Decomposing Irrigation Water Use in Equilibrium Models
Top-Down vs Bottom-Up

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Abstract

This paper measures the importance of different drivers of change in irrigation water use regionally and globally. We followed Heckscher–Ohlin theory, Ricardian specific-factor model, and Melitz-type theories of trade to introduce a method for decomposing irrigated water use. We apply the decomposition method on the results of Liu et al. (2014) on the impacts of future irrigation shortfalls. We find that rain fed substitution (specific-factor impact) contributes to 62% of change in water use; substitution to non-crops (Heckscher–Ohlin impact) accounts for 16% of the change; and moving to farms with higher water productivity (Melitz impact) contributes to 7% of it, globally. The importance of drivers varies by region but usually these three drivers are the most important factors in adaptation to water shocks.

Keywords: Water intensity, International agricultural trade, Irrigation, Adaptation, Heckscher–Ohlin, Melitz

JEL classification: Q25, F17, Q17, Q52

1 Introduction

Despite the fact that global water resources are expected to be sufficient to feed the world in the coming decades (Alexandratos and Bruinsma, 2012), the pattern of water endowments is expected to result in some severe local scarcity – reaching a deficit of more than 50% in some areas by 2030 (Addams et al., 2009). There is a growing literature examining potential avenues for adaptation to such projected scarcity. One solution is international agricultural trade (Falkenmark et al., 2009) which provides the possibility of "virtual water trade" (Konar et al., 2013, Dalin et al., 2012 and Lenzen et al., 2013). This idea, based on the Heckscher–Ohlin theory of trade, suggests that relatively water-abundant country will export more water intensive goods, leaving deficit regions to import 'virtual water' by buying these goods in international markets instead of purchasing them locally. Thus, water scarcity alters the crop mix production which is produced. The Ricardian, specific-factor model of trade also has a role to play in this literature. Water is often considered to be a specific factor input in irrigated production, whereas land can be transferred from rain fed to irrigated land. In this environment, substitution towards rain fed crop production creates another source of adaptation to water scarcity (Liu et al., 2014). Another important avenue for adaptation builds on Melitz-type theories of heterogeneous firms (Melitz, 2003). In this context, firms within the industry have differing productivities, including producing the same irrigated crop with varying amounts of water. In this context, water scarcity may shift industry output from low irrigation productivity to high irrigation productivity farms (Fleming and Alber, 2013).

Economic analysis of water scarcity has been improving over the past decade (Dudu and Chumi, 2008; Ponce et al., 2012). However, in light of the complexity of this problem, most existing water models focus on a single country or sub-national region. This literature is relatively rich in terms of modeling disaggregated sectoral demand-supply of water, especially within agricultural sectors (Kahsay et al., 2015). Some authors also model diverse sources of water supply including: surface water, ground water, desalinated water, and even recycled waste water (Gómez et al., 2004; Luckmann et al., 2014). Competition for water is another important concept in the literature and it typically has a strong spatial component. Depending on the resolution of source data, the sub-national water market is defined by irrigation catchment (Dixon et al., 2011), by wet or dry regions (Decaluwe et al., 1999), or by sub-national agricultural areas (Cakmak et al., 2009).

Recently, a set of global, equilibrium models with explicit analysis of water have emerged. One of the first was IMPACT-WATER (Rosegrant et al. 2002) which focuses on projections of water availability at the level of about two hundred river basins and its role in global future food security (Rosegrant et al., 2013). WATERSIM introduces integrated water and food analysis at the global and basin level (de Fraiture, 2007). The IGSM-WRS modeling group has also been working to incorporate the global water resource system into a global integrated assessment model (Strzepek et al. 2010). More recently, several GTAP-based models have emerged, seeking to address issues related to water. Calzadilla et al. (2011) treats water as a specific factor input into each sector of the economy. The GTAP-BIO-W model explicitly disaggregates water by river basin and models competition for both land and water at global scale. GTAP-BIO-W has been used for analyzing the interplay between water availability and global land use change (Taheripour et al., 2013), the interplay between water scarcity and international trade (Liu et al., 2014), and the relationship between agricultural production, irrigation, climate change, and water scarcity in India (Taheripour, et al. 2015).

However, it is often quite difficult to understand which margins of adaptation are at work in these models, as well as assessing their relative importance. Understanding the role of margins of adjustment in a large, global model is complex and requires further exploration. To our knowledge, none of the above studies actually decomposes the margins of adjustment in irrigation water use in the face of external shocks.

Thus, it is hard to understand the source of differences across models, and it is also hard to compare these results to econometric studies of land and water use.

This study introduces a pair of decomposition tools which are applied via a combination of top-down and bottom-up approaches. The top-down approach considers the water use and production of each crop at regional level. Then it decomposes the change in national irrigation water use into its main drivers. While the bottom-up approach assumes heterogeneous production at grid-cell farms or AEZ (Agro Ecological Zone) by agricultural crops. It decomposes the change in water use at farm levels and relates them to national variables. The comprehensive decomposition is employed in assessing changes in regional and global water use in the GTAP-BIO-W (Liu et al., 2014) in the face of water scarcity projected using the IMPACT-WATER model (Rosegrant et al., 2013). However, the methodology can be applied to any other general equilibrium or partial equilibrium irrigation models of water use. The change in irrigation water used is divided into significant component parts. The main components are capital-labor-fertilizer substitution, rain-fed substitution, crop switching, geographical relocation, irrigation technical change, domestic scale, and global scale. Each component represents a channel of transmission from shocks to changes in irrigation water use patterns.

2 Methodology

Three decomposition approaches for three different model structures: an aggregate approach, the top-down approach and a bottom-up approach. The aggregate approach is helpful when assuming aggregate or homogeneous production function for irrigated production across one region. Thus, there is only one water productivity index for each crop. The top down approach has one production technology for each irrigated crop but considers heterogeneous land and water. The bottom up approach introduces heterogeneous land and water as well as heterogeneous production functions for each farm unit.

2.1 Aggregate approach

Equation (1) identifies the main drivers of aggregate water use, *W*, in a given region:

$$W = G\frac{C}{G}\frac{I}{C}\frac{W}{I} \tag{1}$$

Water use in production of crops depends on GDP (Gross Domestic Product) of the region, *G* (for a partial equilibrium model, this would refer to gross agricultural product); as higher aggregate output requires higher water use. It also depends on the portion of GDP which is generated via crop production, *C*. (We focus on crop production here, since irrigated agricultural accounts for 70% of global freshwater withdrawals.) The aggregate crop-to-GDP ratio is an indicator of the relative importance of agriculture (crop production) in the economy. In general, the greater the importance of crop production, the greater the water requirements for production of crops. Moving from crop production to non-crop production is expected to reduce overall water use. Since we do not focus on 'green water' use (rainfed crops), the critical factor is really share of irrigation production of crops, $\left(\frac{I}{C}\right)$. In an economy with lower share of irrigation, water use is expected to be lower. Production technology is another important factor. If the water input, *W*, is small relative to other inputs (labor, capital, fertilizer, etc.), $\left(\frac{W}{I}\right)$ we expect lower water use, relative to the overall level of output. This ratio can be further decomposed as follows:

$$W = G\,\frac{C}{G}\,\frac{I}{C}\underbrace{\left(\frac{WLVA}{I}\right)\left(\frac{WL}{WLVA}\right)\left(\frac{W}{WL}\right)}_{\frac{W}{I}} \tag{2}$$

In general, crop production requires water (*W*), land (*L*), capital and labor as value added (*VA*), fertilizer, and other material inputs. The $\left(\frac{WLVA}{I}\right)$ ratio shows the importance of water-land-value-added in crops production. A decline in this ratio demonstrates the substitution from *WLVA* composite towards higher application of fertilizer and other material inputs. However, the production technology can be different in relative share of value added to water-land composite. Thus, changes in $\left(\frac{WL}{WLVA}\right)$ ratio shows the possible substitution of capital-labor with water-land. If the combined water-land input, *WL*, is small relative to other inputs (labor, capital, fertilizer, etc.), we expect lower water use, relative to the overall level of output. Finally, the amount of water, *W* applied to a given hectare of land, $\left(\frac{W}{WL}\right)$ is another important factor in overall water use.

Although the crop-to-GDP ratio is important in determining the level of water use, another important factor is the mix of crop production, since some crops are irrigation intensive while others are not. The share of crop *i* in total crop production of the economy, is denoted $\left(\frac{C_i}{C}\right)$. If crop *i* is water-intensive, then a rise in its share will boost overall water use in the economy. Hence, the decomposition can take the form of the following equation:

$$W = G\,\frac{C}{G}\,\sum_i\left(\frac{C_i}{C}\frac{I_i}{C_i}\frac{W_i}{I_i}\right), \quad i:crops \tag{3}$$

2.2 Top-down approach

In the top-down approach, we introduce the possibility of intra-regional shifts in water use. Following GTAP-AEZ-BIO, we allow for sub-national disaggregation of land into Agro-Ecological Zones (AEZs) which are indexed by a, and water into river basins, indexed by b. Finally, individual grid cells – the most detailed spatial unit, and one which aggregates to either AEZs or river basins, are indexed by d. In this approach there are several heterogeneous water-land inputs distinguished by geographical location. Water-land in each location has different productivity. The ratio of WL_b to WL shows each river basin's share of the water-land composite. The following ratios also show the share of each AEZ in the river basin, and each grid cell in each AEZ. We distinguish AEZs as the water can be mobile inside a given river basin. Also, water productivity can be different in each grid cell.

$$W = G\frac{C}{G}\underbrace{\sum_i\frac{C_i}{C}\frac{I_i}{C_i}\frac{WL_i}{I_i}}_{\text{crop-mix}}\underbrace{\left[\sum_b\frac{WL_{i,b}}{WL_i}\left(\sum_a\frac{WL_{i,b,a}}{WL_{i,b}}\left(\sum_d\frac{WL_{i,b,a,d}}{WL_{i,b,a}}\frac{W_{i,b,a,d}}{WL_{i,b,a,d}}\right)\right)\right]}_{\text{relocation-across-riverbasins-AEZ-gridcells}} \tag{4}$$

2.3 Bottom-up approach

In the bottom-up approach, we decompose the change in water use in smallest farm unit in the model. In other words, each unit has its own unique production function. In this approach there are heterogeneous farms distinguished by grid cell. The following ratios show the production share of each AEZ in river basin, and each grid cell in each AEZ.

$$W_{i,a,b,d} = G\frac{C}{G}\underbrace{\left(\frac{C_i}{C}\,\frac{C_{i,b}}{C_i}\,\frac{C_{i,b,a}}{C_{i,b}}\,\frac{C_{i,b,a,d}}{C_{i,b,a}}\right)}_{\substack{\text{relocation}-across\\ \text{riverbasins-AEZ-gridcells}}}\underbrace{\left(\frac{I_{i,b,a,d}}{C_{i,b,a,d}}\right)}_{\substack{\text{rainfed}\\ \text{substitution}}}\underbrace{\left(\frac{W_{i,b,a,d}}{I_{i,b,a,d}}\right)}_{\frac{WLVA}{I}\frac{W}{WLVA}} \tag{5}$$

2.4 Experiment

This paper decomposes changes in water use for GTAP-BIO-W model by Liu et al. (2014) who impose an external estimate of the change in irrigation water availability, by river basin, based on Rosegrant et al. (2013). These are reported in table A1. The structure of their model is illustrated in figure A1, and A2. The GTAP-BIO-W model structure follows our top-down functional form assumptions. They assume one production function with many heterogeneous water-land inputs (varying by AEZ and river basin). A description of the standard GTAP model can be found in Hertel et al. (1997). Details about the GTAP-BIO-W model can be found in Taheripour et al. (2013). As shown in Figure A1, each region's crop production is split into two sectors - irrigated and rainfed. They produce the same commodity and share the same cost structure for non-water inputs. Thus, any additional productivity associated with the irrigated crop is completely explained by the use of irrigation. The revenue difference generated by water is assumed to be equal to the shadow value of water in production of a given crop at a given location. The total water endowment is fixed at the river basin level, but water within in river basin can be drawn upon by different AEZs. To represent this fluid water movement, the authors assign a relatively large elasticity of substitution parameter (Ω=20) to land parcels that reside in the same river basin. Irrigated farming in different AEZs competes for 'blue water'. Livestock, rainfed crops and forestry compete for land.

The model also allows for land conversion between rainfed and irrigated agriculture by assigning a relatively large elasticity of substitution parameter (Ω=10) to the nesting of managed land. Crop production using value added inputs is depicted with a production tree with four different nests (Figure A2). Leontief (fixed proportion) functional form is used for the nest of land and water, indicating the two primary inputs are complementary. For the other nests, Constant Elasticity of Substitution (CES) functional form is used to allow substitution between inputs. The irrigation availability shock is applied to the water endowment associated with specific river basins.

We construct a regional production index using their results. This allows for use of the bottom–up decomposition approach. For decomposing changes in water use, we totally differentiate the above equations and generate a percentage change form appropriate for use in the GEMPACK modeling software suite (Harrison and Pearson, 1996). Water use in each region adds up the water use in production of various crops in different AEZs in all river basins of the region. Then, corresponding variable levels for each of the component parts are used from their result. Finally, these pieces are assembled to demonstrate irrigation water decomposition. Then any individual component is explored in more details to find out where the results are coming from.

3 Results

Liu et al. (2014) employ a model which includes 6 crops, 19 regions, up to 18 Agro Ecological Zones and 20 river basins in each region, and 126 river basins globally. Their experiment is shown in table A1 and implies global water use will decrease by almost 5.5% due to the shock, with the largest reductions coming in South Asia and China.

This study measures the importance of different drivers in decline in water use. We find that aggregate decomposition, top-down decomposition, and bottom-up decomposition yields the same results. Note that simple add-up of bottom-up water use leads to misleading results as it ignores the weight of each farm unit in each different driver.

Figure 1 shows the decomposition of Liu et al. (2014) results. Here, substitution to rain fed production (the light blue bar) contributes to 62% of the change; substitution by non-crop products explains 16% of it; changes in crop mix account for 6% of the reduction; while relocation in river basins and AEZs are responsible for 7% of the change.

The regional decomposition demonstrates different importance of each drivers. Figure 2 shows the final change in water use in each region. Then, figure 3 illustrates the regional decomposition. We find that in regions with higher water reduction, the main drivers are rain fed substitution, change in crop mix, and value added substitution. However, for USA, EU, Brazil, Japan, and Central America crop mix is changed towards more crops and production moves to more water intensive locations. For the EU, Brazil, and Central America, the rain fed production is decreased while irrigation is increased.

Figure 4, shows the decomposition by crops. Water use reduction is bigger for wheat and other agricultural products. The rainfed substitution is important for other agricultural production. According to figure 5, 32% of water use reduction is due to other agriculture, 27% due to wheat, and 19 % due to sugar production.

4 Summary and Implications for the Water

This paper measured the importance of different drivers of change in irrigation water use regionally and globally. A decomposition tool is introduced which is applied via top-down and bottom-up approaches. We use the results of Liu et al. (2014) on the impacts of future irrigation shortfalls. We find that rain fed substitution, change in the crop mix, and moving to farms with higher water productivity are the most important factors in adaptation to a water shock.

Our findings suggest that rain fed substitution is the likely response to water shocks. However, some regions can adapt to water shocks by changing their crop mix and relocating crop production. Relocation can be solution for China and India while China and Rest of south Asia can also benefit by optimizing the crop mix.

We find that relocation is not always leading to lower water use; In Middle East, Africa, and Rest of South East Asia, relocation will increase the water use. However rain fed substitution and non-crop substitution is an option for these regions.

Future studies can address the possible puzzles in the results of different studies of water use. These puzzles can be addressed using the decomposition tools outlined above.

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6 Tables and figures

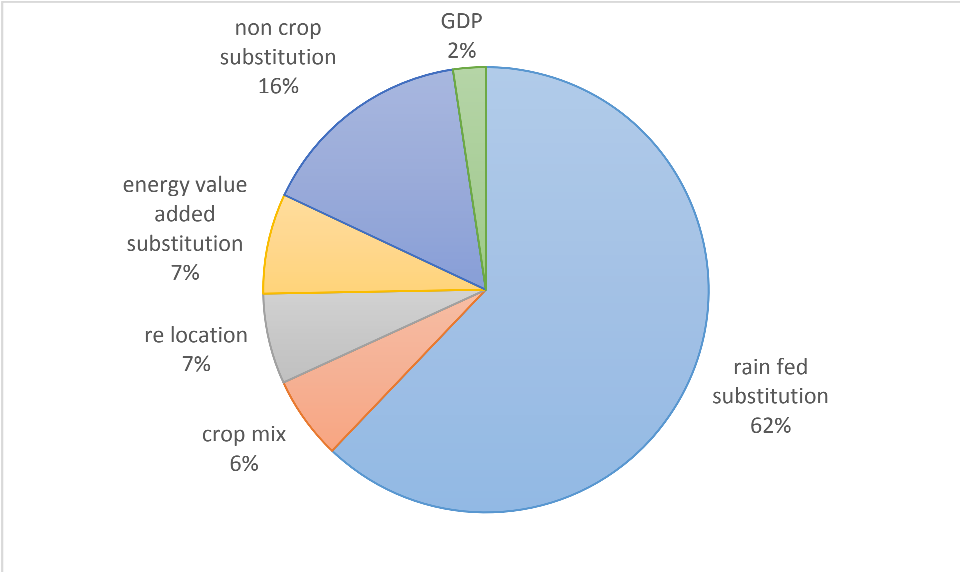

Figure 1: **Global decomposition, relative importance of main drivers of change in irrigation water use**

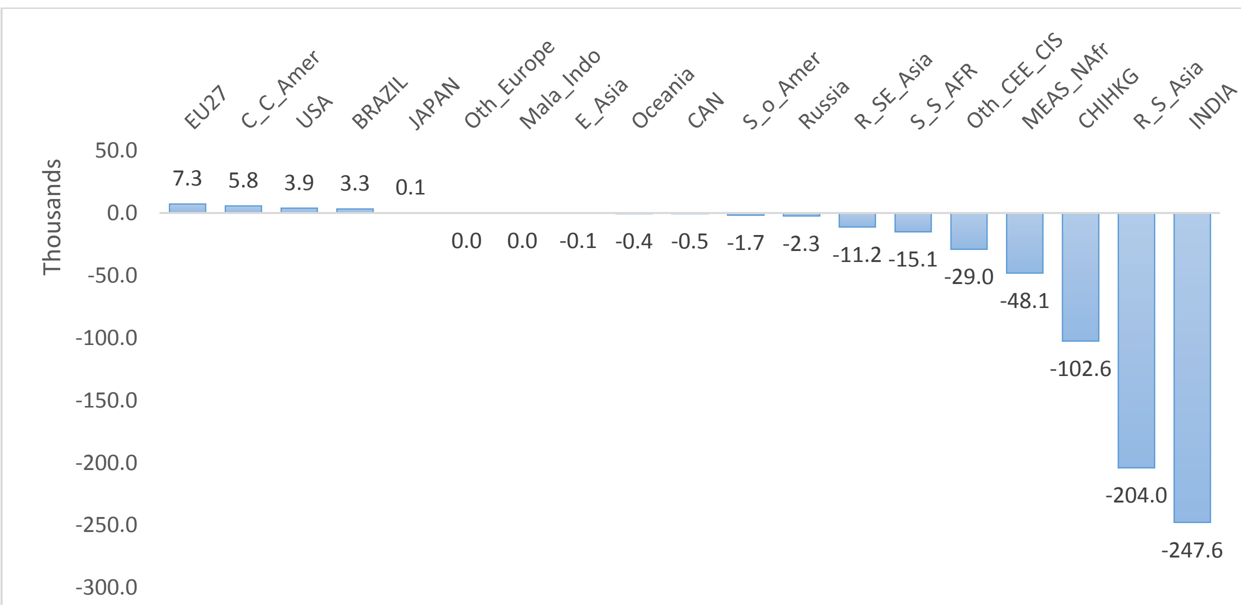

Figure 2: **Regional decrease in irrigation water use, in Million M3**

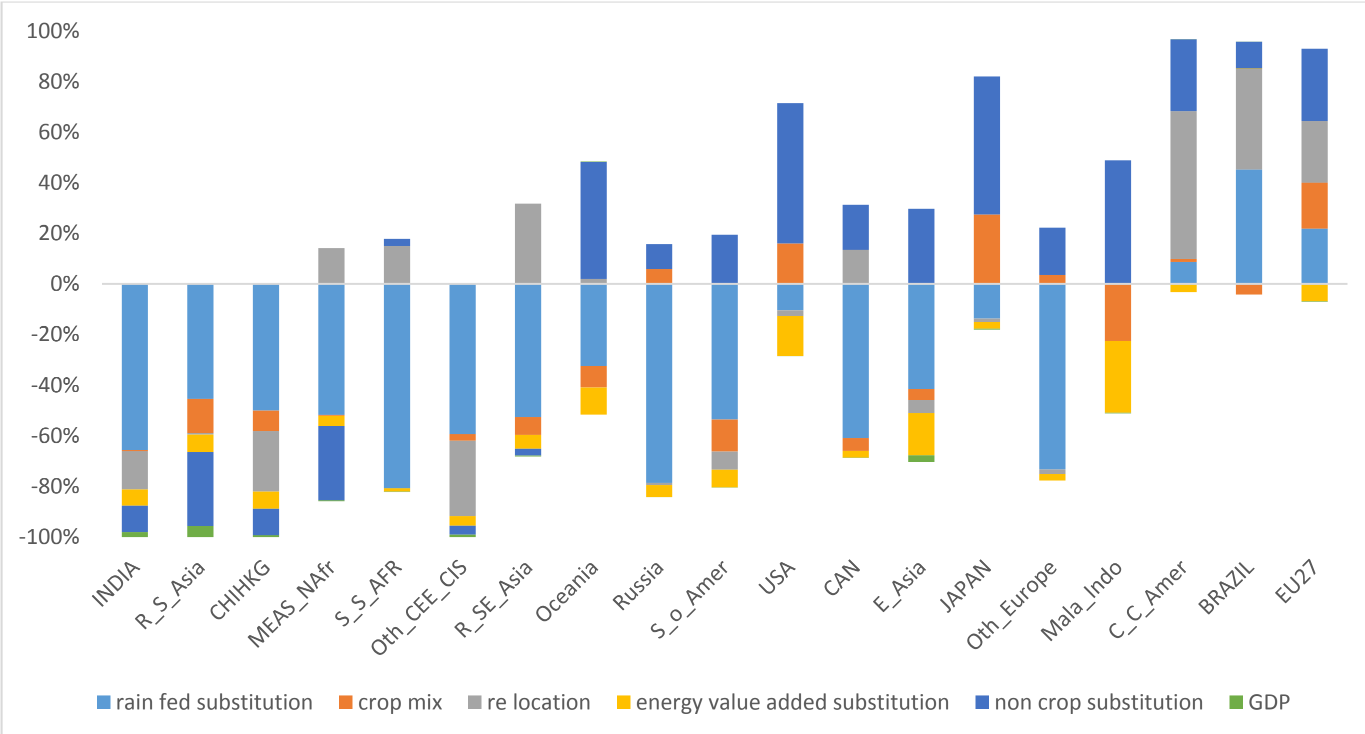

Figure 3: **Regional decomposition, relative importance of main drivers of change in irrigation water use**

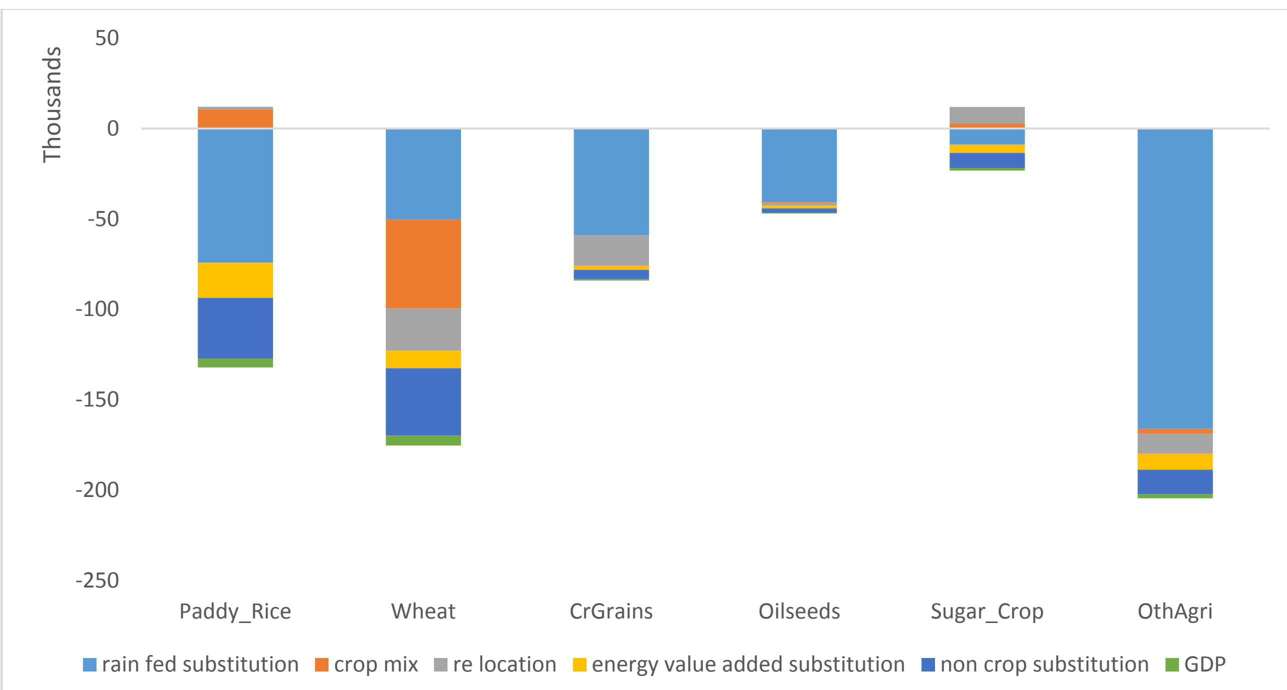

Figure 4: Global decomposition by crop, reduction of irrigation water use by crop in Million m3

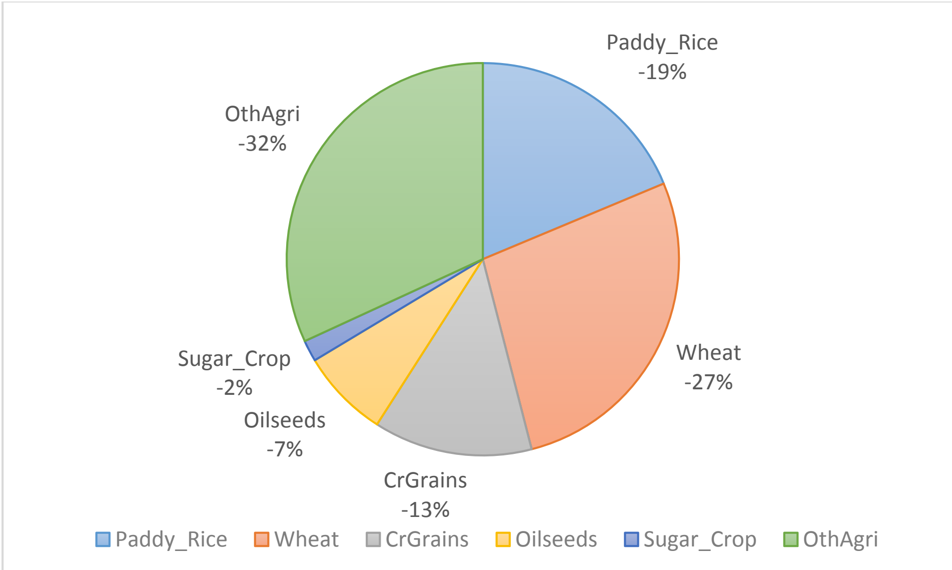

Figure 5: contribution of crops in reduction in irrigation water use

7 Appendix

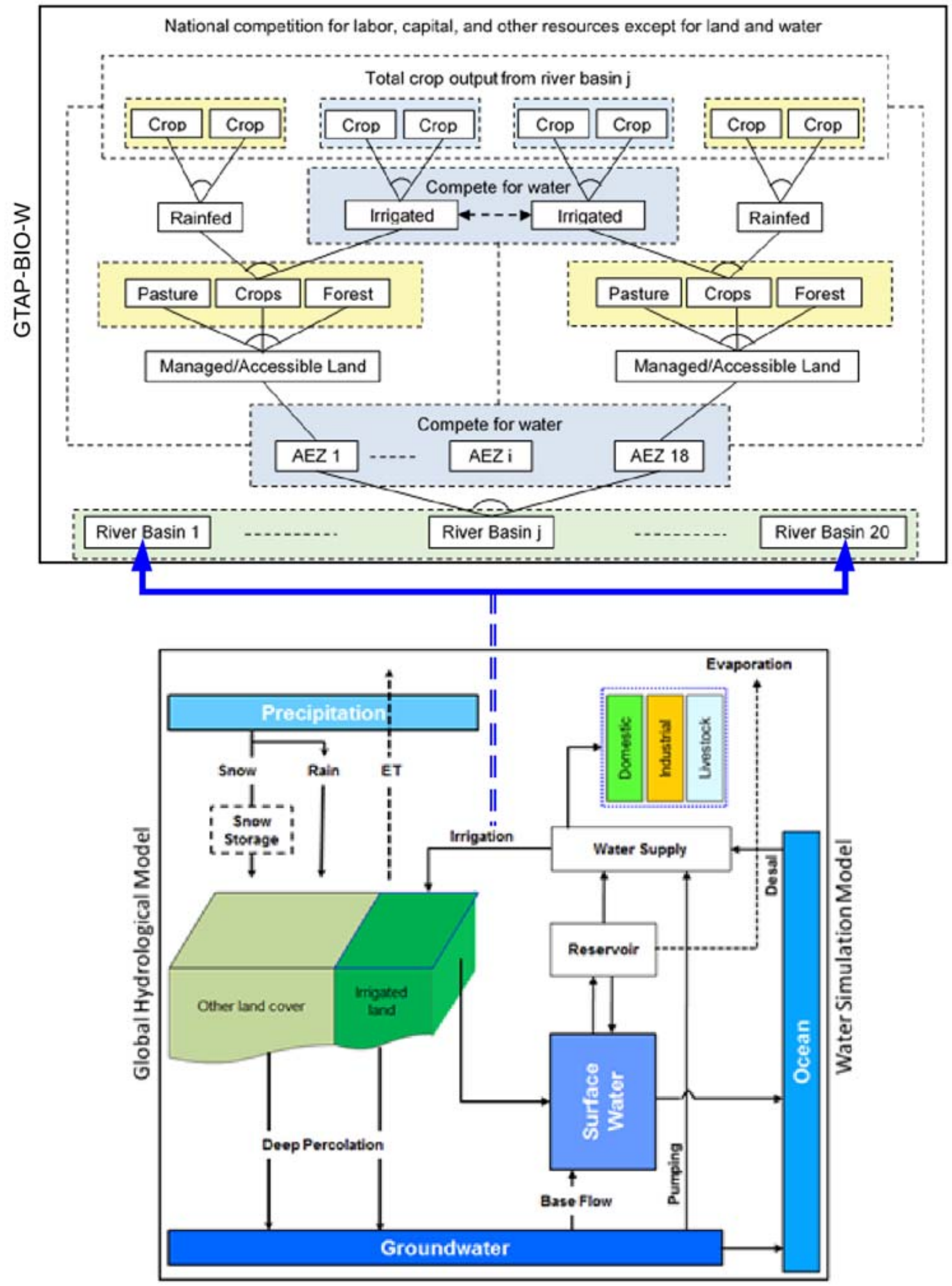

Figure A1. Schematic of GTAP-BIO-W and IMPACT-WATER. The upper part of the schematic illustrates the production of crops in the GTAP-BIO-W model. The lower part of the schematic illustrates how the irrigation water availability is determined by the IMPACT-WATER model. The two models are applied separately and sequentially. The blue lines connecting them show that the output of IMPACT-WATER (i.e. irrigation availability) is used as an input of GTAP-BIO-W. Structure of the global hydrological model IGHM and water simulation model IWSM is adapted from Zhu et al. (2013).

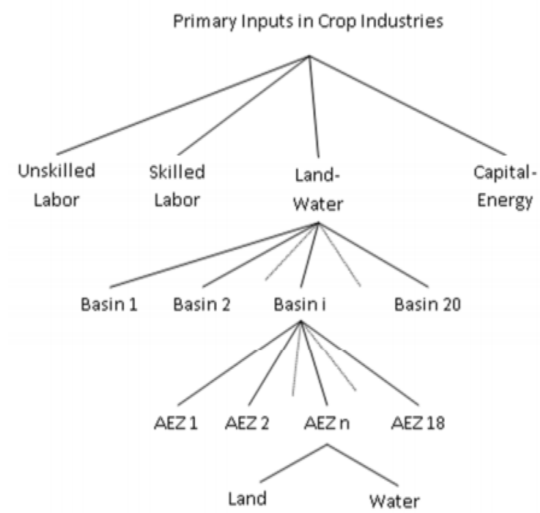

Figure A2. Structure of primary inputs for crop production (extracted from Taheripour et al. 2013a)

Table A1: Shocks on irrigation availability (%).

Region	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
USA	0	0	0	0	0	10.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EU27	0	0	0.7	0	0	18.1	0	0	0	0	0	-2	-11.4	0	0	0	0	0	0	0
BRAZIL	0	0	-16.1	0	0	0	-50	45.4	0	0	0	0	0	0	0	0	0	0	0	0
CAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JAPAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHN&HK	-23	-13.1	-1	-2	-64.3	-24	-32	0	13.1	0	0	0	-0.6	-15.5	-0.1	0	0	0	0	0
INDIA	-0.1	0	0	-10.6	-22	-9.2	2.9	-2.6	-7.9	-20	0	-61.3	0	0	0	0	0	0	0	0
Central America	19.1	0	11.8	0	0	0	0	-2.3	0	0	0	0	0	0	0	0	0	0	0	0
South America	0	0	0	0	0	0	0	0	-7.9	0	-15	0	0	0	0	0	0	0	0	0
East Asia	-10.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MLYS & IDN	5.1	0	0	0	-0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R. Southeast Asia	0	13.5	-0.1	0	-26.7	-2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R. South Asia	-0.6	-2	-1	-43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Russia	0	-58.4	0	0	0	0	0	0	-14.2	-8	-0.1	-16.2	0	0	0	0	0	0	0	0
E-Europe-RFSU	-0.6	0	-29.7	12.3	0	-0.2	18.1	0	0	-11.7	0	-0.3	-13.8	-8.3	-30.3	0	0	0	0	0
R. Europe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M-East-N-Africa	-4.8	-34.6	-30.1	0	-4.3	0	0	-0.4	0	0	0	0	0	0	0	0	0	0	0	0
SSA	-1.2	0	-84.5	-20.5	0	-1.1	-2.4	-26.6	-3	0	0	0	-0.7	-21	-0.2	9.8	0	-27.6	-1.2	0
Oceania	0	0	0	0	0	-24.4	15	0	0	0	0	0	0	0	0	0	0	0	0	0

Source: Liu et al. (2014)