Achieving Sustainable Irrigation Water Withdrawals: Global Impacts on Food Production and Land Use

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Abstract

Human activities are increasingly leading to overuse of surface water and nonrenewable groundwater, challenging the capacity of water resources to ensure food security and continuous growth of the economy. Adaptation policies targeting specifically water security can easily overlook its interaction with other sustainability metrics and unanticipated local responses to the larger-scale policy interventions. Using a recently developed global partial equilibrium, grid-resolving model, nick-named SIMPLE-on-a-Grid and coupling it with the global Water Balance Model, we simulate the impacts of reducing unsustainable irrigation water withdrawals on land use change and food supply, under a variety of future (2050) scenarios with and without adaptations. Comparisons are made among three policy interventions: inter-basin water transfers, investments in agricultural productivity-enhancing technologies, and the promotion of virtual water trade. Although each of these scenarios affects regional food supply in a similar fashion, their implications for land cover change, carbon emissions and global food security are quite different. By allowing for a systematic comparison of these alternative adaptations to future scarcity, the global gridded modeling approach offers unique insights into the multiscale nature of the water scarcity challenge.

Keywords: Sustainable development, irrigation scarcity, land use change
JEL Codes: O13, Q18, Q25

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Contents

1 Introduction **4**

2 Method **6**

2.1 *SIMPLE-on-a-Grid* model 6
2.2 Hydro-economic link 7
2.3 Water demand and availability for irrigation 8
2.4 Data 9

3 Experimental design **10**

3.1 Irrigation scarcity index 10
3.2 Experiments description 10

4 Results **12**

4.1 Future irrigation scarcity 12
4.2 Changes in crop output and price 13
4.3 Cropland use change and sub-national distribution of irrigated area 14

5 Conclusion **15**

Appendices **26**

Appendix A Analytical model of gridded impacts of environmental constraints **26**

Appendix B Projection of non-agricultural water consumption **29**

List of Figures

1 Irrigation scarcity index 2006. 18
2 Experimental design. 19
3 Evolving irrigation scarcity, 2050 relative to 2006. 20
4 Impacts on crop output and prices. 21
5 Impacts on land use change. 22
6 Grid-level change in irrigated cropland area. 23
A-1 *SIMPLE-on-a-Grid* core model structure. 33
A-2 Water Balance Model 34

List of Tables

1 Change in cropland area by 2050. 17
A-1 Mapping between countries and regions in *SIMPLE-on-a-Grid* 31

A-2 Experiment comparison 32

1 Introduction

Regions facing growing water demand will increasingly rely on unsustainable freshwater withdrawal: 30% percent of the present human water consumption is supplied from overuse of surface water and nonrenewable groundwater resources, and this is projected to increase further to 40% by the end of the century (Wada and Bierkens, 2014). Geographically, these overexploited aquifer systems and groundwater depletion (a permanent decrease in the volume of water stored in aquifers) are mainly concentrated in India, northeastern China, the western US, Mexico, Middle East and northern Africa (Aeschbach-Hertig and Gleeson, 2012). In the recently released Sustainable Development Goals (SDGs) (UN, 2015), one target the United Nations set forth is to ensure sustainable withdrawal and supply of freshwater in the coming decades. Water usage for irrigation, which accounts for 70% of global annual water withdrawal (Alexandratos and Bruinsma, 2012), constitutes a crucial part of this agenda.

Depending on how and to what extent reducing unsustainable freshwater withdrawal will affect water availability for irrigation, achieving this goal may have two opposing effects on future food supply. Designing interventions to simultaneously enhance food and water security (Wada et al., 2014) can facilitate optimal water allocation across space, time and economic activities, resulting in "more crop per drop". Conversely, restricting irrigation - in the absence of efficiency gains - will increase water stress in crops and have an adverse impact on yields (Elliott et al., 2014).

A large number of water scarcity studies focus on the compounding effects of water scarcity on a future world that is subject to some mixture of the previously mentioned two forces (Schmitz et al., 2013; Hanjra and Qureshi, 2010), whereas much less attention has been given to understanding the individual role of each component - namely efficiency improvements, on the one hand, and water quantity restrictions, on the other. Yet this is often what is needed to inform decision makers. One simple example is to identify where and by how much the sustainable policy should intervene. This requires to identify the hotspot locations with high "use-to-availability ratio" for irrigation water. The pattern, which closely depends on the underlying drivers such as changing population, affluence, technology, and climate1, is likely to change as the world economy evolves (Amarasinghe and Smakhtin, 2014). Understanding how economic growth and water scarcity interact is a key first step on the path to informing decision making over the coming decades.

The next step in this chain of analysis is to investigate potential adaptations - particularly in regions or sectors where scarcity is likely to become more severe in the future. This paper examines three types of adaptations that have been previously shown as effective technological and socioeconomic approaches to combat water scarcity. The first focuses on importing water into the regions with most severe water scarcity, via inter-basin transfers. This direct intervention on water cycles can significantly alter local water availability and demand. Haddeland et al. (2014) report that the impacts in parts of Asia and the western US even exceed the expected impact from moderate levels of global warming. The second involves increasing efficiency of water use in agriculture. Investing in improving agricultural water productivity can hold the increase in global evapotranspiration down to 20-30% (Molden et al., 2010) from the otherwise twofold in the next 50 years (De Fraiture et al., 2010). The third type of adaptation is characterized by enhanced trade in agricultural commodities - in effect relying on virtual water trade in place of physical water trade. The law of one price makes it less profitable to produce water-intensive commodities in places where the opportunity cost of irrigation is high, thereby directing away irrigation demand from water stressed regions (Liu et al., 2014).

Pursuing these investigations requires a quantitative model. The model must capture the way in which global drivers of economic growth operate, yet it must also capture the rich geo-spatial information in hydrological conditions and water use efficiency in agriculture. In water-focused economic models, ignoring the geophysical variation within an economy can mispredict local water demand and supply (Amarasinghe and Smakhtin, 2014; Liu et al., 2016), making the simulation of policies of little use to decision makers (Dinar, 2014). This paper utilizes such a global model of the crops, land use and the environment with sub-national detail, dubbed *SIMPLE-on-a-Grid*. This economic model is further coupled with the global Water Balance Model (WBM) (Grogan et al., 2015; Wisser et al., 2010) to study the economic impacts of sustainable irrigation.

2 Method

2.1 *SIMPLE-on-a-Grid* model

SIMPLE-on-a-Grid is a multi-region, partial equilibrium model of gridded cropland use, crop production, consumption and trade. It is an extension of the SIMPLE model that has been applied to study long run sustainability issues in agriculture (Baldos and Hertel, 2014). In this model, the world is composed of sixteen regions (see Table A-1 for aggregation). The consumption set contains four commodities (crop, livestock, processed food and non-food) produced by two sectors (crop and non-crop) (Figure A-1). Regional demand can be boosted by external factors such as more population, higher per capita income, and policies (e.g. biofuels mandates).

The present extension constitutes two major modifications. One has to do with establishing disaggregated equilibrium of crop production (irrigated and rainfed) at the grid-cell level. Regional crop output is distributed to grids using the output share of grid g in the region. The same algorithm is applied to distribute regional cropland area to grids. The size of the grid is 30 arc-min (or half degree), which covers approximately an area of 50km by 50km at the equator. Another modification distinguishes between irrigated and rainfed crop sectors ($Crop^I$ and $Crop^R$ in Figure A-1). The two sectors produce the identical crop commodity, following a nested constant elasticity of substitution (CES) production function. Water is an explicit input used by the irrigated sector only. Water demand is computed as the product of irrigated cropland area and a water content parameter, both of which are at the grid-cell level initially and aggregated to sub-basins (will be explained later). The supply of water is assumed exogenous at each sub-basin. The shadow price of irrigation water is determined by the equilibrium price of water at the same level.

Box 1 lists the linearized equations in the core-model. When accompanied by initial conditions and update equations, and implemented via the GEMPACK software suite, we are able to solve the underlying non-linear equations for a new equilibrium - in this case the focus is on projections from 2006 to 2050. Depending on the trade specification, the equilibrium crop price can be determined either regionally (segmented-markets) or globally (integrated-markets). Both irrigated and rainfed production are subject to a zero profit condition, whereby the percentage change in national output price must equal the cost share-weighted percentage changes of input prices (Equations A.1 and A.2). Cost shares may vary by grid-cell, as well as by irrigation regime.

The model assumes that crop production follows a CES function, with inputs grouped into land and non-land factors. Accordingly, the derived demand for agricultural inputs is determined by the change in output, the relative price of inputs with respect to crop output, as well as the substitution between land and non-land inputs (Equation A.3, A.4, A.6 and A.8). The supply of non-land inputs is determined at the national level by the prices of inputs and their supply elasticity (Equation A.5). The supply of land (irrigated and rainfed) is determined by the grid cell-specific land rent and a land supply elasticity (Equation A.7 and A.9). The national commodity market is cleared at the equilibrium commodity price. The factor market clearing condition determines the input prices for rainfed and irrigated land, water, and other non-land-water inputs at the grid-, basin- and the regional-level, respectively. Equation A.11 formulates the change of regional output, which is aggregated from the change at the grid-level.

2.2 Hydro-economic link

Water balance and the economic activities associated with water are reconciled at sub-basins. These hydrological boundaries are identified using river network and drainage area thresholds. Small drainage basins along coastlines were merged, resulting in a total of 958 sub-basins globally. Using this mask, the gridded hydrologic output data (approximately 62,000 cells) can be conveniently aggregated into sub-basins. Our definition of sub-basin rules out trans-boundary basins. Any shared basin will be split into separated sub-basins and mapped to corresponding regions.

Total water supplied to each sub-basin is affected by a complex set of processes which evolve dynamically over time, depending on climate, land use, river flows and hydrological infrastructure (Figure A-2). These were simulated by a modular, grid-based global Water Balance Model (WBM) (Grogan et al., 2015; Wisser et al., 2010) for three sources - surface water, reservoir stored water, and renewable groundwater. WBM predicts spatially and temporally-varying water volume and water quality variables operating at 30 arc-minute (or half degree) grid cells at daily time steps. These were aggregated to yearly and long-term means for the hydrologically-defined sub-basins. WBM was run for the historical period (1980-2012) using MERRA climate drivers and bias-corrected GISS-E2-R climate drivers. Future simulations were carried out for the same GCM over the period 2013-2099. Climate projections follow the RCP 8.5 scenario to represent the "business-as-usual" world economy with relatively high emissions. The MERRA historical run was combined with the GISS future runs.

2.3 Water demand and availability for irrigation

The demand for irrigation water changes at the same rate as irrigated land, assuming a constant water content of crops in any one grid cell (but varies across grids) (Equation A.10). Irrigation water and irrigable land are treated as complementary inputs (zero substitution). Demand for irrigable land is endogenously determined by the equilibrium land rent at each grid. The grid-level irrigation demand is then aggregated to sub-basins to be equated with sub-basin irrigation supply under the equilibrium condition.

Irrigation availability is restricted by the amount of residual water after the demand for domestic and industrial uses has been satisfied. Domestic and industrial water demand time series (1980-2099) were generated by applying a projected growth rate to the baseline year water demand. The baseline national domestic and industrial water withdrawal data were extracted from the FAO AQUASTAT data (FAO, 2015). The sources of these data originated from several different years centered around 2010, which we assume to be the base year for hydrological projections. In the absence of efficiency improvement in water use, domestic water demand would grow faster than does population, reflecting that water use per capita increases as consumers become wealthier. According to a review by Nauges and Whittington (2010), the income elasticity of water demand is typically in the range 0.1-0.3. We adopt the midpoint value of 0.2 in this study. In other words, the demand for domestic water is expected to grow at a rate of population growth plus one-fifth of the growth rate of per capita GDP. Annual population and per capita GDP growth rate was computed from the IIASA population and GDP decadal projections (IIASA, 2007) under the B2 scenario, which assumes medium level of population and GDP growth, and technological change by 2100 (see Appendix for detail).

2.4 Data

National scale data and parameters are inherited from the standard SIMPLE model (Baldos and Hertel, 2013). Specifically, information on GDP (in constant 2000 USD) and population are extracted from the World Development Indicators (2011) and from the World Population Prospects (2011). Data on cropland cover, crop production, utilization, and crop prices are obtained from FAOSTAT (2011). Consumption data are constructed based on GTAP v.6 dadabase, which represents the level of expenditure in 2006. The amount of crop feedstock used by biofuel sector is proportionate to total crop output, using the sale shares provided in the GTAP-BIO v.6 basedata. Shares constructed from crop utilization are used to split the remaining crop quantities into other uses, namely food, feed, and raw material for processed food.

Several additional data sources are involved for the present model extensions. The share of irrigated land and output at the grids follows the Monthly Growing Area Grids (MGAG) data for 26 crops (Portmann et al., 2010). Before computing the aggregated shares, all crop outputs are converted to corn-equivalent values by weighting the output of crop k (in tons) by the price of crop k relative to corn in the base period. Using these shares, the initial value of regional land and output are downscaled to grid cells, and split into rainfed and irrigated categories. The grid-level irrigation coefficient (cubic meter per hectare) is computed as the ratio of irrigation requirements to irrigated area. Irrigation water requirements (or blue water use) are supplied by the output of the Global Crop Water Model (GCWM) (Siebert and Döll, 2010).

3 Experimental design

3.1 Irrigation scarcity index

In order to identify where the sustainable water use policy should target, we construct an irrigation scarcity index at the sub-basin level to locate the "hotspot" where freshwater for irrigation tends to be overused. This index is defined as the ratio of irrigation demand to water available for irrigation, at each sub-basin. Water available for irrigation, as explained precedingly, is the residual after subtracting residential, industrial and livestock uses. It is assumed exogenous and the quantity is determined by the output exported from WBM. The demand for irrigation water is the aggregation of irrigation demand from all the grids that fall in the same sub-basin. This demand is endogenously determined by the partial equilibrium model, which allows farmers to adjust the amount of water used for irrigation as water becomes scarce and expensive.

Following Alcamo et al. (2000), a country is considered as irrigation scarce if the annual freshwater withdrawal for irrigation is larger than 20% of annual irrigation water supply. Therefore, 20% is selected as the threshold for unsustainable irrigation in the present assessment. Above this threshold, we expect irrigated agriculture to be more vulnerable to shortfalls in water supply. Using irrigation water supply and demand provided in the base data (representing year 2006), we calculate this index for the sub-basins that provide water for irrigated farming (Figure 1). South Asia, Central US, Middle East, East and North China, as well as Southern Australia are among the regions where irrigation is widely implemented. In these regions, the present freshwater withdrawal of many basins already surpasses the critical value of 20%. This index will be updated by simulations when a new equilibrium condition is reached.

3.2 Experiments description

We are interested in using *SIMPLE-on-a-Grid* to investigate two issues. One has to do with comparing the impacts of imposing sustainable irrigation standards alternately on the current and then on the future economy, while ignoring possible adaptations. Given the evolving natural and socio-economic conditions, it is likely that the imbalance between irrigation demand and supply is driven by different factors in different parts of the world. Examining across consequences from different baseline economy helps us understand the mechanisms by which these exogenous drivers lead to varying degrees of irrigation scarcity, and subsequently how the scarcity is felt by local farming activities.

Another issue concerns the effectiveness of alternative sustainable adaptations and their environmental implications. In particular, our investigation focuses on three strategies: (a) inter-basin water transfers, (b) investments to accelerate agricultural total factor of productivity (TFP) growth, and (c) promoting commodity market integration to allow virtual water trade to ameliorate scarcity. Each will be discussed in more detail below.

The diagram in Figure 2 synthesizes the experimental design. In Experiments 1, 3, and 3a-c, we shock the irrigation scarcity index at the sub-basin level to target the sustainable water withdrawal, i.e. 20% of irrigation supply. The only difference between these experiments is the initial economy upon which the sustainable shock is applied. Different future economies are defined on a set of water demand and supply determinants such as TFP growth, infrastructure change, and market conditions. These differentiated future economies are updated from the baseline (2006 economy) by running Experiment 2 and 2a-c, in which irrigation is not constrained by the sustainability threshold.

The water transfer experiment E2-a identifies the sub-basins that are connected by large-scale hydro-projects, and treat them as an integrated basin. In this case, water market is cleared at the integrated basin level, rather than at the individual sub-basin level. Experiment E2-b allows increasing R&D investment in agriculture and a faster growing TFP by 2050, drawing on the work of Ludena et al. (2007); Fuglie et al. (2012); Griffith et al. (2004); Evenson and Gollin (2003). In the integrated market experiment E2-c, the law of one price is assumed to hold globally. This is in contrast with all the other experiments, where commodity markets are segmented and commodity prices are determined at the regional level, based on an Armington structure in which the domestic and international goods are imperfect substitutes. A comparison of the experiments can also be seen in Appendix Table A-2.

4 Results

4.1 Future irrigation scarcity

What is the outlook for irrigation scarcity in 2050 after taking into account a host of factors that affect irrigation water demand and supply? WBM simulates total water supply and non-agricultural water uses in 2050, thus providing the amount of water available for irrigation at each sub-basin (as the residual of the total). *SIMPLE-on-a-Grid* projects future demand for food and the irrigation water requirements to achieve the predicted level of crop output. Using these two components, we update the irrigation scarcity index to 2050. A comparison of the 2050 and 2006 scarcity indexes is shown in Figure 3.

Comparing the index value at two time points 2006 and 2050, we find that future irrigation vulnerability is predicted to deteriorate in South Asia, Central China, the Mediterranean region, the Pampas, and Southeast Africa. Two cases are of particular concern: sub-basins where the index value was below 0.2 but rises above the threshold (sub-basins marked as red in Figure 3), and the currently irrigation-stressed sub-basins that will draw an even larger share of the irrigation water supply in the future (pink in Figure 3). By contrast, it is predicted that irrigation will become more sustainable in Central US, Iran, East Europe, and Southern Australia. Again, these regions can be classified into two groups: the sub-basins which suffer from vulnerable irrigation today but will not in 2050 (green in Figure 3), and the sub-basins that remain scarce but wherein the degree of scarcity will be lower in the coming decades (blue in Figure 3).

These predictions are based on a future world without external constraints on irrigation withdrawals. Sustainable development policies would logically target the basins with the most severe shortages to ameliorate the adverse consequences of unsustainable irrigation. A natural question to ask is the following: to what extent will restrictions on irrigation water withdrawals affect food supplies and prices? Furthermore, since curtailing irrigation will likely suppress the growth of crop yields (the intensive margin of supply), it can be expected to place more pressure on boosting food supply from the extensive margin, i.e. cropland expansion. That too will raise environmental concerns of increased greenhouse gas (GHG) emissions and loss of biodiversity from cropland conversion. We will discuss below these effects based on results from *SIMPLE-on-a-Grid*.

4.2 Changes in crop output and price

Crop output in sub-basins experiencing curtailed excessive water withdrawals is expected to fall. This reduction, however, can be offset by the expansion of rainfed output in the same sub-basin, or by promoting irrigated and rainfed production in the other sub-basins where irrigation water withdrawals are below the 20% threshold. Simulation results suggest that the net effect of sustainable irrigation constraints on crop output tends to be negative in the heavily irrigated regions, i.e. South Asia, China and Middle East. The magnitude of the impact, however, differs depending on whether the current or future economy is examined (E1 vs. E3: Figure 4). Except for the EU, the impact is generally smaller in the future economy. This is particularly true for Australia, the US and Middle East region where the irrigation reliability of major irrigation sub-basins is expected to improve in the future (as suggested by Figure 3). The improvement is quite significant in Australia, such that imposing the sustainability requirement will no longer decrease total crop output (Figure 4 left panel).

Comparing the adaptations represented by Experiments 3a-c, water transfer projects appear to be more effective than faster TFP growth in moderating output reductions in the water-stressed regions. Promoting market integration has a stronger impact on both the scale of regional output and the distribution of global production across regions. For Latin America and sub-Saharan Africa (SSA) - both regions that have considerable potential to expand cropland areas, and also regions experiencing relatively less irrigation stress, output increases more strongly in response to the global, irrigation-constrained crop price rise. By contrast, in South Asia and China where irrigation scarcity is most severe and uncultivated suitable land is quite limited, production falls sharply.

In all experiments, regional crop prices increase (Figure 4 right panel), relative to without irrigation withdrawal constraint. Inter-basin water transfer projects (E3a in Figure 4) show a larger price-stabilizing effect than the other adaptations. The integrated market ensures the same market price rise across all regions (E3c in Figure 4). This common integrated-market price is lower in the most severely constrained regions of South Asia and China. In other regions, the price rise under integrated market is higher, thereby eliciting a stronger output response.

4.3 Cropland use change and sub-national distribution of irrigated area

Globally, more than 1,485 million hectares (Mha) of cropland are cultivated in 2006. How will the total cropland area, its split into irrigated and rainfed, as well as the geographical distribution of cropland change in the future? This will obviously depend on the availability of water for irrigation. The *SIMPLE-on-a-Grid* model projects the grid-cell level irrigated and rainfed cropland area in 2050. Aggregating the gridded results into regions and subtracting the baseline area in 2006 reveals the regional cropland area change, as presented in Table 1. In the absence of any sustainability constraint, both irrigated and rainfed land expand in all regions in 2050. The total expansion amounts to 240 Mha. Most of this comes from cultivating new rainfed land (208 Mha), especially in the land-abundant SSA and South America regions. Irrigated land expansion contributes only a small share (13%) to the total, with South Asia expected to be the most important contributor in the absence of irrigation supply constraints.

In the presence of the sustainability constraint, total expected cropland expansion falls from 240 to 156 Mha, and most of the reduction is due to the contraction of irrigated area. The most substantial contraction occurs in South Asia and China. Rainfed area, in contrast, will expand more than without the sustainable irrigation constraint. The spatial pattern of the expansion remains similar to the no constraint case.

The implications of the three adaptations for land use are quite different (Figure 5). The most obvious example is the faster TFP growth experiment (E3b). It helps increase total output and suppress prices rise (relative to E3), and reduces predicted land expansion by 50% because of the higher land productivity. Market integration (E3c) pulls down total land expansion as well (relative to E3), but it shows a different picture of where the expansion is likely to take place. Sub-Saharan Africa, the most important source of new land in other experiments, loses his dominant position due to the rate of productivity growth. Land in SSA, in spite of its abundance, is not profitable enough to draw production away from the other regions. Instead, the uniform world crop price encourages more cropland expansion in Eastern Europe. Water transfer projects (E3a) keep China from losing more than 10 Mha of irrigated cropland - playing a larger role in moderating land use change in that region.

Given these regional level land use changes, it is useful to pinpoint where, within a region, the sustainable policy is felt most strongly. Our gridded model can help with this. The geospatial detail added to the model provides better policy targeting by showing the local response to larger-scale shocks. This feature is particularly valuable when it comes to the analysis of land use change, because land quality typically varies considerably within a region. Figure 6 depicts the grid-level change in irrigated land area under two cases: with and without the sustainable irrigation constraint. An interesting case to examine is China, where significant expansion and contraction are observed simultaneously in the eastern part of the country. Such a heterogeneous spatial response would otherwise be masked by the aggregated national change in coarse spatial-resolution models.

5 Conclusion

Using the Water Balance Model, we identify sub-basins vulnerable to irrigation scarcity, in the context of both current and future economy. Further, we investigate how food security and land use change will be affected if irrigation water withdrawals at each of these hotspot locations is forced down to a sustainable level. To this end, the recently developed *SIMPLE-on-a-Grid* model is employed to simulate sustainable irrigation induced changes in crop output, market price, and land use, under a variety of economic conditions.

Several findings emerge from our analysis. First of all, based on the projections made in this paper, achieving the goal of sustainable irrigation in today's economy places more stress on food security (i.e. larger crop output reduction and higher food price increase) than will be the case in 2050. This result is obviously dependent on the water demand projections in WBM, which, in turn hinge on the elasticity of water use with respect to income and economic activity. This is a topic worthy of further investigation. It also depends on the rate of productivity growth in agriculture - a subject which is not without controversy. In short, further investigations of the robustness of this finding are required.

The second major finding is that, while all the examined adaptation strategies strive to achieve better water security, they may raise other environmental concerns, such as GHG emissions from the additional land conversion. Conserving irrigation water will inevitably restrict the growth of food supply at the intensive margin, leaving more pressure on agricultural extensification. Different adaptation measures, although they affect crop output and price in a comparable fashion, can have very different implications for where and how crops are produced. Understanding the interplay of changing land and water use with improved productivity, inter-basin transfers of water, and improved trading of agricultural commodities is a subject worthy of further investigation.

Finally, this application illustrates the value of grid-resolving modeling for mediating between global drivers of change and local environmental constraints, which, in turn, may affect regional and global outcomes. There is great value in this type of global-local-global framework for analyzing sustainability issues in general, and water scarcity, in particular.

Region	With sustainable constraint			Without sustainable constraint		
	Irrigated	Rainfed	Total	Irrigated	Rainfed	Total
S_Asia	-40.2	22.3	-17.9	14.0	17.1	31.2
CHN_MNG	-23.3	3.4	-19.8	1.9	1.5	3.4
M_East	-4.0	2.5	-1.5	1.2	2.2	3.4
US	-3.3	11.8	8.5	1.6	10.4	12.0
EU	-2.6	2.9	0.2	0.3	2.5	2.8
N_Afr	-1.0	1.2	0.1	0.4	1.0	1.4
C_Asia	-0.5	1.9	1.4	1.6	1.6	3.1
E_Euro	-0.5	5.4	4.9	0.2	4.3	4.5
S_Afr	-0.2	1.3	1.2	0.2	1.1	1.4
JPN_KR	0.0	0.0	0.0	0.0	0.0	0.0
CAN	0.1	4.4	4.5	0.1	4.2	4.2
AUS_NZ	0.1	6.7	6.7	0.3	6.1	6.4
CC_Amer	1.3	3.5	4.8	1.3	3.4	4.7
S_Amer	1.9	27.6	29.5	2.2	26.7	28.9
SSA	2.6	118.0	120.6	2.9	116.8	119.7
SE_Asia	2.9	9.7	12.6	3.3	9.4	12.7
Total	-66.7	222.5	155.8	31.3	208.3	239.6

Table 1: Change in cropland area by 2050.

Cropland change in 2050 with and without the sustainable constraint on irrigation water withdrawal, relative to cropland area in 2006. Unit is million hectares.

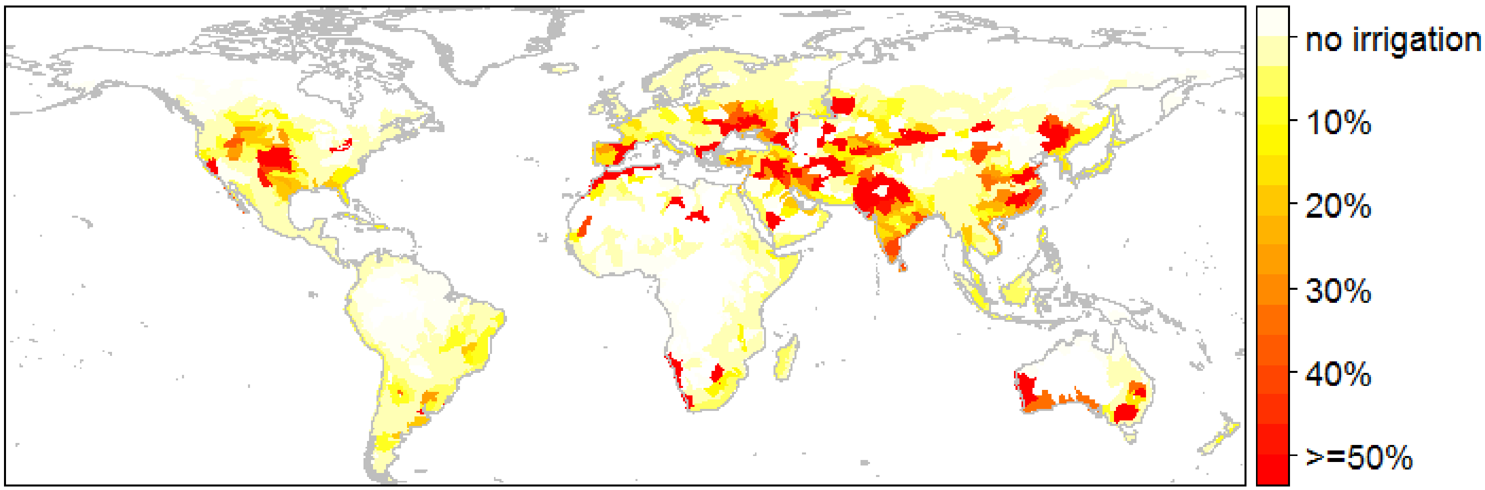

Figure 1: Irrigation scarcity index 2006.

Irrigation scarcity index calculated as the ratio of irrigation demand to water available for irrigation at the sub-basin level in 2006. A larger value indicates more water is withdrawn relative to irrigation supply. Source: Authors' calculation, based on the ten-year average (2001-2010) irrigation demand and supply simulated by WBM.

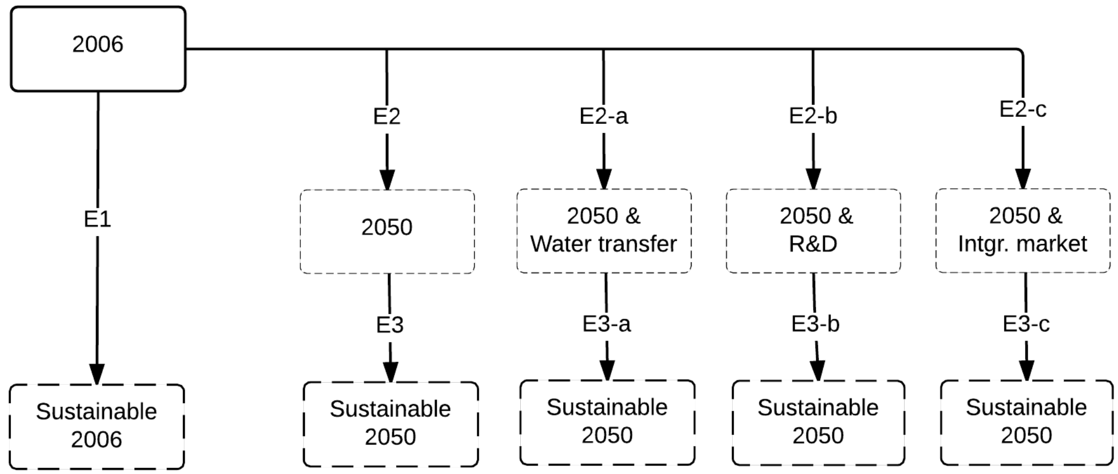

Figure 2: Experimental design.

Experiment 1, sustainable irrigation in current economy; Experiment 2, updating current economy to future, no sustainable irrigation constraint; Experiments 2-a,b,c, updating current economy to the future of no sustainable irrigation constraint but allowing for inter-basin water transfer, higher R&D investment, and market integration, respectively. Experiment 3, sustainable irrigation in future economy but without adaptations; Experiments 3-a,b,c, sustainable irrigation in future economy and with adaptations.

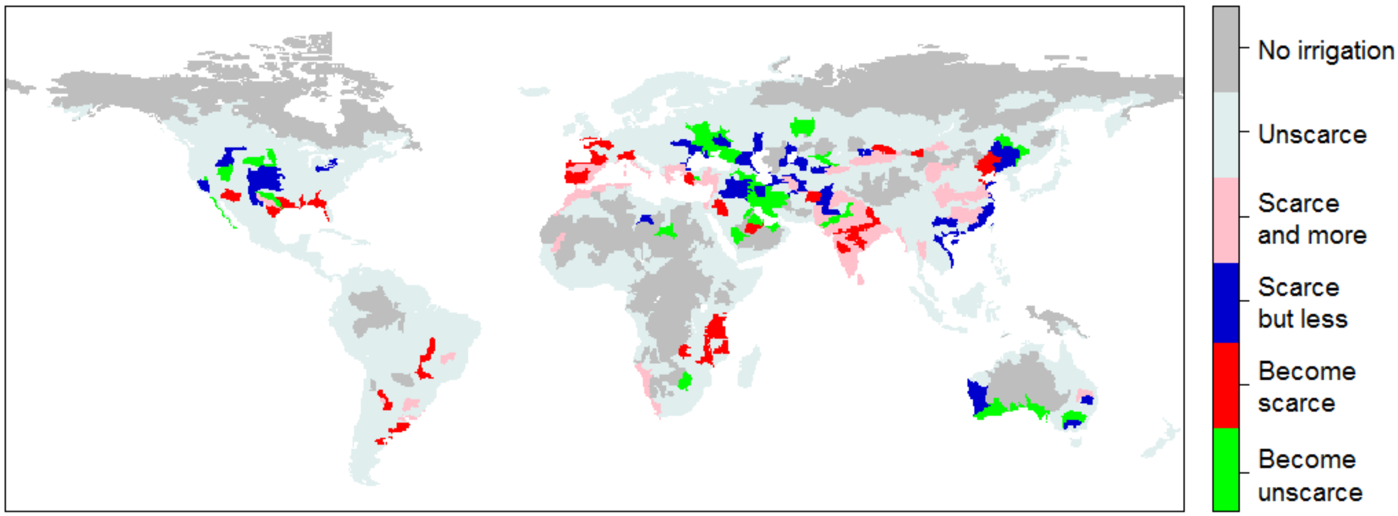

Figure 3: Evolving irrigation scarcity, 2050 relative to 2006.
In this comparison, a "business-as-usual" future in 2050 is assumed, which means no sustainability requirement and policy intervention, high emissions scenario RCP8.5, and a stagnant TFP growth. Source: Authors' calculation, based on irrigation demand and supply simulated by WBM and *SIMPLE-on-a-Grid*.

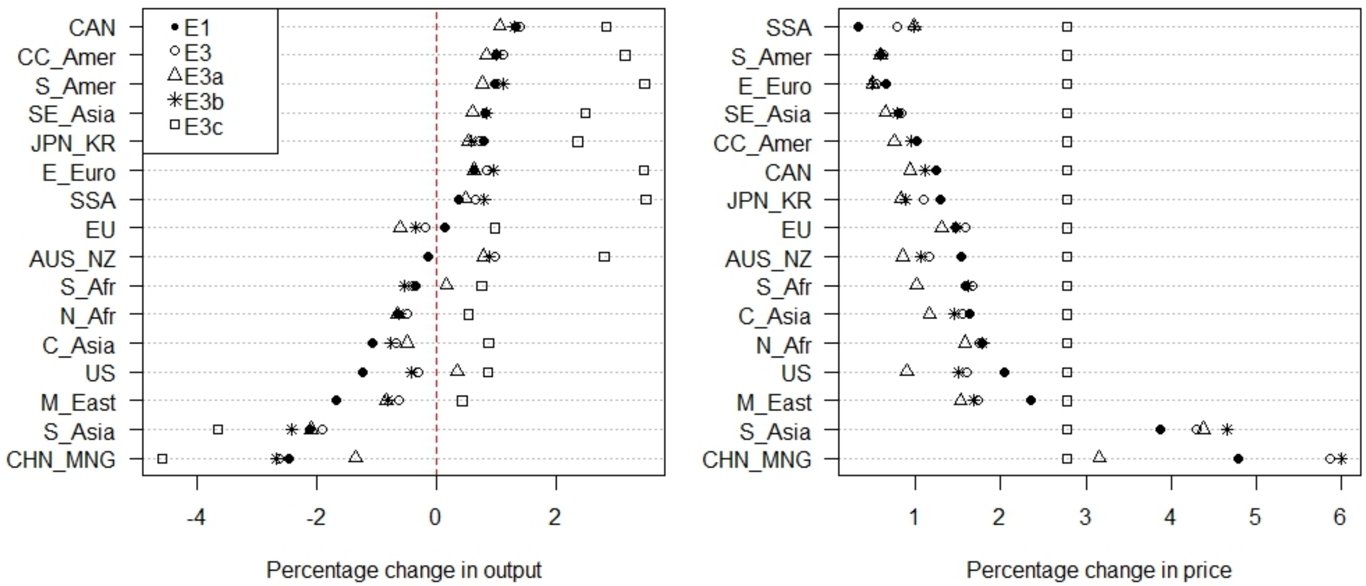

Figure 4: Impacts on crop output and prices.
Percentage change in regional crop output (left) and crop price (right). X-axis numbers indicate percentage points.

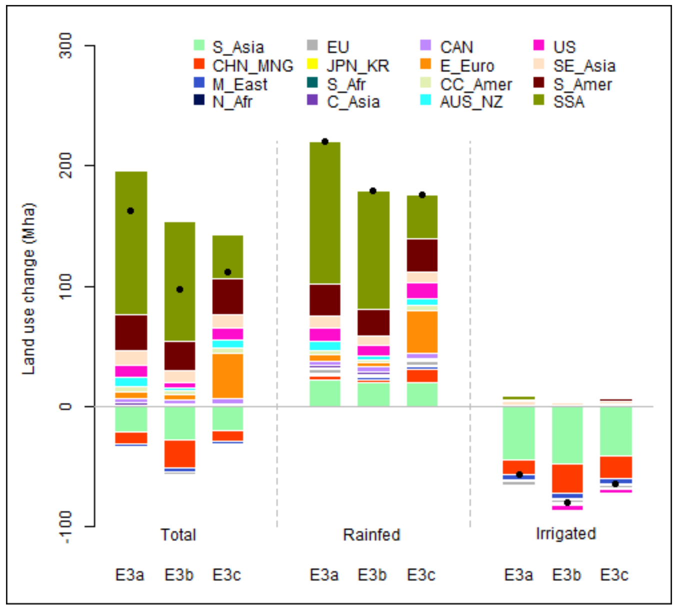

Figure 5: Impacts on land use change.

The change of cropland area (total, rainfed, and irrigated) caused by performing sustainable irrigation in 2050. Each panel compares the results simulated under different adaptations (E3a-c). All changes are relative to the 2050 world when the corresponding adaptation exists but no sustainability constraint. Black dots indicate the world's total. Colored segments indicate the contributions from each region.

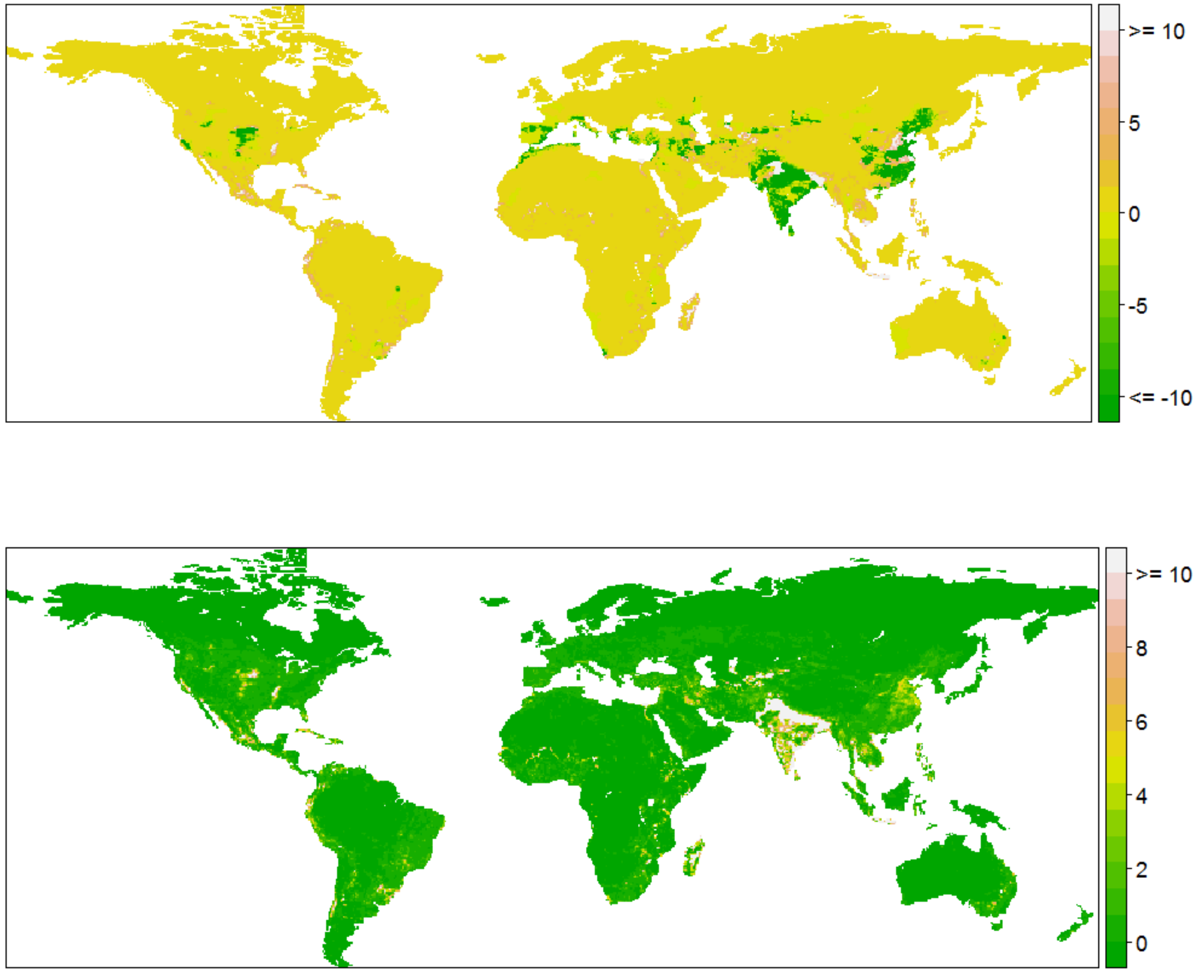

Figure 6: Grid-level change in irrigated cropland area.
Comparison of grid-level irrigated cropland change in 2050 between with (top) and without (bottom) sustainable irrigation constraint. Unit is 1000 ha. Positive number means land expansion in 2050 relative to 2006.

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Appendix A Analytical model of gridded impacts of environmental constraints

$$po + ao = \theta_g^{iLand} p_g^{iLand} + (1 - \theta_g^{iLand}) p^{nLand} \tag{A.1}$$

$$po + ao = \theta_g^{rLand} p_g^{rLand} + (1 - \theta_g^{rLand}) p^{nLand} \tag{A.2}$$

$$q_g^{nLand} = \sum_j \beta_j^{nLand} \big(qo_{g,j} - ao - \sigma_{g,j} (p_{g,j}^{nLand} - po) \big), j = irr, rfd \tag{A.3}$$

$$q^{nLand} = \sum_g \beta_g^{nLand} q_g^{nLand} \tag{A.4}$$

$$q^{nLand} = \nu^{nLand} p^{nLand} \tag{A.5}$$

$$q_g^{iLand} = qo_{g,irr} - ao - \sigma_{g,irr} (p_g^{iLand} - po) \tag{A.6}$$

$$q_g^{iLand} = \nu_g^{iLand} (p_g^{iLand} - \lambda_g^{iLand}) \tag{A.7}$$

$$q_g^{rLand} = qo_{g,rfd} - ao - \sigma_{g,rfd} (p_g^{rLand} - po) \tag{A.8}$$

$$q_g^{rLand} = \nu_g^{rLand} p_g^{rLand} \tag{A.9}$$

$$q_B^{Water} = \sum_{g \in B} \gamma_g q_g^{iLand} \tag{A.10}$$

$$qo = \sum_g \sum_j \alpha_{g,j} qo_{g,j} \tag{A.11}$$

$$p_{g,j}^{nLand} = (1 - \delta_{g,j}^{nLand}) p^{nLand} + \delta_{g,j}^{nLand} t_{g,j}^{nLand} \tag{A.12}$$

Notation:

- po: percentage change in national price of agricultural output
- qo: percentage change in crop output
- q^X: percentage change in demand for agricultural input X
- p_g^X: percentage change in the price of agricultural input X
- θ^{iLand}: cost share of irrigated land input in grid g
- θ^{rLand}: cost share of rainfed land input in grid g
- $\alpha_{g,j}$: national output share of crop j grown in grid g
- ao: input-neutral efficiency index in crop sectors
- $\delta_{g,j}^{nLand}$: tax share of crop j non-land input cost in grid g
- γ_g: share of grid g water demand in sub-basin B
- λ_g^{iLand}: per hectare shadow price of irrigation water in sub-basin B
- $\sigma_{g,j}$: elasticity of substitution between land and non-land inputs
- ν_g^{iLand}: elasticity of irrigated land supply in grid g
- ν_g^{rLand}: elasticity of rainfed land supply in grid g
- ν^{nLand}: elasticity of non-land input supply in the region
- β_g^{nLand}: share of grid g non-land input in regional total
- β_j^{nLand}: share of crop j non-land input in grid g
- $t_{g,j}^{nLand}$: percentage change in specific tax on non-land input in crop j on grid g

(B.1) Zero profits for irrigated crop sector in grid g

(B.2) Zero profits for rainfed crop sector in grid g

(B.3) Grid-level demand for non-land inputs by crops

(B.4) Regional demand for non-land inputs by crops

(B.5) Regional supply of non-land inputs to crop sectors

(B.6) Grid-level demand for land inputs by irrigated crop

(B.7) Grid-level supply of irrigated land input to irrigated crop sector

(B.8) Grid-level demand for land inputs by rainfed crop

(B.9) Grid-level supply of rainfed land input to rainfed crop sector

(B.10) Sub-basin level demand for water by irrigated crop sector

(B.11) Regional crop output

(B.12) Land-type specific tax on non-land input usage

Appendix B Projection of non-agricultural water consumption

This section documents the method applied to project and downscale national-level annual domestic and industrial water demand to the grid-level. The following equations are for country N. Subscript N is omitted.

1. Gather base year (2010) national domestic and industrial water withdrawal data from FAO AQUASTAT
2. Calculate water use intensity of each, assuming constant intensity over time
   (a) Domestic water use intensity

$$\eta_D = \frac{DWU^{2010}}{\sum_{g \in N} P_g^{2010} G_g^{2010}} = \frac{DWU^t}{\sum_{g \in N} P_g^t G_g^t}, \quad t = 1981, ..., 2100 \tag{B.1}$$

   (b) Industrial water use intensity

$$\eta_I = \frac{IWU^{2010}}{\sum_{g \in N} P_g^{2010} G_g^{2010}} = \frac{IWU^t}{\sum_{g \in N} P_g^t G_g^t}, \quad t = 1981, ..., 2100 \tag{B.2}$$

3. Predict national level water use time series
   (a) Domestic water use: $DWU^t = DWU^{2000}[1 + r_{pop}^t + 0.2 \times r_{gpc}^t]$
   (b) Domestic water use: $IWU^t = IWU^{2000}[1 + 0.2 \times r_{gdp}^t]$
   (c) Annual growth rate of GDP per capita: $r_{gpc}^t = r_{gdp}^t - r_{pop}^t$
4. Multiply water use intensity with gridded population and GDP to obtain grid-level water use
   (a) Domestic water use: $DWU^t = \eta_D P_g^t G_g^t$
   (b) Industrial water use: $IWU^t = \eta_I P_g^t G_g^t$
5. Verify that aggregating grid-level water use returns national water use
   (a) Domestic water use:

$$\sum_{g \in} DWU_g^t = \sum_{g \in N} \eta_D P_g^t G_g^t \tag{B.3}$$

$$= \sum_{g \in} \frac{DWU^t}{\sum_{g \in N} P_g^t G_g^t} P_g^t G_g^t \tag{B.4}$$

$$= DWU^t \sum_{g \in} \frac{DWU^t}{\sum_{g \in N} P_g^t G_g^t} = DWU^t \tag{B.5}$$

(b) Industrial water use:

$$\sum_{g\in} IWU_g^t = \sum_{g\in N} \eta_I P_g^t G_g^t \tag{B.6}$$

$$= \sum_{g\in} \frac{IWU^t}{\sum_{g\in N} P_g^t G_g^t} P_g^t G_g^t \tag{B.7}$$

$$= IWU^t \sum_{g\in} \frac{IWU^t}{\sum_{g\in N} P_g^t G_g^t} = IWU^t \tag{B.8}$$

Table A-1: Mapping between countries and regions in *SIMPLE-on-a-Grid*

Region	Country
AUS_NZ	aus,nzl
C_Asia	kgz,tjk,tkm,uzb
CAN	can
CC_Amer	blz,cri,cub,dom,slv,gtm,guy,hti,hnd,mex,nic,pan,pri,sur,tto
CHN_MNG	chn,mng
E_Euro	alb,arm,aze,blr,geo,kaz,mda,rom,rus,ukr,ysr,mkd,bih,hrv,svn
EU	aut,bgr,cyp,dnk,est,fin,fra,deu,grc,hun,isl,irl,ita,lva,ltu,nld,nor,pol,prt,esp,swe,che,gbr,bel,lux,cze,svk
JPN_KR	jpn,kor
M_East	irn,irq,isr,jor,lbn,omn,sau,syr,tur,are,yem
N_Afr	dza,egy,lby,mar,tun
SSA	ago,ben,bfa,bdi,cmr,caf,tcd,com,cog,zar,civ,gnq,eri,eth,gab,gmb,gha,gin,gnb, ken,lbr,mdg,mwi,mli,mrt,moz,ner,nga,rwa,sen,sle,tza,tgo,uga,zmb,zwe
S_Afr	bwa,lso,mus,nam,zaf,swz
S_Amer	arg,bol,bra,chl,col,ecu,pry,per,ury,ven
S_Asia	bgd,btn,ind,npl,pak,lka
SE_Asia	khm,fji,idn,lao,mys,png,phl,slb,tha,tmp,vut,vnm
US	usa

Table A-2: Experiment comparison

Experiment	Economy	Sustainable Irrigation	Inter-basin water transfer	R&D investment	Integrated market
Baseline	2006	-	-	-	-
E1	2006	✓	✗	✗	✗
E2	2006	✗	✗	✗	✗
E2-a	2050	✗	✓	✗	✗
E2-b	2050	✗	✗	✓	✗
E2-c	2050	✗	✗	✗	✓
E3	2050	✓	✗	✗	✗
E3-a	2050	✓	✓	✗	✗
E3-b	2050	✓	✗	✓	✗
E3-c	2050	✓	✗	✗	✓

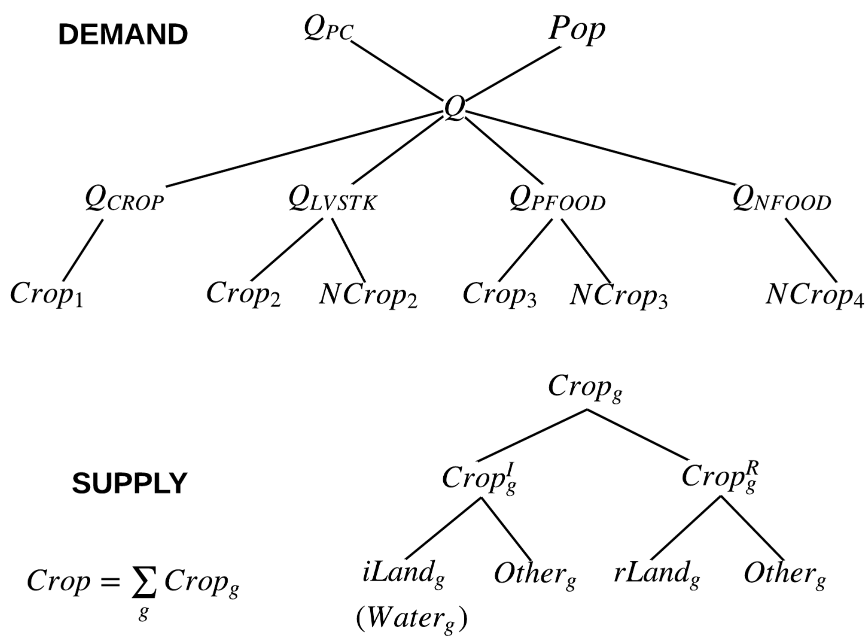

Figure A-1: *SIMPLE-on-a-Grid* core model structure.

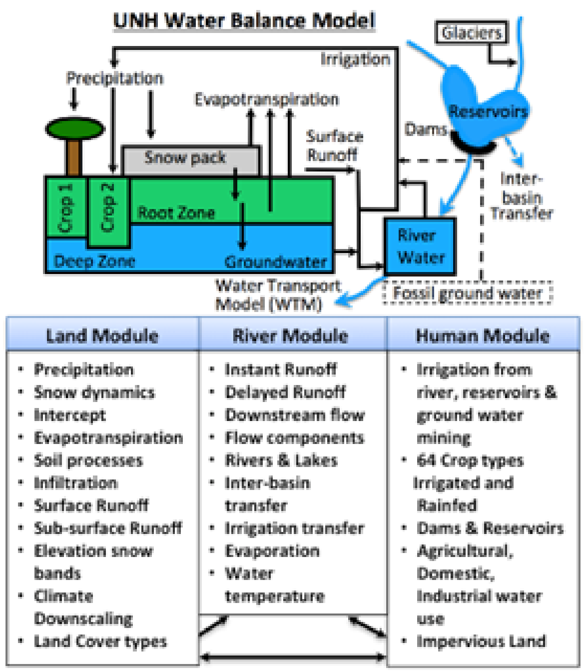

Figure A-2: Water Balance Model

Schematic diagram showing major components of the UNH Water Balance Model with a list of processes over the land, river and human interactions.