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International trade buffers the impact of future irrigation shortfalls

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ABSTRACT

There is increasing interest in the water–food nexus, especially the restrictive effect of water on food production in hot spots where irrigation stress is growing. However, little is known about the larger-scale implications of future irrigation shortfalls for global trade and economic welfare, as well as of the potential buffering impacts of international trade on the local impacts of irrigation shortage. In this paper, we utilize a recently developed model, GTAP-BIO-W, to study the economic effects of changes in irrigation outlook for 126 river basins, globally by 2030. Projected irrigation availability is obtained from the IMPACT-WATER model, and imposed upon the present-day economy. Irrigation availability in 2030 is expected to drop by 30–60% in several key rivers basins, including: Hai He, Indus, Luni, and the Eastern Mediterranean basin, leading to significant output declines in China, South Asia, and the Middle East. We find that the regional production impacts of future irrigation water shortages are quite heterogeneous, depending on the size of the shortfall, the irrigation intensity of crop production, the possibility of expanding rainfed areas, as well as the crop mix. These changes in regional output significantly alter the geography of international trade. To compensate for the loss of productivity caused by the irrigation constraint, an estimated 7.6 million hectares of cropland expansion is needed to meet the demand for food. In spite of the remarkable reduction of irrigation in some basins, the resulting welfare impact is relatively modest as a result of the buffering capacity of global markets. The global welfare loss amounts to $3.7 billion (2001 prices) and results from a combination of the reduction in irrigation availability as well as the interplay with agricultural support policies.

1. Introduction

Agriculture is by far the largest user of the world's water resources, with 70% of global freshwater withdrawals being directed to irrigation (Molden, 2007). Agriculture's heavy reliance on water is largely driven by climate – in arid and semi-arid regions production would not be possible in the dry season without irrigation, by intensification needs on smaller land areas (irrigation often allows to grow a second crop) and by the type of crop grown (rice thrives under irrigated conditions). Indeed, 60% of cereal production in the developing world originates from irrigated lands (Bruinsma, 2009). However, when faced with water shortages, irrigated agriculture is also the most likely candidate for water rationing or is sometimes even abandoned (California's Colorado River Water Use Plan, 2000; Rosegrant and Ringler, 2000). Irrigators typically pay a small fraction of the water price charged to residential, industrial and commercial uses (Cornish and Perry, 2003), suggesting a relatively low-value use, at the margin – another factor pointing to irrigation as the balancing variable when supply shortages arise. This raises an important question: As competition for water intensifies in many parts of the world over the coming decades, what will be the impact on irrigated cropping, agricultural trade and food security?

The world appears to be facing a looming water challenge. By 2030 global water requirements are likely 40% greater than current supplies, and one-third of the world's population, mostly in developing countries, might live in areas where this deficit is larger than 50% (Addams et al., 2009). Alexandratos and Bruinsma (2012) argue that global water resources will be sufficient to feed the world, but the "devil is in the details" with water shortages causing high stress in specific localities. Falkenmark et al. (2009) argue that water shortages in some countries could be offset by food imports from water rich countries. In this vein, there is an emerging body of literature documenting the role of "virtual water trade" as a vehicle for achieving global water savings in the face of local shortfalls (Konar et al., 2013; Dalin et al., 2012; Lenzen et al., 2013).

Fig. 1 offers a conceptual overview of the water–food nexus. Most of the existing literature in this area focuses on some subset of the linkages portrayed in this figure. One set of studies, denoted by the blue arrow, aims to assess water footprints of agricultural

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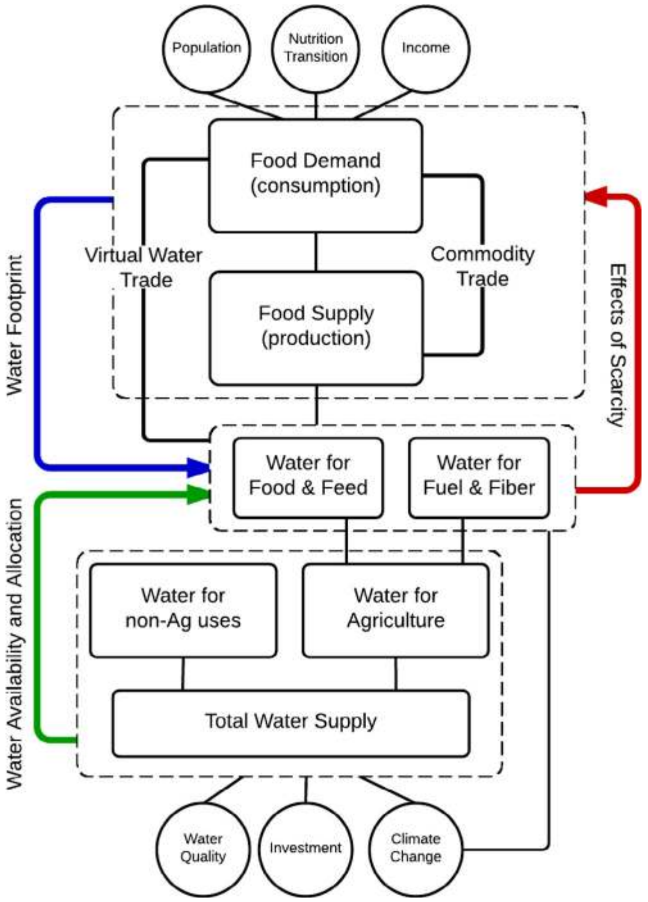


Fig. 1. Conceptualizing the water–food nexus.

production for domestic consumption and export at the global (Hoekstra and Mekonnen, 2012), national (Fader et al., 2011; Hoekstra and Chapagain, 2007) and city levels (Hoff et al., 2013). Because the assessment is based on the concept of a crop's virtual water content, this line of research often contains discussions about virtual water trade. The second key linkage in the water–food nexus focuses on water use for food production and factors that potentially exacerbate or mitigate the future water availability for food production (Gerten et al., 2011; Rosegrant and Cai, 2002). This is denoted by the green arrow in Fig. 1. Among these factors, agriculture's considerable dependence on irrigation has been a long-standing concern, which is drawing greater attention as more water is being claimed for municipal, industrial and environmental uses, thereby posing serious threats to water for food (Strzepek and Boehlert, 2010). Moreover, during the past decade, there has been a surge of interest in climate change and its impact on long-term and interannual variability of water demand and supply (Hejazi et al., 2013a,b; Kummu et al., 2013). More recently, the Renewable Fuel Standard enacted in 2005 and 2007 added a bioenergy link to water consumption, and started research on the "blue impacts of green energy" (De Fraiture et al., 2008; Gerbens-Leenes et al., 2009, 2012; Rosegrant et al., 2012a). Moreover, in water-stressed regions water resources are often already subject to degradation of water quality, thereby exacerbating shortages (Pereira et al., 2009). To address these growing shortages, investment in water infrastructure and on-farm technologies, crop breeding strategies, implementation of innovative water conservation measures and changes in policies can increase water use efficiency in both the agricultural and non-agricultural sectors, which, in turn, can make more water available for food (Rosegrant et al., 2009; De Fraiture and Wichelns, 2010).

Research related to the themes of water footprints and water availability and allocation aspects usually leans heavily on hydrological modeling (e.g. the LPJmL model by Gerten et al. (2004), CLIRUN-II by Strzepek et al. (2011) and WGHM by Döll et al. (2003)) or water management models (e.g. GCWM by Siebert and Döll (2010) and IWSM by Zhu et al. (2013)) to answer the questions "will there be enough water for food" and "what to do to secure the future of water for food". In contrast, the objective of this study is to explore a third aspect of the water–food nexus denoted by the red arrow in Fig. 1. Specifically, we seek to evaluate the impact of projected irrigation shortfalls on the overall economy and international trade in food products as well as on patterns of food production and demand. Understanding these broader impacts of irrigation stress is important since the large gaps between irrigation demand and supply in key producing regions will have to be closed by trade, and investment in and adoption of technologies; all of which will come at a cost. Thus, the consequences of less available irrigation will not only be felt at the local but also at the macro-economic level, the focus of this study.

We are aware of a few global-scale modeling studies that have attempted to understand the impacts of water availability through an integrated hydrologic–economic analysis approach, but most of them are partial equilibrium models which take macro-economic activity as given. These include: IMPACT (Rosegrant et al., 2012b), GLOBIOM (Schneider et al., 2011; Havlík et al., 2013), MAgPIE (Lotze-Campen et al., 2008; Schmitz et al., 2012) and WATERSIM (De Fraiture, 2007). Although a partial equilibrium model can provide excellent sectoral detail, it does not account for interactions across the economy through labor and capital markets or inter-industry linkages. These models also treat international trade in a simple way and abstract altogether from international capital flows. In seeking to overcome these limitations, Calzadilla et al. (2010) disaggregate irrigation in the GTAP global general equilibrium model. However, this pioneering work had serious limitations. Firstly, rainfed and irrigated production were treated as part of the same aggregate, national production function. So it was not possible to shut down irrigation in one region in favor of rainfed agriculture, or expanding irrigation in another region. Secondly, the model ignores the competition for rainfed land between agriculture and forestry. Thirdly, by specifying aggregate production relationships at the national scale, the model is unable to deal with scenarios in which different river basins in one country/region are differentially affected. As we will see below, this is a very common situation.

In this study, we first use the IMPACT-WATER model to assess the degree of irrigation stress at the scale of individual river basins, and then (in a sequential fashion) we embed these estimates within an extended version of the GTAP model GTAP-BIO-W to explore how changes in future irrigation availability for irrigation will affect crop production, food prices, and the resultant effects of these changes on bilateral trade patterns (Fig. A1). (Note that irrigation availability is defined as the share of potential irrigation demand realized through actual consumption, and it is estimated using the 1951-2000 monthly climatology representing average climate condition over that period.) Compared with previous studies, our approach allows for new interactions across sectors, which includes inter-sectoral linkages through intermediate inputs and competition for land, water, labor, capital and energy. Moreover, the model we proposed has the special advantage of analyzing bilateral trade flows and providing macro-economic impacts of irrigation shortfalls.

2. Methods

2.1. Model

The standard GTAP model is a multi-region, multi-sector, computable general equilibrium model, with perfect competition and constant returns to scale (Hertel, 1997). To estimate the impacts of changes in irrigation availability on agricultural production and trade, we use a special version of this model which takes into account irrigation water as an explicit input into irrigated agriculture. This new model is dubbed GTAP-BIO-W and is documented in Taheripour et al. (2013a, hereinafter THL). An important improvement THL made to the GTAP model is to distinguish irrigated and rainfed cropping such that water enters irrigated production as a complementary input of land (Fig. A1). Meanwhile, the land-water composite is substitutable for other value-added inputs (labor, capital and energy), allowing for a modest endogenous yield response to prices.

Another key modification in this model is the introduction of river basins. An earlier version of the model employed agro-ecological zones (AEZ) in recognition of the fact that significant climate and soil variations within economic regions require more refined spatial units for modeling. However, the presence of irrigation water, drawn from a given river basin, further complicates this picture. When AEZs cut across river basins, production conditions may differ, even within the same AEZ. Therefore, the GTAP-BIO-W model allows crops to compete for land within the AEZ, in addition to a second layer of competition in which irrigated cropping activities compete for irrigation water within a river basin. The total water available for irrigation is exogenously specified in each river basin.

2.2. Data

The core data we are using is the GTAP v6 database, which represents the level of production, consumption and trade in 2001. The reason for adopting this older GTAP data set is that it is compatible with the land and water data currently available on a global basis (Portmann et al., 2010; Monfreda et al., 2008). Each crop sector is split into two distinct sectors – irrigated and rainfed, based on the share of irrigated versus rainfed output as reported in the MIRCA2000 data (Portmann et al., 2010). In addition, this source provides estimates of the irrigated/rainfed yield differential, as well as the water used for irrigation by crop type. We attribute the value of higher irrigated yields within a given AEZ to the presence of irrigation. Subtracting this imputed input value from the water-land composite yields the (residual) contribution of land. The third step is to distribute the land and water value-added to each river basin-AEZ. We assume that the spatial distribution of value-added follows that of output across basin-AEZs. Segmentation of each region into Basin-AEZs is achieved by overlaying the Global Agro-Ecological Zone map (IIASA/FAO, 2000) with the IWSM river basin map (Rosegrant et al., 2012b). Because each segment is matched with grids using geographical coordinates, we are able to aggregate grid-cell level output provided by Monfreda et al. (2008) into values at basin-AEZs. The procedures for preparing the dataset follow Taheripour et al. (2013a,b). Our GTAP-BIO-W data base breaks out 19 GTAP regions. Each region contains up to 18 AEZs and 20 river basins. Globally, the water system is divided into 126 river basins (Table A1). See Table A2 for a breakdown of the sectors that comprise each regional economy.

2.3. Experimental design: Shocks on irrigation availability

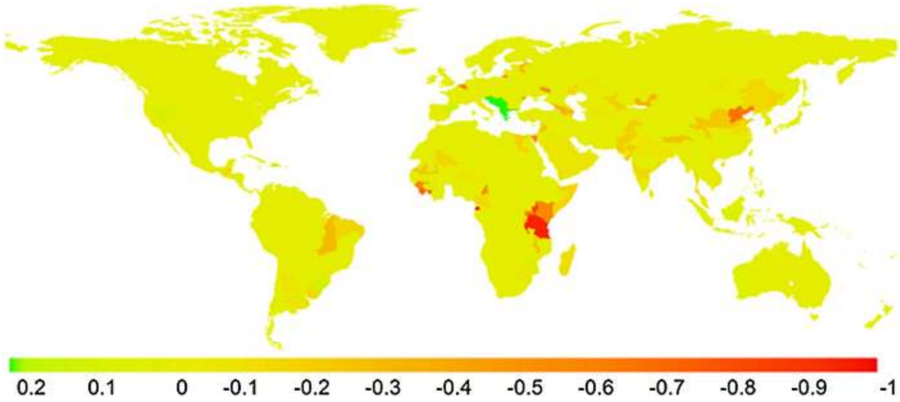
Not only does irrigated agriculture account for most global freshwater withdrawals, it is also typically the residual claimant on water within a given river basin. Therefore, in order to deduce the supply of water for irrigation at any point in time, it is important to understand not only the hydrological flows, but also the residential, industrial and environmental demands for water. If the latter expand, and total water availability in the river basin is unchanged, then the effective supply of water for irrigation purposes is likely to be reduced. Conversely, if there are strong efficiency gains in industrial water use, for example, this might translate into increased water availability for irrigation, even though supply in the river basin is unchanged. To this one must add investments in dams and other infrastructure for capturing water. In short, estimating future water availability for irrigation is a significant challenge.

In this study, we adopt the Irrigation Water Supply Reliability (IWSR) index as the metric of irrigation water availability. IWSR is defined as the share of potential irrigation demand that is realized through actual consumption, on an annual basis. Potential demand is the demand for irrigation water in the absence of any water supply constraints, whereas actual consumption of irrigation water is the realized water demand, given the limitation of water supply for irrigation. If this index equals one, then all demand is met and there is no irrigation shortfall. In a global analysis undertaken at the level of 126 hydrological basins and 281 “food-producing units” (FPUs), Rosegrant et al. (2012a) estimate IWSRs for 2000 and 2030 using the IMPACT-WATER model (see Appendix A.2). Since the analysis was focused on demand side changes, the 1951-2000 monthly climatology was used to derive irrigation availability, which represents average climate condition over that period. Therefore, extreme weather events such as droughts and floods were not considered.

The IWSR in 2030 depends on several water supply and demand drivers. For our study we use the Rosegrant et al. (2012a) “business as usual” scenario, which assumes a continuation of current trends in population and economic growth, water use efficiency in agricultural, industrial and domestic uses, and the implementation of existing plans for investments in water supply infrastructure capacity (e.g. reservoir storage, surface water withdrawals and groundwater withdrawals). Under the BAU scenario, the global IWSR (1.0 is ideal) falls from 0.77 in 2000 to 0.69 in 2030, with particular sharp declines in East and South Asia. The regional changes range from −16.3% to +2.4%. The impact of climate change is not included in these projections due to the high degree of uncertainty in precipitation projections. Moreover, several studies have shown that the effects of changes in population on water resources are much more important than changes in water availability as a result of climate change would be (Kummu et al., 2013; Vörösmarty et al., 2000).

Rosegrant et al. (2012a) also estimate the IWSR under the Bioeconomy (BIO) scenario, which allows for faster agricultural productivity growth due to increased R&D expenditure, as well as significant improvements in water use efficiency – particularly for the non-agricultural uses. Under the BIO scenario, more sustainable agricultural production and water use allow for a global IWSR of 0.75 in 2030, with far smaller declines in the Asian regions. The range of regional changes is also more narrow, from −5.3% to 4.7%. Here we adopt the most likely case – the BAU scenario in order to provide an assessment of the likely impacts in the absence of additional investments in R&D aimed at crop productivity.

Map 1 depicts the results of the underlying water modeling based on Rosegrant et al. (2012a). This map provides the basis for our experiment in which basin level water supply for irrigation is shocked by the percentage change in the IWSR index from 2000 to 2030 (Table A3). By subtracting the 2030 results from their 2000 counterparts, we see an increase of irrigation stress in parts of Asia – particularly Pakistan (Indus basin, −43%), China (Haihe basin, −64%) and India (Luni basin, −61%), as well as in East Africa and parts of South America. Among the nineteen regions in our global economic model, eleven will experience reduced availability of irrigation by 2030, with the largest reductions occurring in South Asia excluding India (−33%) and China (−22%) as demand for irrigation outpaces significant investments. Irrigation availability will remain virtually unchanged in Canada and Japan, and will slightly increase in the US,



Map. 1. Change in irrigation availability. The map depicts changes in absolute value of irrigation water supply reliability (IWSR) index at river basin level from 2000 to 2030 (Rosegrant et al., 2012a). Negative numbers indicate that irrigation demand is less satisfied by actual water consumption in 2030 compared with that in 2000.

the EU, Central America and Oceania as a result of anticipated investment in irrigation infrastructure.

It is important to note that our experimental design amounts to investigation of the impact of future irrigation shortfalls on the pattern of economic activity in the current economy. In this way, we isolate the effect of irrigation shortage from the effects of other factors which will inevitably alter the shape of the global economy in 2030. According to our experience, such projections introduce a great deal of uncertainty into the experimental design, with relatively little payoff in terms of additional insights. Therefore, we run a comparative static simulation in which only basin water supply is shocked to reflect water available for irrigation in 2030. This approach is analogous to Hertel et al. (2010) when assessing the poverty impacts of climate change.

Nonetheless, as described below, we do recognize several pathways through which future economies and climate could exacerbate or buffer the impacts of less available irrigation. For example, larger population and increased income will tend to increase cropland area, provided yields do not grow as fast as these demands. Larger extensive and intensive margins of irrigation will increase absolute water shortages (holding irrigation efficiency constant). With more investment, water use efficiency might be increased and storage supply augmented, and thus shortages reduced; or irrigated area extended without efficiency and storage improvements and thus shortages might be increased. Rising temperatures and altered precipitation patterns from climate change will likely increase the gap between dry land and irrigated yields in many parts of the world. This will increase the value of irrigation and therefore increase economic losses from irrigation stress.

2.4. Model validation and systematic sensitivity analysis (SSA)

In practice it is hard to exhaustively validate a global CGE model. Therefore, we focus our discussion of model validation on the central dimensions of the problem at hand – namely the model's characterization of international trade and the robustness of the results. One critical characterization of international trade is the "Armington assumption", which assumes differentiated products by country of origin. Villoria and Hertel (2011) have empirically examined this assumption in their study of global land use change due to regional shortfalls in the supply-demand balance for coarse grains. They contrast this approach to the commonly employed assumption of integrated world markets and reject the latter in favor of the Armington specification. Those authors also show that results under the two competing assumptions could be quite different – thereby reinforcing the strength of a model which takes into account the geography of trade as does GTAP-BIO-W.

Having settled on the Armington specification for international trade, it remains to determine the size of the so-called "Armington elasticities" of substitution amongst imports from competing sources of supply. For this, we rely on the econometric study of trade elasticities published by Hertel et al. (2007) who use variation in bilateral trade and transport costs in order to estimate these elasticities. These point estimates and the associated standard errors are a direct input to our study. In addition, we conduct a SSA with respect to four sets of key parameters that govern land mobility, substitution in production, consumption and trade in the model. The SSA varies each parameter over the range: +/− 30% of the baseline value. We assume the variation takes the symmetric triangular distribution. This permits us to place confidence intervals on the resulting production (Fig. 2) and welfare impacts (Table B1) to reflect the uncertainty inherited from the behavioral parameters in the model. The error bars show reasonably small deviations from the point estimates, suggesting that our findings are robust.

3. Results and discussion

3.1. Impacts on agricultural output

A reduction in water available for irrigation might be expected to result in a reduction in irrigated output, but this is not necessarily the case. One of the key determinants is the location of the irrigated crop production. With current irrigated areas and crop composition unchanged, less irrigation may lower yields and output. However, if irrigated farming is allowed to migrate from arid AEZs to less arid AEZs within the same river basin, it is not impossible that at least the same crop production can be achieved from less water. Furthermore, even though irrigated production is negatively affected due to insufficient irrigation, total output may not fall by much if irrigated farming accounts for only a small portion of total crop production in that country, and if the supply of rainfed land is relatively price responsive.

Fig. 2 plots the change in regional crop output in response to irrigation stress in 2030. While more secure irrigation raises total crop output in every case, less irrigation does not always mean lower regional output. The biggest output reductions occur in South Asia (excluding India), the Middle East and North Africa (MENA), China and India. These regions face significant and growing irrigation stress and also rely heavily on irrigation. Sub-Saharan Africa and Russia, on the other hand, are projected to increase agricultural output, despite experiencing a rise in unmet irrigation demand. The reason is that irrigated farming is modest in these regions, providing only 14.3 and 5.5% of total crop output value, respectively. In the face of higher crop prices, these regions

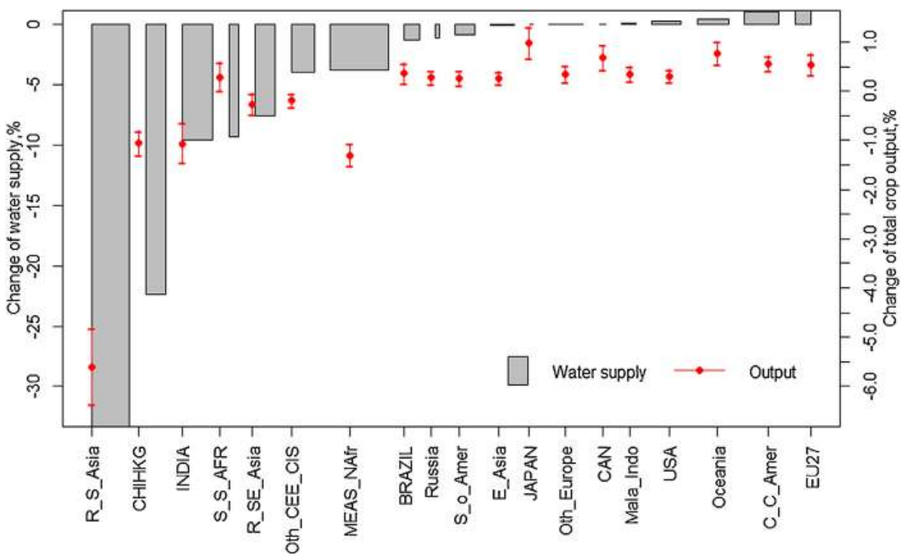


Fig. 2. Crop output (left axis) response to regional irrigation shortfalls (right axis). Output change is computed as the weighted-average of each individual crop's output change. The weight is determined by the crop's contribution to total output value. Regional change in irrigation availability is computed as the weighted-average of basin-level changes. The share is determined by each basin's contribution to the region's output value added by water. Bar width is proportional to the share of output value that is from irrigated crops in the region. Error bars associated with output indicate the 95% confidence interval of the mean for a normal distribution.

expand rainfed production and therefore increase overall output. Globally, the large output losses in Asian and MENA countries outweigh the gains elsewhere, leading to a reduction in world crop output (Fig. B1). Livestock and processed food sectors, which use crops as primary inputs, are negatively affected as well. The only exception is the processed feed sector, the supply of which goes up marginally (0.29%), primarily driven by the strong demand for processed feed inputs from the US, EU and China. Moreover, producing processed feed uses a substantial amount of oilseeds meal, a by-product of vegetable oil, making it an appealing substitute for higher priced crops.

3.2. Land use change

With sufficient inputs to allow production to take place at competitive prices, water-rich regions tend to produce more from both irrigated and rainfed land, not only to substitute domestic goods for imports, but also to expand their exports. By contrast, regions confronted with water stress are more likely to cut back irrigated acreage and switch production to rainfed areas if and when precipitation is sufficient for crops to grow. Given the fact that irrigated land is generally more productive, farmers using less irrigation will need more land to produce the same amount of output. If the yield differential is large enough, even producing less would need more acreage. Within our framework, this additional rainfed crop area must be converted from either forest or pasture land. Less pasture land leads to higher grazing costs. This imposes pressure on livestock supply, which - when combined with climbing demand for meat – could further drive up prices of livestock products. In addition, forests and grazing land are generally more carbon-rich than cropland (Plevin et al., 2011). That means land use change is likely to create more carbon emissions in regions where the expansion of irrigated area is constrained (Taheripour et al., 2013b).

To examine the land use effects of projected changes in irrigation water availability, we partition the total output change into contributions from two categories, irrigated and rainfed (Fig. 3).

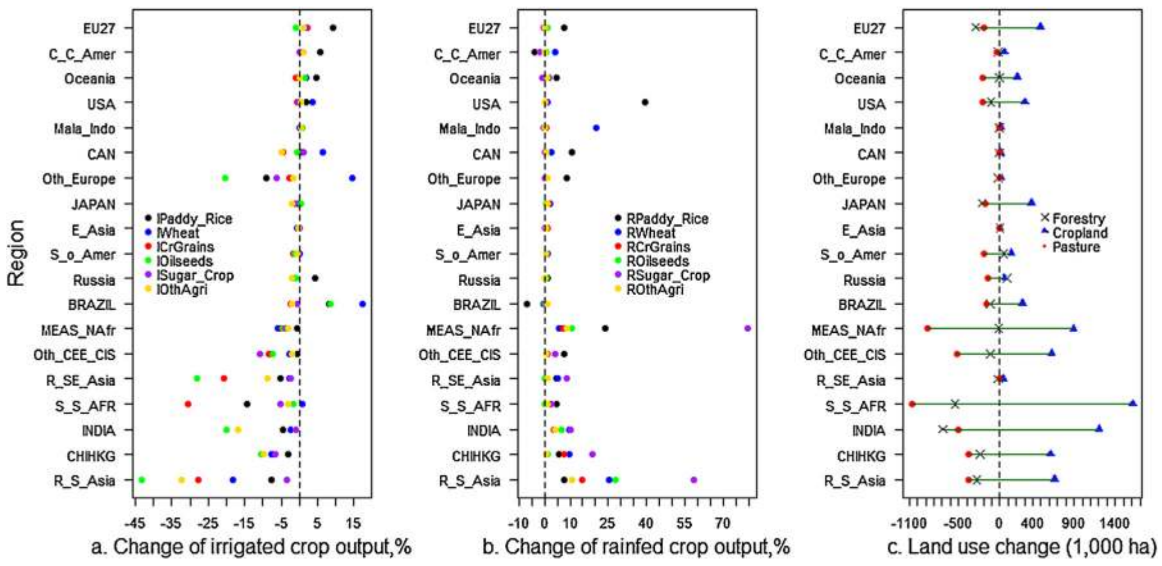
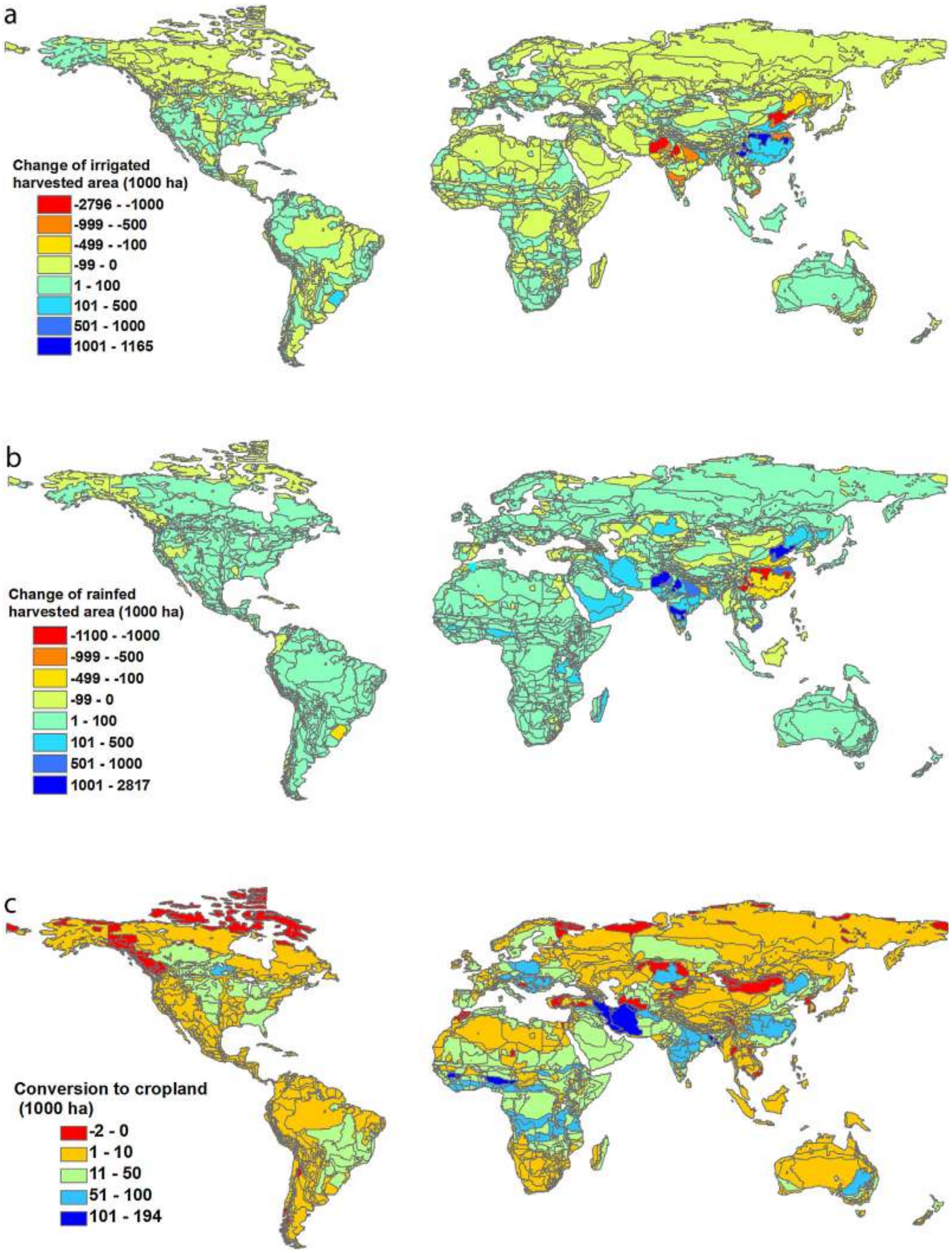


Fig. 3. Change of irrigated (a) and rainfed (b) crop output and subsequent land use change (c). Panels (a) and (b) show percentage change in irrigated and rainfed crops by region. Panel (c) shows the induced land use change. The sum of reduction in pasture and forest land equates to the expansion of cropland.

Not surprisingly, irrigation stress leads to reduced irrigated output and expanded rainfed output provided precipitation is sufficient to allow for growing rainfed crops. Map 2 displays the change of irrigated and rainfed harvested areas and land conversion between cropland and other land cover types, compared to the pre-experiment situation. We find that land use conversion toward agriculture is highest in sub-Saharan Africa, followed by India and the MENA region, with area increases of 1.61, 1.20 and 0.89 million hectares, respectively. Globally, 7.61 million hectares of land need to be converted from forest and range for cropping. This amount is equivalent to 0.5% of the world's total cropland resource, and is roughly equal to the area of Panama.

It is important to bear in mind that cropland expansion potential in GTAP-BIO-W is largely driven by agro-ecological suitability. Related social, economic, political and ecological tradeoffs are not yet taken into account. For instance, lack of transportation infrastructure, landscape fragmentation, and zoning schemes may all hinder land use conversion, but gauging the associated cost to overcome these limitations is still challenging (Lambin et al., 2013). Thus, it is possible that current assessment of land use change overstates the actual potentials of



Map. 2. (a) Change of irrigated harvested area (Global total reduction: 11.45 million hectares). (b) Change of rainfed harvested area (Global total increase: 19.06 million hectares). (c) Total land conversion to cropland (Global total conversion: 7.61 million hectares). Global harvested area change and land conversion, shown at river basin-AEZ level. In (a) and (b), positive numbers indicate area expansion compared to the pre-experiment situation. Conversion in (c) is calculated as the sum of (a) and (b), in which positive numbers indicate that forest and pasture are converted to cropland (could be either irrigated or rainfed cropland).

cropland expansion and represents the upper limits of the estimation.

3.3. Impacts on international trade

Availability of irrigation can change the global patterns of trade in farm and processed food products as it raises the cost of crop production and, as a result, domestic commodity prices. Indeed, in this scenario, prices rise almost everywhere, but much more in regions with severe irrigation stress, making it more appealing to buy from the international market. For the same reason, these regions lose their price advantages in overseas markets and export less than before. We use Fig. 4 to show changes in bilateral net flows of food (including crops, livestock and processed food) between regions, compared to the pre-experiment status. After the shock, South Asia, China, and the MENA countries' status as net food importers are strengthened. They import primarily from North and South America, Europe and Southeast Asia. South Asia, excluding India, is the only region fails to increase net exports to any other regions. Even irrigation-short China increases net exports to one region – namely South Asia excluding India. This result is consistent with the fact that South Asia excluding India experiences the largest reduction in IWSR.

Next, we consider the trade balance. As discussed above, regions with reduced irrigation availability tend to net export less volumes, but at higher prices. The aggregate effect on trade is usually dominated by changes in quantities. Thus, the export value falls in regions that are losing water for irrigation. The import value rises due to both larger quantities and higher prices. Higher import and lower export values together explain the worsened agricultural trade balance in the negatively shocked regions. Model projections suggest the largest agricultural and food trade deficit owing to irrigation stress for South Asia excluding India ($ −1.35 billion), with a relatively large gap also for China ($ −1.08 billion), India ($ −0.44 billion) and the MENA region ($ −0.6 billion).

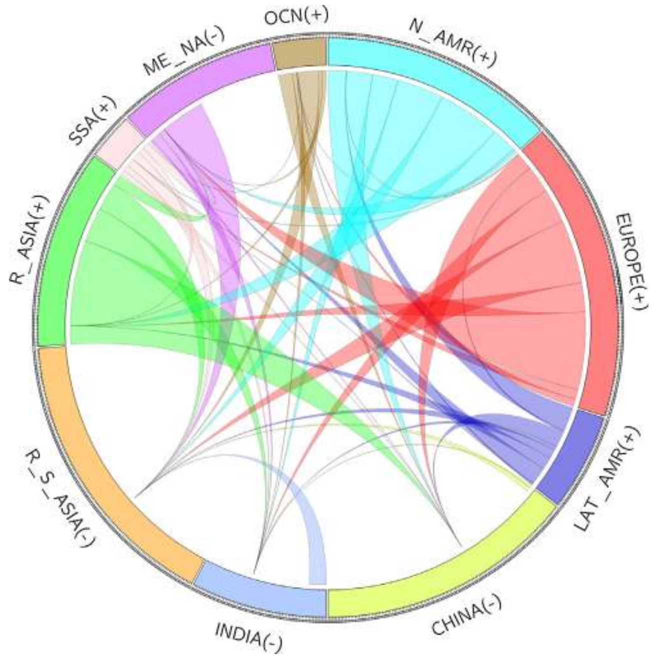


Fig. 4. Change in net bilateral trade flow of food and agricultural products. Here food and agricultural products include crops, livestock and processed livestock products and processed food products (see Table A2 for detailed information). The arc length is proportional to the magnitude of the flow. Wide end is the sending region; pointed end is the receiving region. "+" means increase in net exporting; "−" means increase in net importing. Trading within the region is excluded.

The 2030 irrigation shock strengthens regional heterogeneity in terms of resource endowment, thereby encouraging international trade. Future irrigation shortfall results in increased global trade volumes for most farm and food commodities. Exceptions include raw sugar crops and dairy cattle (both very lightly traded internationally), processed ruminant meats, processed rice and processed food. One reason for the reduced trading in these commodities is that regions facing irrigation stress are the major suppliers in the global market. For example, Asian and MENA countries currently supply more than 60% of global processed rice exports. Another reason is that, the US and EU, the world's largest processed ruminant and processed food suppliers, produce less as inputs are diverted to crop sectors. Besides, a significant portion of the exports of these products are traded with Japan, North American and EU countries, where demand for imports has not been increased as much as in Asian developing countries.

Apart from its macroeconomic implications, international trade in food products is closely intertwined with food security and the debate on food self-sufficiency versus specialization in agriculture. The degree of self-sufficiency is normally measured by a food self-sufficiency ratio or the share of domestic production in total domestic use. Our results show that this ratio falls slightly for most of the Asian countries, indicating their increasing dependence on international food markets. This signals a likely rise in virtual water trade, as has been projected in several studies (Konar et al., 2013; Rosegrant et al., 2002) since exporting less water-intensive crops allows for the import of a greater amount of more water-intensive foods than what would be produced if the domestic production were devoted to high water-consuming crops.

3.4. Water productivity and water content over land

When water becomes expensive, it is expected that crop production will become more water-saving. This can happen in two different ways. First, the distribution of crop production can change, so that it is produced in AEZs where less irrigation water is required. The significance of this composition effect can be observed by comparing pre- and post-experiment regional water content over land. If this content is lower after the simulation, irrigated production is shifted away from a parcel that needs a large amount of irrigation. We find that water content per hectare of land harvested drops the most in regions with severe irrigation stress (Fig. B2). The second mechanism for sparing irrigation water is to substitute water with other value-added inputs, which could involve increased capital or labor costs. Comparing the rate of irrigated output change relative to the rate of input change, we find that, in most cases, the "crop per drop" of irrigation water increases, indicating that water productivity rises (Fig. 5). This enhancement is particularly prominent in China, and South and Southeast Asia.

3.5. Macro-economic effects of irrigation shortfalls

Welfare change in a CGE model is measured based on the concept of *Equivalent Variation* (EV). Intuitively, this approach assesses how much money has to be provided to (or taken away from) the household in the base economy in order to leave them as well off as they are following the irrigation availability shock. So if the shock hurts the household, then the EV measure is negative, and reflects a reduction in welfare. Globally, welfare declines by $3.7 billion with the 95% confidence interval ranging from $2.37 billion to $5.14 billion (2001 prices) as a result of the changes in irrigation availability between 2000 and 2030. At the global scale the loss is modest, amounting to 1.44% of the value-added in irrigated crop production. For the most severely affected regions, South Asia (excluding India), China and India, the figures are larger,

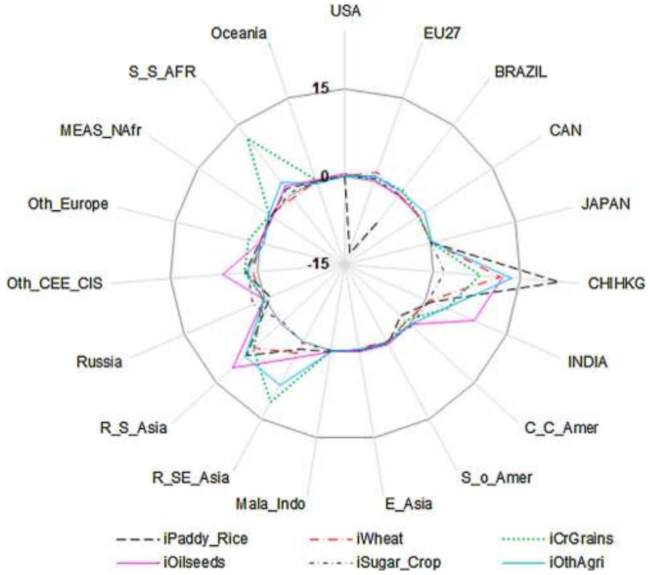


Fig. 5. Change in aggregate water efficiency. What is plot is the percentage change of irrigated output minus the percentage change of irrigation water input. Positive number means that the rate of output increase is faster than input increase, or conversely the rate of output reduction is slower than input reduction. In other words, there is an irrigation efficiency gain after the water shock.

amounting to 9%, 3.3% and 2.4%, of value-added, respectively. Table B1 reports results for all regions as well as the estimated confidence intervals.

The modest welfare response, although seemingly contradictory to the widely shared concerns about irrigation scarcity, is actually quite sensible if we revisit the market perspective incorporated in the general equilibrium model. Rational agents adjust their behavior according to economic and policy incentives, thus providing a mechanism to buffer the impacts of reduced irrigation water availability. To assess the role of trade in moderating welfare losses due to reduced irrigation water, we ran a comparison experiment in which this adaptation potential of international trade was significantly suppressed. In particular, we reduce the size of the trade-related substitution parameters by 75%. The comparison experiment finds much larger regional welfare losses (57–108% increase) in the most stressed regions, mainly the Rest of South Asia, China, India, and Middle East and North Africa. (The global welfare change remains at a similar level since one region's terms of trade losses are another region's gains.)

About one-third of the welfare loss is attributed to less efficient resource allocation (both for water and non-water resources), while the rest is attributed to the reduced water availability for irrigation. The latter is not surprising, given the reduction in supply of irrigation water in many regions. Although irrigation contributes to only 20% of total crop evapotranspiration, in many parts of the world irrigation is supplementary to precipitation, which means a small amount of irrigation may lead to significant increase in yields (Molden, 2007). The former, however, is a little complicated because inefficiency occurs both in regions with and without irrigation reduction, but for different reasons. The intuition behind the welfare change associated with resource allocation is that, increasing (decreasing) the level of a subsidized (taxed) activity will tend to harm the economy, since it further encourages the inefficient resource usage that already exists under the protection of subsidy. Agriculture in the US and EU was subsidized, but was taxed in China at the time this data base was constructed. Thus, future irrigation shortfalls shift agricultural production toward relatively high cost regions where farming is heavily subsidized, thereby reducing global welfare. However, as Anderson and Martin (2009) and Huang et al. (2011) note, the nominal rate of assistance to agriculture in China has been evolving from taxation to subsidization. If we reran this analysis with more current data (not yet available), we would expect this aspect of the efficiency impacts to diminish. While the terms of trade do not affect global welfare, they are the second largest contributor to regional welfare changes following the effects of endowment loss. Because of the higher commodity prices in the global market, aggregate net exporters benefit from the price change while aggregate net importers lose.

It is also important to note that, since our analytical framework does not model water usage by municipal and industrial sectors or aquatic ecosystems, the corresponding welfare changes are not included in the assessment. Moreover, as mentioned earlier, land use conversion based on agro-ecological suitability – ignoring institutional constraints – may overstate the potential for land use adaptation and thereby underestimate the actual endowment loss. Hence, the welfare loss estimation provided here serves only as a lower bound of the possible range of impacts.

4. Conclusion

This study contributes useful insights into research concerned with irrigation availability and its interaction with agriculture and international trade. We conclude that studies examining the water–food nexus will likely overstate the negative effect of irrigation shortfalls on regional and global food supplies, if they overlook the economic responses to this localized irrigation scarcity. The first part of these findings is that global irrigation shortfalls do not always translate into less total regional crop output. The outcome depends on price effects and regional supply response. In affected regions where irrigation is less dominant (e.g. sub-Saharan Africa) crop output may rise due to higher world prices induced by the overall reduction in global agricultural capacity. Since irrigated cropland has higher yields than rainfed agriculture, on average, these regional shortfalls induce an overall expansion in crop land area which rises by about 7.6 million hectares.

Second, regional irrigation shortfalls tend to boost international agricultural trade as well as altering its geography. Although the overall increase in world food exports is only modest, some types of inter-regional food trade are strengthened as America and Europe export more to Asia. Some Asian countries that used to rely on imports from China and India are expected to trade more heavily with non-Asian partners as their neighbors facing irrigation stress export less agricultural and food commodities. This change may also have implications for trade policies and incentives to engage in regional trade agreements.

Third, many water–food nexus studies focus on crop production impacts, but this tells only part of the story. Apart from the direct effect of irrigation shortages on yields and crop areas, macroeconomic outcomes are also affected by prices and international trade. Despite experiencing negative output shocks due to reduced irrigation availability, some countries may gain from higher commodity prices. Regions can also take advantage of trade to adjust the composition of agricultural income and specialize in more beneficial commodities. All these buffering effects, which are mediated by markets, significantly attenuate the first order effect of reduced water availability in farming. Our approach has the advantage of capturing these economic adaptations and spillover effects, as well as providing a monetary metric of welfare losses from future irrigation shortfalls – which we estimate at a loss of $3.7 billion at 2001 prices. However, this modest global impact belies larger regional impacts – losses which are exacerbated when the global trading system's functionality is restricted.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.07.010.

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