SIMPLE-G Model and Database for Global Groundwater

Global Groundwater Sustainability and Virtual Water Trade

Chapter 16 of the SIMPLE-G Book

Iman Haqiqi[1]

October 19, 2024

Abstract

For sustainability challenges with significant spatial heterogeneity, gridded economic analysis is required to examine spatially diverse locations characterized by unique economic and biophysical attributes while effectively capturing complex interactions across agricultural markets. This document illustrates how to employ the SIMPLE-G Global model, a multiscale gridded economic framework, to facilitate high-resolution analysis of land use, water use, and environmental impacts. This version introduces virtual water trade, farm employment, a detailed water module, and txt output files. This manuscript shows how to analyze the impacts of large-scale groundwater conservation policy on agriculture and virtual water trade and how to use GEMPACK to solve a large system of equations provided by SIMPLE-G.

Keywords: computational economics, gridded economic model, sustainability, food security, agriculture, water resources, equilibrium, system of equations, policy.

Acknowledgments

The model introduced here is a product of long-term collaborations. The idea behind the SIMPLE-G model is from Tom Hertel and Uris Baldos. Mark Horridge created the first pilot code in TABLO. His suggestions and guidance were invaluable in the computation of the model. Uris Baldos, Jing Liu, and Iman Haqiqi initiated the first SIMPLE-G-US models and databases. Multiple grants supported the development of the model introduced here. I acknowledge the support from the United States Department of Energy, Office of Science, Biological and Environmental Research Program, Earth and Environmental Systems Modelling, MultiSector Dynamics Contract DE-SC0022141; the National Science Foundation HDR award # 2118329: "NSF Institute for Geospatial Understanding through an Integrative Discovery Environment (I-GUIDE); and the United States Department of Agriculture AFRI Grant #2019-67023-29679: "Economic Foundations of Long Run Agricultural Sustainability"; and the National Science Foundation INFEWS award #1855937: "Identifying Sustainability Solutions through Global-Local-Global Analysis of a Coupled Water-Agriculture-Bioenergy System".

[1] Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University
Mailing address: 403 Mitch Daniels Blvd., West Lafayette, Indiana 47907-2056 USA
Email: ihaqiqi@purdue.edu

Code and data availability

The SIMPLE-G model introduced here is an open-source model used in Chapter 16 of the SIMPLE-G Book. The model code files, input datasets, parameters, and command files are available at: https://www.gtap.agecon.purdue.edu/simple-g/

Useful resources

- SIMPLE Book: https://doi.org/10.1007/978-3-319-22662-0
- 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 YouTube Videos: https://tinyurl.com/SIMPLE-G-Book
- SIMPLE-G Short Course: https://mygeohub.org/courses/sustainability_shortcourse_2024
- SIMPLE-G visualization:
  - Analyze SIMPLE-G Results in Jupyter Notebook and R: https://tinyurl.com/simpleg-handout
  - SIMPLE-G Web Application: https://mygeohub.org/resources/simpleus
  - SIMPLE-G Online: Computation: https://mygeohub.org/resources/simplegus

Table of contents

Abstract 1
Acknowledgments 1
Code and data availability 2
Useful resources 2
1 Introduction 5
1.1 Economic Theory 5
1.1.1 Consumption 5
1.1.2 Production 5
1.1.3 Trade 5
1.1.4 Market Equilibrium 5
1.2 SIMPLE-G specification (Global, Allcrops, 2017, 5 arc-min) 5
1.2.1 Spatial resolution and scope 6
1.2.2 Time steps and reference year 6
1.2.3 Commodity aggregation 6
1.2.4 Land types 6
1.2.5 Water sources 6
1.3 Contribution 7
1.3.1 Virtual water trade 7
1.3.2 Water resources 7
1.3.3 Standard decomposition 7
1.3.4 Decomposition of adaptation channels 7
1.4 Software requirement 8
1.5 Operating systems 8
2 Model files 9
2.1 TAB file for variables and equations 9
2.2 EXE file as pre-compiled executable 10
2.3 Other files 10
2.4 Known issues 10
3 Data files 10
3.1 GRIDDATA includes the reference value of variables 11
3.2 GRIDPARM includes the value of behavioral parameters 11
3.3 GRIDSETS includes set elements and mappings 12
3.4 Model dimensions 13
4 Command files 13
4.1 Overall options 13
4.2 Section 1: paths for old and new files 14
4.3 Section 2: model closure 14
4.4 Section 3: solution method 15
4.5 Section 4: experiment design and shocks 15
5 Results 16
5.1 Run the model with a batch file 16
5.2 View solution files: SL4 and TXT 16
5.3 Change in crop production 18
5.4 Change in land use 19
5.5 Changes in virtual water trade 19
5.6 Changes in labor employment 20
6 Conclusions 22
Reference 23

List of boxes

Box 1. List of files in the main folder of SIMPLEG 9
Box 2. List of data files for SIMPLE-G-US-Allcrops 10

Box 3. List of command files for SIMPLE-G-US-Allcrops 13
Box 4. Options in the CMF file for SIMPLE-G-US-Allcrops 13
Box 5. List of options for CMF files 13
Box 6. Introducing files in the CMF file for SIMPLE-G-US-Allcrops 14
Box 7. Closure in the CMF file for SIMPLE-G-US-Allcrops 15
Box 8. Solution methods in the CMF file for SIMPLE-G-US-Allcrops 15
Box 9. Simulation scenario in the CMF file for SIMPLE-G-US-Allcrops 16
Box 10. List of batch files for SIMPLE-G-US-Allcrops 16
Box 11. Content of a batch file used for SIMPLE-G-US-Allcrops 16
Box 12. List of output files for test simulation for SIMPLE-G-US-Allcrops 17

List of Figures

Figure 1. Screenshot of the headers available in GRIDDATA_wint.har 11
Figure 2. Screenshot of the headers available in GRIDPARM_wint.har 12
Figure 3. Screenshot of home screen of SL4 file in ViewSOL 18
Figure 4. Changes in crop production due to global groundwater conservation policy 19
Figure 5. Changes in land area due to global groundwater conservation policy 19
Figure 6. Changes in virtual groundwater trade 20
Figure 7. Changes in virtual surface water trade 20
Figure 8. Percentage changes in labor employment in rainfed production 21
Figure 9. Percentage changes in labor employment in irrigated production 21
Figure 10. Changes in labor employment (number of jobs, red: irrigated, green: rainfed) 21

1 Introduction

The SIMPLE Model, the Simplified International Model of agricultural Prices, Land use and the Environment, was developed for global analysis of sustainability and food security (Hertel and Baldos 2016). Its gridded version, SIMPLE-G, is a model designed for multiscale gridded economic analysis with a focus on land, water, labor, and the environment. As detailed in the SIMPLE-G Book (Haqiqi and Hertel 2024), the model captures interactions across regions, providing insights into resource use and policy impacts at fine spatial resolutions.

1.1 Economic Theory

The foundation of the SIMPLE-G model is based on international trade theories, agricultural production, and consumer food demand.

1.1.1 Consumption

In the SIMPLE-G model, consumption is driven by population, per capita income, and prices. In general, when income rises, the overall demand for food increases. This relationship is captured by a demand function that incorporates both income elasticity (the % change in food consumption in response to a 1% change in income) and price elasticity (the % change in food consumption in response to a 1% change in prices). Prices are determined in local and global markets.

1.1.2 Production

Agricultural production in the SIMPLE-G model is a function of inputs such as land, labor, water, and capital. The model employs a nested constant elasticity of substitution (CES) production function to represent the substitution possibilities between different inputs. This allows the model to simulate how changes in the availability or cost of one input (e.g., water) can impact the overall production technology.

1.1.3 Trade

Trade in the SIMPLE-G model is linked to relative prices, which are represented in export and import decisions that consider domestic prices and world prices.

1.1.4 Market Equilibrium

The standard SIMPLE-G model ensures market equilibrium by adjusting prices until supply equals demand in each market. This involves solving a system of equations that represent the supply and demand for various agricultural commodities and production factors. The equilibrium prices and quantities reflect the interactions between consumption, production, and trade, as well as the impacts of external factors such as climate change and policy interventions.

1.2 SIMPLE-G specification (Global, Allcrops, 2017, 5 arc-min)

The model described here is an extension of the SIMPLE-G1 (Liu et al. 2017) and then SIMPLE-G-US (Baldos et al. 2020). The current model is labeled as SIMPLE-G Global (Haqiqi, Perry and Hertel 2022).

For more information about the model equation and analysis, look at the SIMPLE-G Book chapter 16.

Table 1. SIMPLE-G- Global Model specifications

Model name	simpleg_grdwater
Grids	Global 5 arc-min
Terrestrial coverage	All agricultural land
Year	Around 2017
Version	v22p2
Crop details	Allcrops composite
Production technology	Irrigated and rainfed
Water module	Groundwater, surface water, irrigation equipment, virtual water trade
Labor module	Linked to non-land
Land module	Quantity preserving constant elasticity of transformation (QCET)
Fertilizer module	Not available
Product differentiation	Sub-regional Armington

1.2.1 Spatial resolution and scope

SIMPLE-G operates on a global scale, employing a spatial resolution that varies according to the specific application. For this particular application, a global gridded approach is applied, dividing the world into 5 arc-minute cells. At the equator, each 5 arc-minute grid cell corresponds to approximately 9.28 kilometers on each side. This measurement is derived by converting 5 arc-minutes into degrees (5 arc-minutes = 5/60 degrees) and using the Earth's circumference—approximately 40,075 kilometers—to calculate the distance represented by this angular measurement. Specifically, at the equator, each degree of latitude or longitude is roughly 111.32 kilometers, making each 5 arc-minute cell approximately 9.28 kilometers on each side.

1.2.2 Time steps and reference year

The model is comparative static, illustrating the change from one economic equilibrium state to a new economic equilibrium state. It can simulate both historical and future scenarios. Time steps can range from annual to short-run or long-run, depending on the specific research question. A reference year, often a recent year with extensive data availability, is used as a baseline for simulations.

1.2.3 Commodity aggregation

SIMPLE-G includes markets for crops, livestock, and processed food. Commodities are often aggregated into groups based on their production and consumption patterns. This aggregation level can vary depending on the specific analysis. For this version, all crops are aggregated into one composite crop, which varies by grid cell. Composite crops are differentiated by the production location and irrigation vs rainfed technology.

1.2.4 Land types

The model distinguishes between different land types, such as irrigated and rainfed cropland. This allows for the analysis of cropland conversion and its impact on agriculture and the environment.

1.2.5 Water sources

SIMPLE-G incorporates the decisions about water resources into its simulations, considering both surface water and groundwater in combination with an index for irrigation technology.

1.3 Contribution

The model introduced here extends previous studies by incorporating virtual water trade in a global gridded economic model. It is among the first global gridded economic models to quantify the gridded labor employment outcomes. It also introduces a novel approach for decomposing the adaptation channels or market adjustment mechanisms.

1.3.1 Virtual water trade

The virtual water exports from each grid cell are calculated based on the share of exports in total domestic production (φ) by country (r) and the water use in each grid cell (g) by source (i):

$$QVW_{g,i} = \varphi_r * QWU_{g,i}\,, \qquad g \in r$$

Here, *QVW* is the virtual water export, and *QWU* is the water used by crops.

1.3.2 Water resources

Three sources of water are included to show the economic supply of water: surface water, shallow groundwater, and unsustainable groundwater. The surface water is determined by reservoir storage and rivers in each grid cell.

1.3.3 Standard decomposition

A key strength of both SIMPLE-G and GEMPACK-based models is their capacity to decompose complex phenomena into individual contributing factors. This decomposition analysis enables the isolation of various drivers' effects on the system. For example, in agriculture, these models can break down changes in crop production into subtotals that reflect influences such as population growth, income shifts, technological advancements, and climate change. By analyzing these subtotals, the models provide insights into how each driver affects the overall outcome, helping to identify significant factors. This approach empowers policymakers to design targeted interventions that address specific challenges. Ultimately, decomposition analysis in SIMPLE-G serves as an effective tool for understanding complex cause-and-effect relationships and developing informed strategies to tackle global issues.

Users could decompose the contribution of remote policies in other countries to domestic production by following the decomposition method in GEMPACK (Harrison, Horridge and Pearson 2000).

1.3.4 Decomposition of adaptation channels

Here, we propose a different decomposition method for evaluating the role of each economic adaptation channel in reducing the negative impacts of shocks and policies. This decomposition is designed for a shock with significant spatial heterogeneity, like groundwater sustainability policy. Here, the final market response in quantity changes are assigned to the following categories:

- Δ: Immediate impact
- Ψ: Local substitution: surface water and groundwater in irrigated production
- Φ: Rainfed conversion:
- Ω: Relocation and international trade

For example, in the case of global groundwater sustainability policy, the immediate impact can be calculated as follows.

$$\Delta_r = \sum_{g \in r, \delta \neq 0} \left(\delta_g * Q_{g,irr}\right) / 100$$

Here, δ_g is the shock on groundwater in % change, and Q_g shows the crop production by grid cell. This shows the reduction in irrigated production if we assume there is a linear relationship between groundwater and irrigated production at each location.

Local substitution for the targeted location is determined considering the difference between the water shock and actual production change:

$$\Psi_r = \sum_{g \in r, \delta \neq 0} (\lambda_{g,irr} - \delta_g) * Q_{g,irr} / 100$$

Here, $\lambda_{g,irr}$ is the percentage change in irrigated crop production in location g. This comes from the definition of substitution based on the ratio of groundwater to total irrigated output. The rainfed conversion at the targeted locations can be calculated based on % change in rainfed production ($\lambda_{g,rfd}$) as follows:

$$\Phi_r = \sum_{g \in r, \delta \neq 0} (\lambda_{g,rfd}) * Q_{g,rfd} / 100$$

Finally, the changes in non-target locations can be assigned to relocation and trade:

$$\Omega_r = \sum_{g \in r, \delta = 0} (\lambda_{g,tot}) * Q_{g,tot} / 100$$

This decomposition can provide a rough estimate of the significance of each adaptation channel in buffering the impacts of local changes and shocks.

1.4 Software requirement

The model is solved in GEMPACK, the General Equilibrium Modelling PACKage (Horridge et al. 2018). The input data is prepared in a format that is efficient for use in GEMPACK. For simulating SIMPLE-G, you need to have access to a machine with the software or install the GEMPACK software on your computer. A free-trail version of GEMPACK is available at https://www.copsmodels.com/gpeidl.htm

1.5 Operating systems

The model is tested on the Windows systems. For MacOS, users may try to install GEMPACK as a container or with a virtual machine with several third-party options:

- CrossOver (https://www.codeweavers.com/crossover/)
- Virtual Box (https://www.virtualbox.org/wiki/Downloads)
- Parallels Desktop (http://www.parallels.com/products/desktop/)
- VMWare Fusion (http://www.vmware.com/products/fusion.html)

For the latest updates on the Linux version, please look at:

- The Centre of Policy Studies: https://www.copsmodels.com/,
- Installation and Use on Linux PCs: https://www.copsmodels.com/gpdocl.htm,
- Demonstration Version for Linux: https://www.copsmodels.com/gpdemol.htm

This manuscript describes the model codes and data files for the model used in Chapter 16 of the SIMPLE-G book. The files are available in the "simpleg_global_grdwater.zip" archive on the SIMPLE-G webpage. This document contains three sections.

- Section 2 provides an overview of files for the SIMPLE-G model files.
- Section 3 introduces the data and parameters for gridded world.
- Section 4 describes the command files and model closures.

2 Model files

The "simpleg_global_grdwater.zip" file includes model data files and codes. Under the main folder of SIMPLE-G, users will find the following files needed to run the executable "simpleg.exe" program.

Box 1. List of files in the main folder of SIMPLEG

```
simpleg.tab
simpleg.exe
simpleg.axs
simpleg.axt
simpleg.inf
simpleg.log
simpleg.min
simpleg-ceqexplen.har

simpleg_old.tab
simpleg_old.exe
simpleg_old.axs
simpleg_old.axt
simpleg_old.inf
simpleg_old.log
simpleg_old.min
simpleg_old -ceqexplen.har

gfortran_link_ltg.fig
LTG.LOG
parcomp.log
```

2.1 TAB file for variables and equations

The file "simpleg.tab" provides the original script containing variable names, parameter labels, relevant headers in SIMPLE-G data source, and equation definitions in TABLO language for use in GEMPACK. Note that "simpleg_old.exe" replicates the results of chapter 16 of the SIMPLE-G Book. While "simpleg.exe" will provide slightly different results, it incorporates a more accurate list of "update" statements.

2.2 EXE file as pre-compiled executable

The "simpleg.exe" file is the pre-compiled executable model for running simulations. Modification of the equations and variables in the TABLO code requires compiling a new model version.

2.3 Other files

All other files are automatically generated when the model is compiled using GFortran.

2.4 Known issues

Search for "%% Known Issues %%" in the Tab file.

(1) The following update is needed but was not active in old versions:

```
Update  (all,g,GRID)(all,l,LTYPE) VCROPgl(g,l)  = p_PCROPgl(g,l) *p_QCROPgl(g,l);
```

(2) The zero-profit condition requires the "AF*" and "AO*" variables, but they were removed in some old versions.

(3) The quantity of water was an index in early versions (based on dollar values).

3 Data files

The SIMPLE-G model data inputs are organized in three main files. Each simulation may contain additional files depending on the model extensions or scenario experiments. The folder "in" contains the input data, stored as header array files (*.har). As their names suggest, GRIDDATA, GRIDPARM, and GRIDSET contain the data, parameters, and sets of the model, respectively. These files provide the key information for conducting simulations with SIMPLE-G. The GRIDPOST file includes data that are provided for use in post-simulation calculations.

The folder "shf" contains the shock files as "USERDATA.har" which includes data for determining the experiment and scenarios. They can also be used in experiments with the command file to determine what variables are to be mounted.

If GEMAPCK is installed, users can open and view these input "*.HAR" files using "viewHAR.exe" which is one of the utilities available in GEMPACK. The data is stored in headers. In addition to main values, each header includes the following metadata:

- Header: 4-character label
- Type: real, integer, string
- Dimension: either in the form of numbers or embedded set labels
- Coefficient: the long coefficient label of the parameter, variable, or set
- Name: description of the header
- Total, min, max, etc.: Numerical summaries of all data in each header

Box 2. List of data files for SIMPLE-G-US-Allcrops

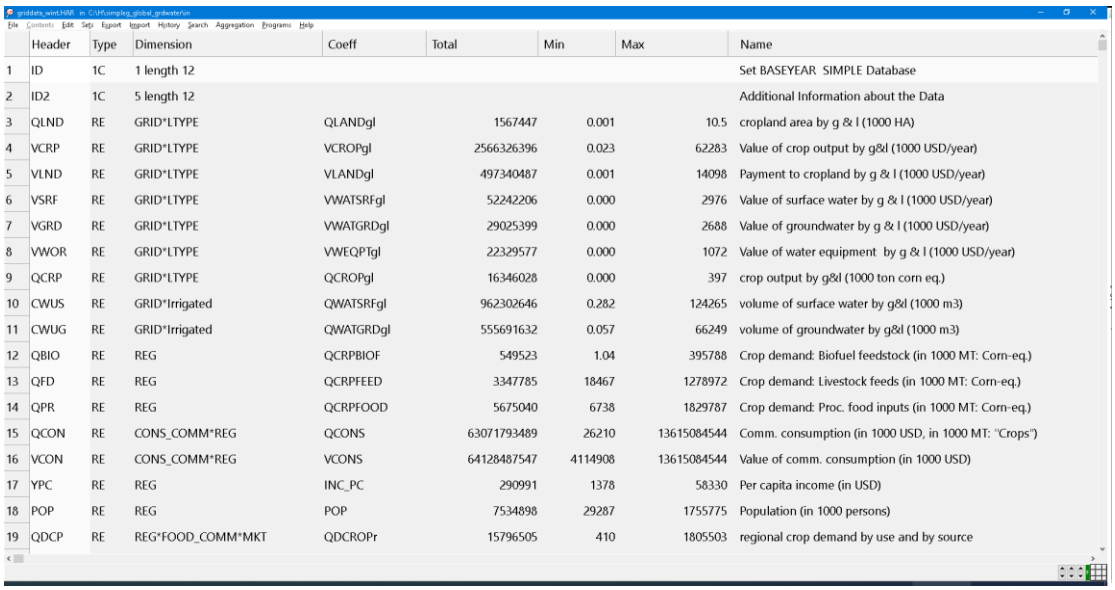
```
in\
       GRIDDATA_wint.har
       GRIDPARM_wint.har
```

```
        GRIDSETS_wint.har
        GRIDPOST_wint.har

shf\
        USERDATA.har
```

3.1 GRIDDATA includes the reference value of variables

The "GRIDDATA_wint.har" file includes regional and gridded information to show the value of the variables for the reference year (2017 for this version). These variables are related to the production, demand, and supply of agricultural commodities as well as other relevant information such as consumption, exports, imports, income, population, etc. Figure 1 is the screenshot showing some of the headers in this file. Here, ID includes the reference year, while ID2 includes information about the module name and versions. More details about the dimensions of these variables (GID, TYPE, REG, etc.) are available in the "GRIDSETS_wint.har".

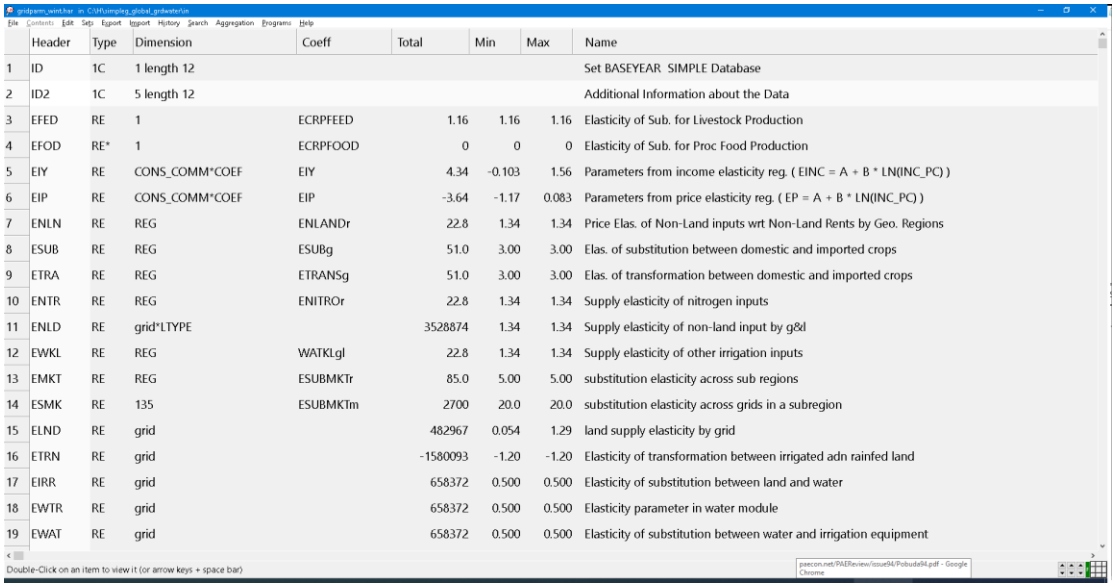


	Header	Type	Dimension	Coeff	Total	Min	Max	Name
1	ID	1C	1 length 12					Set BASEYEAR SIMPLE Database
2	ID2	1C	5 length 12					Additional Information about the Data
3	QLND	RE	GRID*LTYPE	QLANDgl	1567447	0.001	10.5	cropland area by g & l (1000 HA)
4	VCRP	RE	GRID*LTYPE	VCROPgl	2566326396	0.023	62283	Value of crop output by g&l (1000 USD/year)
5	VLND	RE	GRID*LTYPE	VLANDgl	497340487	0.001	14098	Payment to cropland by g & l (1000 USD/year)
6	VSRF	RE	GRID*LTYPE	VWATSRFgl	52242206	0.000	2976	Value of surface water by g & l (1000 USD/year)
7	VGRD	RE	GRID*LTYPE	VWATGRDgl	29025399	0.000	2688	Value of groundwater by g & l (1000 USD/year)
8	VWOR	RE	GRID*LTYPE	VWEQPTgl	22329577	0.000	1072	Value of water equipment by g & l (1000 USD/year)
9	QCRP	RE	GRID*LTYPE	QCROPgl	16346028	0.000	397	crop output by g&l (1000 ton corn eq.)
10	CWUS	RE	GRID*Irrigated	QWATSRFgl	962302646	0.282	124265	volume of surface water by g&l (1000 m3)
11	CWUG	RE	GRID*Irrigated	QWATGRDgl	555691632	0.057	66249	volume of groundwater by g&l (1000 m3)
12	QBIO	RE	REG	QCRPBIOF	549523	1.04	395788	Crop demand: Biofuel feedstock (in 1000 MT: Corn-eq.)
13	QFD	RE	REG	QCRPFEED	3347785	18467	1278972	Crop demand: Livestock feeds (in 1000 MT: Corn-eq.)
14	QPR	RE	REG	QCRPFOOD	5675040	6738	1829787	Crop demand: Proc. food inputs (in 1000 MT: Corn-eq.)
15	QCON	RE	CONS_COMM*REG	QCONS	63071793489	26210	13615084544	Comm. consumption (in 1000 USD, in 1000 MT: "Crops")
16	VCON	RE	CONS_COMM*REG	VCONS	64128487547	4114908	13615084544	Value of comm. consumption (in 1000 USD)
17	YPC	RE	REG	INC_PC	290991	1378	58330	Per capita income (in USD)
18	POP	RE	REG	POP	7534898	29287	1755775	Population (in 1000 persons)
19	QDCP	RE	REG*FOOD_COMM*MKT	QDCROPr	15796505	410	1805503	regional crop demand by use and by source

Figure 1. Screenshot of the headers available in GRIDDATA_wint.har

3.2 GRIDPARM includes the value of behavioral parameters

The "GRIDPARM_wint.har" file includes the value of the model parameters. These are mostly elasticity parameters. The parameters are those components of the model that are not allowed to change during the simulation, contrary to variables that are allowed to change.



	Header	Type	Dimension	Coeff	Total	Min	Max	Name
1	ID	1C	1 length 12					Set BASEYEAR SIMPLE Database
2	ID2	1C	5 length 12					Additional Information about the Data
3	EFED	RE	1	ECRPFEED	1.16	1.16	1.16	Elasticity of Sub. for Livestock Production
4	EFOD	RE*	1	ECRPFOOD	0	0	0	Elasticity of Sub. for Proc Food Production
5	EIY	RE	CONS_COMM*COEF	EIY	4.34	-0.103	1.56	Parameters from income elasticity reg. (EINC = A + B * LN(INC_PC))
6	EIP	RE	CONS_COMM*COEF	EIP	-3.64	-1.17	0.083	Parameters from price elasticity reg. (EP = A + B * LN(INC_PC))
7	ENLN	RE	REG	ENLANDr	22.8	1.34	1.34	Price Elas. of Non-Land inputs wrt Non-Land Rents by Geo. Regions
8	ESUB	RE	REG	ESUBg	51.0	3.00	3.00	Elas. of substitution between domestic and imported crops
9	ETRA	RE	REG	ETRANSg	51.0	3.00	3.00	Elas. of transformation between domestic and imported crops
10	ENTR	RE	REG	ENITROr	22.8	1.34	1.34	Supply elasticity of nitrogen inputs
11	ENLD	RE	grid*LTYPE		3528874	1.34	1.34	Supply elasticity of non-land input by g&l
12	EWKL	RE	REG	WATKLgl	22.8	1.34	1.34	Supply elasticity of other irrigation inputs
13	EMKT	RE	REG	ESUBMKTr	85.0	5.00	5.00	substitution elasticity across sub regions
14	ESMK	RE	135	ESUBMKTm	2700	20.0	20.0	substitution elasticity across grids in a subregion
15	ELND	RE	grid		482967	0.054	1.29	land supply elasticity by grid
16	ETRN	RE	grid		-1580093	-1.20	-1.20	Elasticity of transformation between irrigated adn rainfed land
17	EIRR	RE	grid		658372	0.500	0.500	Elasticity of substitution between land and water
18	EWTR	RE	grid		658372	0.500	0.500	Elasticity parameter in water module
19	EWAT	RE	grid		658372	0.500	0.500	Elasticity of substitution between water and irrigation equipment

Figure 2. Screenshot of the headers available in GRIDPARM_wint.har

3.3 GRIDSETS includes set elements and mappings

The "GRIDSETS_wint.har" file includes the metadata and elements of the sets that are used in the model. For example, the set "REG" defines a domain of the regions included in the model, as shown in Table 2.

Table 2. Regions in SIMPLE-G

No.	REG	Description
1	E_Euro	Eastern Europe
2	N_Afr	North Africa
3	SSA	Sub Saharan Africa
4	S_Amer	South America (except Brazil)
5	BRA	Brazil
6	AUS_NZ	Oceania
7	EU	European Union
8	S_Asia	South Asia
9	CC_Amer	Central America
10	S_Afr	Southern Africa
11	SE_Asia	Southeast Asia
12	CAN	Canada
13	US	USA
14	CHINA	China and Mongolia
15	M_East	Middle East
16	JPN_KR	Japan / Korea
17	C_Asia	Central Asia

In addition, this file includes "mapping" information that shows how a subset of elements from one set are linked to an element of another set. For example, mapping MAP1 maps set GID to REG. Each row of MAP1 represents the corresponding grid cell in GID, and it records the region (by its index) to which the grid cell is mapped.

Note that LON and LAT show the coordinates longitude or latitude for the center of grid cells at 5 arc-min size following “coord. ref. lon/lat WGS 84”.

3.4 Model dimensions

GRIDSETS also includes details on model dimensions. For this SIMPLE-G-Global Allcrops 2017 version, we have:

- REG: 17
- GID: 1,316,744
- SMKT: 135 (GTAP regions)

4 Command files

The folder “CMF” contains command files (*.cmf). They contain important information for simulation, including the path of input and output files, parameters for model solving, closure of the current model, and shock (policy levers) to be changed in the experiment. Each experiment is stored in a separate command file. For this exercise, there are two main CMF files:

Box 3. List of command files for SIMPLE-G-US-Allcrops

```
cmf\
       simpleg_water_gsp1_wnt1.cmf
       simpleg_old.cmf
```

4.1 Overall options

The CMF file usually starts with some comments followed by general options. For example, the command below will set the initial memory allocation, which can vary by model version, and users can update it after changing the model.

Box 4. Options in the CMF file for SIMPLE-G-US-Allcrops

```
! Options
! ------------
 start with mmnz = 23730;
 LU decompose transpose = yes ;
 dpn = yes ;
 cpu = yes ;
 slc file = No;
! -------------------
```

There are other options that users may decide to use. For a list of “XXX=yes|no” commands, look at the GEMPACK manual.

Box 5. List of options for CMF files

```
CPU = yes|NO ; ! yes means report CPU times
EAA = yes|no ; ! yes means echo activity to screen
NRP = yes|NO ; ! yes means do not re-use pivots
NEQ = yes|NO ; ! yes means do no equations, only formulas
```

4.2 Section 1: paths for old and new files

The CMF file determines the name and location of the input files (data, sets, parameters). It also determines the name and location of output files that should be saved. The output files are mainly LOG files, SL4 files, and updated GRIDDATA.

Box 6. Introducing files in the CMF file for SIMPLE-G-US-Allcrops

```
! ****************************************
! files and paths
! ****************************************

! Input files
! ------------
 File GRIDSETS = in\GRIDSETS_wint.har ; !  sets and mapping information
 File GRIDDATA = in\GRIDDATA_wint.har ; !  base data: gridded and regional
 File GRIDPARM = in\GRIDPARM_wint.har ; !  parameter data
 File GRIDPOST = in\GRIDPOST_wint.har ; !  labor employment & virtual water

! Output files
! ------------
 File out_pct      = out\simpleg_water_gsp1_wnt1_pct.txt ;
 File out_post     = out\simpleg_water_gsp1_wnt1_post.txt ;

 LOG file      = out\simpleg_water_gsp1_wnt1.LOG;
 Solution file = out\simpleg_water_gsp1_wnt1;
 Updated file GRIDDATA = out\simpleg_water_gsp1_wnt1-data.upd ;
 Updated file GRIDPOST = out\simpleg_water_gsp1_wnt1-post.upd ;

 condensation information file = out\simpleg_water_gsp1_wnt1-cond.txt;
```

4.3 Section 2: model closure

Model closure refers to the process of determining which variables in the model are exogenous and which are endogenous in response to shocks or changes in policy. This defines the boundaries of changes and the scope of its analysis.

Exogenous variables are variables that are assumed to be fixed or predetermined and do not change in response to changes in other variables within the model. Examples include policies, technological progress, and global population growth.

Endogenous variables are variables that are allowed to vary freely within the model in response to changes in exogenous variables. Examples include prices, production levels, consumption patterns, and trade flows.

Closure rules also include specific assumptions that determine which model setup to be used. Common closure rules in SIMPLE-G are:

- Integrated market closure.
- Mini model closure to fix crop prices.
- Input spatial mobility closure to select input supply equations.
- Input local allocation closure to determine the allocation to different practices.

Different closure rules can lead to different model outcomes.

4.4 Section 3: solution method

Users can determine the solution methods, steps, and sub-intervals in the CMF file. The solution methods include:

- Johanson Method: It is used for solving linearized versions of a model, where changes are calculated around a known equilibrium.
- Midpoint Method: Involves solving at the midpoint of each step for higher accuracy in approximating changes.
- Euler Method: A straightforward numerical approach that solves models by approximating derivatives through finite steps.
- Gragg's Method: An advanced, extrapolation-based approach that improves the accuracy of solutions by using Richardson extrapolation. It is often employed for more precise results.

Box 7. Closure in the CMF file for SIMPLE-G-US-Allcrops

```
! ****************************************
! Closure
! ****************************************
 Exogenous  p_INC_PC    ;!per capita income by inc. reg.
 Exogenous  p_POP       ;!population by inc. reg.
 Exogenous  p_QCRPBIOF  ;!crop demand for global biofuel use
 Exogenous  s_QCRPBIOFr ;!crop demand for biofuel use | alternative

 Exogenous  p_P(NFOOD_COMM,REG) ;!price of non-food commodities by inc. reg.
 Exogenous  p_PNCRPFEED ;!price of non-feed inputs used in livestock prod.
 Exogenous  p_PNCRPFOOD ;!price of non-crop inputs used in proc. food prod.

 Exogenous  s_QWATGRDgl ;! Slack to control groundwater

 REST Endogenous;
```

Note that the number of subintervals is set to "2" for relication of Chapter 16.

Box 8. Solution methods in the CMF file for SIMPLE-G-US-Allcrops

```
! ****************************************
! Verbal description and solution method
! ****************************************
 Verbal Description = <cmf>;
 Method = Gragg;
 Steps = 2 4 6;
 subintervals = 2;
```

4.5 Section 4: experiment design and shocks

Experiment design involves introducing changes to "exogenous variables" in the model as determined by the closure. Users may apply multiple changes at a time. Box 9 shows a scenario that involves a change in the slack variable for the supply of groundwater for SET9 (target locations).

Box 9. Simulation scenario in the CMF file for SIMPLE-G-US-Allcrops

```
! ***************
! Shocks Section
! ***************

Shock s_QWATGRDgl(SET9,"Irrigated") = file shf\USERDATA.har header "sust";
```

5 Results

It is possible to run the model by opening the TAB file in "TABmate.exe" and clicking on "RUN CMF". This requires the CMF and TAB files to be in the same directory.

5.1 Run the model with a batch file

The "do_simpleg_*.bat" files are batch files that automatically run the model and specific simulations by double-clicking them, running in the command line, or using them in other programs like R.

Box 10. List of batch files for SIMPLE-G-US-Allcrops

```
do_simpleg_gsp1.bat
do_simpleg_wnt1.bat
```

The batch file manages model simulations. This file can be opened with any text editor. The content of this file is similar to box 11:

Box 11. Content of a batch file used for SIMPLE-G-US-Allcrops

```
call simpleg -cmf simpleg_water_gsp1_wnt1.cmf
pause
```

This command means:

- `call`: the command to run the compiled model as executable file (simpleg.exe)
- `simpleg`: the name of the executable file under the same folder, here it refers to "simpleg.exe"
- `-cmf`: it indicates the model should be simulated with command files
- `cmf\simpleg_water_gsp1_wnt1.cmf`: this is the relative path of the command file.

The last line, "pause", asks the console window to remain open after all simulations, for the convenience of users to check if simulations are conducted successfully or not. Users can also get the same report from log files (*.log) in the folder "out". For multiple simulations, it is possible to use separate batch files for each simulation or a combined call in one batch file.

5.2 View solution files: SL4 and TXT

After running the simulations, the out folder includes output files, log files, and updated data files for each simulation.

Box 12. List of output files for test simulation for SIMPLE-G-US-Allcrops

```
out\
     simpleg.log
     simpleg.sl4
     simpleg.slc
     simpleg.upd
     simpleg-cond.txt
```

The typical output files for each simulation are:

- LOG file: Records the sequence of commands, errors, warnings, and reports from running the simulation. It provides a useful trail for debugging.
- SL4 file: Contains detailed solution results, including percentage changes in variables, pre- and post-simulation values, and subtotals if available.
- SLC/UDC file: Contains the values of the model's coefficients at the pre/post simulation levels.
- UPD file: Updated data file.
- TXT files: User-specified output files or condensation files. The condensation process reduces the size of the original model equations by substituting or eliminating redundant variables and equations (Baldos et al. 2020).

There are two general ways to see the results:

- Double-click to open the solution file with ViewSOL.exe (a tool installed together with GEMPACK), which will list variables and their descriptions for further checking.
- Access the solution file in R using the "HARr" package (Ivanic 2023), which allows users to save simulation results as data frames with scripts for saving or further analysis.

For the results of each variable in the percentage form (starts with "p_"), the solution file will report the percentage of that variable in the first column (here 10 means 10% increase). If the variable also contains the level form (the quantity at base), the solution file will also report its value before the shock (the second column), after the shock (the third column), and the difference in net values, not percentage change (the fourth column). The easiest way of exporting simulation results is to "Export – Copy" in ViewSOL, which can be pasted to spreadsheets and other editors.

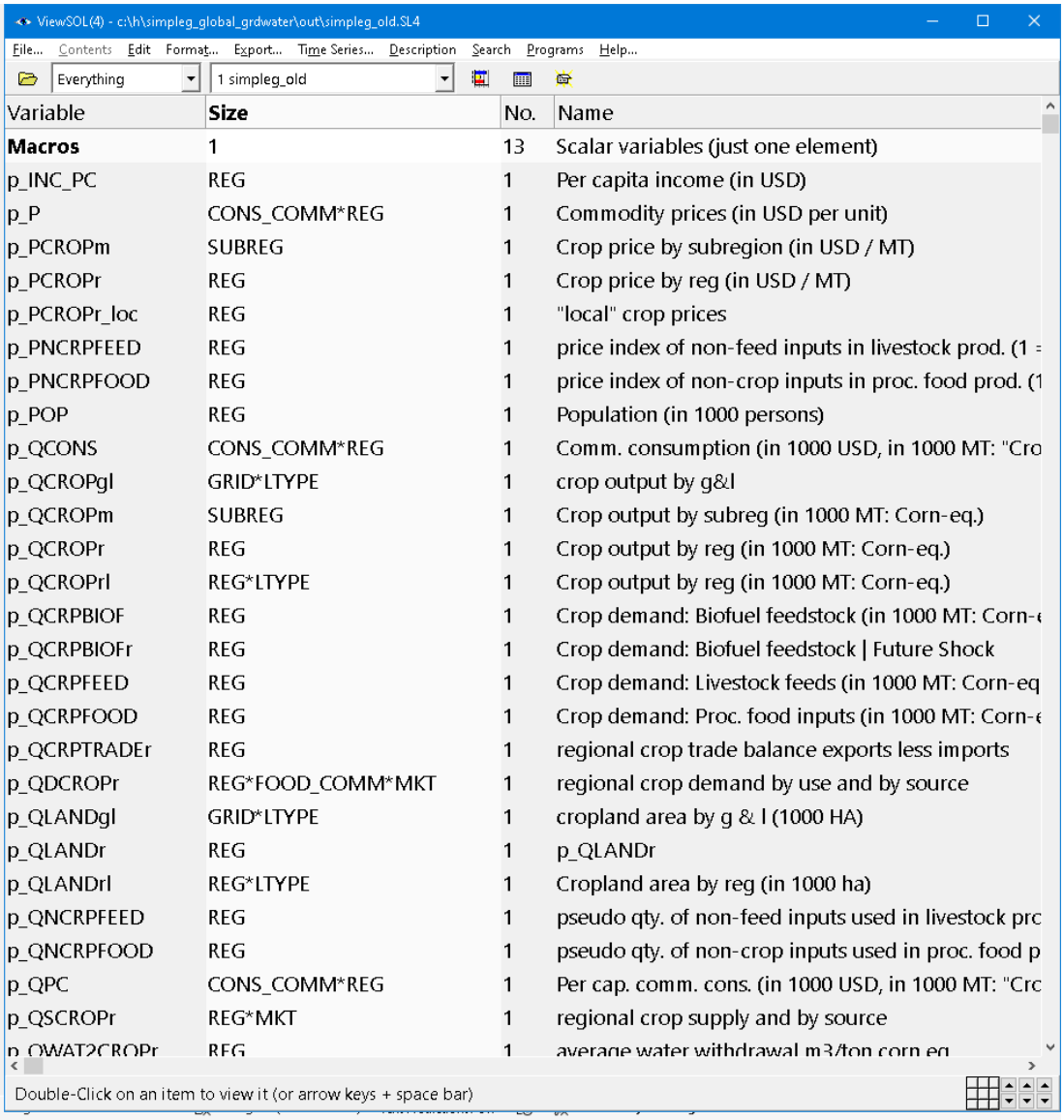
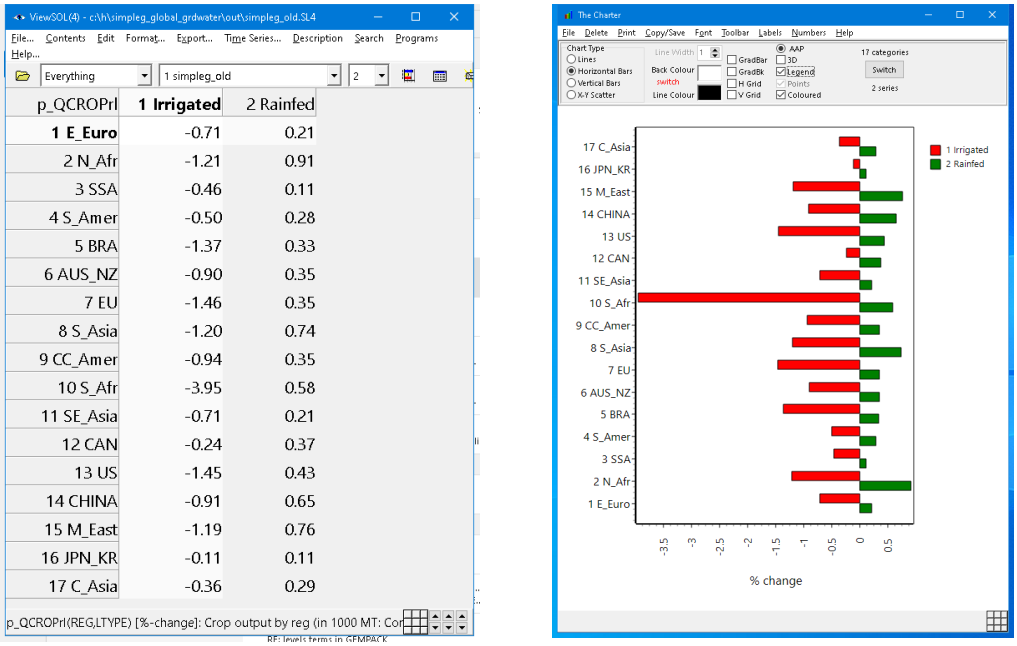


Figure 3. Screenshot of home screen of SL4 file in ViewSOL

5.3 Change in crop production

Figure 4 shows the results of the global groundwater sustainability policy on % change in crop production and land use. This data was used to generate Table 16.2 of the SIMPLE-G Book.

According to this table, irrigated production declines in all regions. However, the rainfed production increases. This table shows a 3.95% reduction in irrigated production in South Africa due to the groundwater sustainability policy. This is partially compensated by a 0.58% increase in rainfed production.

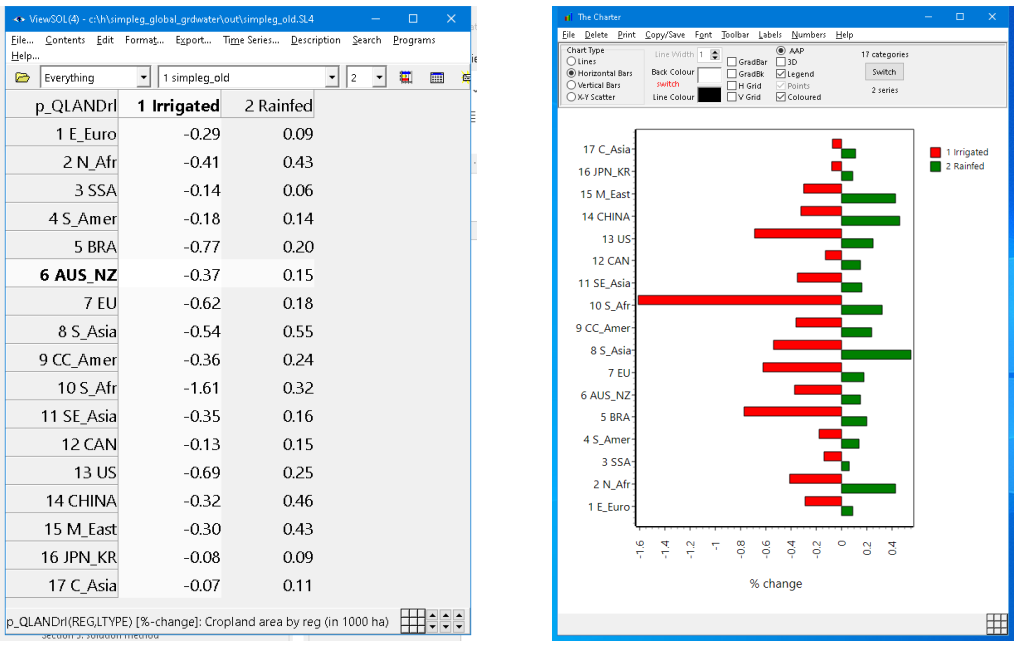


p_QCROPrl	1 Irrigated	2 Rainfed
1 E_Euro	-0.71	0.21
2 N_Afr	-1.21	0.91
3 SSA	-0.46	0.11
4 S_Amer	-0.50	0.28
5 BRA	-1.37	0.33
6 AUS_NZ	-0.90	0.35
7 EU	-1.46	0.35
8 S_Asia	-1.20	0.74
9 CC_Amer	-0.94	0.35
10 S_Afr	-3.95	0.58
11 SE_Asia	-0.71	0.21
12 CAN	-0.24	0.37
13 US	-1.45	0.43
14 CHINA	-0.91	0.65
15 M_East	-1.19	0.76
16 JPN_KR	-0.11	0.11
17 C_Asia	-0.36	0.29

Figure 4. Changes in crop production due to global groundwater conservation policy

5.4 Change in land use

Changes in the cropland area are shown in Figure 5. In general, irrigated areas have declined, and rainfed areas have increased. Also, the changes in area are generally smaller than changes in crop production for both irrigated and rainfed practices.



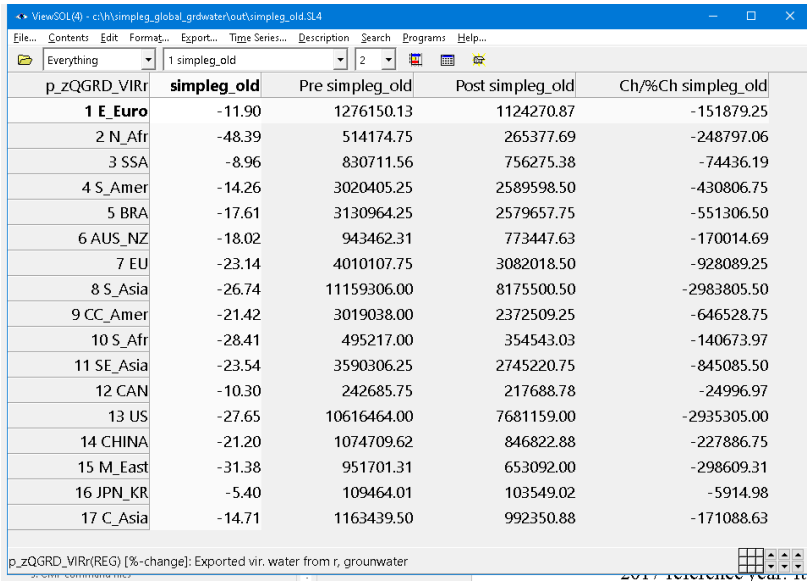
p_QLANDrl	1 Irrigated	2 Rainfed
1 E_Euro	-0.29	0.09
2 N_Afr	-0.41	0.43
3 SSA	-0.14	0.06
4 S_Amer	-0.18	0.14
5 BRA	-0.77	0.20
6 AUS_NZ	-0.37	0.15
7 EU	-0.62	0.18
8 S_Asia	-0.54	0.55
9 CC_Amer	-0.36	0.24
10 S_Afr	-1.61	0.32
11 SE_Asia	-0.35	0.16
12 CAN	-0.13	0.15
13 US	-0.69	0.25
14 CHINA	-0.32	0.46
15 M_East	-0.30	0.43
16 JPN_KR	-0.08	0.09
17 C_Asia	-0.07	0.11

Figure 5. Changes in land area due to global groundwater conservation policy

5.5 Changes in virtual water trade

Figures 5 and 6 show the results of the groundwater sustainability scenario on virtual water trade. This information was used to create Table 16.4 of the SIMPLE-G Book.

The findings suggest that virtual groundwater exports have declined significantly. However, virtual surface water exports have increased but with a smaller magnitude.



ViewSOL(4) - c:\h\simpleg_global_grdwater\out\simpleg_old.SL4

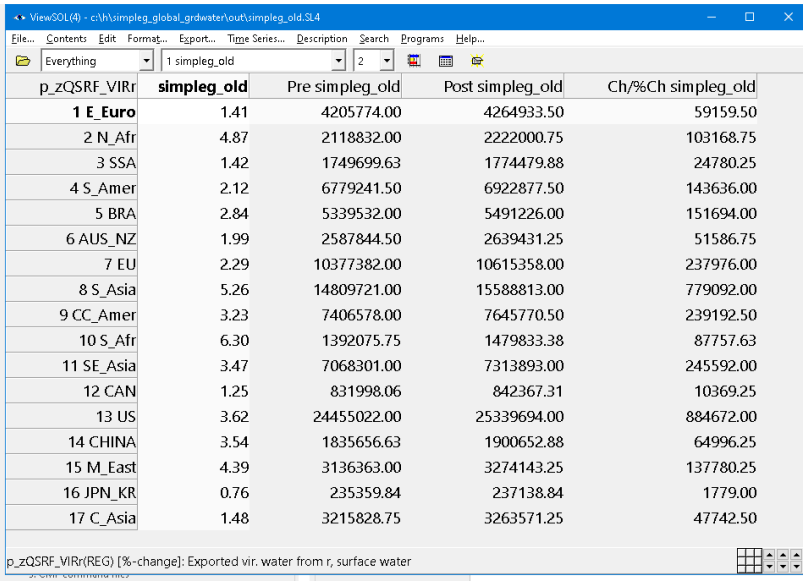
File... Contents Edit Format... Export... Time Series... Description Search Programs Help...

Everything | 1 simpleg_old | 2

p_zQGRD_VIRr	simpleg_old	Pre simpleg_old	Post simpleg_old	Ch/%Ch simpleg_old
1 E_Euro	-11.90	1276150.13	1124270.87	-151879.25
2 N_Afr	-48.39	514174.75	265377.69	-248797.06
3 SSA	-8.96	830711.56	756275.38	-74436.19
4 S_Amer	-14.26	3020405.25	2589598.50	-430806.75
5 BRA	-17.61	3130964.25	2579657.75	-551306.50
6 AUS_NZ	-18.02	943462.31	773447.63	-170014.69
7 EU	-23.14	4010107.75	3082018.50	-928089.25
8 S_Asia	-26.74	11159306.00	8175500.50	-2983805.50
9 CC_Amer	-21.42	3019038.00	2372509.25	-646528.75
10 S_Afr	-28.41	495217.00	354543.03	-140673.97
11 SE_Asia	-23.54	3590306.25	2745220.75	-845085.50
12 CAN	-10.30	242685.75	217688.78	-24996.97
13 US	-27.65	10616464.00	7681159.00	-2935305.00
14 CHINA	-21.20	1074709.62	846822.88	-227886.75
15 M_East	-31.38	951701.31	653092.00	-298609.31
16 JPN_KR	-5.40	109464.01	103549.02	-5914.98
17 C_Asia	-14.71	1163439.50	992350.88	-171088.63

p_zQGRD_VIRr(REG) [%-change]: Exported vir. water from r, grounwater

Figure 6. Changes in virtual groundwater trade



ViewSOL(4) - c:\h\simpleg_global_grdwater\out\simpleg_old.SL4

File... Contents Edit Format... Export... Time Series... Description Search Programs Help...

Everything | 1 simpleg_old | 2

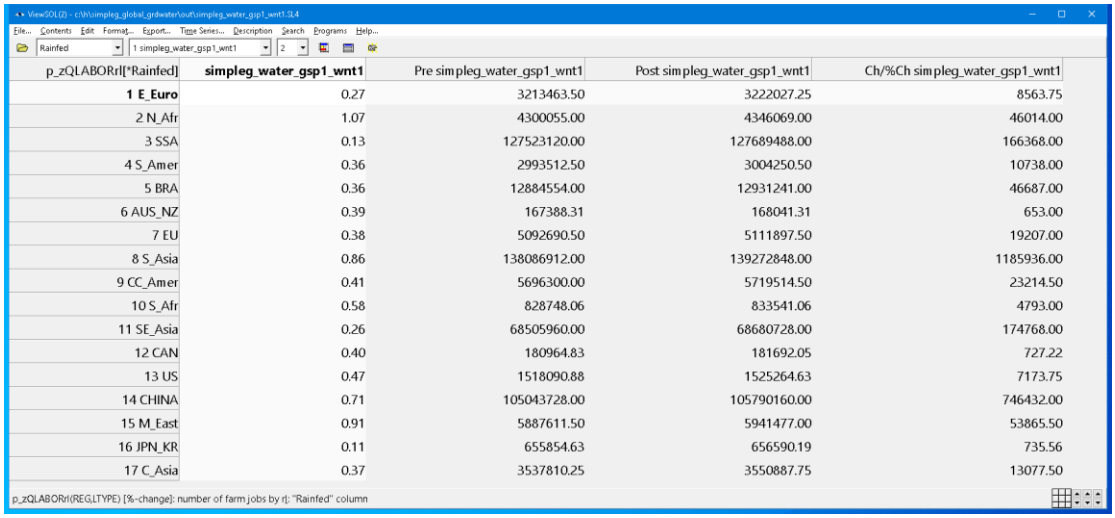
p_zQSRF_VIRr	simpleg_old	Pre simpleg_old	Post simpleg_old	Ch/%Ch simpleg_old
1 E_Euro	1.41	4205774.00	4264933.50	59159.50
2 N_Afr	4.87	2118832.00	2222000.75	103168.75
3 SSA	1.42	1749699.63	1774479.88	24780.25
4 S_Amer	2.12	6779241.50	6922877.50	143636.00
5 BRA	2.84	5339532.00	5491226.00	151694.00
6 AUS_NZ	1.99	2587844.50	2639431.25	51586.75
7 EU	2.29	10377382.00	10615358.00	237976.00
8 S_Asia	5.26	14809721.00	15588813.00	779092.00
9 CC_Amer	3.23	7406578.00	7645770.50	239192.50
10 S_Afr	6.30	1392075.75	1479833.38	87757.63
11 SE_Asia	3.47	7068301.00	7313893.00	245592.00
12 CAN	1.25	831998.06	842367.31	10369.25
13 US	3.62	24455022.00	25339694.00	884672.00
14 CHINA	3.54	1835656.63	1900652.88	64996.25
15 M_East	4.39	3136363.00	3274143.25	137780.25
16 JPN_KR	0.76	235359.84	237138.84	1779.00
17 C_Asia	1.48	3215828.75	3263571.25	47742.50

p_zQSRF_VIRr(REG) [%-change]: Exported vir. water from r, surface water

Figure 7. Changes in virtual surface water trade

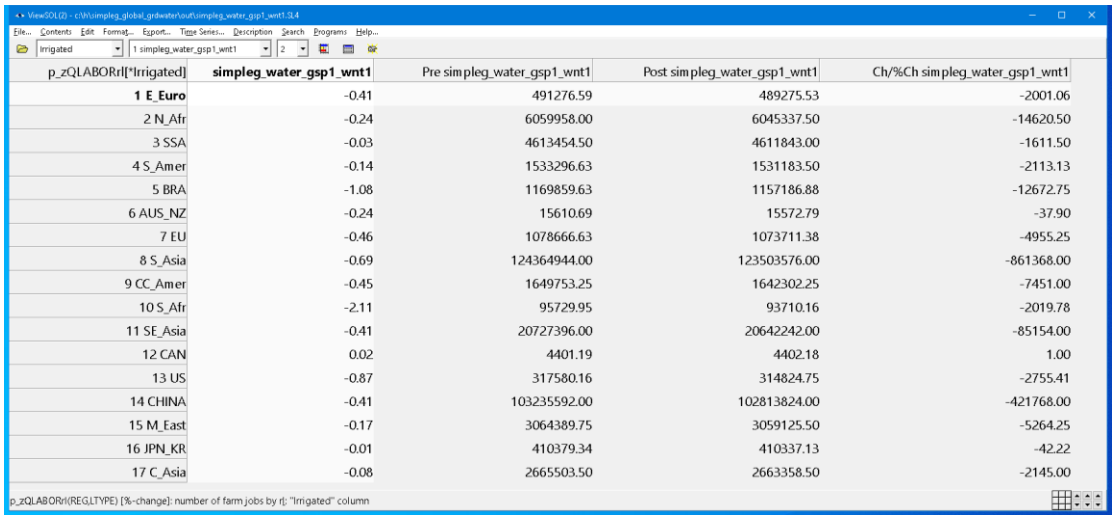
5.6 Changes in labor employment

Figures 8, 9, and 10 show the changes in employment. In general, employment in irrigated production has declined, but in rainfed production, it has increased. The numbers are significant for Asia, with South Asia showing a 1.1 million increase in rainfed production jobs.



p_zQLABORrl[*Rainfed]	simpleg_water_gsp1_wnt1	Pre simpleg_water_gsp1_wnt1	Post simpleg_water_gsp1_wnt1	Ch/%Ch simpleg_water_gsp1_wnt1
1 E_Euro	0.27	3213463.50	3222027.25	8563.75
2 N_Afr	1.07	4300055.00	4346069.00	46014.00
3 SSA	0.13	127523120.00	127689488.00	166368.00
4 S_Amer	0.36	2993512.50	3004250.50	10738.00
5 BRA	0.36	12884554.00	12931241.00	46687.00
6 AUS_NZ	0.39	167388.31	168041.31	653.00
7 EU	0.38	5092690.50	5111897.50	19207.00
8 S_Asia	0.86	138086912.00	139272848.00	1185936.00
9 CC_Amer	0.41	5696300.00	5719514.50	23214.50
10 S_Afr	0.58	828748.06	833541.06	4793.00
11 SE_Asia	0.26	68505960.00	68680728.00	174768.00
12 CAN	0.40	180964.83	181692.05	727.22
13 US	0.47	1518090.88	1525264.63	7173.75
14 CHINA	0.71	105043728.00	105790160.00	746432.00
15 M_East	0.91	5887611.50	5941477.00	53865.50
16 JPN_KR	0.11	655854.63	656590.19	735.56
17 C_Asia	0.37	3537810.25	3550887.75	13077.50

Figure 8. Percentage changes in labor employment in rainfed production



p_zQLABORrl[*Irrigated]	simpleg_water_gsp1_wnt1	Pre simpleg_water_gsp1_wnt1	Post simpleg_water_gsp1_wnt1	Ch/%Ch simpleg_water_gsp1_wnt1
1 E_Euro	-0.41	491276.59	489275.53	-2001.06
2 N_Afr	-0.24	6059958.00	6045337.50	-14620.50
3 SSA	-0.03	4613454.50	4611843.00	-1611.50
4 S_Amer	-0.14	1533296.63	1531183.50	-2113.13
5 BRA	-1.08	1169859.63	1157186.88	-12672.75
6 AUS_NZ	-0.24	15610.69	15572.79	-37.90
7 EU	-0.46	1078666.63	1073711.38	-4955.25
8 S_Asia	-0.69	124364944.00	123503576.00	-861368.00
9 CC_Amer	-0.45	1649753.25	1642302.25	-7451.00
10 S_Afr	-2.11	95729.95	93710.16	-2019.78
11 SE_Asia	-0.41	20727396.00	20642242.00	-85154.00
12 CAN	0.02	4401.19	4402.18	1.00
13 US	-0.87	317580.16	314824.75	-2755.41
14 CHINA	-0.41	103235592.00	102813824.00	-421768.00
15 M_East	-0.17	3064389.75	3059125.50	-5264.25
16 JPN_KR	-0.01	410379.34	410337.13	-42.22
17 C_Asia	-0.08	2665503.50	2663358.50	-2145.00

Figure 9. Percentage changes in labor employment in irrigated production

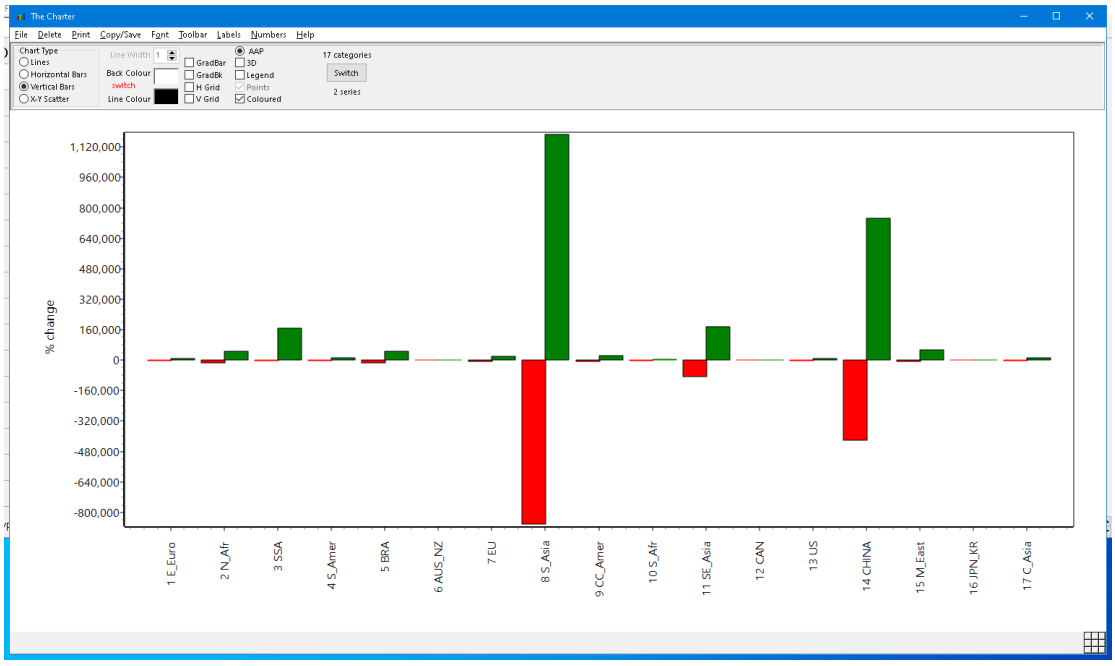
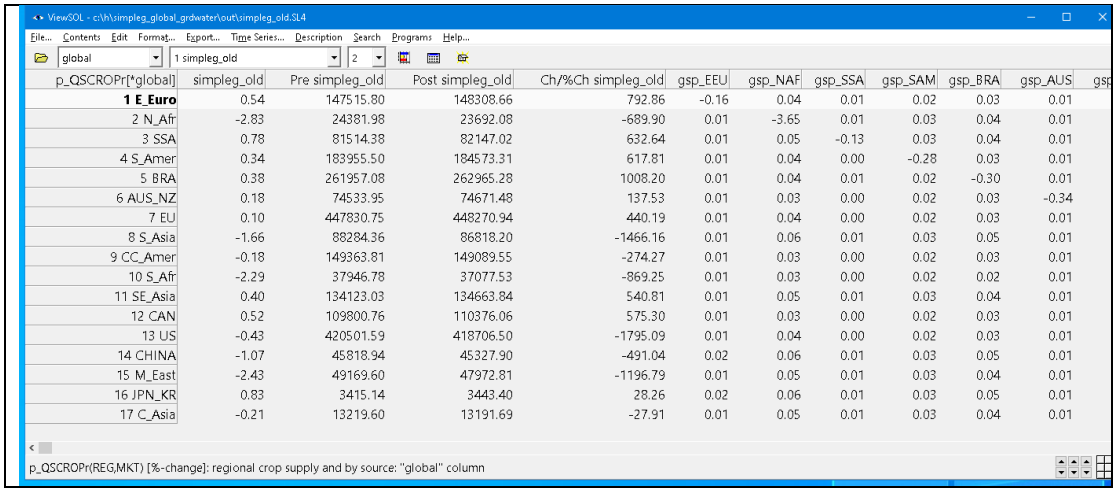


Figure 10. Changes in labor employment (number of jobs, red: irrigated, green: rainfed)

6 Standard decomposition and subtotals

Figure 11 displays the subtotals related to exports of crops. Here, the subtotal columns are labeled by region abbreviations. In general, domestic sustainability policies lead to a reduction in exports, while distant sustainability policies contribute to an increase in exports. For example, while exports from East Europe increased by 0.54%, the domestic groundwater sustainability is -0.16% (column gsp_EEU).


ViewSOL - c:\h\simpleg_global_grdwater\out\simpleg_old.SL4

File... Contents Edit Format... Export... Time Series... Description Search Programs Help...

global | 1 simpleg_old | 2

p_QSCROPr[*global]	simpleg_old	Pre simpleg_old	Post simpleg_old	Ch/%Ch simpleg_old	gsp_EEU	gsp_NAF	gsp_SSA	gsp_SAM	gsp_BRA	gsp_AUS	gsp
1 E_Euro	0.54	147515.80	148308.66	792.86	-0.16	0.04	0.01	0.02	0.03	0.01	
2 N_Afr	-2.83	24381.98	23692.08	-689.90	0.01	-3.65	0.01	0.03	0.04	0.01	
3 SSA	0.78	81514.38	82147.02	632.64	0.01	0.05	-0.13	0.03	0.04	0.01	
4 S_Amer	0.34	183955.50	184573.31	617.81	0.01	0.04	0.00	-0.28	0.03	0.01	
5 BRA	0.38	261957.08	262965.28	1008.20	0.01	0.04	0.01	0.02	-0.30	0.01	
6 AUS_NZ	0.18	74533.95	74671.48	137.53	0.01	0.03	0.00	0.02	0.03	-0.34	
7 EU	0.10	447830.75	448270.94	440.19	0.01	0.04	0.00	0.02	0.03	0.01	
8 S_Asia	-1.66	88284.36	86818.20	-1466.16	0.01	0.06	0.01	0.03	0.05	0.01	
9 CC_Amer	-0.18	149363.81	149089.55	-274.27	0.01	0.03	0.00	0.02	0.03	0.01	
10 S_Afr	-2.29	37946.78	37077.53	-869.25	0.01	0.03	0.00	0.02	0.02	0.01	
11 SE_Asia	0.40	134123.03	134663.84	540.81	0.01	0.05	0.01	0.03	0.04	0.01	
12 CAN	0.52	109800.76	110376.06	575.30	0.01	0.03	0.00	0.02	0.03	0.01	
13 US	-0.43	420501.59	418706.50	-1795.09	0.01	0.04	0.00	0.02	0.03	0.01	
14 CHINA	-1.07	45818.94	45327.90	-491.04	0.02	0.06	0.01	0.03	0.05	0.01	
15 M_East	-2.43	49169.60	47972.81	-1196.79	0.01	0.05	0.01	0.03	0.04	0.01	
16 JPN_KR	0.83	3415.14	3443.40	28.26	0.02	0.06	0.01	0.03	0.05	0.01	
17 C_Asia	-0.21	13219.60	13191.69	-27.91	0.01	0.05	0.01	0.03	0.04	0.01	

p_QSCROPr(REG,MKT) [%-change]: regional crop supply and by source: "global" column

Figure 11. Changes in exports due to local and distant shocks

7 Conclusions

This document described the model and databases related to the SIMPLE-G-Global model for the 2017 reference year with virtual water trade. This is a global gridded economic model of water and land use, designed for "what-if" policy analysis or evaluating the impacts of environmental and climate shocks. By describing data files, command files, model codes, and solution files, this document facilitates a detailed analysis of complex interactions between water and land use and their implications for food markets.

This study evaluated the significance of individual adaptation channels. The likely channels are surface water substitution, irrigation conversion, relocation, and international trade. However, labor mobility can affect the relocation effect. The current model can provide insights into equity concerns as it impacts labor employment. However, future research requires a comprehensive labor module to provide a more accurate picture of labor wages and employment (Ray et al., 2023).

The SIMPLE-G model is continuously improving to provide researchers with advanced models and datasets with innovative tools for computation and visualization. This ongoing effort is part of the Global-to-Local-to-Global framework, which highlights the significance of market-mediated effects on sustainability and food security—an aspect often overlooked in global studies. Advanced research and refined methodologies will provide robust analytical capabilities that empower users to address the pressing challenges of our time.

Reference

Baldos, U.L.C., I. Haqiqi, T.W. Hertel, M. Horridge, and J. Liu. 2020. "SIMPLE-G: A multiscale framework for integration of economic and biophysical determinants of sustainability." *Environmental Modelling & Software* 133:104805.

Haqiqi, I., and T.W. Hertel eds. 2024. *SIMPLE-G: A Gridded Economic Approach to Sustainability Analysis of the Earth's Land and Water Resources* 2025th edition. Springer.

Haqiqi, I., C.J. Perry, and T.W. Hertel. 2022. "When the virtual water runs out: local and global responses to addressing unsustainable groundwater consumption." *Water International* 47(7):1060–1084.

Harrison, W.J., J.M. Horridge, and K.R. Pearson. 2000. "Decomposing Simulation Results with Respect to Exogenous Shocks." *Computational Economics* 15(3):227–249.

Hertel, T.W., and U.L.C. Baldos. 2016. *Global Change and the Challenges of Sustainably Feeding a Growing Planet*. New York: Springer International Publishing. Available at: http://link.springer.com/10.1007/978-3-319-22662-0.

Horridge, J.M., M. Jerie, D. Mustakinov, and F. Schiffmann. 2018. *GEMPACK manual*. Victoria University, Centre of Policy Studies/IMPACT Centre.

Ivanic, M. 2023. "GEMPACK simulations in R: Ademonstration of running the GTAP modeland processing its results entirely in R using packages HARr and tabloToR." *Journal of Global Economic Analysis* 8(1):1–20.

Liu, J., T.W. Hertel, R.B. Lammers, A. Prusevich, U.L.C. Baldos, D.S. Grogan, and S. Frolking. 2017. "Achieving sustainable irrigation water withdrawals: global impacts on food security and land use." *Environmental Research Letters* 12(10):104009.