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

Jing Liu[1], Thomas Hertel[1], Richard Lammers[2], Alexander Prusevich[2], Uris Baldos[1], Danielle Grogan[2] and Steve Frolking[2]
[1]Department of Agricultural Economics, Purdue University, West Lafayette, IN 47907, USA
[2]Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA

Selected Paper prepared for presentation at the 2017 Agricultural & Applied Economics Association Annual Meeting, Chicago, Illinois, July 30-August 1

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

Jing Liu[1], Thomas Hertel[1], Richard Lammers[2], Alexander Prusevich[2], Uris Baldos[1], Danielle Grogan[2] and Steve Frolking[2]
[1] Department of Agricultural Economics, Purdue University, West Lafayette, IN 47907, USA
[2] Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA

Abstract

Human activity induced unsustainable water use challenges the capacity of water resources to ensure food security and continued growth of the economy. Adaptation policies targeting future water security can easily overlook its interaction with other sustainability metrics and unanticipated local responses to the larger-scale policy interventions. Using a global partial equilibrium grid-resolving model SIMPLE-on-a-Grid, and coupling it with the global Water Balance Model, we simulate the consequences of reducing unsustainable irrigation for food security, land use change, and terrestrial carbon under a variety of future (2050) scenarios that interact future irrigation productivity with two policy interventions - inter-basin water transfers and international commodity market integration. We find that pursuing sustainable irrigation may erode other development and environmental goals due to higher food price and cropland expansion. This results in over 800 million more undernourished people and 0.87 GtC additional emissions. Faster total factor productivity growth in irrigated sectors will encourage more aggressive irrigation water use in the basins where irrigation vulnerability is expected to be reduced by inter-basin water transfer. By allowing for a systematic comparison of these alternative adaptations to future irrigation vulnerability, the global gridded modeling approach offers unique insights into the multiscale nature of the water scarcity challenge.

Keywords

Sustainable development, irrigation vulnerability, multi-scale hydro-economic modeling

1. Introduction

Excessive groundwater extraction for irrigation in areas of slow recharge is the main cause of groundwater depletion (a persistent decrease in the volume of water stored in aquifers) in regions including India, northeastern China, the western US, Mexico, Middle East and northern (Aeschbach-Hertig and Gleeson, 2012), as well as Midwest, south and west US (Konikow, 2013). Facing growing water demand, many of these regions will increasingly rely on unsustainable freshwater withdrawals. Wada and Bierkens (2014) estimate that 30% of the human water consumption is currently supplied from overuse of surface water and nonrenewable groundwater resources, and this is projected to increase to 40% by the end of the century. In the recently released Sustainable Development Goals (SDGs), one target set forth by the United Nations 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.

Reducing unsustainable water consumption poses a significant challenge for future food supplies. Interventions which simultaneously enhance food productivity and water security can facilitate optimal water allocation across space, time and economic activities, resulting in “more crop per drop” (Wada et al., 2014). However, restricting irrigation in the absence of significant efficiency gains will increase water stress in crops and have an adverse impact on yields (Elliott et al., 2014). Most studies of future irrigation scarcity focus on the compounding effects in a world that is subject to some mixture of these two forces (Hanjra and Qureshi, 2010; Schmitz et al., 2013), 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 common question is: where and by how much must water use be reduced to ensure sustainability? This requires first identifying the hotspot locations with high “use-to-availability ratios” for irrigation water. The pattern, which closely depends on the underlying drivers such as changing population, affluence, technology, and climate, 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 two types of adaptations that have been previously shown effective to combat water scarcity. One involves transferring water via inter-basin transfers. This direct intervention into the water cycle can significantly alter local water availability and demand. Haddeland et al. (2014) reported that the impacts of inter-basin water transfers on the water cycle in parts of Asia and the western US even exceed the expected impact from moderate levels of global warming. The other type of adaptation is characterized by enhanced trade in agricultural commodities - in effect relying on virtual water trade in place of physical water trade. With commodity price equalized across regions, the profitability of producing water-intensive commodities falls wherever the opportunity cost of irrigation is high, thereby directing irrigation demand away from water stressed regions (Liu et al., 2014).

Analysis of the impacts of enforcing sustainable water use 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 about hydrological conditions and irrigation productivity in agriculture. In water-focused economic models, ignoring the geophysical variation within an economy can result in misleading projections of local water demand and supply (Amarasinghe and Smakhtin, 2014; Liu et al., 2016), rendering the simulation of policies of little use to decision makers (Dinar, 2014). Recognizing the issue, this paper introduces a global model of crops, land use and carbon emissions with sub-national detail, dubbed SIMPLE-on-a-Grid. This economic model is further coupled with the global Water Balance Model (WBM) (Grogan, 2016; Wisser et al., 2010) to study the economic implications of pursuing sustainable irrigation as well as impacts on food production and land use.

2. Methods

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 split into sixteen economic regions (Table S1). Regional consumption is disaggregated into four commodities (crops, livestock, processed foods and biofuels). Regional demand is driven by population, per capita income, and biofuel mandates (all exogenous to the model) as well as prices (endogenous in the model).

SIMPLE-on-a-Grid extends the existing SIMPLE model by disaggregating rainfed and irrigated production and modeling these processes at the individual grid-cell level (Figure S1). Regional crop output is obtained by aggregating across the grid cells (30 arc-min resolution) within each region. Crop production follows a nested constant elasticity of substitution (CES) function. Water is an explicit input used by the irrigated sector only. Water consumption is computed as the product of gridded irrigated cropland area and a grid cell-specific consumptive water use parameter in m^3/ha. By aggregating water use across grid cells within a sub-basin (defined below), we obtain total irrigation consumption. Water availability at each grid cell is exogenous in SIMPLE-on-a-Grid, and is obtained from the hydrological model. The shadow price (the estimated price of water when its actual market price does not exist) of irrigation water in each sub-basin is adjusted to equate availability and consumption of water. Appendix A lists the linearized form of the equations in the core-model. When accompanied by initial conditions (baseline year 2006) and updated equations, and implemented via the GEMPACK software suite (Harrison and Pearson, 1996), we are able to solve the underlying non-linear equations for a new equilibrium - in this case 2050.

2.2 Water Balance Model

The Water Balance Model (WBM) (Grogan, 2016; Wisser et al., 2010) is a global, gridded model representing the land surface component of the hydrologic cycle. Water mass balance is resolved at each grid cell within the global (approximately 62,000 cells) WBM and aggregated spatially to sub-basins. The hydrological boundaries of sub-basins are identified by sub-diving the digitized river network over large drainage basins, and merging small coastal drainage basins, to achieve sub-basin areas between 90,000 and 200,000 km^2, resulting in a total of 958 sub-basins globally (Figure S2). Hydrologic sub-basins are used instead of full drainage basins because large basins can have significant spatial heterogeneity in water supply and demand.

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 C4). These were simulated by WBM for three water sources - surface water flows, reservoir water, and renewable shallow groundwater. WBM predicts spatially and temporally-varying water volume and water quality variables at daily time steps. These were aggregated to yearly long-term means over the hydrologically-defined sub-basins. WBM was run for the historical period (1980-2012) using historical MERRA climate drivers (GMAO, 2011), and for bias-corrected GISS-E2-R climate projections (Schmidt et al., 2014) for 2013-2099 following the RCP 8.5 scenario representing the future economy under high emissions growth.

2.3 Model calibration and hindcasting

Before looking forward, it is important to first look backwards in time to establish model validity for long run projections. Appendix C4 and Grogan (2016) describe in detail the validation of WBM. The SIMPLE model has undergone extensive validation over the period 1961-2006 (Baldos and Hertel, 2014, 2013; Hertel and Baldos, 2016). In this paper, we extend this to an examination of irrigated agriculture as well.

Beginning in the 1960s, a distinct pattern of global crop production emerged from the "Green Revolution" involving the planting of high-yielding varieties which required intensive cultivation, i.e. increased applications of fertilizers, pesticides and irrigation water (FAO, 1996). The amount of land equipped for irrigation has more than doubled during 1961-2006 (Siebert et al., 2015), whereas total cropland area has only risen by 12.8% (Alexandratos and Bruinsma, 2012). These changes led to a rise in the Total Factor Productivity (TFP: an index of crop output relative to an index of all inputs) of irrigated vs. rainfed agriculture which will likely continue to be a critical determinant of crop yield increase and the change of total cropland area. However, the literature provides very limited information about this relative rate of growth at global scale, leading us to elicit this from the model, by asking "How much faster must the irrigated sector's TFP in a given region have grown, relative to the rainfed productivity, in order to be consistent with the observed change in this period"?

The results from this exercise suggest roughly 10% faster cumulative irrigated TFP growth in China, South Asia and developed countries over the 1961-2006 period (Table S2). The global average irrigated TFP rises by 8.8%, relative to rainfed productivity over this entire period. Whether this trend of more rapid irrigated TFP growth will persist into the future is an open question. Given this uncertainty, we consider two sets of experiments reflecting two distinct worlds going forward to 2050 – one with and one without faster TFP growth in the irrigated sectors.

2.4 Experimental design

Two economic equilibrium states - before and after a shock to a set of exogenous variables are compared. In this context, the shock is based on the attainment of a sustainable level of water use measured by an "irrigation vulnerability index", which is constructed as the consumption-to-availability ratio (Appendix B). This index permits us to locate the hotspots where freshwater for irrigation tends to be overused. The magnitude of the shocks depends on the exceedance of this index over the sustainability threshold. Alcamo et al. (2000) considered a country to be water scarce if the annual freshwater withdrawal is larger than 20% of total annual water supply. We follow this literature and adopt 20% as the threshold for unsustainable irrigation in the present assessment. In our context, this 20% threshold could be more or less stringent than Alcamo et al. (2000), which referred to overall water scarcity, including water for both agricultural and non-agricultural purposes. A scarcity index for irrigation requires subtracting the non-agricultural portion from both the numerator and the denominator of the ratio. Also, we use irrigation water consumption, which is normally far less than water withdrawal, due to irrigation inefficiencies (FAO, 2016; Gleick, 1993).

The experiments designed for these investigations are summarized in Table 1 and Appendix B. The experiments are implemented under two alternative assumptions about the relative rate of TFP growth for irrigated and rainfed crops. In the first case, they both grow at the same rate in the future, whereas in the second, the historical global average cumulative difference (8.8% faster in irrigation) persists into the future but is the same for all regions. In both cases, the overall rate of TFP growth in the crops sector is the same. Each assumption is interacted with three scenarios – no adaptation, inter-basin water transfer and integrated world markets. This experimental design yields six sets of results in total.

Note that, in each of these six possible future worlds, the sub-basins identified as unsustainable will also be different due to the combination of these external drivers. After each simulation, the sub-basin level irrigation vulnerability index is recomputed within the model. If the resulting index is greater than 0.2, the sustainability experiment shocks the index such that no more than 20% of the total water available for irrigation at each sub-basin is consumed in the sustainable equilibrium (see B.3 for details).

3. Results

3.1 Irrigation vulnerability evolves differently among sub-basins due to their heterogeneous response to the external drivers

What is the outlook of irrigation vulnerability in 2050 after taking into account the factors that affect irrigation water demand and supply? A comparison of the 2050 and 2006 vulnerability indices is shown in Figure 1. Future irrigation is predicted to be more vulnerable in South Asia, Central China, the Mediterranean region, the Pampas, and Southeast Africa. Two cases are of particular concern from a sustainability point of view: sub-basins where the index value was originally below 0.2 but rises above the threshold ("become unsustainable"), and the currently irrigation-stressed sub-basins that will consume an even larger share of the irrigation water supply in the future (“remain unsustainable and more”). There are also regions where irrigation is currently unsustainable, but is projected to become more sustainable in the future. These regions, mainly the central US, Iran, parts of East Europe, northeast China and Southern Australia, experience higher rainfall under the RCP 8.5 climate scenario, exceeding the increase in consumptive irrigation. Again, these regions can be classified into two groups: the sub-basins that suffer from vulnerable irrigation today but will not in 2050 (“become sustainable”), and the sub-basins that remain vulnerable but wherein the index falls in the coming decades (“remain unsustainable but less”).

These projections are based on a future world without external constraints on irrigation withdrawals. Sustainable irrigation policies must target the basins with the most severe shortages to eliminate the adverse consequences of unsustainable irrigation. A natural question to ask is the following: to what extent will restrictions on irrigation water consumption affect food supplies, food prices and the number of people at risk from malnutrition? 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 the extensive margin, namely cropland expansion. This too will raise environmental concerns of increased greenhouse gas (GHG) emissions and loss of biodiversity from cropland conversion and therefore warrants consideration. We discuss these effects next.

3.2 Restricting irrigation tends to raise food prices and the prevalence of undernourishment in less-developed countries

Irrigated crop output in sub-basins experiencing curtailed irrigation water consumption 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 remains sustainable. Simulation results suggest the net effect on crop output to be negative in the heavily irrigated regions like China, South Asia, Middle East and North Africa (MENA), and Central Asia, whereas the expansion of rainfed production in less irrigation-vulnerable regions such as Latin America, Southeast Asia and Sub-

Saharan Africa (SSA) outweighs the contraction of irrigated output and boosts total crop output (Figure 2A). Crop prices increase even in regions where total output rises (Figure 2B), because of the more expensive water input. As a result, food consumption declines, causing over 800 million more people globally to be undernourished if no adaptation is made (Figure 2C).

What about the role of inter-basin water transfers in improving food security? These projects act as shock buffers in irrigation-vulnerable regions, as demonstrated by diminished output reduction, milder price rise (circle vs. asterisk in Figure 2A and 2B) and fewer additional malnourished people (IBT vs. BAU, equal TFP in Figure 2C). However, this is true only if productivity in the irrigated sector does not grow faster than its rainfed counterpart. Otherwise, the productivity advantage of irrigated agriculture will attract more inputs (including irrigation water) to produce crops. The existence of large-scale hydrological transfer projects, in this case, may encourage more aggressive water use for irrigation, leaving a larger number of merged basins to be unsustainably exploited. This in turn will generate more severe impacts on food production, price (dot vs. circle in Figure 2A and 2B) and increase malnutrition prevalence by 36% (IBT faster TFP vs. IBT equal TFP in Figure 2C) once the sustainability constraint is imposed.

Moving to sustainability in an integrated market results in a uniform increase of 0.39% in world crop price, a change which is larger (smaller) than if the market is not integrated in the less (more) vulnerable regions (asterisk vs. dash line in Figure 2B). Under integrated markets, price transmission through trade forces Sub-Saharan Africa, Latin America, and Southeast Asia – all regions facing fewer sustainability constraints, to bear the more of the consequences of irrigation constraints in the other regions (INT vs. BAU, equal TFP in Figure 2C). When combined with the scenario of faster irrigated TFP growth, the effect of integrated markets is amplified – more pronounced changes in output (filled triangle in Figure 2A) and global food price (0.63%), as well as higher prevalence of malnutrition (INT faster TFP vs. INT equal TFP in Figure 2C). The reason is the strengthened regional comparative advantage caused by additional irrigated TFP growth. That fosters the growth of irrigated production in the already heavily irrigated regions. In many cases, expansion takes place at locations where irrigated farming is competitive and unsustainable water consumption is high. These unsustainable hotspots will experience heightened irrigation vulnerability, larger sustainability shocks, and stronger impacts on output, price and undernutrition.

3.3 Restricting irrigation encourages cropland expansion into rainfed area and increases carbon emissions

Given the yield-boosting effect of irrigation, cutting back irrigation water consumption requires expansion in rainfed cropland areas to compensate for the productivity loss. This is particularly true in the South Asia and the MENA regions (Figure 3) where unsustainable irrigation is considerable and the yield gap between irrigated and rainfed cultivation is large. As for adaptations, again the hydrological infrastructure tends to suppress land use change (12.7 vs. 11.5 Mha and 1.4 vs. -1.24 Mha). However, this is not the case with market integration (12.7 vs. 14.3 Mha and 1.4 vs. 3.9 Mha), because of the cropland expansion in some regions (see Table S3). The net cropland area change caused solely by imposing the sustainability constraint is generally small, ranging from 12.7 to 14.3 Mha if assuming equal rates of TFP growth. This change becomes even smaller if the productivity of irrigated farming grows faster, reflecting the land-saving effect of intensive agriculture. Nonetheless, the split of the gross changes into irrigated and rainfed cropland is more substantial in South Asia, China and the MENA regions. The spatial distribution of area change could contain valuable information about the carbon emissions associated with land use change, given the high variability of carbon stocks (in C/ha) within regions (West et al., 2010). Our grid-resolving model is important in understanding these site-specific effects.

Figure 4 shows the net cropland change at each 30 arc-min grid from the six experiments. Cropland contraction in India is concentrated in Indus and Ganga basins, while the expansion extends to almost the entire country. In China, water transfer prevents cropland loss in the North and Northeast China Plain. Cropland expansion is mainly clustered in the eastern part of China, especially the Yangtze river basin. This pattern, however, is altered by the more rapid technological change in irrigated agriculture, and cropland contraction starts to appear in the Eastern China. The productivity advantage in this area further intensifies irrigation, which when restricted in the sustainable irrigation scenario, leads to net cropland loss.

These fine-scale maps allow for more precise assessment of potential carbon emissions from land use change. Here carbon emissions at each half-degree grid-cell are computed by multiplying net cropland area change (in ha) with carbon stock (in C/ha) at the same resolution. According to West et al. (2010), conversion to cropland corresponds to negative carbon sequestration (i.e., emissions). Therefore, net cropland expansion in Figure 4 translates into net carbon emissions in Figure 5. Some high and medium-high carbon stock hotspots in West et al's map such as the West African coast, Southern Brazil, South and East China, and India experience significant net cropland expansion in our results, contributing most to the total carbon emission change (see Figure S4 for a Spearman correlation plot between grid-cell level carbon stock factor and net cropland area change). Under the no adaptation, equal irrigated TFP growth scenario, carbon emissions due to restricted unsustainable irrigation may increase by 0.871 GtC, which amounts to an additional 9% of global carbon emissions in 2014. This amount is attributed solely to the land use change caused by imposing sustainability constraint to the 2050 baseline, but not to any area change between 2006 and 2050 baseline. Implications for CH_4 and N_2O are not examined.

4. Discussion and Conclusions

Several findings emerge from our analysis. First of all, pursuing sustainable irrigation without significant gains in the productivity of irrigation water may erode other development and environmental goals. In our case, curtailing irrigation raises food prices in less-developed countries and causes more carbon emissions from cropland conversion. This suggests that the SDG targets should be approached through policies that simultaneously address the socio-economic as well as ecological dimensions of the problem. It is also necessary to distinguish between sustainable irrigation and the overall conservation of the extent of irrigated land. In fact, in order to meet the increasing demand for food, irrigation should be encouraged whenever and wherever it is considered as environmentally sustainable. The key is to improve the spatial and temporal allocation of water used for irrigation.

Second, adaptation through moving water directly by means of inter-basin hydrological transfers and indirectly through virtual water trade can help resolve divergences in local water demand and supply, and therefore mitigate the pressure of excessive water consumption. These adaptation measures do, however, have different implications for individual regions. For example, the malnutrition status in SSA is improved by one (inter-basin transfers) but exacerbated by the other (integrated crop markets), relative to the BAU scenario. Interpreting the distinction automatically as an indicator of policy preference would be a myopic response that one should try to avoid. These counterfactual simulations provide useful insights into the possible cost of taking no action, but at the decision-making point it would be necessary to rely on more sub-national detail to conduct a case study.

Third, relatively faster productivity growth in irrigated agriculture leads to different outcomes of pursuing sustainable irrigation. Its role is more salient to land use change than to crop output, because the former depends directly on agricultural intensification while the latter can be affected by both the intensive and extensive margin of crop production. Persistence of this productivity advantage into the future may complicate the evaluation of adaptation measures. Our results show that higher irrigated productivity encourages more aggressive consumption of irrigation water in the receiving sub-basins of inter-basin transfers, which may counteract the potential benefit of these hydrological infrastructures. On the other hand, unless productivity grows faster in currently less agro-technologically developed countries, the comparative advantage gap will be further widened by the amplifier effect of TFP difference. The disadvantaged countries may suffer from higher food prices in the wake of sustainability constraints, once the market becomes more integrated. These observations by no means imply abandoning investment in R&D in the relevant regions; rather they suggest the need to counteract the effects of sustainability policies by investing in productivity-enhancing R&D in the relatively disadvantaged regions.

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. Our results clearly show considerable within-region variation in the extent of irrigation vulnerability, land use change, and the associated carbon emissions. These spatially heterogeneous responses would be masked by the aggregated regional impacts in many of the coarser resolution global economic models. There is great potential in this type of multi-scale framework for analyzing sustainability issues in general, and water scarcity, in particular.

References

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5, 853–861. doi:10.1038/ngeo1617

Alcamo, J., Henrichs, T., Rosch, T., 2000. World water in 2025: Global modeling and scenario analysis. World Water Scenar. Anal.

Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050: The 2012 Revision (ESA Working Paper No. 12-03). Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Amarasinghe, U.A., Smakhtin, V., 2014. Global Water Demand Projections: Past, Present and Future. IWMI.

Baldos, U.L.C., Hertel, T.W., 2014. Global food security in 2050: the role of agricultural productivity and climate change. Aust. J. Agric. Resour. Econ. doi:10.1111/1467-8489.12048

Baldos, U.L.C., Hertel, T.W., 2013. Looking back to move forward on model validation: insights from a global model of agricultural land use. Environ. Res. Lett. 8, 034024. doi:10.1088/1748-9326/8/3/034024

Dinar, A., 2014. Water and Economy-Wide Policy Interventions. Found. Trends® Microecon. 10, 85–165. doi:10.1561/0700000059

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. 111, 3239–3244. doi:10.1073/pnas.1222474110

FAO, 2016. FAO Statistical Database. Food and Agriculture Organisation of the UN, Rome, Italy.

Gleick, P.H., 1993. Water in crisis: a guide to the worlds fresh water resources.

Global Modeling and Assimilation Office (GMAO), 2011. Global Modeling and Assimilation Office (GMAO) and the GES DISC for the dissemination of MERRA.

Grogan, D.S., 2016. Global and regional assessments of unsustainable groundwater use in irrigated agriculture. UNIVERSITY OF NEW HAMPSHIRE.

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256. doi:10.1073/pnas.1222475110

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35, 365–377. doi:10.1016/j.foodpol.2010.05.006

Harrison, W.J., Pearson, K.R., 1996. Computing solutions for large general equilibrium models using GEMPACK. Comput. Econ. 9, 83–127. doi:10.1007/BF00123638

Hertel, T.W., Baldos, U.L.C., 2016. Attaining food and environmental security in an era of globalization. Glob. Environ. Change 41, 195–205. doi:10.1016/j.gloenvcha.2016.10.006

Konikow, L.F., 2013. Groundwater depletion in the United States (1900−2008) (Scientific Investigations Report No. 2013–5079). U.S. Geological Survey.

Liu, J., Hertel, T., Taheripour, F., 2016. Analyzing Future Water Scarcity in Computable General Equilibrium Models. Water Econ. Policy 1650006. doi:10.1142/S2382624X16500065

Liu, J., Hertel, T.W., Taheripour, F., Zhu, T., Ringler, C., 2014. International trade buffers the impact of future irrigation shortfalls. Glob. Environ. Change 29, 22–31. doi:10.1016/j.gloenvcha.2014.07.010

Schmidt, G.A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G.L., Aleinov, I., Bauer, M., Bauer, S.E., Bhat, M.K., Bleck, R., Canuto, V., Chen, Y.-H., Cheng, Y., Clune, T.L., Del Genio, A., de Fainchtein, R., Faluvegi, G., Hansen, J.E., Healy, R.J., Kiang, N.Y., Koch, D., Lacis, A.A., LeGrande, A.N., Lerner, J., Lo, K.K., Matthews, E.E., Menon, S., Miller, R.L., Oinas, V., Oloso, A.O., Perlwitz, J.P., Puma, M.J., Putman, W.M., Rind, D., Romanou, A., Sato, M., Shindell, D.T., Sun, S., Syed, R.A., Tausnev, N., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M.-S., Zhang, J., 2014. Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. J. Adv. Model. Earth Syst. 6, 141–184. doi:10.1002/2013MS000265

Schmitz, C., Lotze-Campen, H., Gerten, D., Dietrich, J.P., Bodirsky, B., Biewald, A., Popp, A., 2013. Blue water scarcity and the economic impacts of future agricultural trade and demand. Water Resour. Res. 49, 3601–3617. doi:10.1002/wrcr.20188

Siebert, S., Kummu, M., Porkka, M., Döll, P., Ramankutty, N., Scanlon, B.R., 2015. A global data set of the extent of irrigated land from 1900 to 2005. Hydrol Earth Syst Sci 19, 1521–1545. doi:10.5194/hess-19-1521-2015

Wada, Y., Bierkens, M.F.P., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9, 104003. doi:10.1088/1748-9326/9/10/104003

Wada, Y., Gleeson, T., Esnault, L., 2014. Wedge approach to water stress. Nat. Geosci. 7, 615–617. doi:10.1038/ngeo2241

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J.A., 2010. Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. Proc. Natl. Acad. Sci. doi:10.1073/pnas.1011078107

Wisser, D., Fekete, B.M., Vörösmarty, C.J., Schumann, A.H., 2010. Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network- Hydrology (GTN-H). Hydrol Earth Syst Sci 14, 1–24. doi:10.5194/hess-14-1-2010

Table 1. Experiment matrix. Experiment (a), (b), and (c) represent the scenarios of business-as-usual, inter-basin transfer, and integrated market when equal irrigated TFP growth is assumed. Experiment (d), (e), and (f) represent the scenarios of business-as-usual, inter-basin transfer, and integrated market when faster irrigated TFP growth is assumed. Business-as-usual means no adaptation (either IBT or INT) involved.

Total factor productivity growth in irrigated sector	Business-as-usual (BAU)	Inter-basin hydrological transfers (IBT)	Integrated market (INT)
Equal	(a)	(b)	(c)
Faster	(d)	(e)	(f)

Figure 1. Irrigation vulnerability index at the sub-basin level, 2050 baseline relative to 2006 baseline. The 2050 baseline assumes the RCP 8.5 forcing scenario, no sustainability requirement, no adaptation, and no incremental TFP growth in irrigated sector. Given that fossil groundwater withdrawal is not included in total water supply, water available for irrigation can be negative in some sub-basins. That means irrigation water in these sub-basins comes from nonrenewable groundwater mining. These basins are defined as "deficit". "Sustainable" and "unsustainable" refer to vulnerability indices that are below and above 0.2, respectively.

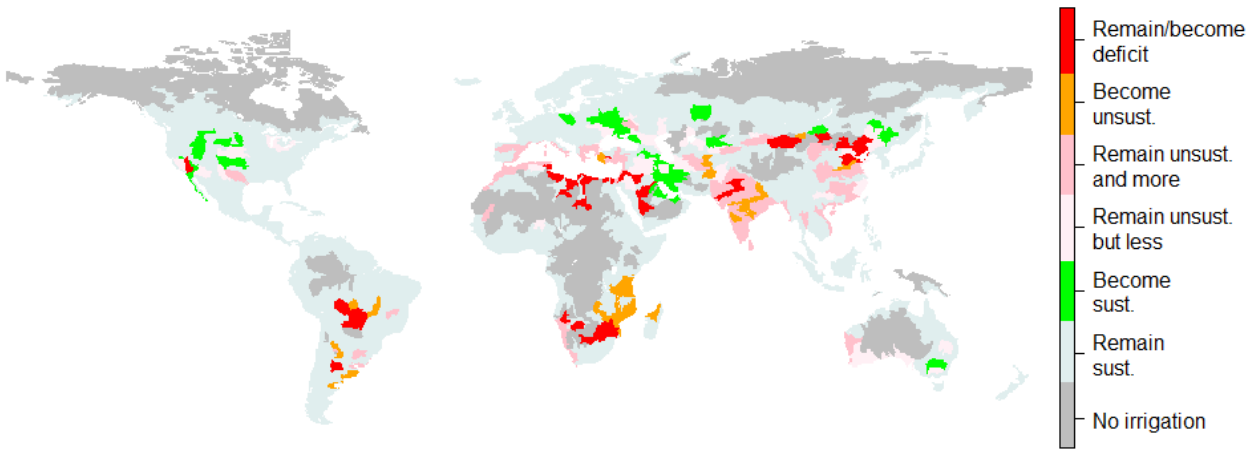
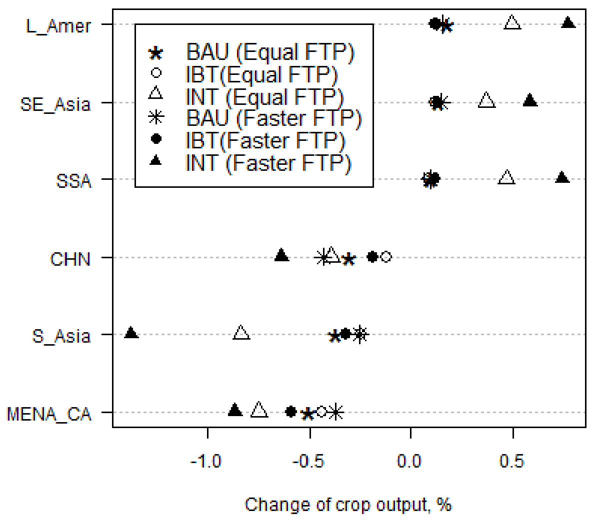
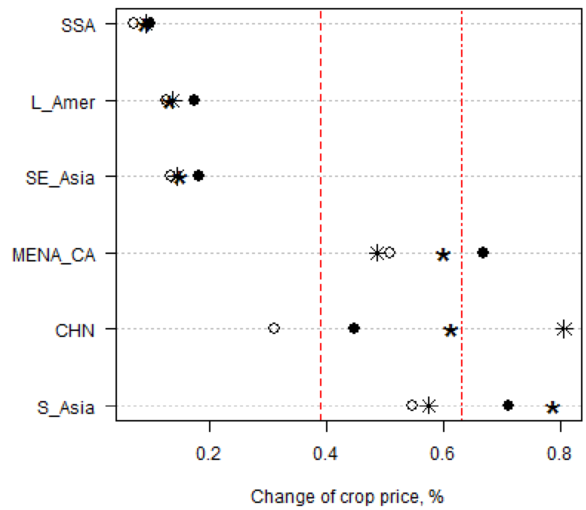


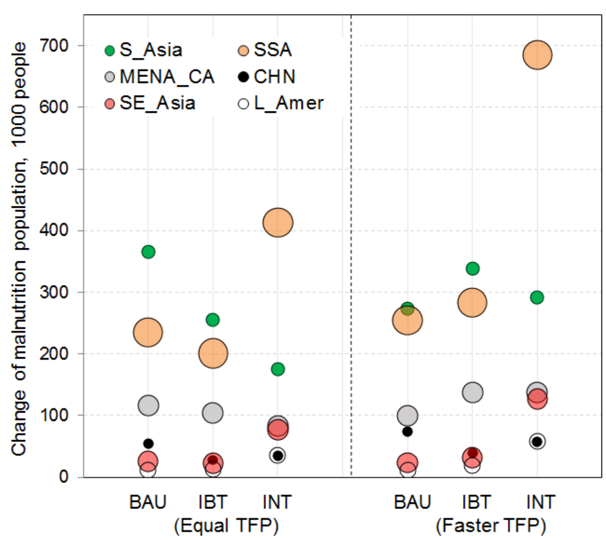
Figure 2. Percent change of crop output (A) and price (B), and change of undernourished population in thousands (C). Only the results related to less-developed countries are reported because of the relevance to malnutrition. For the ease of presentation, M_East, N_Afr, and C_Asia are further aggregated into MENA_CA; CC_Amer and S_Amer are aggregated into L_Amer. Dashed and dashed dotted vertical lines in sub-figure (B) show the integrated market crop price change when TFP growth in irrigated sector is equal to or faster than its rainfed counterpart. When the market is integrated, crops are sold at one world price. The change of this global uniform price can be intuitively understood as the weighted average of segmented regional price change. Bubbles in sub-figure (C) are scaled by the proportion of undernourished population in the region in the baseline.



(A)



(B)



(C)

Figure 3. Regional cropland area change (unit: million hectares). Net area change and the change of rainfed and irrigated cropland are represented by the bars, solid lines and dotted lines, respectively.

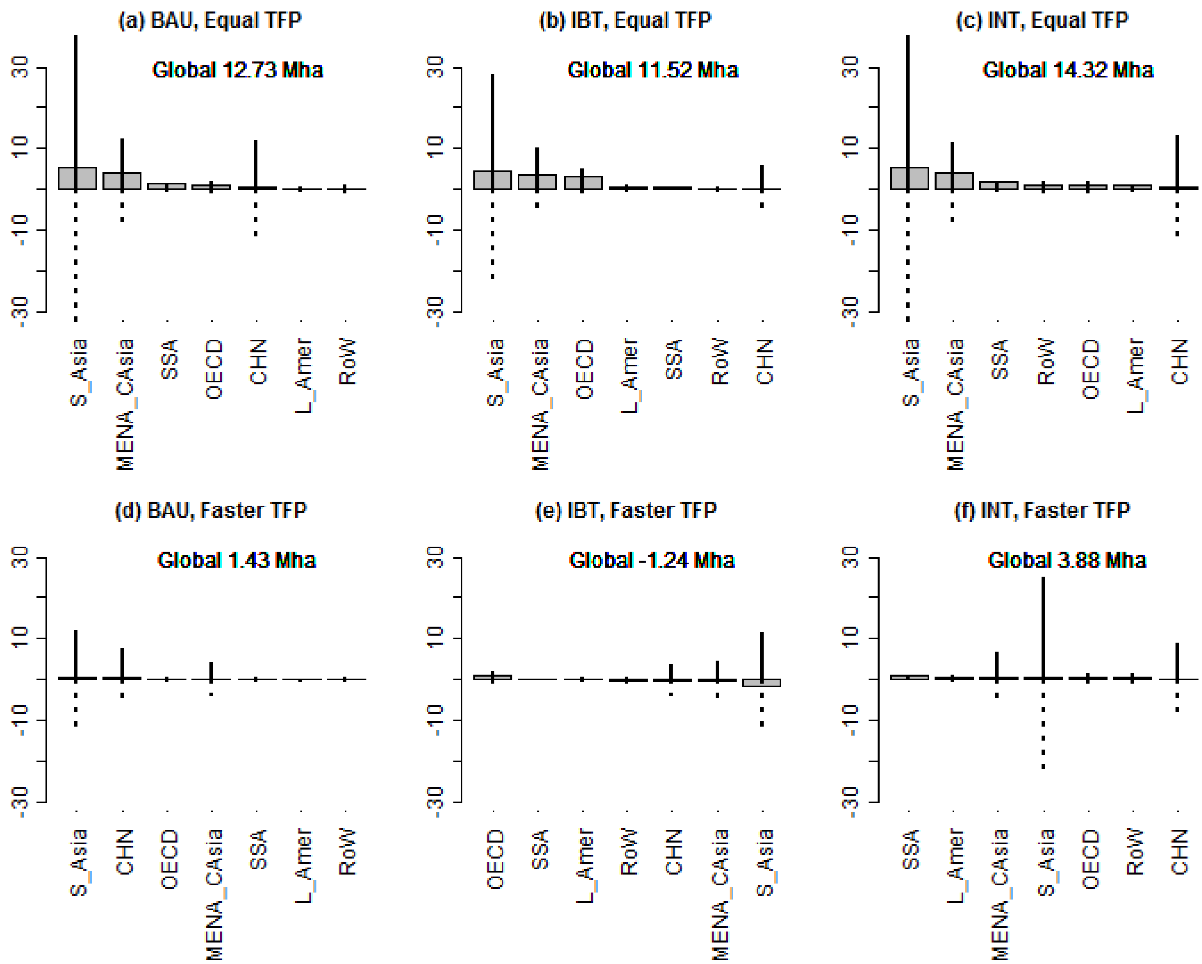


Figure 4. Net cropland area change at the 30 arc-min grid-cell level (unit: thousand hectares). See Figure S3 for separate maps of irrigated and rainfed cropland area change.

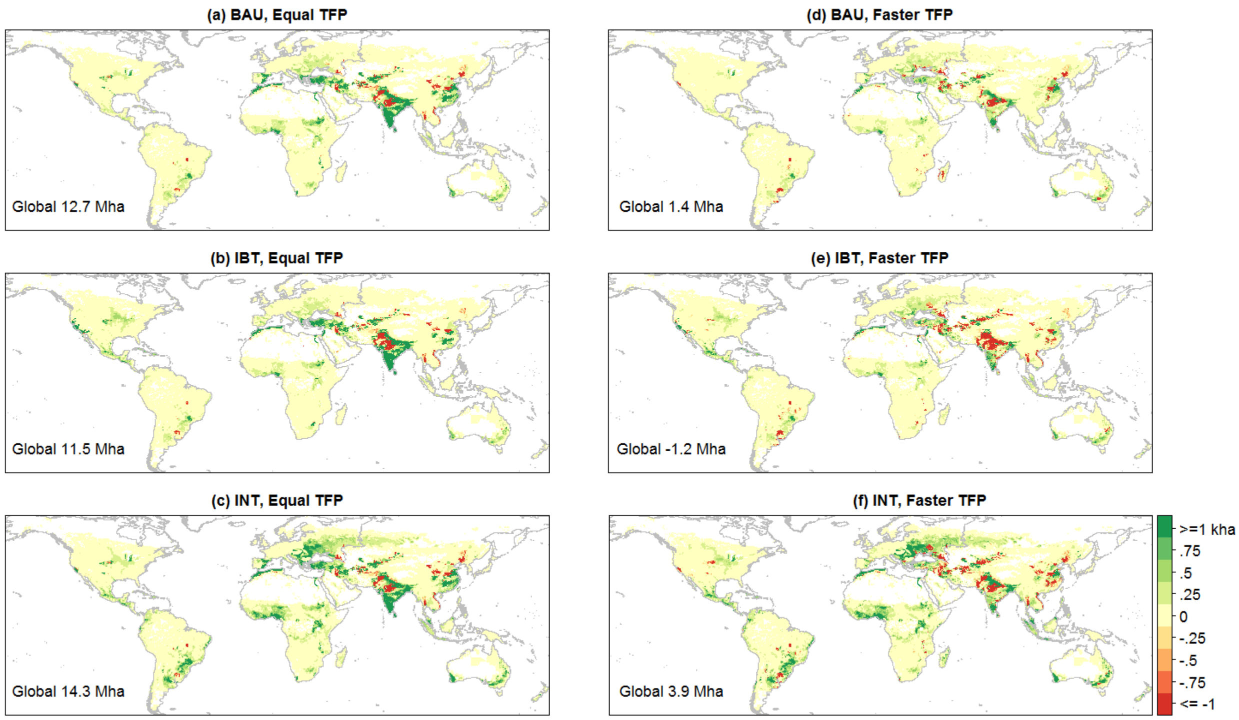


Figure 5. Net carbon emissions at the 30 arc-min grid-cell level (unit: thousand metric tonnes of carbon).