The GTAP-W model: accounting for water use in agriculture

Article · January 2011

3 authors:

Alvaro Calzadilla
University College London

Katrin Rehdanz
Christian-Albrechts-Universität zu Kiel

Richard S.J. Tol
University of Sussex

Kiel
Working Papers

Kiel Institute
for the World Economy

The GTAP-W model: accounting for water use in agriculture

by Alvaro Calzadilla, Katrin Rehdanz and Richard S.J. Tol

No. 1745 | November 2011

Web: www.ifw-kiel.de

Kiel Working Paper No. 1745 | November 2011

The GTAP-W model: accounting for water use in agriculture

Alvaro Calzadilla, Katrin Rehdanz and Richard S.J. Tol

Abstract:
Water and agriculture are intrinsically linked. Water is essential for crop production and agriculture is the largest consumer of freshwater resources. However, this link is commonly ignored by economic models mainly because water use is not reported in the national economic accounts. Few regions have markets for water. This paper describes the new version of GTAP-W, a multi-region, multi-sector computable general equilibrium model of the world economy. The new version of GTAP-W distinguishes between rainfed and irrigated agriculture and introduces water as an explicit factor of production for irrigated agriculture. Moreover, the new production structure accounts for substitution possibilities between irrigation and other primary factors. The new model has been used to study a variety of topics including: irrigation efficiency, sustainable water use, climate change and trade liberalization. This paper is a technical description of the data and features added to the standard GTAP model.

Keywords: Computable General Equilibrium, Irrigation, Water Policy

JEL classification: D58, Q17, Q25

Alvaro Calzadilla
Kiel Institute for the World Economy
24100 Kiel, Germany
Telephone: +49 431 8814-401
E-mail: alvaro.calzadilla@ifw-kiel.de

Katrin Rehdanz
Kiel Institute for the World Economy
24100 Kiel, Germany
Telephone: +49 431 8814-407
E-mail: katrin.rehdanz@ifw-kiel.de

Richard S.J. Tol
Economic and Social Research Institute
Dublin 2, Ireland
Telephone: +353 1 8632000
E-mail: richard.tol@esri.ie

1. Introduction

Most economic activities require water as an input of production but in many regions of the world, there are no markets for water. Water is also often underpriced, free or even subsidized, creating little incentives to conserve water and limiting the scope for efficient allocation of water resources. Because there is often no economic transaction, water use is not commonly reported in the national economic accounts, which hampers the analysis of water resources with economic models. Despite these problems, partial and general equilibrium models have been used to analyze water use and the effect of water policies. Most of these studies focus at the farm-level, the river-catchment-level or the country-level, and thus miss the international trade dimension of water use. The model presented here is a multi-region, multi-sector model of the world economy, which explicitly includes water as a factor of production.

Agriculture is by far the largest consumer of freshwater resources. Globally, around 70 percent of all freshwater withdrawals are used for irrigation, 20 percent are used by industry (including energy) and 10 percent are used for residential purposes (United Nations 2009). Although irrigated agriculture covers only about 20 percent of the world's cultivated land today, it is responsible for around 40 percent of the world's crop production (United Nations 2009). Over the past four decades, irrigation has undoubtedly contributed to an increase in global crop yields, allowing global food production to keep pace with population growth (United Nations 2006).

Local and global food markets are closely interconnected. The volume of world agricultural trade has grown even more rapidly than the volume of world agricultural production (Tangermann 2010). Agriculture, however, is not only linked with the food processing sector. Since the ethanol boom in 2006, energy and agricultural markets are becoming integrated and national biofuels policies have spread from local agricultural markets to global production and trade (Tyner 2010).

In this paper, we present a new version of the GTAP-W model, which introduces water as an explicit factor of production in the agricultural sector and discriminates between rainfed and irrigated agriculture. The GTAP-W model is a global computable general equilibrium (CGE) model. The sectoral and regional focus of the model captures the economy-wide reallocation of resources at the inter-sectoral and inter-regional levels—essential to model direct and indirect effects of agricultural policies. Thus, GTAP-W allows for a rich set of economic feedbacks and for a complete assessment of the welfare implications in the context of international trade.

The remainder of the paper is organized as follows: the next section briefly reviews the literature on economic models of water use focusing on the role of water in the production structure. Section 3 describes in detail the revised version of the GTAP-W model. Section 4 shows an illustrative simulation exercise. Section 5 concludes.

2. Water use in economic models

Economic models of water use have generally been applied to look at the direct effects of water policies, such as water pricing or quantity restrictions, on the allocation of water resources. Both partial and general equilibrium models have been used to assess the economic and social effects of water policies (for an overview of this literature see Dudu and Chumi 2008). While partial equilibrium models focus on the sector affected by a policy measure assuming that the rest of the economy is not affected, general equilibrium models consider other sectors or regions as well to determine economy-wide effects. Partial equilibrium models tend to have more detail, at least in the sector under consideration.

Most of the studies analyze pricing of irrigation water only (for an overview of this literature see Johansson et al. 2002). Rosegrant et al. (2002), for example, use the IMPACT model to estimate demand and supply of food and water to 2025. As a partial equilibrium model of agricultural demand, production, and trade, IMPACT uses a system of food supply-and-demand equations to analyze baseline and alternative scenarios for global food demand, food supply, trade, income, and population. Supply-and-demand functions incorporate supply and demand elasticities to approximate the underlying production and demand functions. De Fraiture et al. (2004) extend this to include virtual water trade, using cereals as an indicator. Their results suggest that the role of virtual water trade in global water use is very modest. While the IMPACT model covers a wide range of agricultural products and regions, it ignores the linkages between agriculture and the whole economy; it is a partial equilibrium model.

Studies of water use using general equilibrium approaches are generally based on data for a single country or sub-national region assuming no effects for the rest of the world from the implemented policy. Decaluwé et al. (1999), for example, analyze the effect of water pricing policies on demand and supply of water in Morocco using an extended CGE model which explicitly models different technologies in water production differentiating between southern and northern regions. They introduce the possibility of substitution in the agricultural production function by using a nested constant elasticity of substitution (CES) function (see Figure A1, Annex A). At the first level of the structure, a first nest combines capital and land and a second nest combines water and fertilizer. Thus Decaluwé et al. (1999) emphasize the relationship between water and fertilizers arguing that the potential for substitution can be greater between intermediate goods than between primary factors. At the second level, both composites are linked with a CES, and the output is combined (at the third level) with labour. Finally, the last level combines the composite from the third level with other intermediate goods using a Leontief technology.

Gómez et al. (2004) use a CGE model of the Balearic Islands to analyze the welfare gains by an improved allocation of water rights. In their CGE model water is a factor of production used by farmers and the firm that supplies water, which owns some concessional water rights. Crop production is modelled by using a nested CES structure (see Figure A2, Annex A). At the first level, a first nest combines capital and land and a second nest combines groundwater and energy. That is, they introduce a water extraction technology where producing water for crops requires groundwater and energy, which are combined using a Leontief technology. At the second level, both composites are combined in a CES, which in a third aggregation level is combined with labour. At the top level, the composite from the third level is combined with other intermediates inputs using a Leontief technology.

Other studies introduce irrigation water at the top level of the nested CES structure. Van Heerden et al. (2008), for example, study the effects of water charges on water use, economic growth, and the real income of 44 types of households using a CGE model of South Africa. The production structure of the model combines raw water with primary factors and intermediate inputs at the top level of the CES structure using a Leontief technology (see Figure A3, Annex A).

Peterson et al. (2004) use the TERM-Water CGE model of the Australian economy to model water trade in the Southern Murray-Darling Basin. Crop production in TERM-Water includes irrigation water as an endowment, which is combined with a bundle of non-water inputs at the top level of the CES production function (see Figure A4, Annex A). Based on the Australian TERM model, Horridge and Wittwer (2008) develop a multi-regional CGE model of China (SinoTERM) to analyze the regional economic impacts of region-specific shocks to water availability.

In a recent analysis, Dixon et al. (2010) use the TERM-H2O model, a dynamic version of the TERM model with detailed regional water accounts, to model the Australian government's buyback scheme. As opposed to TERM-Water, water resources in TERM-H2O are introduced at the bottom of the nested CES production structure (see Figure A5, Annex A). Dixon et al. (2010) assume that crop production is a Leontief function of intermediate inputs and primary factors. The composite primary factor is a CES combination of physical capital, hired labour and land-operator. The composite land-operator is a CES nest of inputs of operator labour (the farmer and family) and total land. The composite total land is a CES combination of effective land and cereal. This nest is relevant only for dry-land livestock industries, assuming that a given amount of livestock can be maintained on less land if more cereals are used. The composite effective land is a CES combination of irrigated land, unwatered irrigable land and dry land. While unwatered irrigable land and dry land is relevant only for rainfed farms, irrigated land is significant only for irrigated farms. Finally, at the bottom of the CES structure, the composite irrigated land is a Leontief combination of unwatered irrigable land and irrigation water.

A few *global* CGE models have been used to analyze the role of water resources in the agricultural sector. Based on the Basic Linked System (BLS), Fischer et al. (1994, 1996) study the impact of climate change on agriculture and the world food system as well as the socio-economic consequences for the period 1990-2060. The BLS model has been used in conjunction with the Agro-Ecological Zone (AEZ) model to analyze potential impacts of climate change in agro-ecological and socio-economic systems up to 2080 (Fischer et al. 2005; Fischer et al. 2007; Tubiello and Fischer 2007). The results suggest regional and temporal asymmetries in terms of impacts due to diverse climate and socio-economic structures. Although water use within the AEZ-BLS systems is consistent with agriculture production, water and crop production are not fully coupled. That is, changes in crop production simulated by BLS are not fully reflected in the AEZ water estimations (Fischer et al. 2007).

Darwin et al. (1995) use the Future Agricultural Resources Model (FARM) to study the role of adaptation in adjusting to new climate conditions. The FARM model differentiates six land classes according to the length of the growing season and is composed of a geographic information system that links climate with land and water resources; and a global CGE model that simulates world production, consumption and trade at regional-level. Darwin (2004) uses the FARM model to analyze climate change impacts on global agriculture. The results suggest that regions with a relatively large share of income from agricultural exports may be vulnerable not only to direct climate-induced agricultural damages, but also to positive impacts induced by greenhouse gas emissions elsewhere. In the FARM model, within each land class, crops are produced from a composite input obtained by combining a composite primary factor with 13 composite commodity inputs using a Leontief technology (see Figure A6, Annex A). The composite primary factor is derived from a CES aggregate of land, labour, capital and water. Each of the 13 composite commodities inputs is composed of domestically produced commodities and imported commodities (Darwin and Kennedy 2000). Although water is a factor of production, the FARM model does not distinguish between rainfed and irrigated crops, which is crucial since rainfed and irrigated agriculture face different climate risk levels.

Using a previous version of the GTAP-W model, a global CGE model including water resources, Berrittella et al. (2006, 2007, 2008a and 2008b) analyze the economic impact of various water resource policies. The first version of GTAP-W combines water, value-added and intermediate inputs at the top level of the nested CES structure using a Leontief technology (see Figure A7, Annex A). That is, water, value-added and intermediate inputs are used in fixed proportions, there are no substitution possibilities between them. Unlike its predecessor, the revised GTAP-W model, used here, distinguishes between rainfed and irrigated agriculture. Furthermore, the new production structure of the model introduces water as an explicit factor of production and accounts for substitution possibilities between water and other primary factors.

3. The GTAP-W model: A GTAP based model for the assessment of water resources and trade

The GTAP-W model is a multiregional world CGE model. The model is a further refinement of the GTAP model (Hertel 1997), a standard static CGE model distributed with the Global Trade Analysis Project (GTAP) database of the world economy. GTAP-W is based on the version modified by Burniaux and Truong (2002) as well as on the previous GTAP-W model introduced by Berrittella et al. (2007). Burniaux and Truong (2002) developed a special variant of the model, called GTAP-E, which is best suited for the analysis of energy markets and environmental policies. GTAP-E introduces two main changes in the basic structure. First, energy factors are separated from the set of intermediate inputs and inserted into a nested level of substitution with capital. This allows for more substitution possibilities. Second, the database and model are extended to account for CO_2 emissions related to energy consumption.

Two crucial features differentiate version 2 of GTAP-W, used here, and version 1, used by Berrittella et al. (2007). First, the new production structure accounts for substitution possibilities between irrigation and other primary factors. Second, version 2 distinguishes rainfed and irrigated agriculture while version 1 did not make this distinction. The remainder of this section describes in detail the irrigation data used and the modifications to the standard GTAP database and model.

3.1. The GTAP-W baseline data

The new GTAP-W model is based on the GTAP version 6 database (Dimaranan 2006), which represents the global economy in 2001, and on the IMPACT 2000 baseline data (Rosegrant et al. 2002). The IMPACT model is a partial equilibrium agricultural sector model combined with a water simulation model. IMPACT encompasses most countries and regions and the main agricultural commodities produced in the world. As a spatial representation, IMPACT uses 281 "food-producing units" (FPUs), which represent the spatial intersections of 115 economic regions and 126 river basins. Water simulation and crop production projections are conducted at the FPU level, while projections of food demand and agricultural commodity trade are conducted at the country or economic region level. The disaggregation of spatial units improves the model's ability to represent the spatial heterogeneity of agricultural economies and, in particular, water resource availability and use.

For each FPU and for 23 crops, the IMPACT model provides information on rainfed and irrigated harvested area, rainfed and irrigated yields, and green and blue water used in rainfed and irrigated production.[1] Green water used in crop production or effective rainfall is part of the rainfall that is stored in the root zone and can be used by plants. The effective rainfall depends on the climate, the soil texture, the soil structure and the depth of the root zone. The blue water used in crop production or irrigation is the applied irrigation water diverted from water systems. The blue water used in irrigated areas contributes additionally to the freshwater provided by rainfall (Rosegrant et al. 2002).

Figure 1 shows a world map indicating the share of irrigated agriculture in total crop harvested area, crop production and water use by FPU. The bluer the color the higher the share of irrigated agriculture, reciprocally the greener the color the higher the share of rainfed agriculture. The upper map in Figure 1 shows that irrigated areas are concentrated in the US, western South America, Libya, Egypt, the Middle East, South Asia and China. Irrigated agriculture becomes more important when irrigated production is compared to total crop production (central map) and even more when the water used for irrigated crop production is considered (lower map). Globally, around 33 percent of the world's crop harvested area is under irrigation. Irrigated agriculture contributes nearly 42 percent to the world's food production and consumes more than half of the total water used for crop production.

The information provided by IMPACT is summarized in Table 1 at the regional and sectoral level according to the GTAP-W aggregation.[2] There are three major irrigation water users: South Asia (35 percent), China (21 percent) and USA (15 percent). Together, these regions use more than 70 percent of the global freshwater used for irrigation (blue water). Globally, irrigated rice production accounts for 73 percent of the total rice production. Although 47 percent of sugar cane and wheat is produced using irrigation, the volume of irrigation water used in sugar cane production is less than one-third of what is used in wheat production. The irrigated production of rice and wheat consumes half of the irrigation water used globally, and together with cereal grains and "other agricultural products" irrigation water consumption rises to 80 percent.

[1] As an example of the IMPACT data, Figures B1 and B2 in Annex B show harvested area, production and water used for the production of vegetables by FPU.

[2] See Table B1 in Annex B for the regional, sectoral and factoral aggregation used in GTAP-W and the mapping between GTAP-W and IMPACT.

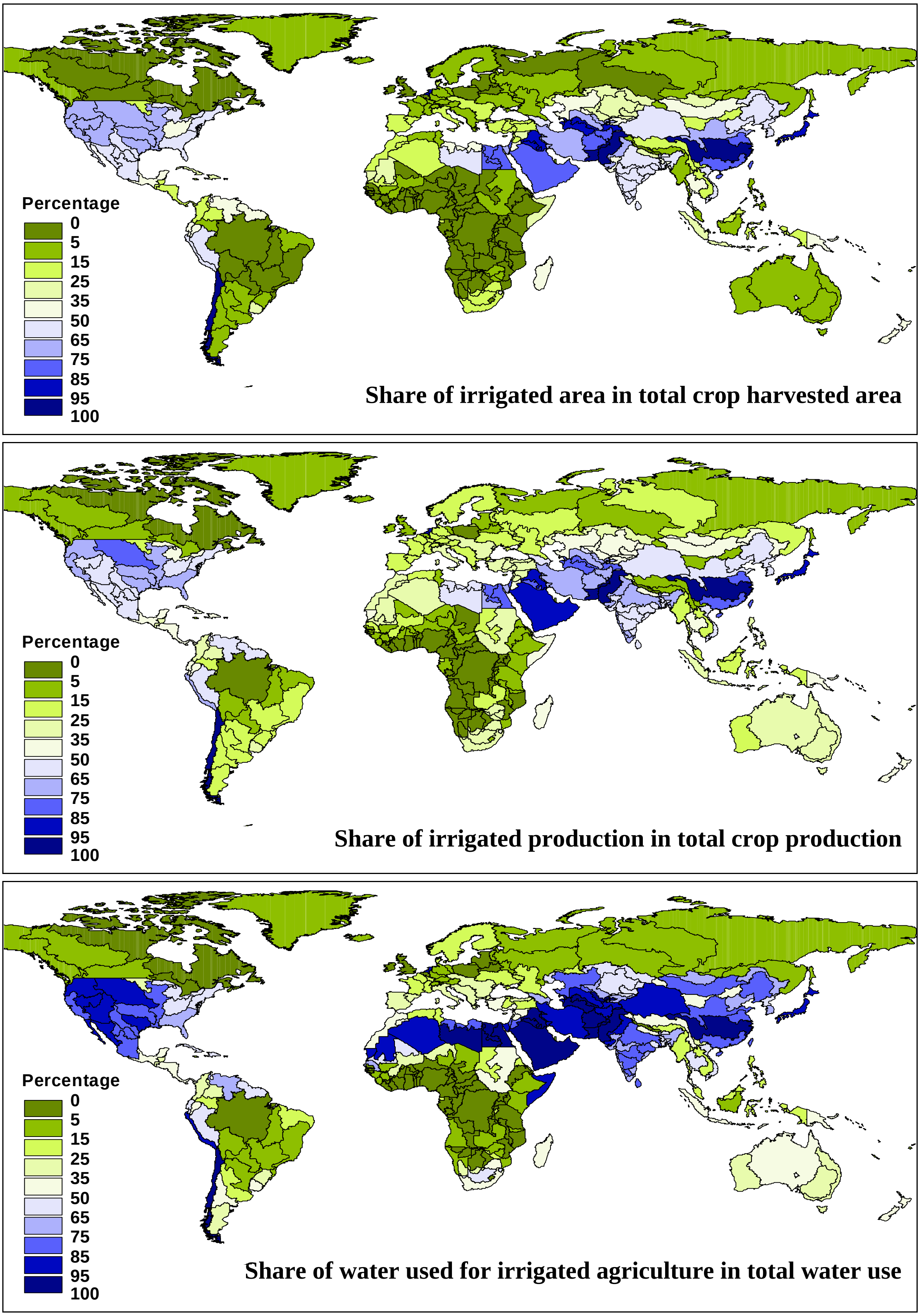


Figure 1. 2000 baseline data: Share of irrigated agriculture in total harvested area, production and water use by food producing units (FPUs)
Source: IMPACT 2000 baseline data (April 2008).

Table 1. 2000 baseline data: Crop harvested area, production and water use by region and crop

Description	Rainfed Agriculture			Irrigated Agriculture				Total			
	Area (thousand ha)	Production (thousand mt)	Green water (km^3)	Area (thousand ha)	Production (thousand mt)	Green water (km^3)	Blue water (km^3)	Area (thousand ha)	Production (thousand mt)	Green water (km^3)	Blue water (km^3)
Regions (total, all crops)											
United States (USA)	35,391	209,833	89	67,112	440,470	159	190	102,503	650,303	248	190
Canada (CAN)	27,267	65,253	61	717	6,065	2	1	27,984	71,318	62	1
Western Europe (WEU)	59,494	462,341	100	10,130	146,768	19	10	69,624	609,108	118	10
Japan and South Korea (JPK)	1,553	23,080	6	4,909	71,056	21	3	6,462	94,136	27	3
Australia and New Zealand (ANZ)	21,196	67,204	45	2,237	27,353	5	15	23,433	94,557	50	15
Eastern Europe (EEU)	37,977	187,468	95	5,958	40,470	16	14	43,935	227,939	111	14
Former Soviet Union (FSU)	85,794	235,095	182	16,793	74,762	25	47	102,587	309,857	208	47
Middle East (MDE)	29,839	135,151	40	21,450	118,989	25	62	51,289	254,140	65	62
Central America (CAM)	12,970	111,615	47	8,745	89,637	28	46	21,715	201,252	76	46
South America (SAM)	79,244	649,419	335	9,897	184,304	40	47	89,141	833,723	375	47
South Asia (SAS)	137,533	491,527	313	114,425	560,349	321	458	251,958	1,051,877	634	458
Southeast Asia (SEA)	69,135	331,698	300	27,336	191,846	134	56	96,471	523,543	434	56
China (CHI)	64,236	615,196	185	123,018	907,302	419	278	187,254	1,522,498	604	278
North Africa (NAF)	15,587	51,056	19	7,352	78,787	4	42	22,938	129,843	23	42
Sub-Saharan Africa (SSA)	171,356	439,492	588	5,994	43,283	19	37	177,349	482,775	608	37
Rest of the World (ROW)	3,810	47,466	12	1,093	23,931	5	5	4,903	71,397	16	5
World	**852,381**	**4,122,894**	**2,417**	**427,164**	**3,005,371**	**1,242**	**1,310**	**1,279,545**	**7,128,265**	**3,659**	**1,310**
Crops (total, all regions)											
Rice	59,678	108,179	264	93,053	294,934	407.55	320.89	152,730	403,113	671	321
Wheat	124,147	303,638	240	90,492	285,080	133.49	296.42	214,639	588,718	374	296
Cereal grains	225,603	504,028	637	69,402	369,526	186.53	221.22	295,005	873,554	824	221
Vegetables, fruits, nuts	133,756	1,374,128	394	36,275	537,730	95.53	81.59	170,031	1,911,858	489	82
Oil seeds	68,847	125,480	210	29,578	73,898	72.54	78.75	98,425	199,379	282	79
Sugar cane, sugar beet	16,457	846,137	98	9,241	664,023	48.86	89.07	25,699	1,510,161	147	89
Other agricultural products	223,894	861,303	574	99,122	780,180	297.22	222.11	323,017	1,641,483	871	222
Total	**852,381**	**4,122,894**	**2,417**	**427,164**	**3,005,371**	**1,242**	**1,310**	**1,279,545**	**7,128,265**	**3,659**	**1,310**

Note: 2000 data are three-year averages for 1999-2001. Green water (effective rainfall) and blue water (irrigation water).
Source: Own calculation based on IMPACT, 2000 baseline data (April 2008).

3.2. The GTAP-W land rents and irrigation rents

In the standard GTAP database, agricultural land is a homogeneous factor of production classified as a sluggish endowment. That is, land is imperfectly mobile across agricultural sectors. While perfectly mobile factors (e.g. capital) earn the same market return regardless of where they are employed, market returns for imperfectly mobile factors may differ across sectors. The header $VFM_{i,j,r}$ (value of purchases of endowment commodity *i* by firms in sector *j* of region *r* evaluated at market prices) in the GTAP database represents the total value-added including land rents. To develop the new version of the GTAP-W model, we split for each region the GTAP sectoral land rents into rents derived from irrigation (*Wtr*), irrigable land (*Lnd*), rainfed land (*RfLand*) and pasture land (*PsLand*).

Land as a factor of production in national accounts represents 'The ground, including the soil covering and any associated surface waters, over which ownership rights are enforced' (United Nations 1993). Therefore, we assume that the value of irrigation water is embedded in the value of land. To accomplish this, we first split, for each region and each crop, the value of land included in the GTAP Social Accounting Matrix (SAM) into the value of rainfed land and the value of irrigated land.[3]

As in all CGE models, economic flows in GTAP are expressed in value terms, where prices are used to weight all underlying quantities. We could arrive at the value of rainfed and irrigated land by simply multiplying the corresponding prices and quantities (i.e. US$ / ha * total ha). However, the lack of market information on land rents by crop and country limits this approach. We therefore use the share of rainfed and irrigated production in total production to split, for each crop and each region, the value of land in the original GTAP database into the value of rainfed land (see equation 1 below) and the value of irrigated land. For example, let us assume that 60 percent of total rice production in region *r* is produced on irrigated farms and that the returns to land in rice production are US$100 million. Thus, we have for region *r* that irrigated land rents in rice production are US$60 million and rainfed land rents in rice production are US$40 million. Regional information on rainfed and irrigated production by crop is based on IMPACT data (Rosegrant et al. 2002) (Table 2).

Table 2. Share of irrigated production in total production by region and crop (percentages)

Region	Rice	Wheat	CerCrops	VegFruits	OilSeeds	Sug_Can	Oth_Agr	Total
USA	51.0	78.9	70.3	34.2	68.4	48.0	100.0	**67.7**
CAN	0.0	1.9	10.4	34.7	3.3	44.1	0.0	**8.5**
WEU	48.8	19.6	16.3	35.3	5.7	40.3	5.0	**24.1**
JPK	93.7	79.7	65.3	66.3	32.1	56.6	81.5	**75.5**
ANZ	48.1	12.8	17.9	33.7	11.7	48.3	9.3	**28.9**
EEU	48.5	30.3	18.8	19.0	5.8	29.0	0.0	**17.8**
FSU	49.4	20.8	9.7	28.3	6.2	40.2	24.6	**24.1**
MDE	55.8	45.4	29.6	51.8	47.1	49.6	44.5	**46.8**
CAM	46.8	55.4	49.0	47.3	56.5	42.0	43.7	**44.5**
SAM	63.3	9.7	12.4	20.5	0.7	27.8	17.6	**22.1**
SAS	70.3	75.5	31.1	33.6	31.5	62.5	41.5	**53.3**
SEA	48.6	49.4	30.7	25.2	45.3	52.0	24.6	**36.6**
CHI	100.0	85.9	73.3	27.0	46.8	41.7	82.7	**59.6**
NAF	82.1	63.9	76.5	56.0	46.8	49.6	65.3	**60.7**
SSA	20.8	28.9	4.7	4.2	5.9	42.1	1.1	**9.0**
ROW	49.5	49.7	10.8	25.4	56.1	39.3	22.4	**33.5**
Total	**73.2**	**48.4**	**42.3**	**28.1**	**37.1**	**44.0**	**47.5**	**42.2**

Source: Own calculations based on IMPACT, 2000 baseline data (April 2008).

[3] For detailed information about the social accounting matrix (SAM) representation of the GTAP database see McDonald et al. (2005).

In the next step, we split the value of irrigated land into the value of irrigable land (see equation 2 below) and the value of irrigation (see equation 3 below). Again, because of lack of market information on land and irrigation rents we use the ratio of irrigated yield to rainfed yield to split, for each region and each crop, the value of irrigated land into the value of irrigable land and the value of irrigation. These ratios are based on IMPACT data (Table 3) and indicate the relative value of irrigated agriculture compared to rainfed agriculture for particular land parcels. For example, let us assume that the ratio of irrigated yield to rainfed yield in rice production in region *r* is 1.5 and that irrigated land rents in rice production in region r are US$60 million. Thus, we have for irrigated agriculture in region *r* that irrigation rents are US$20 million and irrigable land rents are US$40 million.

Table 3. Ratio of irrigated yield to rainfed yield by region and crop

Region	Rice	Wheat	CerCrops	VegFruits	OilSeeds	Sug_Can	Oth_Agr
USA	1.42	1.42	1.42	1.41	1.35	1.42	1.31*
CAN	--	1.36	1.38	1.39	1.30	1.41	1.31*
WEU	1.42	1.36	1.36	1.39	1.30	1.39	1.26
JPK	1.39	1.37	1.36	1.42	1.35	1.43	1.33
ANZ	1.41	1.39	1.38	1.39	1.32	1.43	1.33
EEU	1.41	1.37	1.36	1.36	1.32	1.38	1.31*
FSU	1.42	1.38	1.38	1.40	1.33	1.40	1.32
MDE	1.33	1.36	1.36	1.38	1.37	1.36	1.29
CAM	1.43	1.41	1.40	1.40	1.33	1.39	1.30
SAM	1.44	1.54	1.36	1.36	1.33	1.47	1.30
SAS	1.43	1.41	1.38	1.40	1.39	1.41	1.32
SEA	1.42	1.40	1.35	1.36	1.34	1.41	1.31
CHI	1.40*	1.42	1.42	1.38	1.40	1.44	1.32
NAF	1.33	1.37	1.33	1.34	1.33	1.34	1.31
SSA	1.37	1.36	1.34	1.36	1.34	1.34	1.32
ROW	1.39	1.41	1.34	1.34	1.33	1.39	1.31

Source: Own calculations based on IMPACT, 2000 baseline data (April 2008).
* We use the world average in regions where all production is rainfed or irrigated.

Finally, in the last step, the value of pasture land is derived directly from the value of land in the livestock breeding sector (see equation 4).

The following equations summarize the whole procedure:

$$VFM_{\text{'RfLand'},j,r} = OLDVFM_{\text{'Land'},j,r} * (1-PS_{j,r}) \quad (1)$$

$$VFM_{\text{'Lnd'},j,r} = OLDVFM_{\text{'Land'},j,r} * PS_{j,r} / YR_{j,r} \quad (2)$$

$$VFM_{\text{'Wtr'},j,r} = OLDVFM_{\text{'Land'},j,r} * PS_{j,r} * (YR_{j,r} - 1) / YR_{j,r} \quad (3)$$

$$VFM_{\text{'PsLand'},\text{'Animals'},r} = OLDVFM_{\text{'Land'},\text{'Animals'},r} \quad (4)$$

$$VFM_{i,j,r} = OLDVFM_{i,j,r} \qquad \text{i = Lab, Capital and NatlRes} \quad (5)$$

Where $OLDVFM_{i,j,r}$ is the original (unmodified) $VFM_{i,j,r}$. $PS_{j,r}$ is the share of irrigated production in total production in sector *j* of region *r* and $YR_{j,r}$ is the ratio of irrigated yield to rainfed yield in sector *j* of region *r*. The value-added of other endowments (labour, capital and natural resources) remains unchanged (see equation 5).

Once the header $VFM_{i,j,r}$ has been split, the headers $EVOA_{i,r}$ (value of endowment commodity *i* output or supplied in region *r* evaluated at agents' prices) and $EVFA_{i,j,r}$ (value of purchases of endowment commodity *i* by firms in sector *j* of region *r* evaluated at agents' prices) in the GTAP database are updated according to the following equations:

$$EVOA_{i,r} = \sum_{j \in PROD} VFM_{i,j,r} - HTAX_{i,r} \quad (6)$$

$$EVFA_{i,j,r} = VFM_{i,j,r} + ETAX_{i,j,r} \quad (7)$$

Where $HTAX_{i,r}$ is the tax on households' supply of primary factor *i* in region *r* and $ETAX_{i,j,r}$ is the tax on endowment *i* used by industry *j* in region *r*. For simplicity, we assume that the new factors of production face the same tax rates as the original land endowment. The TABLO files (GEMPACK based program) used to modify the GTAP database for GTAP-W are available on request.

The procedure described above to introduce the four new endowments (irrigation, irrigable land, rainfed land and pasture land) allows us to avoid problems related to model calibration. In fact, since the original database is only split and not altered, the original regions' social accounting matrices are balanced and can be used by the GTAP-W model to assign values to the share parameters of the mathematical equations.

Table 4 shows the world total value-added (header VFM in the GTAP database) including rents for irrigation, irrigable land, rainfed land and pasture land. At the global level, almost half of the original land rents are allocated to rainfed land, 26 percent to irrigable land, 15 percent to pasture land and 10 percent to irrigation. Global land rents differ by crop, while irrigable land rents and irrigation rents in rice production account for more than 70 percent of the original land rents, the share of rainfed land rents is larger in the production of cereals, vegetables, fruits and oil seeds (between 60 and 70 percent). These global figures mask differences in regional land and irrigation rents, as shown in the next section.

Table 4. GTAP-W land and irrigation rents. VFM, world total (million US$)

Description	Rice	Wheat	CerCrops	VegFruits	OilSeeds	Sug_Can	Oth_Agr	Animals	Total
1 Irrigation water (Wtr)	4,951	3,406	3,142	7,546	1,567	1,058	7,184	0	28,854
2 Irrigable land (Lnd)	12,163	8,438	7,810	19,401	4,233	2,581	22,847	0	77,473
3 Rainfed land (RfLand)	6,778	13,156	16,976	53,169	12,192	3,282	37,569	0	143,122
4 Pasture land (PsLand)	0	0	0	0	0	0	0	45,365	45,365
Sub-total (= original land rents)	*23,892*	*25,000*	*27,928*	*80,116*	*17,992*	*6,921*	*67,600*	*45,365*	*294,814*
5 Labour (Lab)	32,404	21,488	24,147	147,140	19,874	9,345	103,418	82,780	440,596
6 Capital (Capital)	12,746	10,663	13,008	59,377	12,011	5,267	59,903	47,868	220,843
7 Natural resources (NatlRes)	0	0	0	0	0	0	0	0	0
Total	**69,042**	**57,150**	**65,083**	**286,634**	**49,876**	**21,531**	**230,921**	**176,013**	**956,250**

Note: Based on the GTAP version 6 database.

3.3. Validation of the GTAP-W land rents and irrigation rents

Based on physical information provided by the IMPACT model (that is, crop harvested area in hectares, crops yields in tonnes per hectare, green water in millimetres and blue water in cubic kilometres), we have developed the GTAP-W database by introducing four new endowments (irrigation, irrigable land, rainfed land and pasture land) to the GTAP database, which is expressed in monetary terms. Therefore, we assume that the monetary values in GTAP-W are consistent with and match food production, land use and water use in IMPACT.

In the GTAP-W benchmark equilibrium, an initial sector and region specific shadow price for irrigation water can be obtained by combining the social accounting matrix information about payments to factors and the volume of water used in irrigation from IMPACT. Figure 2 shows regional ranges and averages (over all crops) of irrigation water prices. The average irrigation water price in most of the regions is between 1 US cents/m^3 and 2.5 US cents/m^3. Prices in Canada, the United States and Southeast Asia are higher, between 3.5 US cents/m^3 and 3.8 US cents/m^3. In Western Europe irrigation water prices reach 14 US cents/m^3. Japan and South Korea seem to be outliers, reporting the highest average irrigation price, around 113 US cents/m^3. However, these prices are consistent with the high land rents observed in this region (see Figure 4 below).

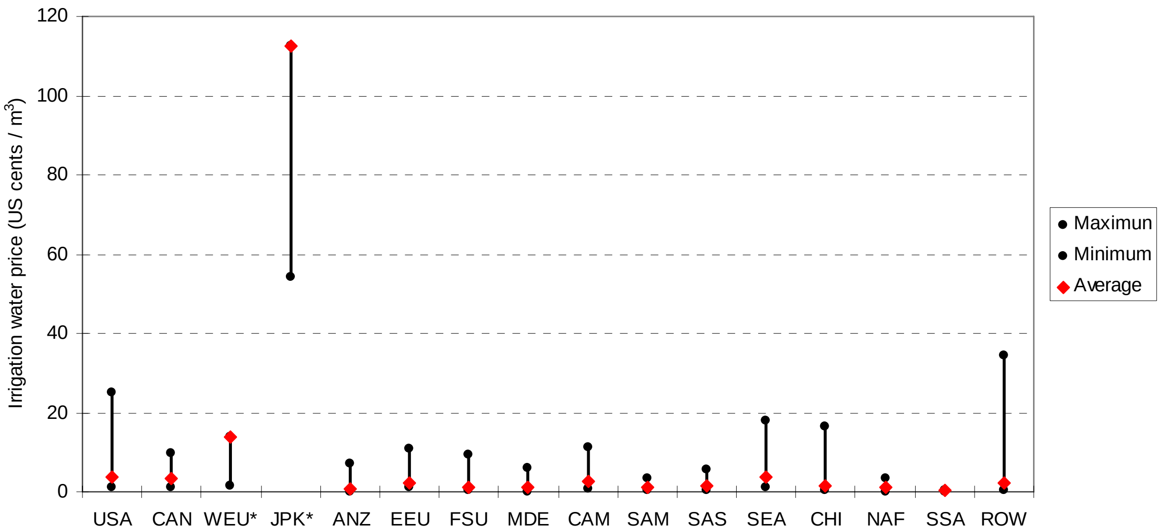


Figure 2. Regional ranges and averages (over all crops) of irrigation water prices per cubic metre

Source: Based on GTAP-W database.

* The maximum value has been deleted for illustrative purposes. Maximum values are: JPK (668 US cents / m^3) and WEU (237 US cents / m^3).

Note: United States (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MDE), Central America (CAM), South America (SAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA) and Rest of the World (ROW).

Regional ranges and averages of irrigation water prices in GTAP-W are consistent with those observed in the literature. Cornish et al. (2004) review an extended literature on irrigation water prices, covering 46 countries worldwide. Their results are summarized in Figure 3. They find important differences in water price and charging mechanisms across countries and within countries, which may reflect different pricing objectives, water sources, degrees of water scarcity and/or irrigation schemes. Besides this heterogeneity in irrigation water charging at the country level, Cornish et al. (2004) suggest that a price of about 2 US cents/m^3 is probably indicative of the average volumetric price charged for irrigation water.

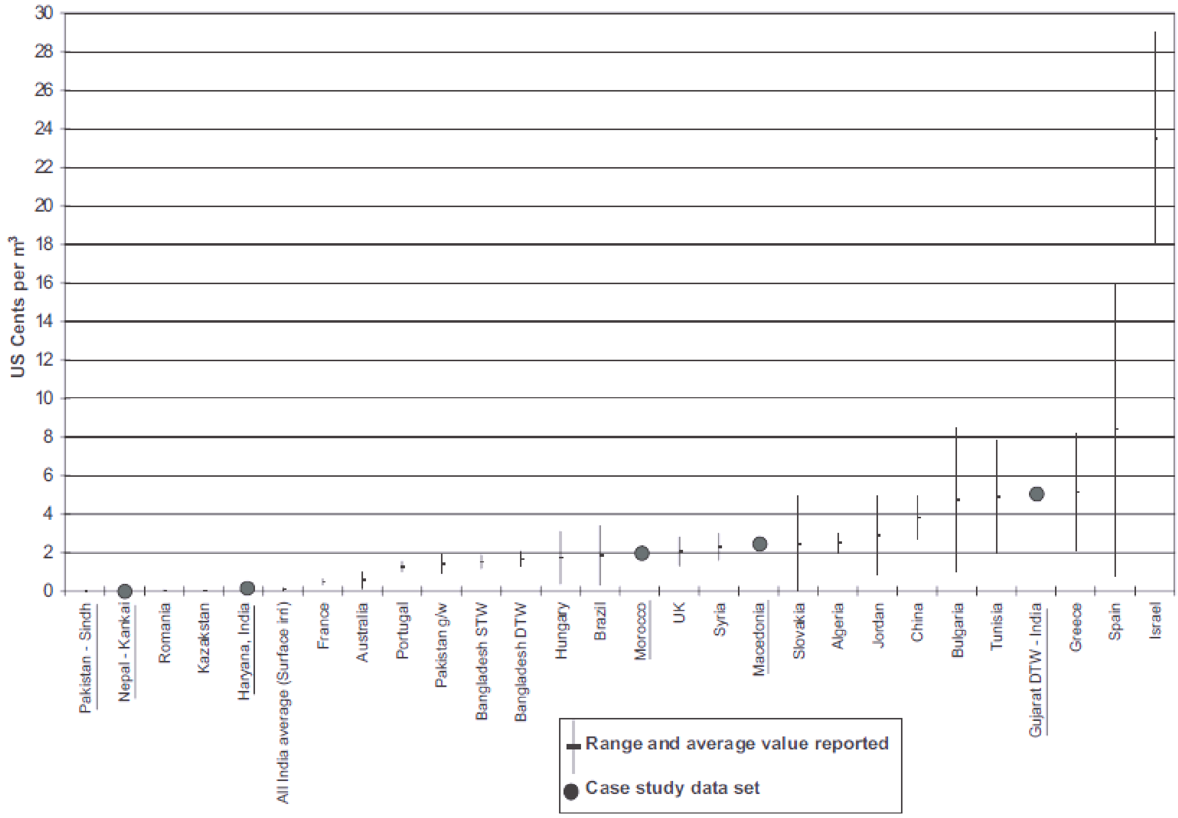
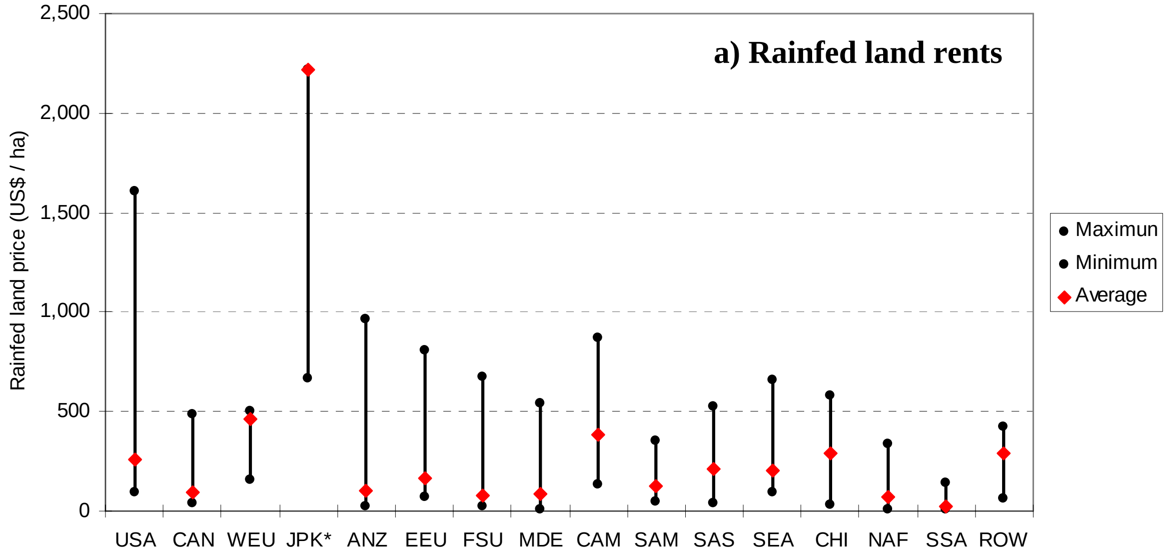


Figure 3. Global range of irrigation water prices per cubic metre
Source: Cornish et al. (2004).
Note: The study includes six case studies in five countries to obtain a more accurate data and identify the realities of water charging in practice.

In a similar way, an initial sector and region specific shadow price for rainfed and irrigable land can be obtained by combining the social accounting matrix information about payments to factors and the rainfed and irrigated harvested areas from IMPACT (Figure 4). As land rents in GTAP-W are generated from the use of a given parcel of land during the calendar year, we use crop harvested area which accounts for multiple cropping in a given parcel of land and year. The results are mostly as expected. Rainfed and irrigable land rents have similar patterns within each region. This is because we assume that the absolute difference in yield between rainfed and irrigated agriculture is explained by the presence of irrigation. Thus, the value of irrigation in GTAP-W includes not only the water but also the equipment necessary for agricultural production. Without irrigation, irrigable land rents should be similar to rainfed land rents because both are expected to face the same yields per hectare.

Rainfed and irrigable land rents in GTAP-W are mostly according to those observed in the literature. Lee et al. (2005) report the average land rents for all 87 regions in the GTAP-AEZ database. GTAP-AEZ disaggregates land use by 18 agro-ecological zones, covering six different lengths of growing period spread over three different climate zones. Lee et al. (2005) point out that the highest land rents are observed in South Korea (3,470 US$/ha), Hong Kong (1,824 US$/ha) and Japan (1,285 US$/ha), high income countries and densely populated. In GTAP-W, the average land rents for Japan and South Korea are around 2,218 US$/ha and 1,810 US$/ha for rainfed and irrigable land, respectively. High income countries in Europe such as the Netherlands, Germany, Finland, Italy and Austria follow the list in GTAP-AEZ with land rents between 396 US$/ha to 619 US$/ha. In GTAP-W, the average land rents in Western Europe are expected to reach at 459 US$/ha and 375 US$/ha for rainfed and irrigable land, respectively.



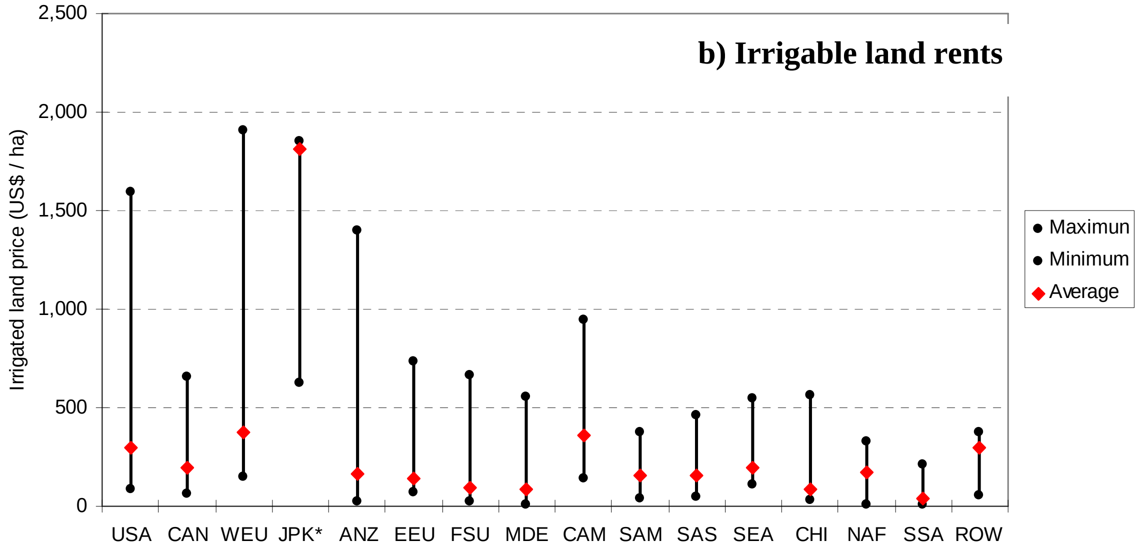


Figure 4. Regional range and average (over all crops) of rainfed and irrigable land rents per hectare

Source: Based on GTAP-W database.

* The maximum value has been deleted for illustrative purposes. Maximum values for JPK are: rainfed land rents (3,503 US cents / ha) and irrigated land rents (3,617 US cents / ha).

Note: United States (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MDE), Central America (CAM), South America (SAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA) and Rest of the World (ROW).

While average land rents in China are around 82 US$/ha in GTAP-AEZ, they reach 84 US$/ha and 289 US$/ha in GTAP-W for rainfed and irrigable land, respectively. Some regional differences are also observed, land rents in Canada reach 51 US$/ha in GTAP-AEZ; in GTAP-W rainfed and irrigable land rents are on average higher (92 US$/ha and 193 US$/ha, respectively). The lowest average land rents in both databases are those observed in

Sub-Saharan Africa, in GTAP-W for example, rainfed land rents reach 23 US$/ha and irrigable land rents reach 37 US$/ha.

3.4. General characteristic of GTAP-W

As in all CGE models, the GTAP-W model makes use of the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modelled through a representative firm, which maximizes profits in perfectly competitive markets. The production functions are specified via a series of nested constant elasticity of substitution functions. Domestic and foreign inputs are not perfect substitutes, according to the so-called ‘‘Armington assumption’’, which accounts for product heterogeneity between world regions.[4]

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, pasture land, rainfed land, irrigable land, irrigation, labour and capital). Capital and labour are perfectly mobile domestically, but immobile internationally. Pasture land, rainfed land, irrigable land, irrigation and natural resources are imperfectly mobile across agricultural sectors. While perfectly mobile factors earn the same market return regardless of where they are employed, market returns for imperfectly mobile factors may differ across sectors. The national income is allocated between aggregate household consumption, public consumption and savings. Constant budget shares are devoted to each category via a Cobb-Douglas utility function assumption. Private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the constant difference in elasticities (CDE) form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods.[5] A money metric measure of economic welfare, the equivalent variation, can be computed from the model output. The equivalent variation measures the welfare impact of a policy change. It is defined as the change in regional household income at constant prices that is equivalent to the proposed change.

In the GTAP model and its variants, two industries are unrelated to any region. International transport is a world industry, which produces the transportation services associated with the movement of goods between origin and destination regions. Transport services are produced by means of factors submitted by all regions, in variable proportions. In a similar way, a hypothetical global bank collects savings from all regions and allocates investments so as to achieve equality of expected rates of return (macroeconomic closure).

In the original GTAP model, land is combined with natural resources, labour and the capital-energy composite in a value-added nest. In our modelling framework, we incorporate the possibility of substitution between land and irrigation in irrigated agricultural production by using a nested CES function (Figure 5). The procedure for obtaining the elasticity of factor substitution between land and irrigation (σ_{LW}) is explained in section 3.6. Next, the irrigable land-water composite is combined with pasture land, rainfed land, natural resources, labour

[4] The Armington assumption of nationally differentiated products is commonly adopted in global trade models to explain cross-hauling of similar products (when a country appears to import and export the same good in the same period) and to track bilateral trade flows.

[5] A non-homothetic utility function implies that with different income levels the households budget shares spent on various commodities changes.

and the capital-energy composite in a value-added nest through a CES structure. The original elasticity of substitution between primary factors (σ_{VAE}) is used for the new set of endowments. The next section describes in detail the new production structure in GTAP-W and its implementation.

3.5. New production structure in GTAP-W

The GTAP-W model is based on the GTAP 6 database and has been calibrated to 2001 using information from the IMPACT model. The model has 16 world regions and 22 sectors, 7 of which are in agriculture.[6] However, the most significant change and principal characteristic of version 2 of the GTAP-W model is the new production structure, in which the original land endowment in the value-added nest has been split into pasture land and land for rainfed and for irrigated agriculture. The last two types of land differ as rainfall is free but irrigation development is costly while yields per hectare are higher. As a result, land equipped for irrigation is generally more valuable. To account for this difference, we split irrigated agriculture further into the value of land and the value of irrigation. The value of irrigation includes the equipment but also the water necessary for agricultural production. In the short-run the cost of irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability.

Water is incorporated into the value-added nest of the production structure (Figure 5). Indeed, water is combined with irrigable land to produce an irrigated land-water composite, which is in turn combined with other primary factors in a value-added nest trough a constant elasticity of substitution function. In addition, as the original land endowment has been split into pasture land, rainfed land, irrigated land and irrigation, the new version of the GTAP-W model allows for discriminating and substituting rainfed and irrigated crop production.

We assume that irrigation water is first combined with irrigable land, and then with other factors of production. We do not consider that irrigation water may be produced by combining raw water with capital and energy (see e.g. Gómez et al. 2004); nor the potential of substitution between water and fertilizers (see e.g. Decaluwé et al. 1999). Even though the production structure of GTAP-W is relatively simple, our model is more flexible than the model by Dixon et al. (2010), for example, where irrigable land and water enter in the production function with fixed Leontief coefficients (see Figure A5 in Annex A). Moreover, GTAP-W differentiates rainfed and irrigated production, while alternative models such as FARM did not make this distinction (see Figure A6 in Annex A).

[6] See Table B1 in Annex B for the regional, sectoral and factoral aggregation used in GTAP-W.

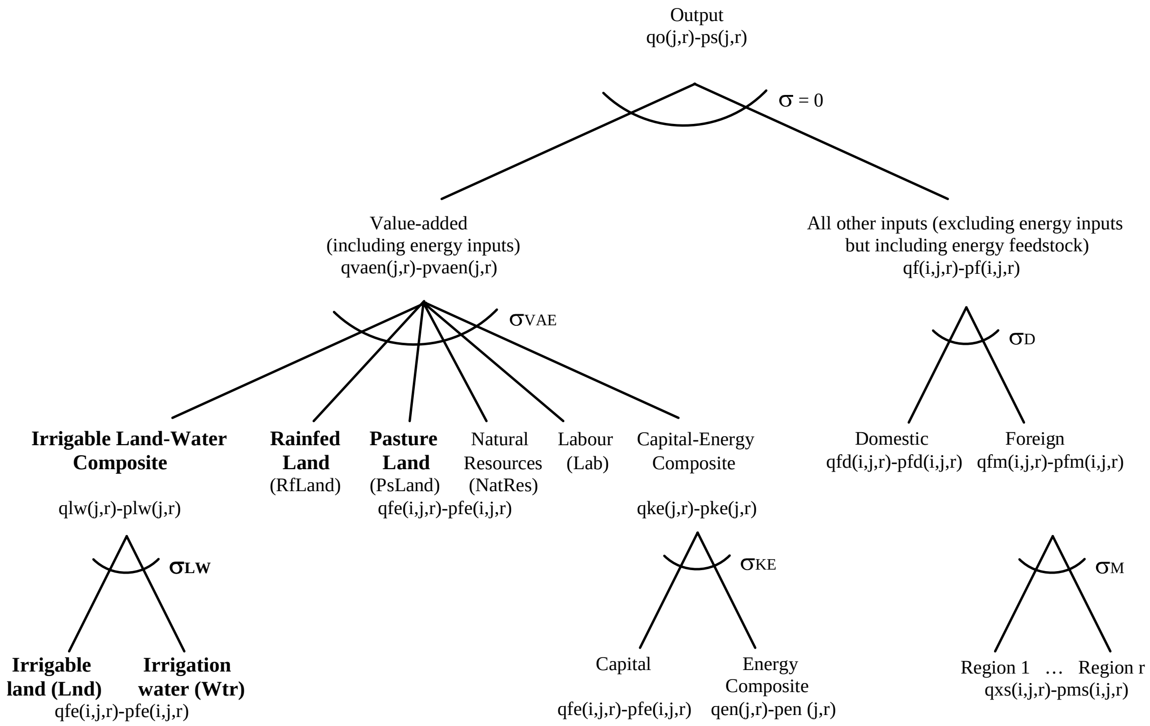


Figure 5. Nested tree structure for industrial production process in the GTAP-W model (truncated)

Note: The original land endowment has been split into pasture land, rainfed land, irrigable land and irrigation (bold letters). Irrigation water is inside the value-added nest, implying substitution possibilities with irrigable land and all other factors of production. σ is the elasticity of substitution between value added and intermediate inputs, σ_{VAE} is the elasticity of substitution between primary factors, σ_{LW} is the elasticity of substitution between irrigable land and irrigation, σ_{KE} is the elasticity of substitution between capital and the energy composite, σ_D is the elasticity of substitution between domestic and imported inputs and σ_M is the elasticity of substitution between imported inputs. The production structure links quantities and prices.

To implement the new production structure in GTAP-W some equations have been changed and added to the original code, which is based on the GTAP-E model.[7] The GTAP-W code is available on request. As shown in Figure 5, a nested CES functional form is used in the representation of producer behaviour in the GTAP-W model. Using a CES production function, Gohin and Hertel (2003) show the conditional factor demands and the unit cost functions derived from the cost minimization problem, and express them in terms of proportional changes, as currently specified in the GTAP model and its variants. Thus, for a CES function with two input factors (x_1 and x_2), Gohin and Hertel (2003) express the linearized conditional demand equations as follows:

$$\hat{x}_i = \hat{y} + \sigma(\hat{\delta}_i + \hat{c}_y - \hat{p}_i) + (\sigma - 1)\hat{\alpha} \qquad \text{i=1, 2} \tag{8}$$

where the hat ^ denotes proportional chances ($\hat{x}$ =dx/x), y is the production level, c_y is the unit cost, p_i are the market prices of the input factors, $\sigma = 1/(1+\rho)$ is the constant elasticity of substitution (with ρ > -1), δ_i are the distribution parameters and α is the efficiency parameter (with α > 0).

[7] For detailed information about the GTAP-E model see Burniaux and Truong (2002).

The unit cost is expressed as follows:

$$\hat{c}_y + \hat{\alpha} = \theta_1(\hat{\delta}_1 / \rho + \hat{p}_1) + \theta_2(\hat{\delta}_2 / \rho + \hat{p}_2) \qquad (9)$$

where $\theta_i = (p_i x_i)/(c_y y)$ are the cost shares (with i = 1, 2).

According the GTAP-W notation and using equations (8) and (9), the nested tree structure in Figure 5 is represented as follows (we only focus on the value-added nest—where all changes made in GTAP-W take place):

Lower level, first nest: Producers combine irrigable land and irrigation water according to a CES function with elasticity of substitution $ELLW_{j,r}$ (σ_{LW}). At this stage, only biased technical change is specified.

Demand for irrigable land (Lnd) and water (Wtr):

$$qfe_{i,j,r} = - afe_{i,j,r} + qlw_{j,r} - ELLW_{j,r} * [pfe_{i,j,r} - afe_{i,j,r} - plw_{j,r}] \quad i=Lnd, Wtr \qquad (10)$$

Unit cost of the irrigable land-water composite:

$$plw_{j,r} = \sum_{k \in ENDWLW} SLW_{k,j,r} * (pfe_{k,j,r} - afe_{k,j,r}) \qquad (11)$$

Lower level, second nest: Producers combine capital and the energy composite according to a CES function with elasticity of substitution $ELKE_{j,r}$ (σ_{KE}). At this stage, only biased technical change is specified.

Demand for capital (Capital) and the energy composite:

$$qfe_{i,j,r} = - afe_{i,j,r} + qke_{j,r} - ELKE_{j,r} * [pfe_{i,j,r} - afe_{i,j,r} - pke_{j,r}] \quad i=Capital \qquad (12)$$

$$qen_{j,r} = qke_{j,r} - ELKE_{j,r} * (pen_{j,r} - pke_{j,r}) \qquad (13)$$

Unit cost of the capital-energy composite:

$$pke_{j,r} = \sum_{k \in ENDWC} SKE_{k,j,r} * (pfe_{k,j,r} - afe_{k,j,r}) + \sum_{k \in EGY} SKE_{k,j,r} * (pf_{k,j,r} - af_{k,j,r}) \qquad (14)$$

Middle level: Producers combine the "irrigable land-water" composite, rainfed land, pasture land, natural resources, labour and the "capital-energy" composite according to a CES function with elasticity of substitution $ESUBVA_j$ (σ_{VAE}). At this stage, only biased technical change is specified.

Demand for rainfed land (RfLand), pasture land (PsLand), natural resources (NatRes) and labour (Lab):

$$qfe_{i,j,r} = - afe_{i,j,r} + qvaen_{j,r} - ESUBVA_j * [pfe_{i,j,r} - afe_{i,j,r} - pvaen_{j,r}] \qquad (15)$$

i=RfLand, PsLand, NatRes, Lab

Demand for the irrigable land-water composite:

$$qlw_{j,r} = qvaen_{j,r} - ESUBVA_j * (plw_{j,r} - pvaen_{j,r}) \qquad (16)$$

Demand for the capital-energy composite:

$$qke_{j,r} = qvaen_{j,r} - ESUBVA_j * (pke_{j,r} - pvaen_{j,r}) \quad (17)$$

Unit cost of the value-added composite (including energy inputs):

$$pvaen_{j,r} = \sum_{k \in ENDW} SVAEN_{k,j,r} * (pfe_{k,j,r} - afe_{k,j,r}) + \sum_{k \in EGY} SVAEN_{k,j,r} * (pf_{k,j,r} - af_{k,j,r}) \quad (18)$$

Upper level: Producers combine the value-added composite with all other inputs according to a CES function with elasticity of substitution $ESUBT_j$ (σ). At this stage, factor biased and neutral technical change are specified.

Demand for the value-added composite (including energy inputs):

$$qvaen_{j,r} = - ava_{j,r} + qo_{j,r} - ao_{j,r} - ESUBT_j * [pvaen_{j,r} - ava_{j,r} - ps_{j,r} - ao_{j,r}] \quad (19)$$

Demand for all other inputs (excluding energy inputs but including energy feedstock):

$$qf_{i,j,r} = D\_NEGY_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qo_{j,r} - ao_{j,r} - ESUBT_j * [pf_{i,j,r} - af_{i,j,r} - ps_{j,r}]]$$

$$+ D\_ELY_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qen_{j,r} - ELELY_{j,r} * [pf_{i,j,r} - af_{i,j,r} - pen_{j,r}]]$$

$$+ D\_COAL_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qnel_{j,r} - ELCO_{j,r} * [pf_{i,j,r} - af_{i,j,r} - pnel_{j,r}]]$$

$$+ D\_OFF_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qncoal_{j,r} - ELFU_{j,r} * [pf_{i,j,r} - af_{i,j,r} - pncoal_{j,r}]] \quad (20)$$

Unit cost of the output:

$$ps_{j,r} + ao_{j,r} = \sum_{i \in ENDW} STC_{i,j,r} * [pfe_{i,j,r} - afe_{i,j,r} - ava_{j,r}]) + \sum_{k \in TRAD} STC_{k,j,r} * [pf_{k,j,r} – af_{k,j,r}]) + profitslack_{j,r} \quad (21)$$

Where: $qfe_{i,j,r}$ demand for endowment *i* for use in industry *j* in region *r*

$qlw_{j,r}$ composite "irrigable land+water" in industry *j* of region *r*
$qke_{j,r}$ composite "capital+energy" in industry *j* of region *r*
$qen_{j,r}$ composite energy (electicity+ non-electricity) in industry *j* of region *r*
$qvaen_{j,r}$ value-added in industry *j* of region *r*
$qo_{i,r}$ industry output of commodity *i* in region *r*
$qf_{i,j,r}$ demand for commodity *i* for use by *j* in region *r*
$qnel_{j,r}$ composite non-electric good in industry *j* of region *r*
$qncoal_{j,r}$ composite non-coal energy good in industry *j* of region *r*
$pfe_{i,j,r}$ firms' price for endowment commodity *i* in industry *j* of region r
$plw_{j,r}$ firms' price of "irrigable land+water" composite in industry *j* of region *r*
$pke_{j,r}$ firms' price of "capital+energy" composite in industry *j* of region *r*
$pen_{j,r}$ price of energy (elec.+ non-elec.) composite in industry *j* of region *r*
$pf_{i,j,r}$ firms' price for commodity *i* for use by industry *j* in region *r*
$pvaen_{j,r}$ firms' price of value-added in industry *j* of region *r*
$ps_{i,r}$ supply price of commodity *i* in region *r*
$pnel_{j,r}$ price of non-electric composite in industry *j* of region *r*
$pncoal_{j,r}$ price of non-coal composite in industry *j* of region *r*
$afe_{i,j,r}$ primary factor *i* augmenting technical change by industry *j* of region *r*

$af_{i,j,r}$ composite intermediate input *i* augmenting technical change by *j* of *r*
$ava_{i,r}$ value added augmenting technical change in sector *i* of region *r*
$ao_{j,r}$ output augmenting technical change in sector *j* of region *r*
$ELLW_{j,r}$ elasticity of substitution between irrigable land and water in *j*
$ELKE_{j,r}$ elasticity of substitution between capital and the composite energy good in *j*
$ESUBVA_{j}$ elasticity of substitution in production of value-added in *j*
$ESUBT_{j}$ elasticity of substitution among composite intermediate inputs in production
$ELCO_{j,r}$ elasticity of substitution between coal and the composite
$ELELY_{j,r}$ elasticity of subs. between electricity and the composite non-electric good in *j*
$ELFU_{j,r}$ elasticity of substitution between remaining fossil fuels in *j*
$SLW_{i,j,r}$ share of *i* in the composite good "irrigable land+water"
$SKE_{i,j,r}$ share of *i* in second level composite good "capital+energy"
$SVAEN_{i,j,r}$ share of *i* in first level composite good "value added+energy"
$STC_{i,j,r}$ share of *i* in total costs of *j* in *r*
$profitslack_{j,r}$ slack variable in the zero profit equation
$D\_VFA_{i,j,r}$ dummy variable for identifying zero expenditures in VFA
$D\_NEGY_{i,j,r}$ dummy variable for intermediate demand: 1 = non-energy; energy = 0
$D\_ELY_{i,j,r}$ dummy variable for intermediate demand: 1 = electricity; others = 0
$D\_COAL_{i,j,r}$ dummy variable for intermediate demand: 1 = coal; others = 0
$D\_OFF_{i,j,r}$ dummy variable for intermediate demand: 1 = oil,gas,petr. products; others = 0

3.6. Elasticity of substitution between water and other primary inputs

The elasticity of substitution between irrigable land and irrigation (σ_{LW} in Figure 5) is estimated from the price elasticity of water use as follows:

Let us assume a simple two inputs production function:

$$Y = f(X, W) \tag{22}$$

where *Y* is output, *W* is water input, and *X* is all other inputs. The cost of production is given by:

$$C = pX + tW \tag{23}$$

where *t* is the price of water and *p* is the composite price of other inputs. Production efficiency implies that the marginal rate of technical substitution equals the resource price ratio:

$$\frac{f_X}{f_W} = \frac{p}{t} \tag{24}$$

Let us now assume that (22) is a CES production function:

$$Y = \left(X^{-\rho} + W^{-\rho}\right)^{-1/\rho} \tag{22'}$$

Production efficiency implies:

$$\frac{f_X}{f_W} = \frac{W^{\rho+1}}{X^{\rho+1}} = \frac{p}{t} \tag{24'}$$

Evaluating production efficiency at two different water prices t and $t(1+\delta)$:

$$\frac{W_1^{\rho+1}}{X^{\rho+1}} = \frac{p}{t} \text{ and } \frac{W_2^{\rho+1}}{X^{\rho+1}} = \frac{p}{t(1+\delta)} \text{ imply:} \tag{25}$$

$$W_1^{\rho+1} = W_2^{\rho+1}(1+\delta) \tag{26}$$

By definition, the price elasticity of demand is given by:

$$\eta = \frac{t\, dW}{W\, dt} \tag{27}$$

This may be rewritten as:

$$W_2 = W_1(1+\eta\delta) \tag{28}$$

Combining equation (26) and (28), the elasticity of substitution between water and other inputs can be defined as:

$$\rho = -\frac{\ln(1+\delta)}{\ln(1+\eta\delta)} - 1 \tag{29}$$

That is, the price elasticity η implies the substitution elasticity ρ, for any price change δ.

Rosegrant et al. (2002) provide estimates of the price elasticity of water use (η) for 15 world regions, we use these estimates to derive the substitution elasticity between irrigable land and irrigation for GTAP-W (Table 5).

Table 5. Elasticity of substitution between irrigable land and irrigation in GTAP-W

Regions	Price elasticity (η)	Substitution elasticity (ρ)
United States	-0.14	0.05
Canada	-0.08	0.08
Western Europe	-0.04	0.14
Japan and South Korea	-0.06	0.10
Australia and New Zealand	-0.11	0.06
Eastern Europe	-0.06	0.10
Former Soviet Union	-0.09	0.07
Middle East	-0.11	0.06
Central America	-0.08	0.08
South America	-0.12	0.06
South Asia	-0.11	0.06
Southeast Asia	-0.12	0.06
China	-0.16	0.04
North Africa	-0.07	0.08
Sub-Saharan Africa	-0.15	0.05
Rest of the World	-0.20	0.04

Note: Price elasticity is based on Rosegrant et al. (2002).

We follow Arndt (1996) to assess the model sensitivity to the uncertainty of the elasticity of substitution between irrigable land and water.[8] Arndt (1996) proposes the Gaussian quadrature method for a systematic sensitivity analysis to test the robustness of model results. The Gaussian quadrature method produces good approximations of the means and associated standard deviations of the model while using a limited number of model evaluations. With 16 elasticity parameters to be evaluated, we need 32 (2x16) model evaluations plus the "central case". We assume that each elasticity follows an independent normal distribution, where the mean is the central estimate (values in Table 5) and the standard deviation is arbitrarily set to 20 percent of the mean value. The results show small variations around the "central case", less than 1 percent for most of the variables, revealing that the model results are not very sensitive to changes in the value of the elasticity of substitution between irrigable land and irrigation.

3.7. Validation of the GTAP-W model

Before exploring concrete policies, we validated the model to evaluate the accuracy of the results. As CGE model results are sometimes highly dependent on values employed for critical exogenous variables, parameters and elasticities, this step includes a systematic sensitivity analysis as the one presented in the previous section. Following Dixon and Rimmer (2010), we verified the code and data performing two homogeneity tests. That is, run a simulation for which the solution has a simple structure which is known *a priori* from the theory of the model.

Price homogeneity test: To check if the model is homogeneous of degree zero in prices we multiply the numéraire by a constant k and verify that in the solution all real values remain unchanged but all nominal values and prices are multiplied by k. Thus, we exogenously increased by 20 percent the world price index of primary factors (pfactwld). This test was passed by the GTAP-W model, showing that the model is homogeneous of degree zero on prices and real variables are sensible only to changes in relative prices.

Real homogeneity test: To check if the model displays constant returns to scale, a property of neoclassical CGE models, we multiply all real exogenous variables by a constant k and verify that in the solution all real endogenous variables are multiplied by k, leaving prices unchanged. Thus, we exogenously increased by 20 percent all regional endowment commodities and population ($qo_{i,r}$ and pop_r). This homogeneity test was met by the GTAP-W model.

4. Illustrative simulation

To illustrate the new features of the GTAP-W model, we present results of a simulation exercise that explores potential water savings and the economic implications of

[8] Although Monte Carlo simulations are more appropriated for a systematic sensitivity analysis, the number of model evaluations makes this method impractical for large CGE models (Arndt 1996).

improvements in irrigation efficiency worldwide. This illustration is based on the article "Water scarcity and the impact of improved irrigation management: a computable general equilibrium analysis" published in Agricultural Economics (Calzadilla et al. 2011a). The necessary data and code to replicate the main results are available in the attached zip file.

Performance and productivity of irrigated agriculture is commonly referred to as irrigation efficiency (Burt et al. 1997; Jensen 2007). In a finite space and time, FAO (2001) defines irrigation efficiency as the ratio of the irrigation water consumed by crops to the water diverted from the source of supply. It distinguishes between conveyance efficiency, which represents the efficiency of water transport in canals, and the field application efficiency, which represents the efficiency of water application in the field. In Calzadilla et al. (2011a), no distinction is made between conveyance and field application efficiency. Any improvement in irrigation efficiency refers to an improvement in the overall irrigation efficiency.

Currently, irrigation efficiency in most of the developing countries is performing poorly (Figure 6), the only exception is water-scarce North Africa, where levels are comparable to those observed in developed regions. Certainly, there are differences in performance within regions. Rosegrant et al. (2002) point out that irrigation efficiency ranges between 25 to 40 percent in the Philippines, Thailand, India, Pakistan and Mexico; between 40 to 45 percent in Malaysia and Morocco; and between 50 to 60 percent in Taiwan, Israel and Japan. For most developing regions that suffer from water scarcity such as the Middle East, North Africa, South Asia and large parts of China and India, irrigated agriculture contributes significantly to total crop production. Just the Middle East, North Africa and South Asia account for around 43 percent of the total global water used for irrigation purposes.

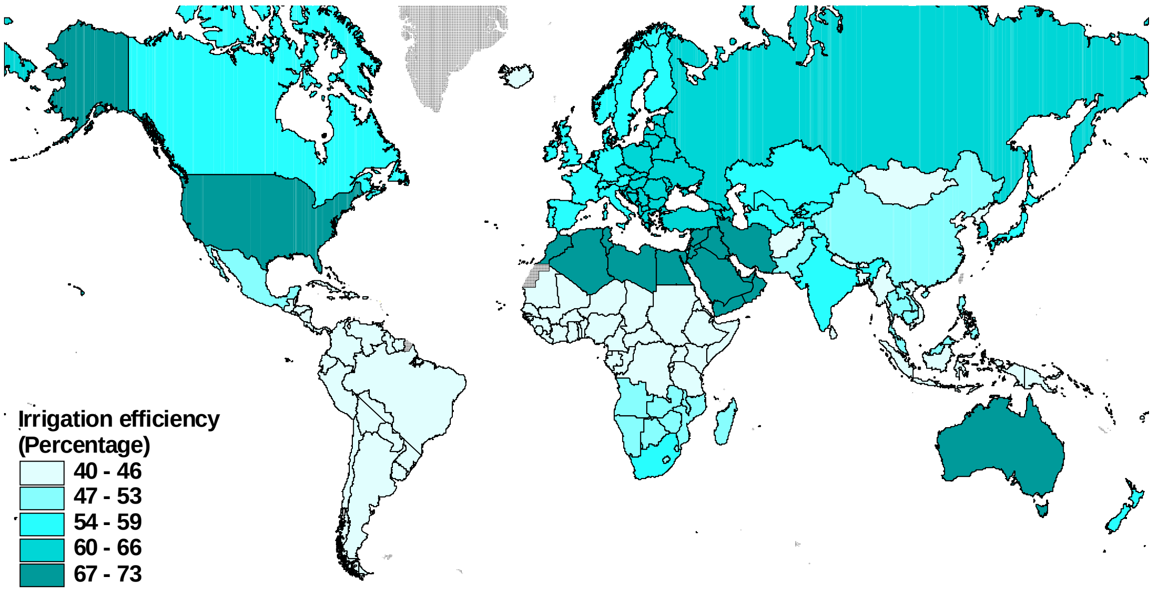


Figure 6. Average irrigation efficiency, 2001 baseline data

Note: Irrigation efficiency is based on the volume of beneficial and non-beneficial irrigation water use according to the IMPACT baseline data (Rosegrant et al. 2002).

4.1. Scenario design

Three different scenarios are used to evaluate the effects of enhanced irrigation efficiency on global agricultural production, water use and welfare. The scenarios are designed so as to show a gradual convergence to higher levels of irrigation efficiency. The first two scenarios assume that an improvement in irrigation efficiency is more likely in water-scarce regions.

In the first scenario irrigation efficiency only in *water-scarce developing regions* improves. We consider a region as water-scarce if, for at least for one country within the region, water availability is less than 1,500 cubic meters per person per year. These regions include South Asia (SAS), Southeast Asia (SEA), North Africa (NAF), the Middle East (MDE), Sub-Saharan Africa (SSA) as well as the Rest of the World (ROW).

In the second scenario irrigation efficiency improves in all *water-scarce regions* independent of the level of economic development. In addition to the previous scenario Western Europe (WEU), Eastern Europe (EEU) and Japan and South Korea (JPK) are added to the list of water-short regions.

In the third scenario, we improve irrigation efficiency in *all regions*. Irrigation efficiency is increased to 73 percent, for all crops, in all selected regions, in all scenarios. This is the weighted average level of Australia and New Zealand (ANZ), which is close to the maximum achievable efficiency level of 75 percent (World Bank 2003). Therefore, our analysis attempts to study potential global water savings and its economic implications, improving irrigation efficiency to the maximum attainable level.

Our scenarios do not add costs, that is, we assume that higher levels of efficiency are possible with the current technology. Jensen (2007) points out that better irrigation scheduling practices, controlling timing of irrigation and amounts applied, can improve irrigation efficiency and productivity of water with little additional cost.

4.2. Results

The irrigated production of rice and wheat consumes half of the irrigation water used globally, together they account for 617 km^3. For brevity, we discuss the results only for these two crops. Figure 7 shows the percentage change in total production, irrigated production and irrigation water used in the production of rice. Note that changes in the “irrigable land-water” composite indicate changes in irrigated production. Regions where irrigation water efficiency improves alter their levels of irrigated and total production, but other regions are affected as well through shifts in competitiveness and international trade. The effects are different for the different scenarios we implemented.

The four major rice producing regions (Japan and South Korea, South Asia, Southeast Asia, and China) are affected differently. In Southeast Asia, for example, where irrigation efficiency was lowest, production increases more compared to the other three regions. In general, higher levels of irrigation efficiency lead to increases in irrigated and total rice production. However, total rice production increases less if more regions have higher levels of irrigation efficiency (*water-scarce regions* and *all regions* scenarios). Although irrigated production increases, demand for irrigation water decreases in most regions (red dots) as the demand for food increases only slightly. The Middle East reduces its total rice production while irrigated production and water demand increase. The relatively high initial level of irrigation efficiency leaves little room for further improvements and water savings.

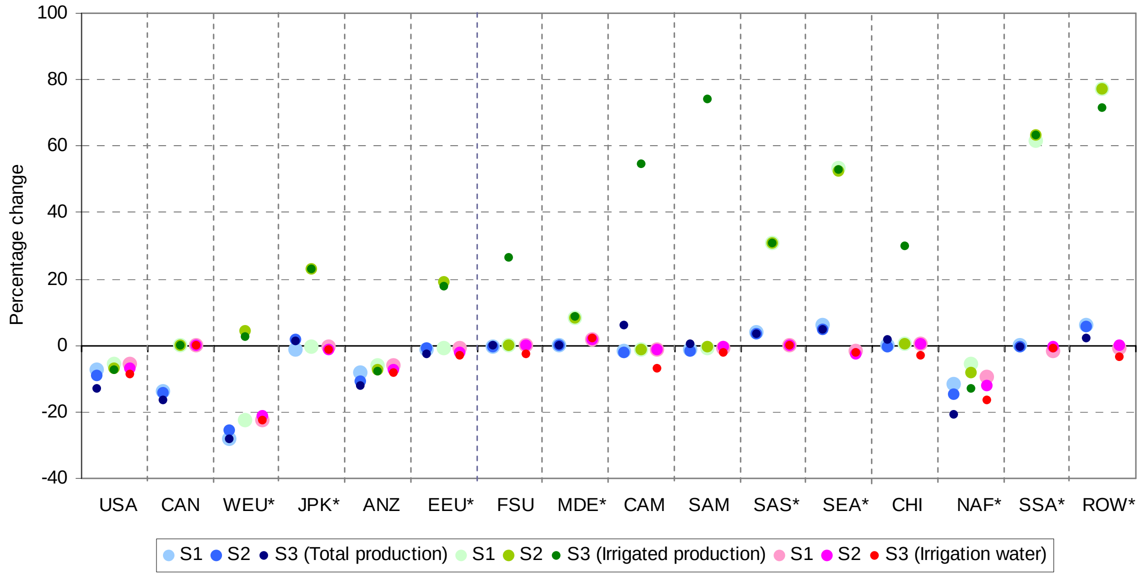


Figure 7. Rice: Percentage change in total production, irrigated production and irrigation water by region

Note: Water-stressed regions are indicated by an asterisk (*). Water-scarce developing regions (S1), water-scarce regions (S2) and all regions (S3) scenarios. United States (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MDE), Central America (CAM), South America (SAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA) and Rest of the World (ROW).

There are seven major wheat-producing regions in the world (South Asia, China, North Africa, USA, Western Europe, Eastern Europe and the former Soviet Union). The first four regions are the major producers of irrigated wheat. Comparing the results of Figure 8 for the different scenarios, higher levels of irrigation efficiency generally lead to increases in irrigated wheat production. As discussed above, the increase is less pronounced when more regions achieve higher levels of irrigation efficiency (*water-scarce regions* and *all regions* scenarios). Irrigation water demand is affected differently in the different regions. In the *all regions* scenario, water demand increases in water-scarce South Asia as well as in the USA and China. In Western and Eastern Europe and North Africa higher levels of irrigation efficiency is mostly followed by a decrease in the demand for water. Total wheat production does not necessarily follow the trend of irrigated production. Only in two of the seven regions (South Asia, Eastern Europe and partly China) total production increases with higher levels of irrigation efficiency.

Improved irrigation efficiency leads to more irrigated and total wheat production in water-scarce regions. In most of these regions (Japan and South Korea, Southeast Asia, Sub-Saharan Africa and Rest of the World) this is followed by an increasing demand for irrigation water. However, production levels are relatively low.

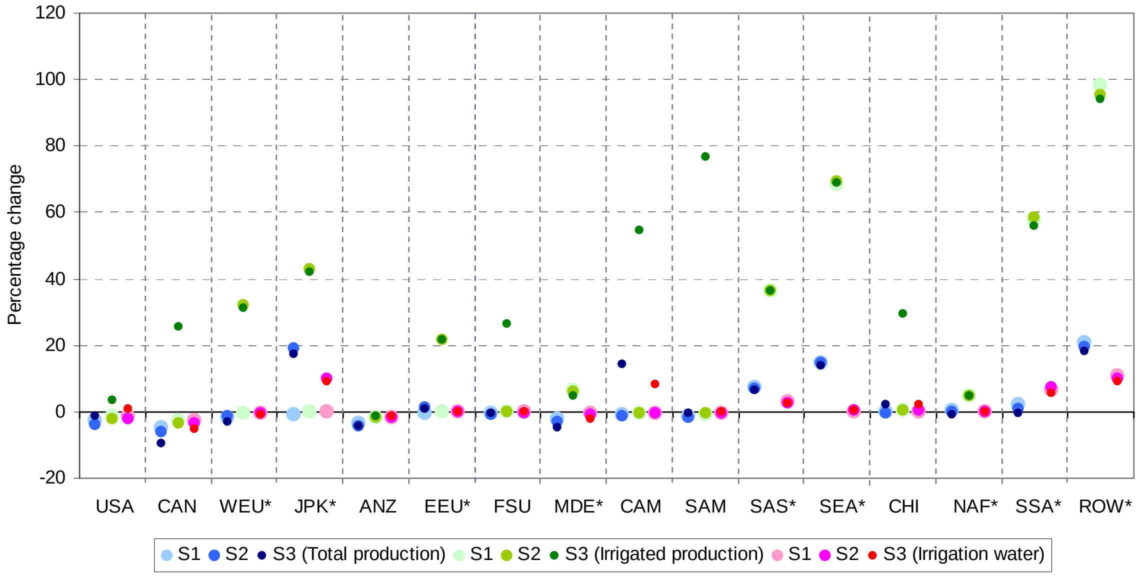
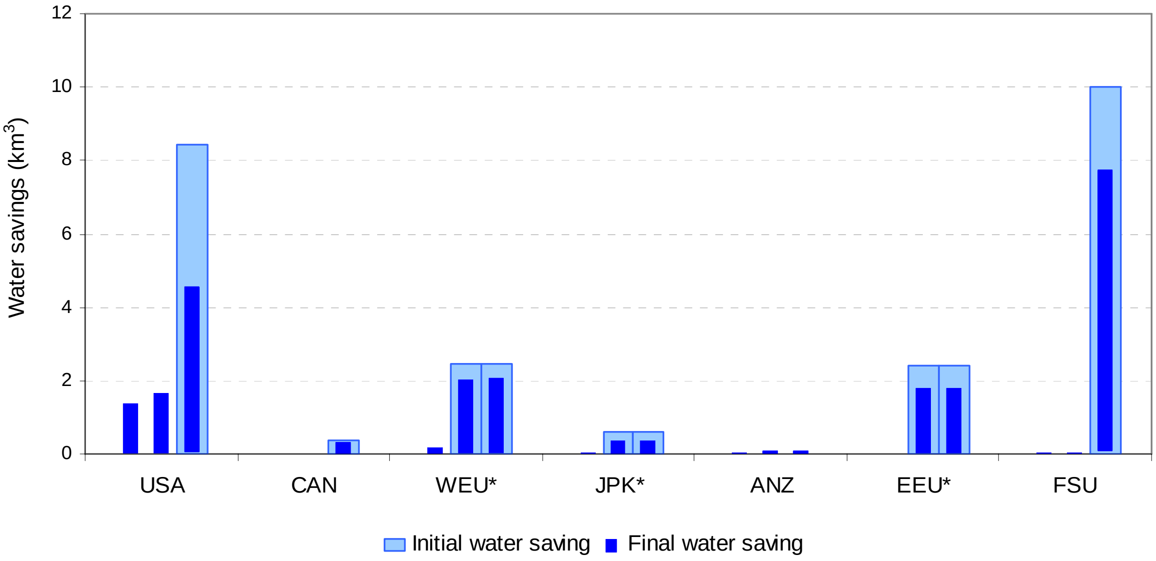


Figure 8. Wheat: Percentage change in total production, irrigated production and irrigation water by region

Note: Water-stressed regions are indicated by an asterisk (*). Water-scarce developing regions (S1), water-scarce regions (S2) and all regions (S3) scenarios. United States (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MDE), Central America (CAM), South America (SAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA) and Rest of the World (ROW).

One reason to increase the efficiency in irrigation is to save water. Figure 9 compares how much water used in irrigated agriculture could be saved by the different scenarios. If markets would not adjust, improved irrigation efficiency would lead to water savings. With adjustments in other markets, the effect is ambiguous. The initial water saving shows the reduction in the irrigation water requirements under the improved irrigation efficiency, without considering any adjustment process in food and other markets. Globally, water savings are 158 km^2 (*water-scarce developing regions*), 163 km^3 (*water-scarce regions*) and 282 km^3 (*all regions*). This is between 12 and 21 percent of the total amount of irrigation water used in agriculture.

Final water savings take into account the additional irrigation water used as a consequence of the increase in irrigated production, and the shifts in demand and supply for all crops in all regions. At the global level, more water is saved as more regions achieve higher levels of irrigation efficiency. At the regional level, the tendency is similar except for only slight decreases in Sub-Saharan Africa, and Australia and New Zealand. Water is saved in all regions, not just in those regions with improved irrigation efficiency. This is evident for the USA and China in the *water-scarce developing regions* and *water-scarce regions* scenarios, where total irrigated production decreases. Only in North Africa the final water savings exceed the initial water savings; and the additional irrigation water saved increases more as more regions improve irrigation efficiency. The final water savings are much lower than the initial water savings. Only about 5 to 10 percent of the total amount of irrigation water used in agriculture could be saved.



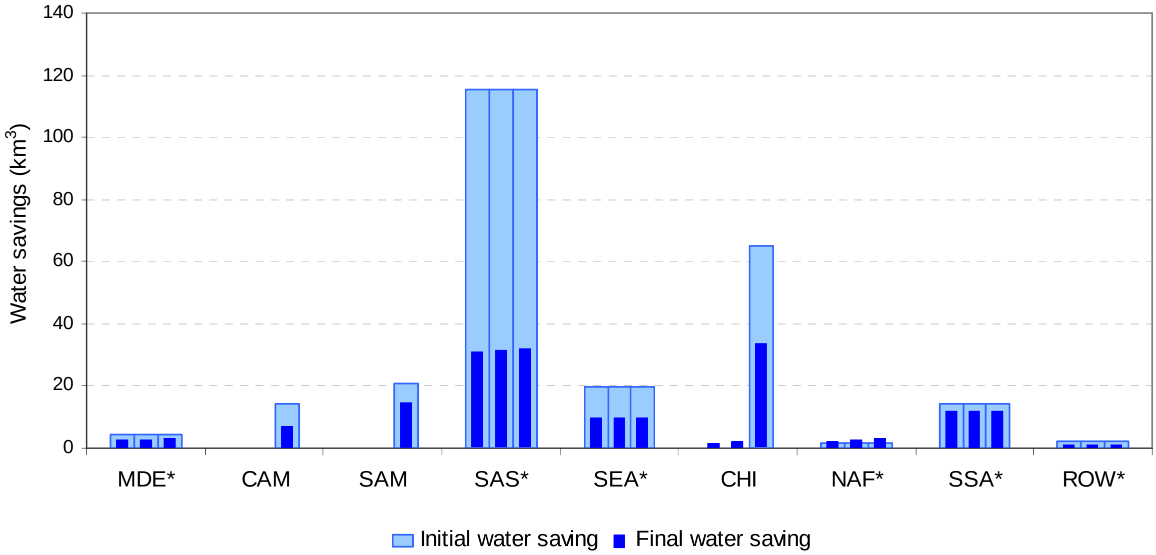


Figure 9. Initial and final water savings by scenario, 2001

Note: Developed regions (top panel) and developing regions (bottom panel). Water-stressed regions are indicated by an asterisk (*). The three bars refer to the three scenarios (*water-scarce developing regions*, *water-scarce regions* and *all regions*, respectively). United States (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MDE), Central America (CAM), South America (SAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA) and Rest of the World (ROW).

Higher levels of irrigation efficiency imply that the same production could be achieved with less water. As irrigation water is explicitly considered in the production of irrigated crops, the production costs of irrigated agriculture decline with higher irrigation efficiency. As the production costs of rainfed agriculture remain the same, the result is a shift in production from rainfed to irrigated agriculture. Table 6 reports the percentage changes in rainfed, irrigated and total agricultural production as well as the changes in world market prices. The increases in irrigated production and the decreases in rainfed production are more pronounced when more regions reach higher efficiency levels (*water-scarce regions* and *all* *regions* scenarios). In the *all regions* scenario, total agricultural production rises by 0.7 percent. This comprises an increase in irrigated production of 24.6 percent and a decline in rainfed production of 15.0 percent. For individual agricultural products, the shift from rainfed to irrigated production varies widely.

Table 6. Percentage change in global total, irrigated and rainfed agricultural production and world market prices by scenario

Agricultural products	Water-scarce developing regions				Water-scarce regions				All regions			
	Agricultural production				Agricultural production				Agricultural production			
	Total	Irrigated	Rainfed	Price	Total	Irrigated	Rainfed	Price	Total	Irrigated	Rainfed	Price
Rice	1.07	14.74	-36.08	-6.78	1.55	17.49	-41.75	-10.03	1.71	19.69	-47.16	-13.79
Wheat	0.45	13.22	-11.03	-2.95	0.73	17.22	-14.09	-3.60	0.87	24.58	-20.45	-5.16
Cereal grains	0.07	4.35	-2.29	-0.95	0.13	7.34	-3.84	-1.34	0.38	21.94	-11.49	-3.44
Vegetable and fruits	0.25	7.38	-3.59	-1.41	0.41	15.46	-7.68	-2.44	0.70	29.01	-14.52	-4.47
Oil seeds	0.58	15.96	-6.36	-2.57	0.62	16.90	-6.73	-2.78	1.00	27.97	-11.18	-4.19
Sugar cane and beet	0.76	21.52	-17.59	-6.26	0.80	26.69	-22.09	-6.87	0.90	37.49	-31.45	-8.25
Other agri. products	0.27	8.83	-4.78	-1.91	0.39	12.72	-6.87	-2.47	0.48	21.43	-11.86	-3.99
TOTAL	**0.35**	**10.02**	**-6.02**		**0.52**	**14.86**	**-8.93**		**0.71**	**24.58**	**-15.00**	

The world market prices for all agricultural products decrease as a consequence of the lower production costs of irrigated agriculture. The world market prices fall more as more regions improve irrigation efficiency. Lower market prices stimulate consumption and total production of all agricultural products increases. In the *all regions* scenario, rice has the greatest price drop (13.8 percent), for an increase in total production of 1.7 percent. The fall in the world market price is smallest for cereals (3.4 percent); total production rises by 0.4 percent.

Changes in production induce changes in welfare. At the global level, welfare increases as more regions implement strategies to improve irrigation. However, at the regional level, the effects might be less positive for some. Figure 10 compares the changes in welfare for the three different scenarios for the 16 regions. Discussing the bottom panel first, changes in welfare in water-scarce developing regions are mostly positive but the magnitude varies considerably. For water-stressed regions, changes are most pronounced for South Asia followed by Southeast Asia, the Middle East, North Africa and Sub-Saharan Africa. Differences between the *water-scarce developing regions* scenario and the *water-scarce regions* scenario are negligible while the *all regions* scenario leads to additional welfare gains. An exception is Sub-Saharan Africa where welfare changes are negative. The gains for food consumers are smaller than the losses incurred by food producers.

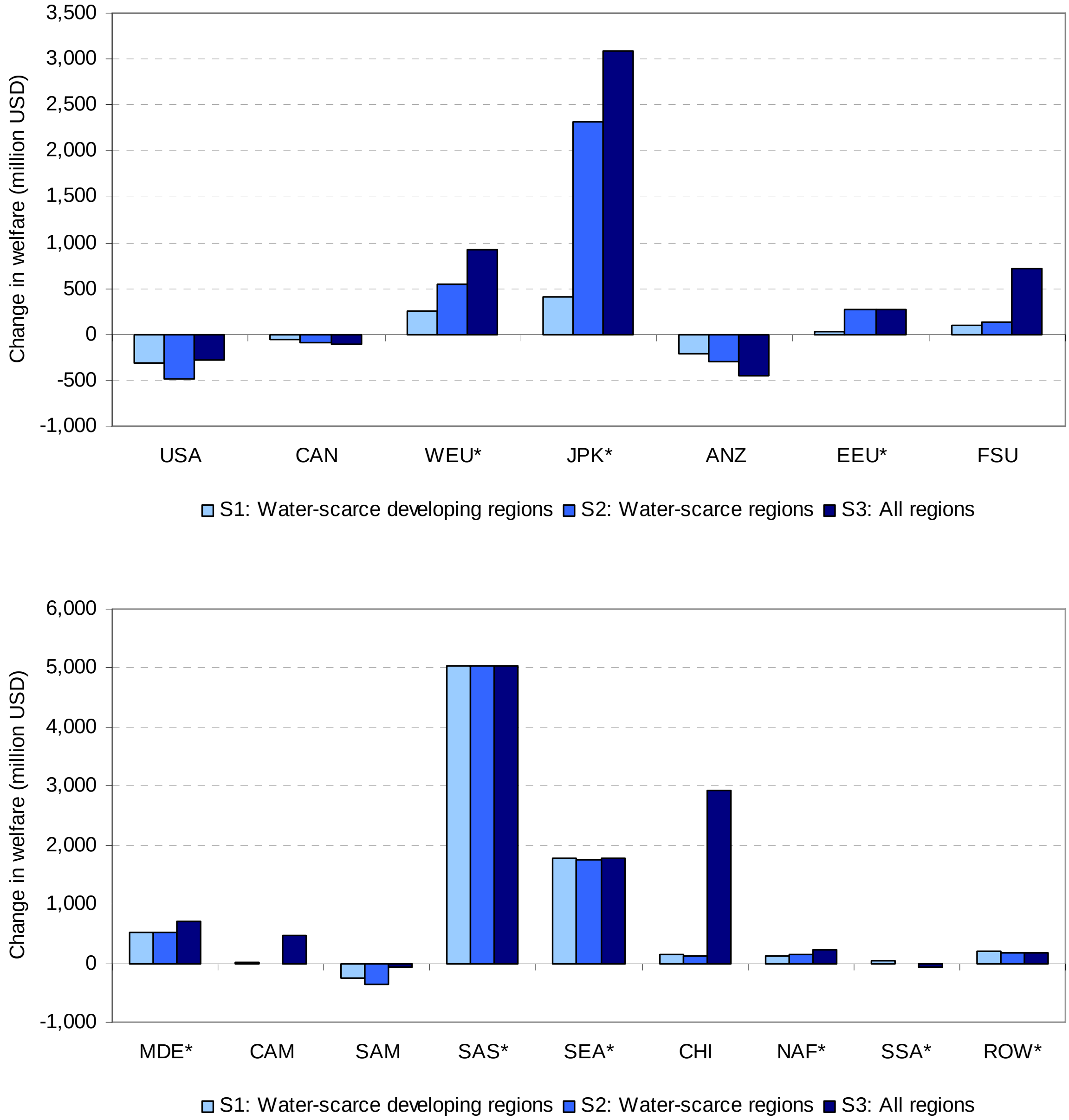


Figure 10. Change in regional welfare by scenario (million USD)
Note: Developed regions (top panel) and developing regions (bottom panel). Water-stressed regions are indicated by an asterisk (*). United States (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MDE), Central America (CAM), South America (SAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA) and Rest of the World (ROW).

5. Discussion and conclusions

In this paper, we present the new version of the GTAP-W model, a computable general equilibrium model of the world economy with water as an explicit factor of production in the agricultural sector. The new production structure of the model allows for substitution between irrigation water, irrigated land, rainfed land, labour, capital and energy. To our knowledge, this is the first global CGE model that differentiates between rainfed and irrigated crops. Previously, this was not possible because the necessary data were missing – at least at the global scale – as water is mostly a non-market good, not often reported in national economic accounts. Earlier studies included water resources at the national or smaller scale. These studies necessarily lack the international dimension, which is important as water is implicitly traded in international markets for agricultural products.

The distinction between rainfed and irrigated agriculture within the production structure of the GTAP-W model allows us to model green (rainfall) and blue (irrigation) water use in agricultural production. This distinction is crucial, because rainfed and irrigated agriculture face different climate risk levels. Thus, in GTAP-W, changes in water availability have different effects on rainfed and irrigated crops. While changes in surface and groundwater use in agriculture modify the use of blue water or irrigation endowment, changes in green water use are modelled exogenously using information from the IMPACT model.

Several applications have been done using the new version of the GTAP-W model. Calzadilla et al. (2011a) analyze the economy-wide impacts of enhanced irrigation efficiency. They found that regional and global water savings are achieved when irrigation efficiency improves. Not only regions where irrigation efficiency changes are able to save water, but also other regions are induced to conserve water. Calzadilla et al. (2010a) investigate the role of green and blue water resources in agriculture. They evaluated different scenarios of sustainable water use in the agricultural sector and found a clear trade-off between economic welfare and environmental sustainability. Calzadilla et al. (2010b) assess potential impacts of climate change and CO_2 fertilization on global agriculture. They found that global food production, welfare and GDP are expected to fall with climate change. Countries are not only influenced by regional climate change, but also by climate-induced changes in competitiveness. Calzadilla et al. (2011b) combine scenarios of future climate change with trade liberalization. They found that significant reductions in agricultural tariffs lead to modest changes in regional water use. Trade liberalization tends to reduce water use in water scarce regions, and increase water use in water abundant regions, even though water markets do not exist in most countries. In a combined analysis using the IMPACT and GTAP-W models, Calzadilla et al. (2009) evaluated the efficacy of two adaptation measures to cope with climate change in Sub-Saharan Africa. They found that an increase in agricultural productivity achieves better outcomes than an expansion of irrigated areas, due to the low initial irrigated areas in the region.

This paper presents a detailed description of the GTAP-W model including the new database and production structure. While GTAP-W provides an attempt to account for water resources in global CGE models, it could be improved in several aspects. First, GTAP-W limits its analysis to water use in the agricultural sector ignoring domestic and industrial uses. Second, GTAP-W considers water quantity and prices but ignores non-market costs/benefits of water use. Finally, the global perspective of GTAP-W has some limitations in terms of the modelling details. These issues should be addressed in future research. Future work will also aim to extend the current version of GTAP-W to incorporate agro-ecological zones.

References

Arndt, C. 1996. "An Introduction to Systematic Sensitivity Analysis via Gaussian Quadrature." GTAP Technical Paper No. 2, Center for Global Trade Analysis, Purdue University.

Berrittella, M., A.Y. Hoekstra, K. Rehdanz, R. Roson, and R.S.J. Tol. 2007. "The Economic Impact of Restricted Water Supply: A Computable General Equilibrium Analysis." *Water Research* 41: 1799-1813.

Berrittella, M., K. Rehdanz, R. Roson, and R.S.J. Tol. 2008a. "The Economic Impact of Water Taxes: A Computable General Equilibrium Analysis with an International Data Set." *Water Policy* 10 (3): 259-271.

Berrittella, M., K. Rehdanz, and R.S.J. Tol. 2006. "The Economic Impact of the South-North Water Transfer Project in China: A Computable General Equilibrium Analysis." Research unit Sustainability and Global Change FNU-117, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Berrittella, M., K. Rehdanz, R.S.J. Tol, and Y. Zhang. 2008b. "The Impact of Trade Liberalisation on Water Use: A Computable General Equilibrium Analysis." *Journal of Economic Integration* 23(3): 631-655.

Burniaux, J.M., and T.P. Truong. 2002. "GTAP-E: An Energy Environmental Version of the GTAP Model." GTAP Technical Paper No. 16.

Burt, C.M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, R.A. Hardy, T.A. Howell, and D.E. Eisenhauer. 1997. "Irrigation performance measures: Efficiency and uniformity." *Journal of Irrigation and Drainage Engineering* 123: 423-442.

Calzadilla, A., K. Rehdanz, and R.S.J. Tol. 2010a. "The Economic Impact of More Sustainable Water Use in Agriculture: A Computable General Equilibrium Analysis." *Journal of Hydrology* 384: 292-305.

Calzadilla, A., K. Rehdanz, and R.S.J. Tol. 2011a "Water scarcity and the impact of improved irrigation management: A computable general equilibrium analysis." *Agricultural Economics* 42(3): 305-323.

Calzadilla A., K. Rehdanz, and R.S.J. Tol. 2011b "Trade Liberalization and Climate Change: A Computable General Equilibrium Analysis of the Impacts on Global Agriculture." *Water* 3(2): 526-550.

Calzadilla, A., K. Rehdanz, R. Betts, P. Falloon, A. Wiltshire, and R.S.J. Tol. 2010b. "Climate Change Impacts on Global Agriculture." Kiel working paper No. 1617, Kiel, Germany: Kiel Institute for the World Economy.

Calzadilla, A., T. Zhu, K. Rehdanz, R.S.J. Tol, and C. Ringler. 2009. "Economy-Wide Impacts of Climate Change on Agriculture in Sub-Saharan Africa." Research unit Sustainability and Global Change FNU-170, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Cornish, G., B. Bosworth, C. Perry and J. Burke. 2004. *Water Charging in Irrigated Agriculture, An Analysis of International Experience*. FAO Water Reports 28. FAO, Rome.

Darwin, R. 2004. “Effects of greenhouse gas emissions on world agriculture, food consumption, and economic welfare.” *Climatic Change* 66: 191-238.

Darwin, R.F., and D. Kennedy. 2000. “Economic Effects of CO_2 Fertilization of Crops: Transforming Changes in Yield into Changes in Supply.” *Environ. Model. Assess.* 5: 157–168.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses. 1995. “World Agriculture and Climate Change: Economic Adaptations.” Agricultural Economic Report 703, U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Decaluwé, B., A. Patry, and L. Savard. 1999. “When water is no longer heaven sent: Comparative pricing analysis in a AGE model.” Working Paper 9908, CRÉFA 99-05, Départment d’économique, Université Laval.

de Fraiture, C., Cai, X., Amarasinghe, U., Rosegrant, M., Molden, D., 2004. Does international cereal trade save water? The impact of virtual water trade on global water use. Comprehensive Assessment Research Report 4, Colombo, Sri Lanka.

Dimaranan, B.V. (editor). 2006. *Global Trade, Assistance, and Production: The GTAP 6 Data Base*. Center for Global Trade Analysis, Purdue University.

Dixon, P.B., and M.T. Rimmer. 2010. “Johansen’s Contribution to CGE Modelling: Originator and Guiding Light for 50 Years.” Centre of Policy Studies, General Paper No. G-203.

Dixon, P.B., M.T. Rimmer and G. Wittwer. 2010. “Modelling the Australian government's buyback scheme with a dynamic multi-regional CGE model.” Centre of Policy Studies and the Impact Project, General Paper No. G-186.

Dudu, H., and S. Chumi. 2008. “Economics of Irrigation Water Management: A Literature Survey with Focus on Partial and General Equilibrium Models.” Policy Research Working Paper 4556. World Bank, Washington, DC.

FAO. 2001. *Handbook on pressurized irrigation techniques*. Rome, FAO.

Fischer, G., F.N. Tubiello, H. van Velthuizen, and D.A. Wiberg. 2007. “Climate change impacts on irrigation water requirements: Effects of mitigation, 1990-2080.” *Technological Forecasting & Social Change* 74: 1083-1107.

Fischer, G., K. Frohberg, M.L. Parry, and C. Rosenzweig. 1994. “Climate change and world food supply, demand and trade: Who benefits, who loses?” *Global Environmental Change* 4(1):7-23.

Fischer, G., K. Frohberg, M.L. Parry, and C. Rosenzweig. 1996. “Impacts of potential climate change on global and regional food production and vulnerability”, in E.T. Downing, ed, *Climate change and world food security*. Springer-Verlag, Berlin.

Fischer, G., M. Shah, F.N. Tubiello, and H. van Velhuizen. 2005. "Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080." *Phil. Trans. R. Soc. B* 360: 2067–2083.

Gohin, A, and T. Hertel. 2003. "A Note on the CES Functional Form and Its Use in the GTAP Model." GTAP Research Memorandum No. 02.

Gómez, C.M., D. Tirado, and J. Rey-Maquieira. 2004. "Water exchange versus water work: Insights from a computable general equilibrium model for the Balearic Islands." *Water Resources Research* 42 W10502 10.1029/2004WR003235.

Hertel, T.W. 1997. *Global Trade Analysis: Modeling and Applications*. Cambridge University Press, Cambridge.

Horridge, J.M. and G. Wittwer. 2008. "The economic impacts of a construction project, using SinoTERM, a multi-regional CGE model of China." *China Economic Review* 19 (4): 628-634.

Jensen, M.E. 2007. "Beyond efficiency." *Irrigation Science* 25(3): 233-245.

Johansson, R.C., Y. Tsur, T.L. Roe, R. Doukkali, and A. Dinar. 2002. "Pricing irrigation water: a review of theory and practice." *Water Policy* 4 (2): 173-199.

Lee, H.L., T. Hertel, B. Sohngen, and N. Ramankutty. 2005. "Towards an integrated land use data base for assessing the potential for greenhouse gas mitigation". GTAP Technical Paper 25. Center for Global Trade Analysis, Purdue University.

McDonald, S., S. Robinson, and K. Thierfelder. 2005. "A SAM Based Global CGE Model using GTAP Data." Sheffield Economics Research Paper 2005:001. The University of Sheffield.

Peterson, D., G. Dwyer, D. Appels and J.M. Fry. 2004. "Modelling Water Trade in the Southern Murray-Darling Basin." Productivity Commission Staff Working Paper, Melbourne.

Rosegrant, M.W., X. Cai, and S.A. Cline. 2002. *World Water and Food to 2025: Dealing With Scarcity*. International Food Policy Research Institute. Washington, DC.

Tangermann, S. 2010. "Agricultural Trade 1980 vs. 2010: "Some Progress, But Still So Far To Go." Featured Paper for the 30th Anniversary Conference of the International Agricultural Trade Research Consortium, Berkeley CA, 12-14 December.

Tubiello, F.N., and G. Fischer. 2007. "Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080." *Technological Forecasting & Social Change* 74: 1030–1056.

Tyner, W.E. 2010. The integration of energy and agricultural markets. *Agricultural Economics* 41: 193-201.

United Nations. 1993. *The System of National Accounts (SNA93)*. United Nations, New York.

United Nations. 2006. *Water, a shared responsibility. The United Nations World Water Development Report 2*. UNESCO and Berghahn Books, Paris and London.

United Nations. 2009. *Water in a Changing World. The United Nations World Water Development Report 3*. UNESCO and Earthscan, Paris and London.

van Heerden, J.H., J. Blignaut, M. Horridge. 2008. "Integrated water and economic modelling of the impacts of water market instruments on the South African economy." *Ecological Economics* 66: 105-116.

Annex A: Production structure in selected CGE models

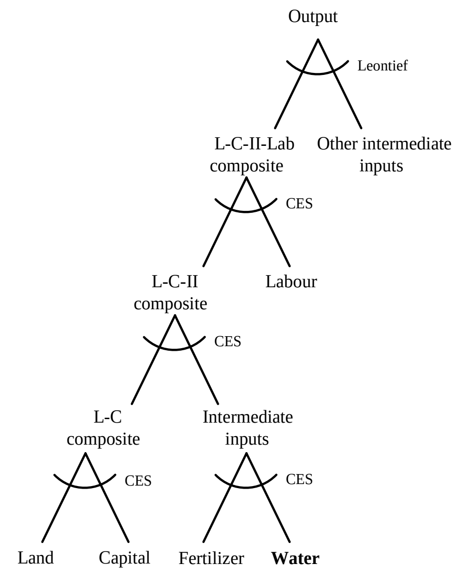


Figure A1. Decaluwé et al. (1999)
Source: Own presentation based on Decaluwé et al. (1999)

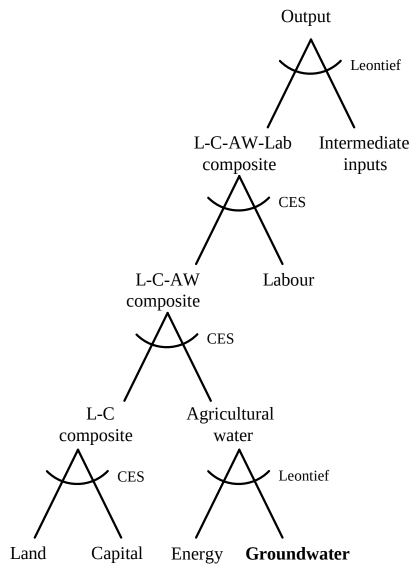


Figure A2. Gómez et al. (2004)
Source: Own presentation based on Gómez et al. (2004)

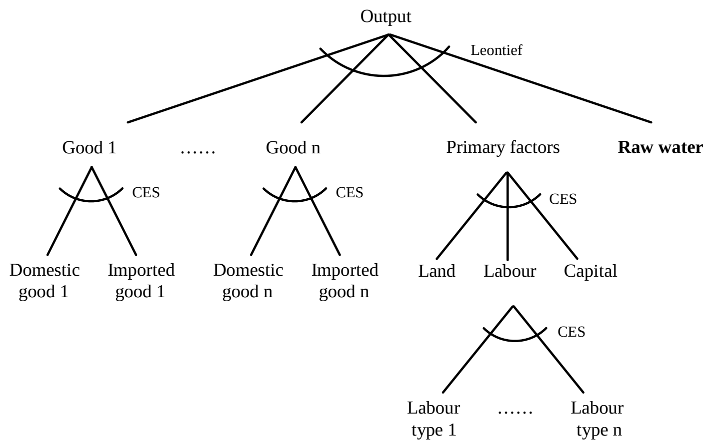


Figure A3. van Heerden et al. (2008)
Source: Own presentation based on van Heerden et al. (2008)

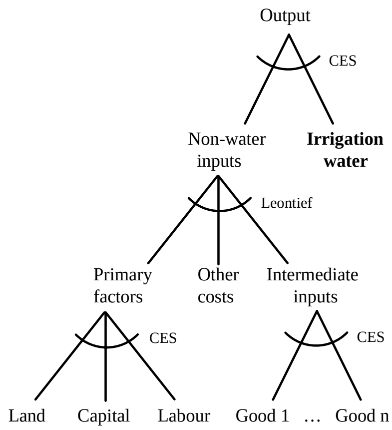


Figure A4. Peterson et al. (2004)
Source: Own presentation based on Peterson et al. (2004)

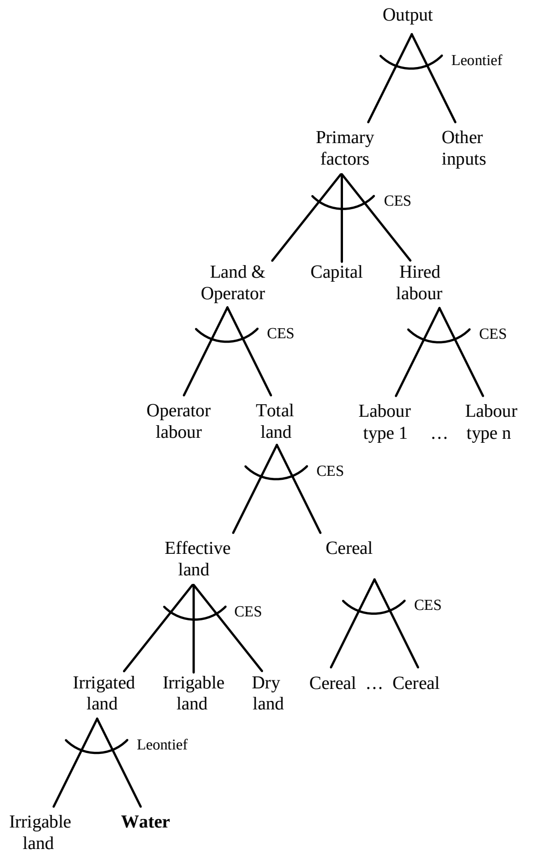


Figure A5. Dixon et al. (2010)
Source: Own presentation based on Dixon et al. (2010)

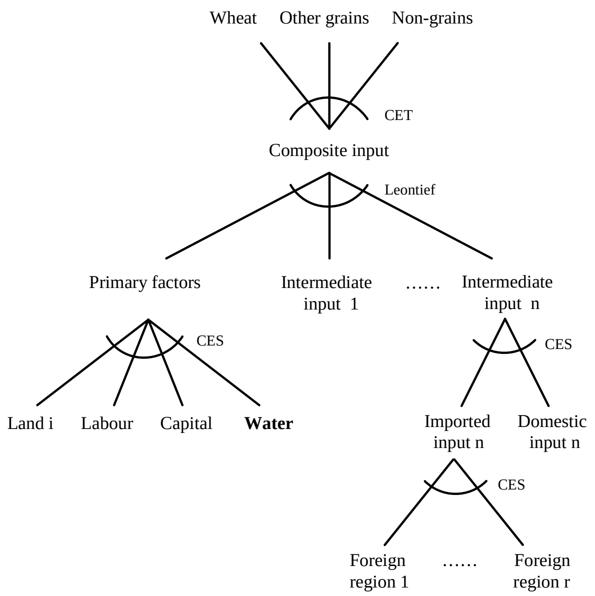


Figure A6. Darwin (2004)
Source: Own presentation based on Darwin et al. (1995)

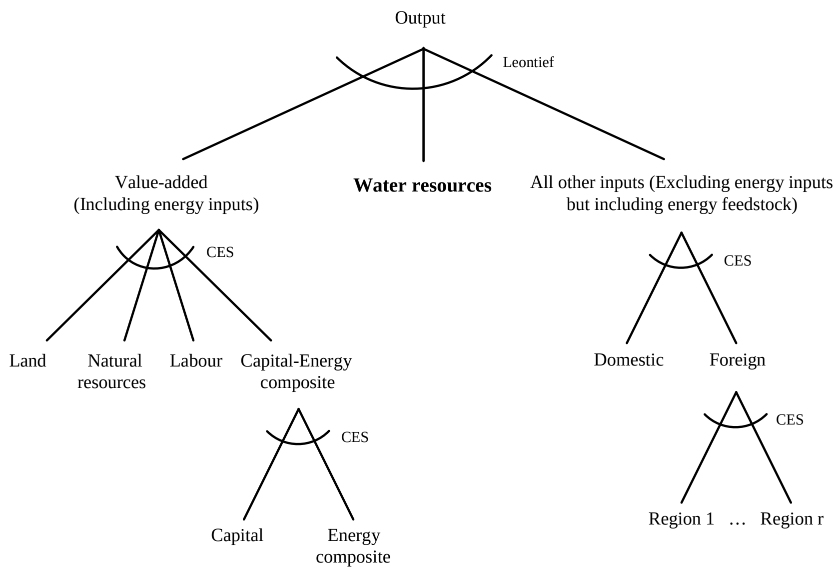
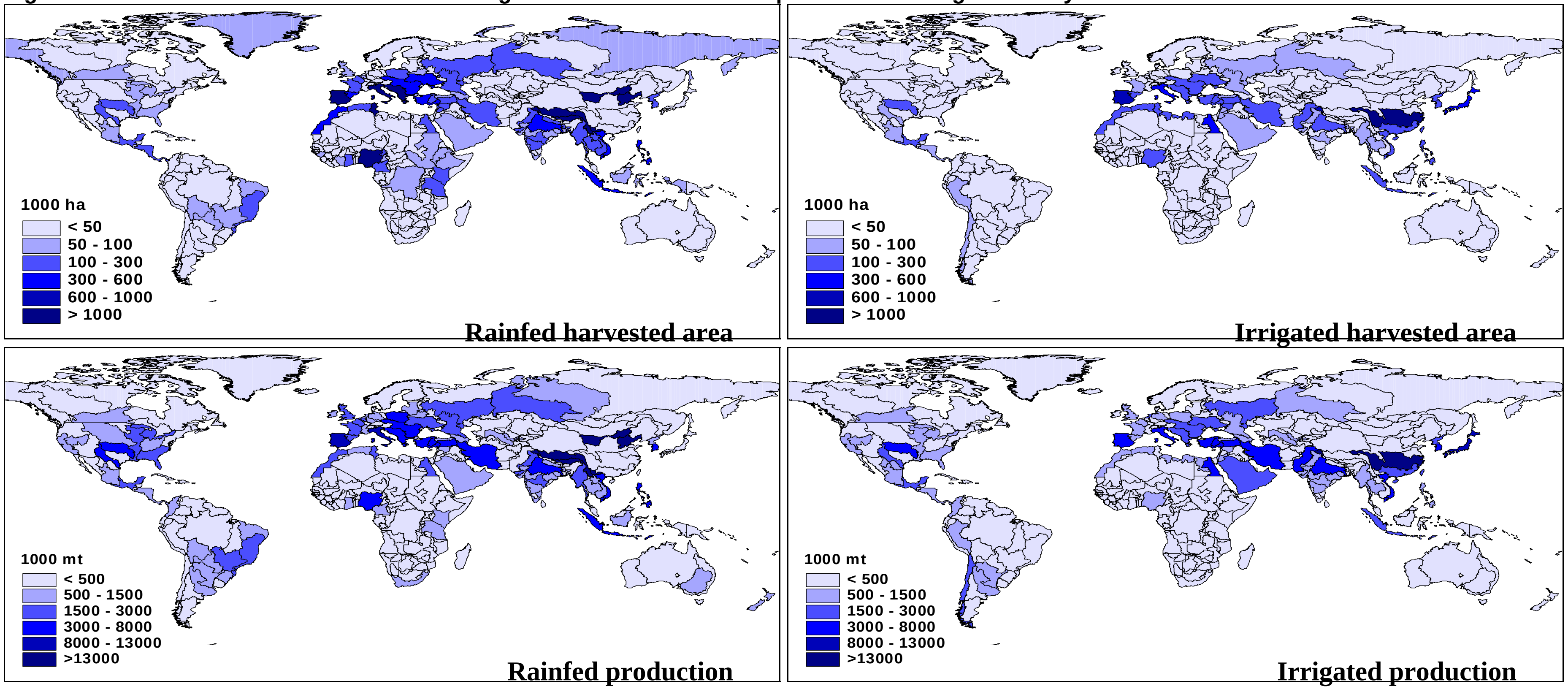


Figure A7. Berrittella et al. (2007)
Source: Own presentation based on Berrittella et al. (2007). Truncated.

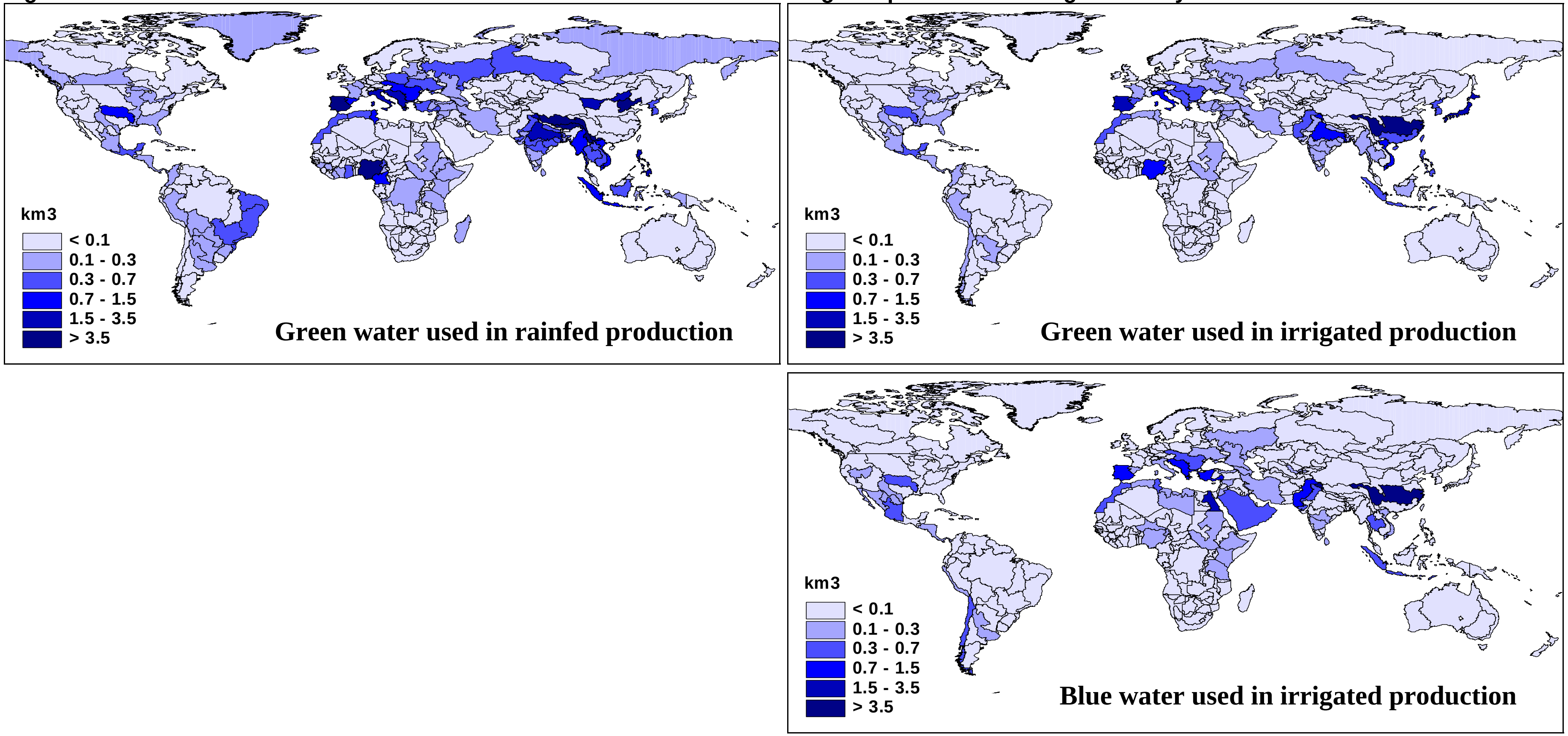
Annex B: Baseline data and aggregation used in GTAP-W

Figure B1. 2000 baseline data: Rainfed and irrigated harvested area and production of vegetables by FPU



Note: 2000 data are three-year averages for 1999-2001.
Source: IMPACT, 2000 baseline data (April 2008).

Figure B2. 2000 baseline data: Green and blue water used for rainfed and irrigated production of vegetables by FPU



Note: 2000 data are three-year averages for 1999-2001. Green water (effective rainfall) and blue water (irrigation water).
Source: IMPACT, 2000 baseline data (April 2008).

39

Table B1. Regional, sectoral and factoral aggregation in GTAP-W and mapping between GTAP-W and IMPACT

GTAP-W - 16 Regions	IMPACT - 115 Regions
United States (USA)	United States
Canada (CAN)	Canada
Western Europe (WEU)	Alpine Europe, Belgium and Luxembourg, British Isles, Cyprus, France, Germany, Iberia, Italy, Netherlands, Scandinavia
Japan and South Korea (JPK)	Japan, South Korea
Australia and New Zealand (ANZ)	Australia, New Zealand
Eastern Europe (EEU)	Adriatic, Central Europe, Poland
Former Soviet Union (FSU)	Baltic, Caucasus, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Middle East (MDE)	Gulf, Iran, Iraq, Israel, Jordan, Lebanon, Syria, Turkey
Central America (CAM)	Caribbean Central America, Mexico
South America (SAM)	Argentina, Brazil, central South America, Chile, Colombia, Ecuador, northern South America, Peru, Uruguay
South Asia (SAS)	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
Southeast Asia (SEA)	Indonesia, Malaysia, Mongolia, Myanmar, North Korea, Philippines, Singapore, Southeast Asia, Thailand, Vietnam
China (CHI)	China
North Africa (NAF)	Algeria, Egypt, Libya, Morocco, Tunisia
Sub-Saharan Africa (SSA)	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Congo, Djibouti, Democratic Republic of the Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
Rest of the World (ROW)	Papua New Guinea, rest of the world
GTAP-W - 7 Agricultural crops	**IMPACT - 23 Crops**
Rice (Rice)	Rice
Wheat (Wheat)	Wheat
Cereal grains (CerCrops)	Maize, millet, sorghum, other grains
Vegetables, fruits, nuts (VegFruits)	Potato, sweet potatoes/yams, cassava/other roots/tubers, vegetables, (sub) tropical fruits, temperate fruits, chickpeas, pigeon peas
Oilseeds (OilSeeds)	Soybeans, oils, groundnuts
Sugarcane, sugar beet (Sug_Can)	Sugarcane, sugar beets
Other agricultural products (Oth_Agr)	Other
--	Meals, cotton, sweeteners
GTAP-W 15 Non-agricultural sectors	
Animals (Animals)	
Meat (Meat)	
Food products (Food_Prod)	
Forestry (Forestry)	
Fishing (Fishing)	
Coal (Coal)	
Oil (Oil)	
Gas (Gas)	
Oil Products (Oil_Pcts)	
Electricity (Electricity)	
Water (Water)	
Energy intensive industries (En_Int_Ind)	
Other industries and services (Oth_Ind)	
Market services (Mserv)	
Non-market services (NMserv)	
GTAP-W - 7 Endowments	
Irrigation (Wtr)	
Irrigable land (Lnd)	
Rainfed land (RfLand)	
Pasture land (PsLand)	
Labour (Lab)	
Capital (Capital)	
Natural resources (NatlRes)	