Analyzing Future Water Scarcity in Computable General Equilibrium Models

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Abstract

Incorporating water into a computable general equilibrium (CGE) model operating at global scale can be extremely demanding due to the absence of standardized data, the sheer dimensions caused by intersecting river basins with countries, and difficulties to model demand for and supply of water. This has led many authors to introduce water in their CGE modeling framework in different ways and at different spatial and sectoral aggregation levels. Of course, simplifying market for water and sacrificing the geographical realism risk introducing errors caused by inappropriate aggregation. In this paper we use a global CGE model which distinguished between rainfed and irrigated crops and traces supply of and demand for water at river basin by agro ecological zone (AEZ) and country to investigate the three most commonly practiced simplifications: 1) tackling global questions in a national level model; 2) collapsing irrigated and rainfed crop production into a single sector; and 3) removing river basin boundaries within a country. In each case, we compare their performance in predicting the impacts of future irrigation scarcity on international trade, crop output, prices and land use change, relative to the full scale model. As might be expected, the single region model does a pretty good job of matching outcomes for that region, although changes in bilateral trade can entail significant errors. When it comes to the elimination of sub-national river basins and irrigation location, we find that, if the research question has to do with changes in national-scale trade, production, consumption, and prices, it may be sufficient to ignore the sub-national water and land heterogeneity in global economic analysis of water scarcity. However, when decision makers have an interest in the distribution of inputs and outputs within a region, preserving the river basin and sectoral detail in the model brings considerable added value to the analysis.

1. Motivation

Economists building computable general equilibrium (CGE) models have long endeavored to deal with two conflicting objectives: model accuracy and affordability. This is particularly true when it comes to the incorporation of water into a global-scale CGE model (Berrittella et al., 2007; Calzadilla et al., 2010). The most obvious reason is of course that water supply and demand are often locally determined. Many economic activities associated with water are confined to geophysical boundaries such as watershed and/or AEZs, which may not be well represented by

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administrative boundaries – the commonly applied level of aggregation in a typical global CGE model. For regions having diverse geophysical conditions, water availability may vary dramatically within the country, depending on local water demand relative to supply, and the mobility of water resources.

In addition to geographical and spatial matters, the appropriate sectoral aggregation of water use appears to be another important concern. Water is a necessary input for almost all economic activities. The relative importance of water, however, differs markedly between industries and its alternative uses. More importantly, unlike other mobile endowments (e.g. labor and capital) and commodities, water can be hard to move due to impaired water rights and the lack of infrastructure. As a result, even at the same geographical location, the marginal value product of water could be very different, depending on whether the water is used by agriculture, manufacture, services or households (Olmstead, 2013). All these arguments point to the need for increasing the dimensionality of the problem: a CGE model with water should offer finer resolution and differentiate between water-intensive and non-intensive industries.

While it is hard to argue with finer resolution in CGE-water modeling, adding such detail is costly. Consider a global model with r regions, i commodities, and j industries. Identifying k river basins within each region and differentiating z agro-ecological zones (representing different types of land and climate conditions) within each river basin can easily increase the number of equations to be solved from $r*i*j$ to $r*i*j*k*z$, and possibly even more if some of the j industries can be further split into water-intensive and non-intensive ones. For each of these dimensions to be added, more data are needed to describe the initial baseline equilibrium. When the work is global in scale, issues of data availability and quality arise. And even though good data exist, without any doubt more computational power is required to solve the model.

Nevertheless, adding more detail can be rewarding and worthwhile, as we will show later. The correct approach depends on which variables are of interest to the decision makers for which the results are destined. Therefore, we seek to answer the following questions:

- To what extent does the added detail matter?
- Is this detail important to all variables?
- Are there some cases in which the added detail is not required?

The understanding of these questions brings multiple benefits to the CGE community. One among them is to address the concern that models lacking full-blown disaggregation cannot be useful. We show that, under some circumstances, sacrificing certain details costs little in terms of analytical accuracy but can translate into enhanced feasibility and viability of CGE modeling of water scarcity. On the other hand, our investigation reveals what kind/level of detail is indeed important and therefore should be preserved. We show that missing these details could be costly to the analysis and policy implications. Future data base development should be guided by these specific needs of decision makers.

2. Literature Review: Water in Global CGE Models

Subject to the nature of the problem and limitations due to model complexity and data availability, many existing water CGE models focus only on one country. Some examples we find include models developed to study water exchange in Balearic Islands by Gomez (2004), the interaction of water market and trade in Morocco by Diao and Roe (2003), and water policy reform in South Africa by Hassan and Thurlow (2011) and Letsoalo et al. (2007). Although these studies typically assume different production structures (i.e. functional forms, nesting structure, and parameter values), a common feature of these modeling frameworks is the disaggregated sectoral demand for water. For example, many of these models differentiate between water uses for crops. Some of them consider also non-agricultural water uses.

In contrast to the considerable attention paid to sectoral disaggregation, the error potentially caused by inappropriate geographical aggregation has rarely been addressed in the literature. The few exceptions include Decaluwe et al. (1999) who divide Morocco into wet (north) and dry (south) regions, Dixon et al. (2011) who draw 19 irrigation catchments within the Australia Murray-Darling Basin, and Cakmak et al. (2009) who break certain cropping and livestock productions into five sub-regions in Turkey. In these studies, explicitly expressing the geographical distribution of water resource was achieved in two ways - a homogeneous water resource enters sub-regions, or heterogeneous water resource enters the same region. What makes the former approach difficult is that the sub-regions are often defined by geographical boundaries rather than by administrative divisions, because water distribution obtained from national accounts is normally not recorded by geographical units. The latter approach too can be cumbersome. It often requires fine-resolution data that is informative enough to describe the heterogeneity of water. Some examples include treating surface and ground water as different endowment, and considering the seasonality of irrigation to capture the temporal in addition to spatial heterogeneity of water demand and water supply.

These elaborate single-region models might be very effective when studying water-related issues that can be addressed in isolation (e.g. changes in domestic policies). However, in the case that the water problem affects multiple regions and/or inter-regional interaction plays an important role in restoring the equilibrium, a single-region model may not be sufficient. Water scarcity, the main interest of this paper, provides exactly such an example. To alleviate the limitations, multi-region water-CGE models have been pursued, but often at the cost of giving up certain features carried by the single-region model.

One such cost has to do with merging irrigated and rain-fed crop sectors, and would normally be the case in a CGE model constructed from national accounts. This is the approach taken by Berrittella et al. (2007) when they built on the GTAP data base and model to construct their GTAP-W model. In this model, agriculture still contains multiple crop sectors but each crop does not differentiate output resulted from the consumption of blue (surface and ground) water and green (soil moisture) water. Instead, water use intensity by crop is computed from total water consumption and total crop output. When the system is perturbed by a water scarcity shock, this structure may dilute the direct impact of irrigation shortage on crop production, especially for regions highly reliant on irrigation.

Another type of cost is incurred when water is assumed to be freely mobile across river basins within a country with no implicit or explicit opportunity cost. Calzadilla et al. (2010) adopted this approach in their work to update Berrittella et al.'s GTAP-W model. They treated each individual region as one integrated watershed, within which water can be costlessly shifted to any sector/location. This treatment forces the value of water to be equalized across the entire country/region. In addition, the uniform basin assumption fails to capture the various degrees of water stress caused by local-specific water supply and demand. These may all become the sources of errors in the analysis. Some of these issues were addressed in a more recently developed global CGE model with water, namely GTAP-BIO-W.

3. Overview of GTAP-BIO-W

3.1 Model structure

GTAP-BIO-W, documented in Taheripour et al. (2013), retains the advantages of GTAP-W (Calzadilla et al., 2010) in using the multi-level CES structure, but it uses a different approach to introduce water into the model. Unlike GTAP-W which divides land input into value contributed by irrigated land, rainfed land, and water, GTAP-BIO-W explicitly considers two distinct sectors for each crop. One represents irrigated crop and another represents rainfed crop. The two sectors are subject to different production technologies. Also unlike the GTAP-W model which uses land and water inputs at national level, GTAP-BIO-W permits competition for water and land to take place at two different spatial levels – irrigated cropping activities compete for irrigation water within a river basin and crops compete for land within an agro-ecological zone (AEZ) (see Figure 1). This design significantly enhances heterogeneity in land and water and hence improves the adaptability of the model. For example, irrigated and rainfed production operate independently from one another, yet produce crops which are identical from the consumers' point of view. That means irrigated crop production can be completely eliminated from a certain part of the country if water supply for irrigation falls short. Moreover, in GTAP-BIO-W, intersections between different river-basins and AEZs are featured by different production functions that reflect water availability, length of growing period, and soil quality peculiar to that area.

The shadow value of water in the GTAP-BIO-W model is obtained from the higher return to land in the irrigated sector within a given river basin-AEZ, as opposed to its rainfed counterpart. This approach is founded upon the assumption that both sectors have the same basic cost structure for non-land inputs, deriving from identical input-output ratios and the same output, and non-land input prices. Subtracting the aggregated non-land input cost share (which is therefore equal for rainfed and irrigation agriculture) from the total (which equals one) yields the cost share of land and water in both sectors. Further, because output per unit of land (tons of crop/hectare) is higher when irrigation is applied, combined land (and water) rents per unit of irrigated land (e.g. hectare) are also higher, given the same cost share of land and water. The “bonus” rent is then attributed to the contribution of irrigation water to total production, within that particular AEZ-river basin.

3.2 Water scarcity experiment and baseline results

In prior work (Liu et al., 2014), we employed the GTAP-BIO-W model to examine the potential consequences of projected irrigation water scarcity in 2030 for patterns of agricultural production, consumption and trade as well as economic welfare. Projected 2030 irrigation shortfalls for 126 river basins around the world were obtained from the IMPACT-WATER model, and imposed upon the present-day economy. We found that regional production impacts were quite heterogeneous, depending on the size of the shortfall, the irrigation intensity of crop production, as well as the crop mix. Projected irrigation scarcity leads to significant output declines in China, South Asia, the Middle East and North Africa, and alters the geography of international trade. These trade adjustments play a key role in moderating the adverse impact on global prices and consumption – thereby highlighting the importance of examining water scarcity in a global framework.

The major problem with undertaking such a global analysis is the challenge of mapping from subnational detail (i.e. river basin-AEZ intersections) to national/international data sets for factor inputs, trade flows, national outputs, etc. While the GTAP data base is commonly used to calibrate international trade models, there is no publicly available data set which maps national production to sub-national river basins. Indeed, in order to construct the data base for the GTAP-BIO-W model, it was necessary to draw on a variety of data sets, including those on rainfed and irrigated agriculture (Portmann et al., 2010; Siebert and Döll, 2010), cropland area and yields (Monfreda et al., 2008; Ramankutty et al., 2008) and water use by river basin (Cai and Rosegrant, 2002). Some of these data are provided at inconsistent resolutions and we were thus required to down-scale the data to the grid-cell level, reconcile them and then re-aggregate to river basins and AEZs. This is a messy process. In the next section, we explore some less onerous modeling alternatives via restrictions on the full-scale GTAP-BIO-W model.

4. Experimental Design: Three Simplifications for Global Water Modelling

4.1 Simplification one: Single-region analysis

Perhaps the most straightforward approach involves focusing on a single country and ignoring potential changes in water scarcity in the rest of the world. Given its importance in global agriculture, as well as the prospects for significant water scarcity in 2030, we focus on China for this experiment. The same model and baseline data are used as in Liu et al. (2014). The only difference is the experiment shock. Here the basin-specific shocks are applied to only river basins within China, while assuming unchanged irrigation availability in the other regions/basins – not unlike the approach taken by Wittwer (2012) in the case of Australia. GTAP-BIO-W defines 17 river basins in China. Except for the LancangJiang basin, most basins are expected to experience increased irrigation shortages in 2030 (Figure 2). The most significant reductions are expected in HaiHe (-13%), HuaiHe (-64%), HuangHe (-32%) and SonghuaJiang (-15%) basin. These watersheds cover many major agricultural areas of China.

4.2 Simplification two: Collapsing rainfed and irrigated agriculture into a single activity

The full GTAP-BIO-W model separates irrigated and rainfed productions, e.g. irrigated rice and rainfed rice. Only the former uses irrigation water as an input. The two sectors initially have their own zero profit conditions determined by the different input structure. In the present experiment (henceforth the I&R model, see red circles in Figure 1), these individual zero pure profit constraints are replaced with a combined equilibrium condition that equates output price with the aggregated input prices for the rice sector. We continue to use the baseline data, but force the irrigated and rainfed production to move synchronously, i.e. irrigated output increases by 1% for every 1% increase in rainfed production. Water and land enter still as separate inputs but in a single production function for (e.g.) rice. This circumvents the need for separating rainfed and irrigated crop land and it also means that the author may not even need to estimate rainfed and irrigated production functions separately. (Some vehicle is still needed to estimate the importance of irrigation water in the production function.)

4.3 Simplification Three: Aggregating river basins to the national level

The third restriction involves unifying the sub-national river basins (henceforth the Unified Basin model, see blue circle in Figure 1). This is achieved by modifying the market clearing condition of water. The demand and supply for water in the benchmark model is equalized at each river basin. Accordingly, the equilibrium price for water is also determined at the river basin level. In the new experiment, we relax these basin-specific constraints and replace them with one single region-specific market clearing condition for water. With this modification, water is competed for by irrigated crop activities that possibly take place at any location within the country. The initial river basin boundaries do not bind water allocation anymore. Another deviation from the benchmark model is that water price is now unified in the region, rather than segmented by hydrological boundaries. The basin-specific shock remains unchanged, but the larger water mobility could cushion the shock and limit its impact on regional crop output. It is important to note that the previously described restrictions are not accumulated. To be specific, the Unified Basin model retains the irrigated and rainfed activity split; and the I&R model confines water within each watershed.

5. Analyzing the Consequences of Global Model Simplifications

5.1 Assessing the impact of future water scarcity on trade

For each of the experiments laid out above, we compare results to what returned from running the full GTAP-BIO-W model and experiment. Three metrics – bilateral trade flow, crop output, and harvested area changes are selected for the comparison, given that they are among the most popular applications of water CGE models. Figure 3 compares the net trade flow of food to China from the rest of the world under different experiments. Apart from the Rest of South Asia and India, the dots representing the broad regions are reasonably well clustered, indicating the fairly close inferences from different models if our interest lies only in China. Nevertheless, compared with the others (including the benchmark one), the single-region model tends to magnify the trade volume change in China because it is the only source of scarcity in this experiment. After taking into account the relative level of irrigation scarcity between regions, the effect on China's trade flows is somewhat muted. This is especially true for the trade partners that experience a more severe irrigation scarcity than China. As a result, net food exports to China from these regions increase less or even decrease. For example, if employing a multi-region model, water scarcity would increase China's exports to South Asia instead of reducing them, as predicted by the single-region model.

5.2 Assessing the effect on crop output

In the case of regional output changes, the single-region model does reasonably well for China, but, not surprisingly, has nothing to say about the other regions (Figure 4). Other regions' crop production may be affected by China's irrigation scarcity, but only indirectly through international trade. When other regions also experience predicted irrigation shortages, results from the I&R model and the Unified Basin model are more aligned with the full model, although the latter generally outperforms its competitor. We find that, in many cases, forcing irrigated and rainfed sectors to move together overestimates the region-wide total output loss in irrigation-scarce regions. The intuition is that rainfed production would have been able to expand and make up for the contracted irrigated output if it were not tied with the latter by entering in the same production function. Additionally, the "errors" caused by this simplification vary across crop sectors. The deviation is relatively larger for rice, coarse grains and sugar crops. Therefore, depending on the research question, breaking out agriculture into rainfed and irrigated sub-sectors may be valuable. In general, the output deviation from the benchmark result is not large in terms of the absolute value (mostly less than 5% in Figure 4).

5.3 Assessing the effect on land use change

We find non-trivial deviations at the subnational scale. Figure 5 shows changes in irrigated harvested area. Depending on the severity of basin-specific irrigation scarcity and the importance of water to the crop at each location (defined by the intersection of country/region, river basin and AEZ), the I&R model and the Unified Basin model could either over- or underestimate the distribution of irrigation production at the local level. Intuitively, the total output change returned from the I&R model approximates the weighted average of the two often opposite output changes in the benchmark model - irrigated and rainfed. Hence, the I&R model tends to underestimate the region-wide contraction of irrigated production while exaggerating the appreciation of irrigated cropland value when irrigation scarcity occurs. This leads to two potential errors. For the country as a whole, the contraction of total irrigated harvested will be understated; whereas within each river basin, the reallocation effect on irrigated production becomes more pronounced, i.e. irrigation-intensive AEZs lose more and vice versa (e.g. the red and navy blue area in India’s Ganges river basin in Figure 5a). Similar deviations from the full model are found in the comparison between the Unified Basin model and the benchmark model. The difference is that, the reallocation is realized within the entire region rather than within the river basin. Relative to the benchmark simulation, irrigated farming is exaggerated in both irrigation scarce and water efficient areas.

6. Summary and Implications for Future Research

Comparing models with differing levels of complexity, we investigate the costs and benefits of simplifications commonly undertaken in the context of global water-related CGE analysis. The single region model generally over-predicts the trade impact on the region itself but understates the global effect since water scarcity in is the rest of the world are left unaffected. However, when it comes to predicting production changes in the focus region, China, the single-region model performs well. Of course it is silent on the production impacts in other regions. So, if one is only interested in the impacts in a particular country, and provided the pattern of trade is not paramount to the decision makers, then a single-region model is likely to be sufficient for the economy-wide analysis of future water scarcity. A multi-region model that aggregates irrigated and rainfed production results in a more modest decline in irrigated area across most crop/river basin combinations when the global irrigation scarcity experiment is run. In other words, when we fail to treat these sectors as distinct, there is too little contraction of irrigated crop production. This is similar to the finding of Wittwer (2012) who found that failure to disaggregate rainfed and irrigated production led to far too little change in irrigated area in the context of the 2002 drought in Australia. When eliminating sub-national river basins, we tend to observe excessive irrigation, relative to baseline, in regions that are water scarce, as well as those that are water efficient. So the pattern of land use change is quite different from that in the benchmark model. However, the change in national production, consumption, trade and food prices is quite similar to that in the benchmark model. This suggests that, if one does not care about the location of production and land use, it may be sufficient to ignore the subnational river basins in global economic analysis of water scarcity.

On the other hand, high-resolution geophysical data can be valuable when decision makers are interested in the subnational distribution of production, land use and water changes. In this case, extending the CGE model to reflect this detail becomes important. The major constraint in doing so is data availability. The recently developed GTAP-BIO-W model has made progress in coping with these issues, but also has some limitations. For example, water in GTAP-BIO-W is used by agriculture but not by other non-agricultural sectors. Besides, the role of ground water is not clearly reflected in the model. Water supply is currently assessed at major river basins that are more relevant to surface water resources.

Since one can never incorporate as much detail in global modeling as one might ideally desire, understanding the trade-offs provides useful insights into the applications. Our study contributes to this objective. In particular, we show that for studying the water scarcity issue, efforts such as simulating water balance at the river basin level and drawing AEZ and watershed within regions would improve the quality of a CGE analysis.

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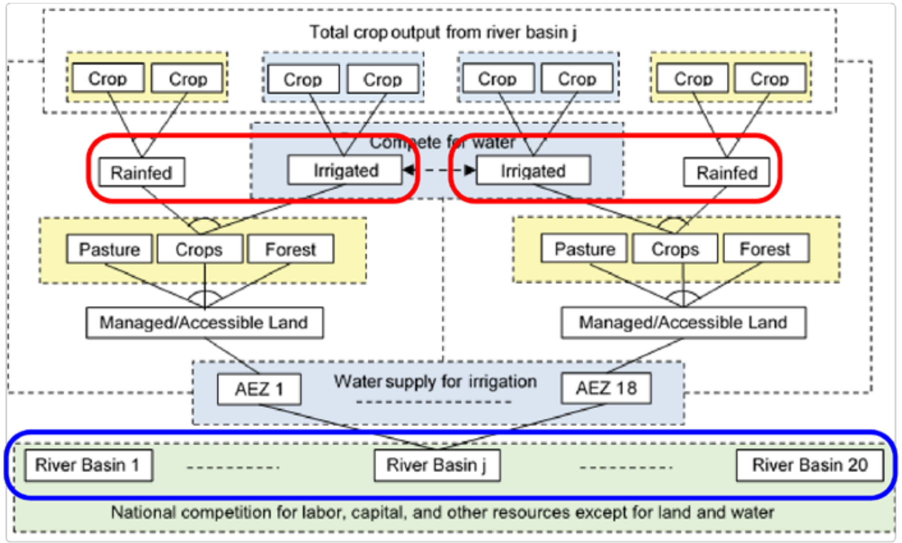


Figure 1. Production structure for crop sectors in the GTAP-BIO-W model. Red circles indicate where the modification arises for the Combined I&R model. Blue circle indicates where the modification arises for the Unified Basin model.

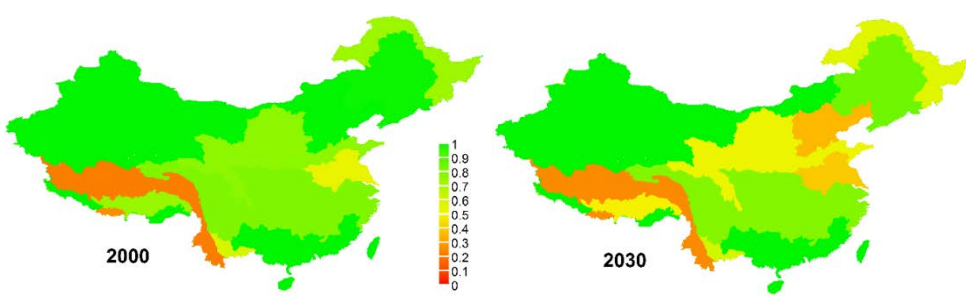


Figure 2. Irrigation water supply reliability in China, 2030 relative to 2000. The value is one if all the potential irrigation demand is satisfied by the actual consumption. (Will add basin labels later.)

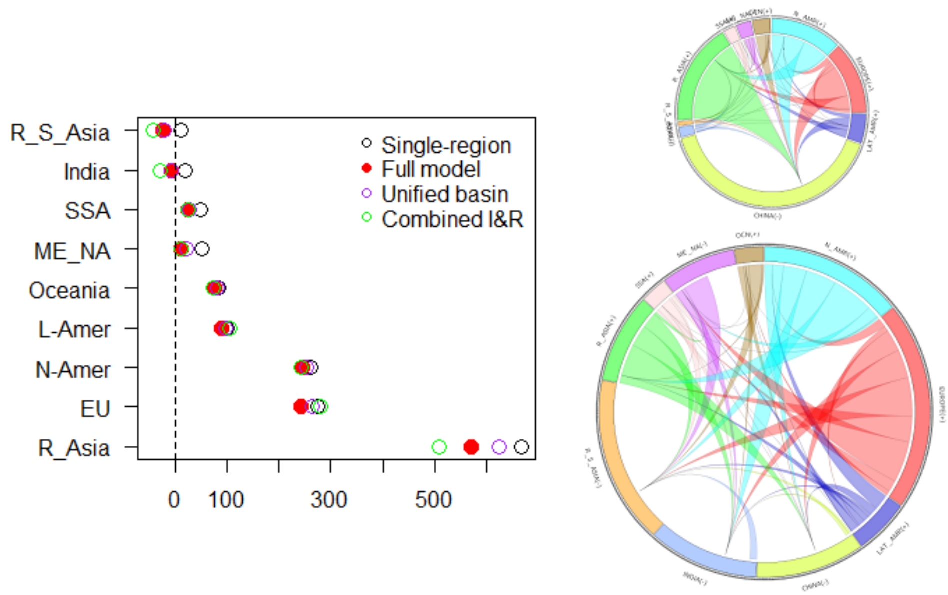


Figure 3. Scattorplot shows changes in net trade flow to China from other regions, in million USD 2001 price. Only food and agricultural products are included (i.e. crops, livestock and processed livestock products and processed food products). Positive number corresponds to increase in net food import. Circles on the right demonstrate bilateral trade flow between all other regions. Top circle presents results from the single-region model, bottom circle full model results. Circle size is proportional to the magnitude of trade 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.

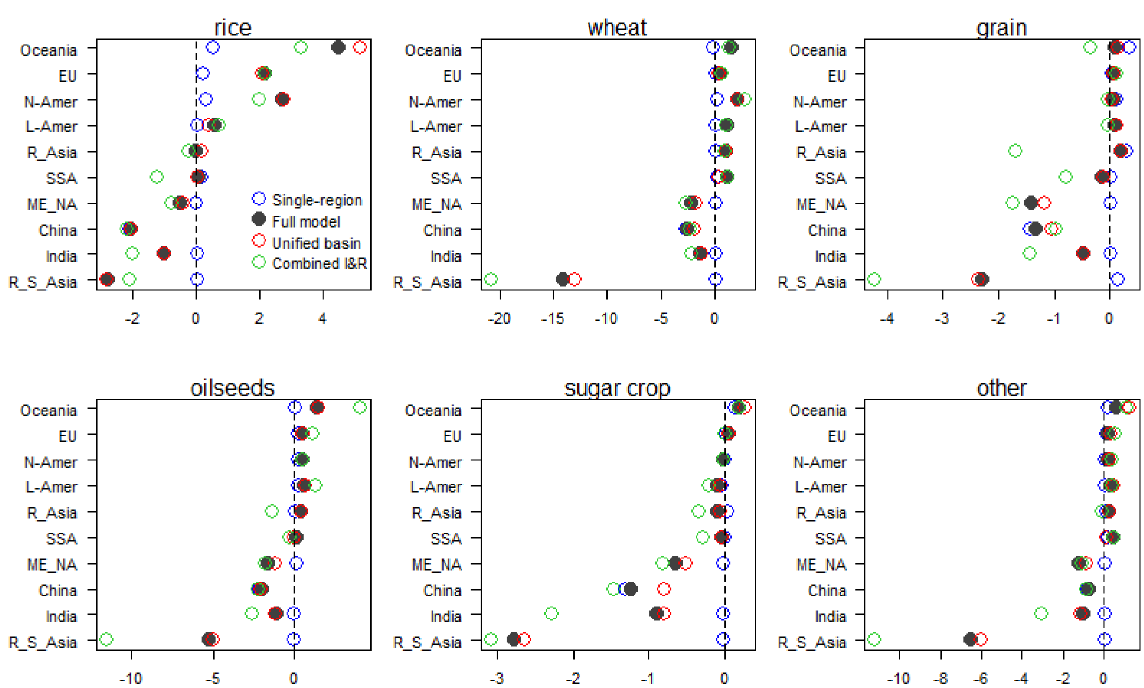
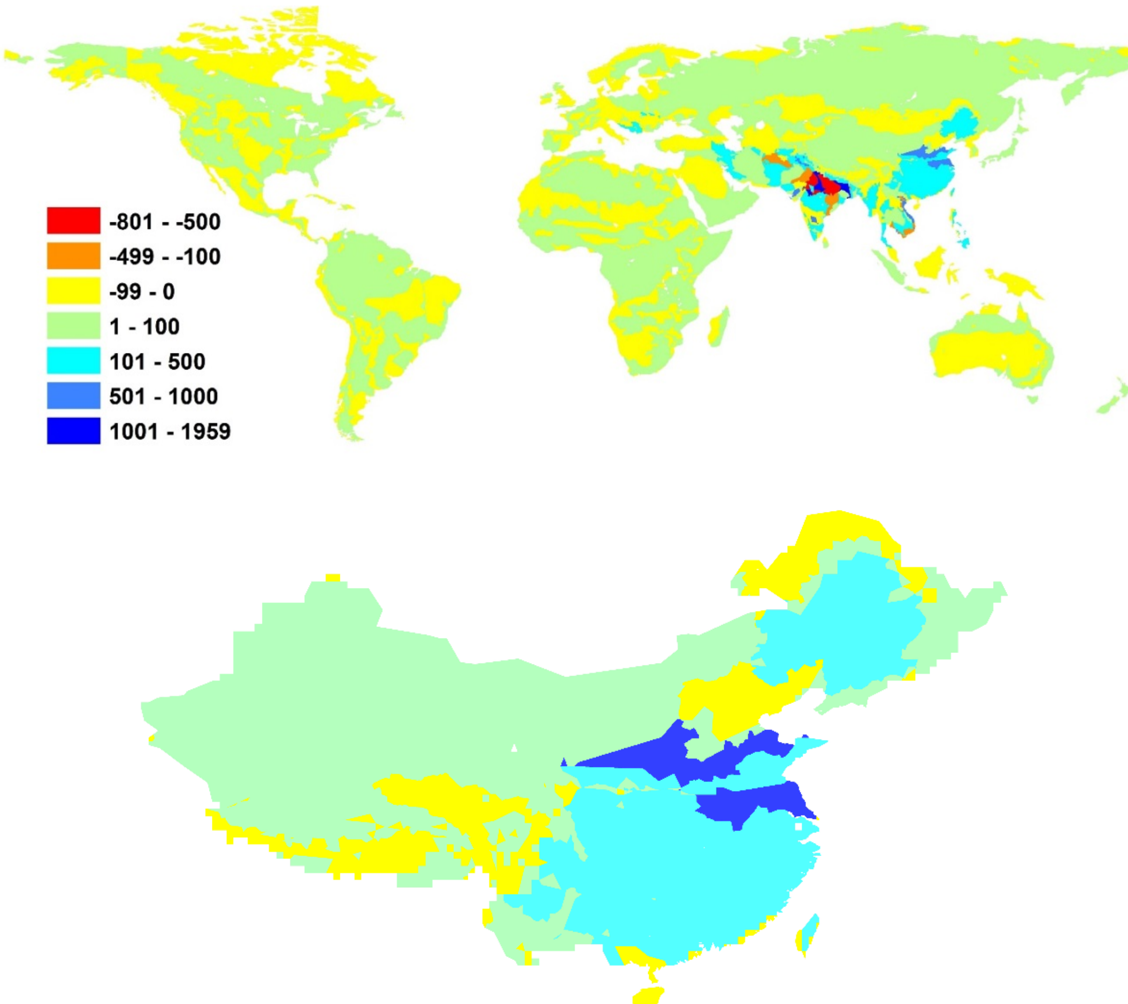
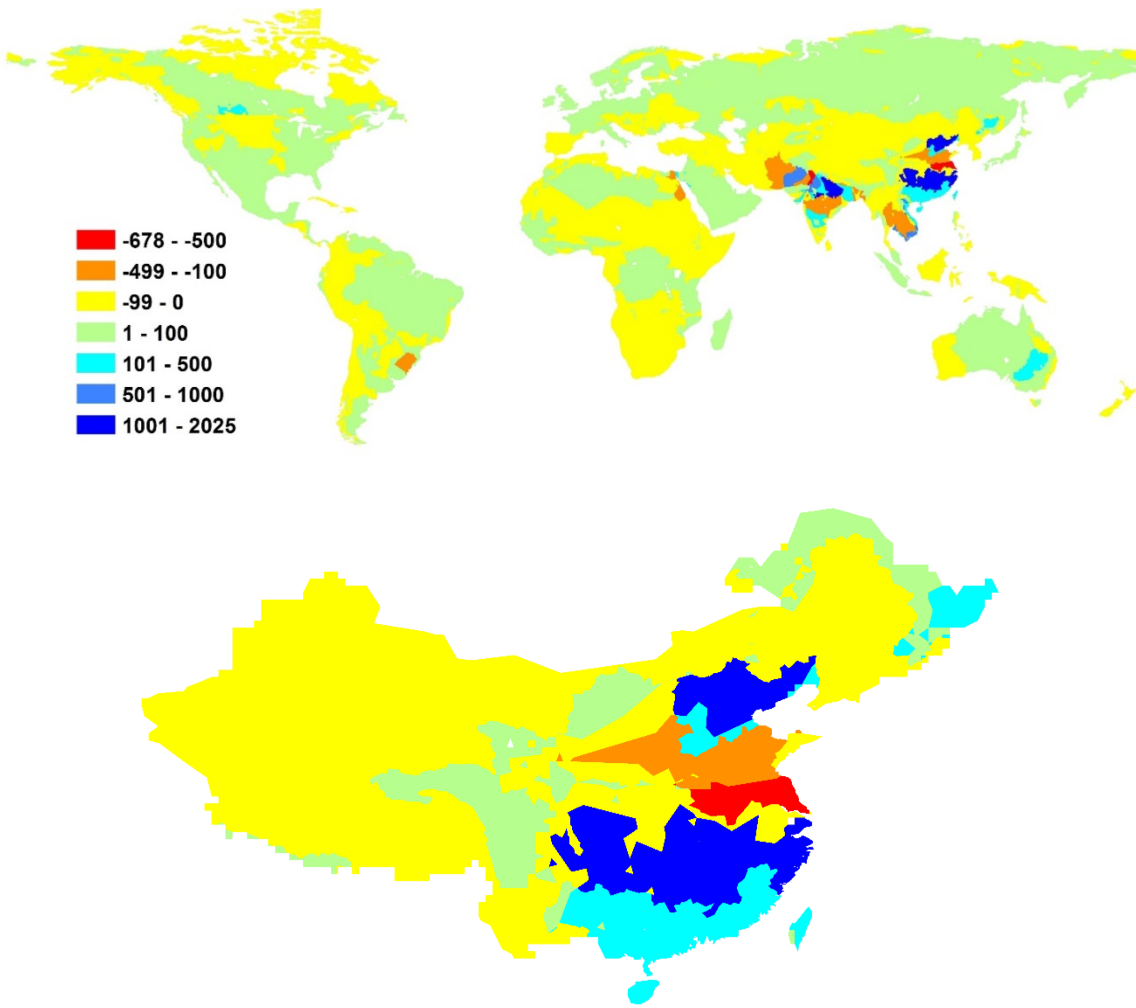


Figure 4. Changes in total output relative to baseline, by region and crop. X-axis refers to percentage point.



(a)



(b)

Figure 5. Deviation of irrigated harvested area (in 1000 hectares) from the full model simulation, based on results returned from the I&R model (a) and the Unified Basin model (b). Positive (negative) number means irrigated harvested area is overestimated (underestimated) than in the baseline simulation. In each panel of figures, a zoom-in of China is provided below the global map.