rainfed harvested area as projected by the model.

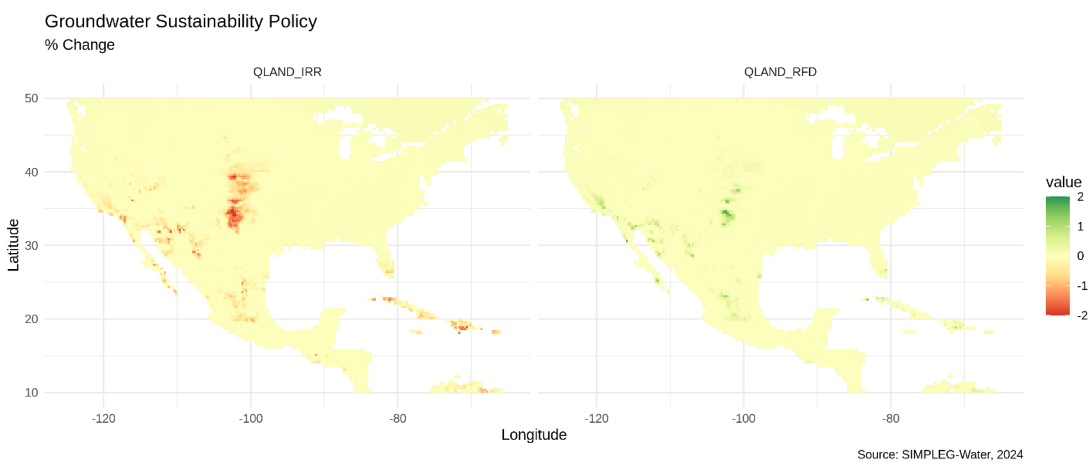

Figure 8. The percentage change in US-MEX irrigated and rainfed area due to conservation policy.

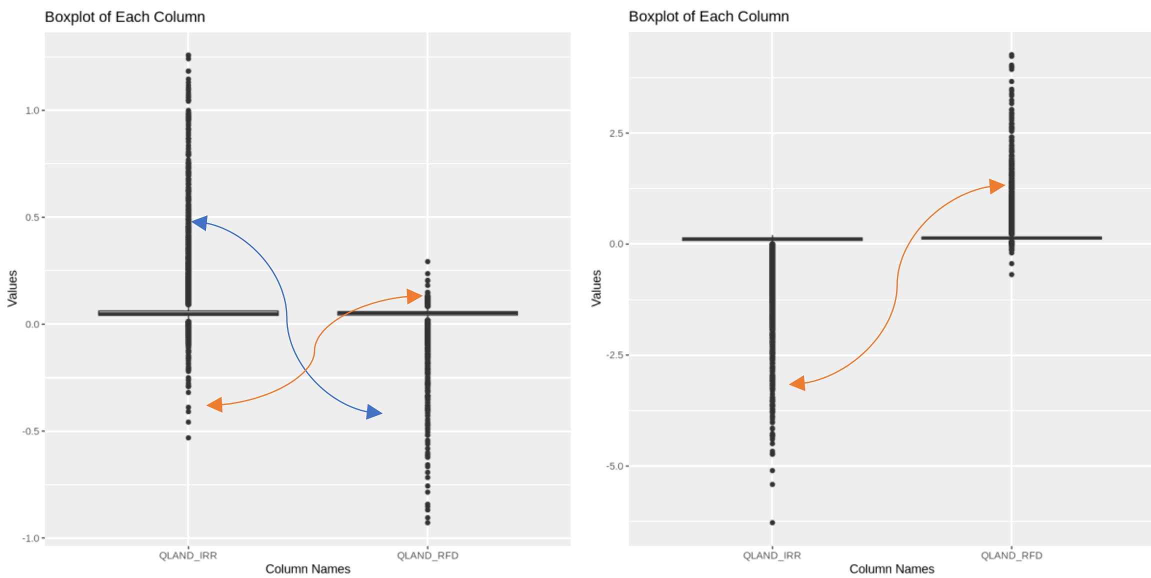

Figure 9. The percentage change in global irrigated and rainfed areas due to conservation policy (left: wnt1, right wnt5 parameter space).

Step 9: Overall Changes and Discussion

Using SIMPLE-G outputs, we looked at changes in agricultural production and input use at each grid cell. Figure 10 summarizes the main results for US-MEX region. When groundwater withdrawals are restricted, farmers may adapt by increasing surface water use if it's cost-effective, adopting more efficient irrigation technologies, and improving overall resource management. They might also use more fertilizer to offset production losses, though irrigation production could decline due to higher costs. Additionally, farmers may convert irrigated land to rainfed agriculture based on land rents, potentially increasing rainfed production if it's more cost-competitive.

These adaptive strategies area happening in real world. Capturing these responses will enable us to simulate realistic responses to environmental changes and restrictions, emphasizing the need for economic analysis for any conservation planning.

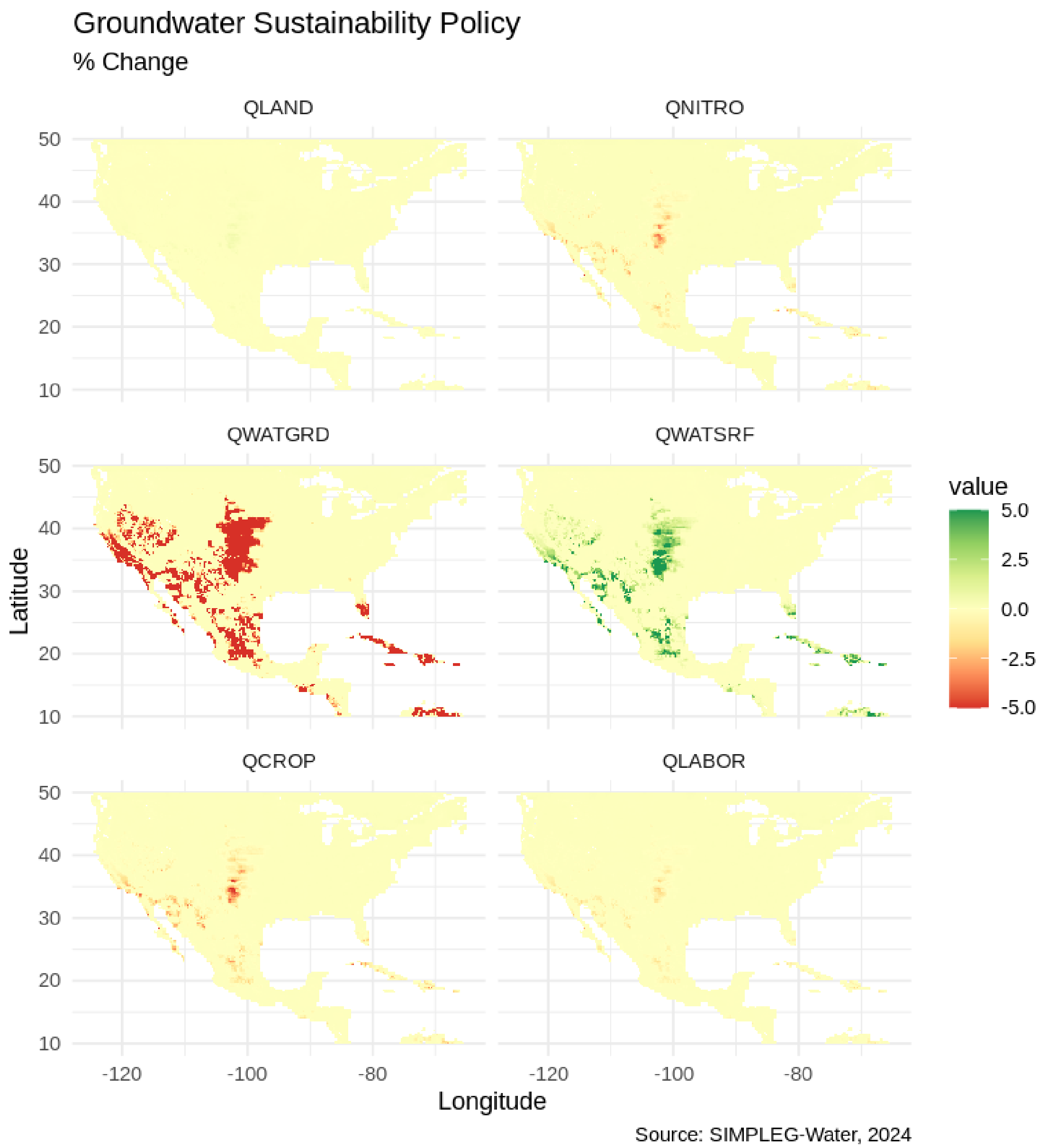

Figure 10. The percentage change in US-MEX variables due to conservation policy.

Decomposition

A crucial strength of both SIMPLE-G and GEMPACK-based models lies in their ability to decompose complex phenomena into contributing factors. This decomposition analysis allows us to isolate the individual and interactive effects of various drivers on the system being modeled. For instance, in the context of agriculture, these models might decompose the changes in crop production into subtotals. These subtotals could represent the impact of factors like population growth, income shifts, technological advancements, and climate change. By examining these subtotals, we gain a deeper understanding of how each driver influences the overall outcome. This not only aids in identifying the most significant drivers but also empowers policymakers to formulate targeted interventions that address specific aspects of the challenge. In essence, decomposition analysis within SIMPLE-G serves as a powerful tool for unpacking complex cause-and-effect relationships, informing more effective strategies for navigating global challenges. Decomposition in the context of SIMPLE-G and GEMPACK refers to the process of breaking down complex economic changes into simpler, more understandable components. This is particularly useful in computable general equilibrium (CGE) models, where the impact of policy changes or external shocks can be dissected into individual effects on various economic variables. Subtotals in decomposition play a significant role as they show the contributions of individual factors to provide an overarching view of the change in a particular economic variable.

The decomposition figure provides insights into the key market-mediated adjustments when facing a policy or change. Figure 11 shows various channels that contribute to a reduction in damage. The major channels are:

- Substitution: surface water, technology, etc.
- Rainfed conversion: with some yield penalty.
- Relocation: production moves to other locations.
- Trade: production moves to other regions.

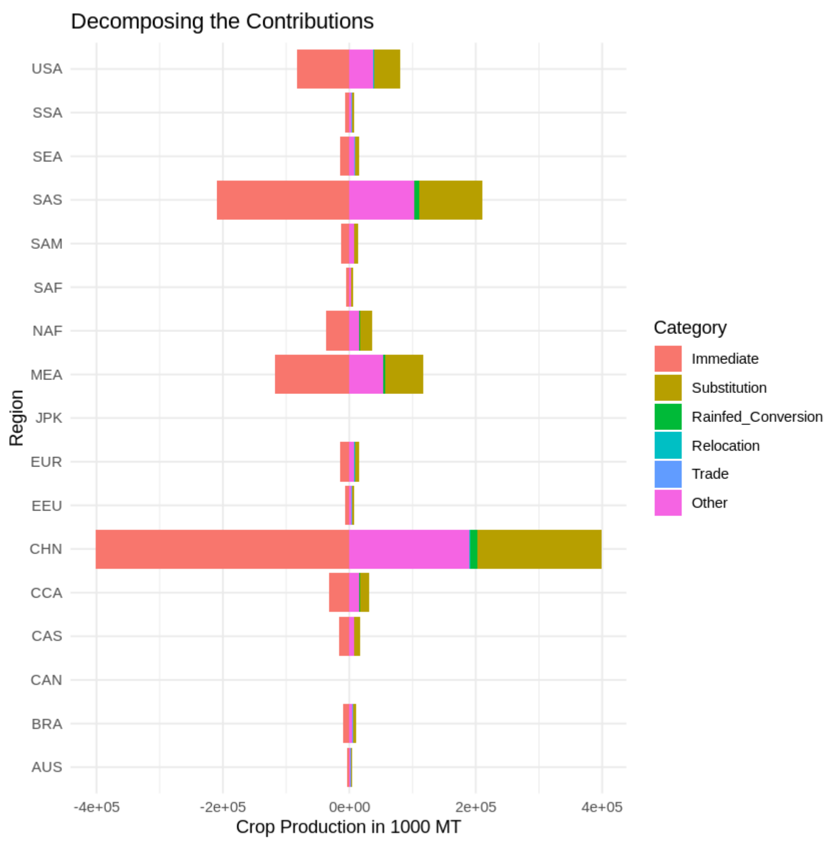

Figure 11. Decomposing market-mediated responses to widespread groundwater conservation policy.

Example 2: Environmental Footprints

Objectives:

- **Compare Land, Water, and Crop Production Before and After Global Changes:**
    - Create map plots to visualize changes in gridded variables.
- **Decompose Factors Affecting Groundwater Withdrawals:**
    - Consider factors like population, income change, technology, and biofuel.

Step 1: Open Jupyter Notebook

The Notebooks for this exercise are stored on GitHub and area available for use on I-GUIDE Platform. Go to https://platform.i-guide.io/notebooks and look for Global Drivers of Local Water Stress.

Step 2: Import Required Libraries

To visualize the outputs generated by simple-G, we employ a combination of popular data visualization packages in R: plotly, ggplot2, raster, and terra. These tools provide useful features for creating informative and visually appealing representations of the model's results. Note that they are substitutable.

Step 3: Get the Model Outputs

Users can get the pre-solved model outputs as a ZIP file for each scenario from MyGeoHub: https://mygeohub.org/resources/1706/supportingdocs

Step 4: Plot the Policy

Take the "in/simpleg_out_pct.txt" file and use one of the visualization packages to plot the percentage change in population, income, biofuel, and technology.

Step 5: Interactive Map of Results

- Use LON and LAT for coordinates
- Double-check the format of LON and LAT: x120

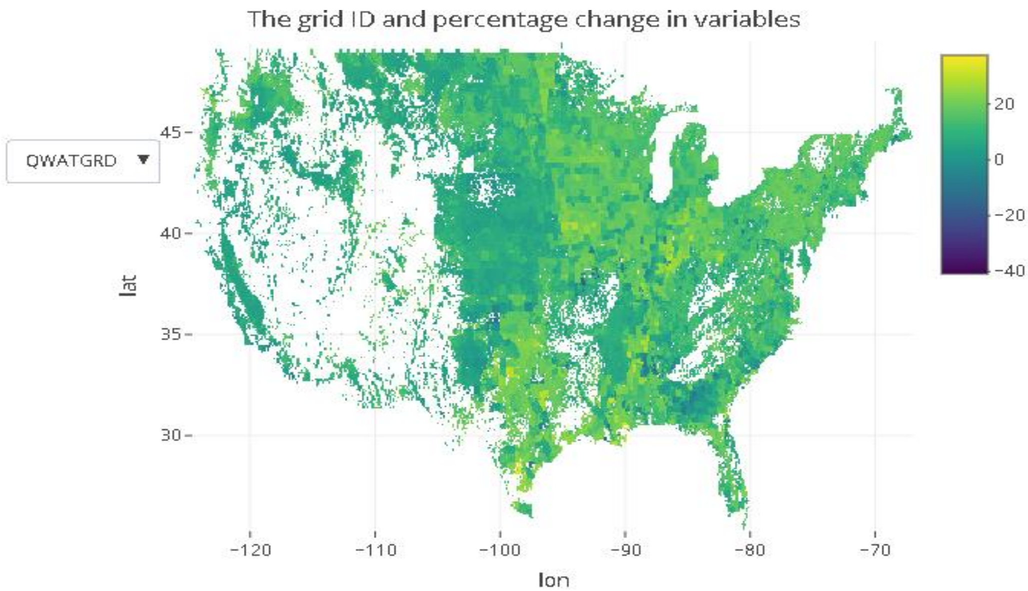

Figure 12. The map illustrates the impacts of change in global population, income, and technology on US agriculture.

Step 6: Interactive Decomposition and Subtotals

A powerful feature of SIMPLE-G is the ability to decompose the impacts of complex phenomena into contributing factors. Decomposition refers to the process of breaking down complex economic changes into driver contribution components. This decomposition analysis considers the individual and interactive effects of various drivers on the system being modeled. For instance, in the context of agriculture, the model decomposes the changes in crop production into "subtotals". These subtotals could represent the impact of factors like population growth, income shifts, technological advancements, and climate change. This not only aids in identifying the most significant drivers but also empowers policymakers to formulate targeted interventions that address specific aspects of the challenge.

Figure 13 shows the decomposition. It is important to note that the contribution of each driver varies across different regions of the world. Therefore, the figure highlights the relative contribution of each driver in different global regions. Additionally, the branches of the figure vary in size, which is an indicator of the relative importance of each country-driver. If we take this grid cell as an example, we can observe that the countries with the most significant impact on water resources are SSA, China, and South Asia. These countries are responsible for a larger proportion of water demand changes compared to other regions of the world for this location.

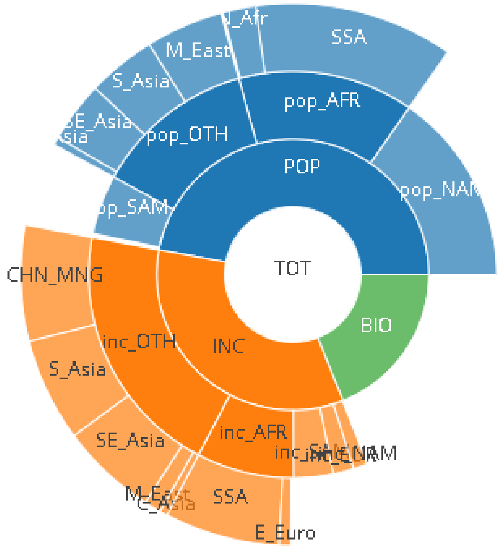

Figure 13. Decomposing the global drivers. This figure shows the key drivers that impact water resources for the selected location. The major drivers that influence water demand are population, income, and biofuel usage.

Wrap up

This guide has provided an overview of how to analyze and interpret the results of a gridded economic model, SIMPLE-G, using Jupyter Notebook and R. By leveraging the capabilities of these tools, researchers can gain insights into the market-mediated tele-coupling and meta-coupling between economic factors, environmental changes, and agricultural production. The ability to visualize and decompose the model's outputs enables a deeper understanding of the drivers of change and supports the development of more effective and targeted policies for sustainable resource management. As the SIMPLE-G model continues to evolve and incorporate new data and methodologies, it promises to be an increasingly valuable tool for addressing the sustainability challenges of a changing world.

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