Water scarcity and the impact of improved irrigation management: a computable general equilibrium analysis

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Abstract

Increasing water scarcity combined with an increasing demand for food and water for irrigation call for a careful revision of water use in agriculture. Currently, less than 60% of all the water used for irrigation is effectively used by crops. Based on the new version of the GTAP-W model we analyze the effect of potential water savings and the welfare implications of improvements in irrigation efficiency worldwide. The results show that a water policy directed to improve irrigation efficiency led to global and regional water savings, but it is not beneficial for all regions. The final effect on regional welfare will depend on the interaction of several different causes. For instance, higher irrigation efficiency changes opportunity costs and reverses comparative advantages, modifying regional trade patterns and welfare. For water-stressed regions the effects on welfare are mostly positive. For nonwater scarce regions the results are more mixed and mostly negative. The results show that exports of virtual water are not exclusive of water abundant regions.

1. Introduction

Water is a scarce resource. Forty percent of the world's population today face shortages regardless of whether they live in dry areas or in areas where rainfall is abundant (CA, 2007). The largest consumer of freshwater resources is the agricultural sector —globally around 70% of all freshwater withdrawals are used for food production. However, less than 60% of all the water used for irrigation is effectively consumed by crops. This article therefore analyzes the extent to which improvements in

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Data Appendix Available Online

A data appendix to replicate main results is available in the online version of this article. Please note: Wiley-Blackwell, Inc. is not responsible for the content or functionality of any supporting information supplied by the author. Any queries (other than missing material) should be directed to the corresponding author for the article.

irrigation management would be economically beneficial for the world as a whole as well as for individual countries and the amount of water savings that could be achieved.

During the coming decades, water scarcity is expected to rise because of a rapid increase in the demand for water due to population growth, urbanization, and an increasing consumption of water per capita. By 2025, the world's population is expected to rise from 6.5 billion today to 7.9 billion. More than 80% will live in developing countries and 58% in rapidly growing urban areas (Rosegrant et al., 2002). Consequently, 1.8 billion people are expected to live in countries or regions with absolute water scarcity, and two-thirds of the world population could be under stress conditions (UN-Water/FAO, 2007). In addition, climate change will influence the supply of water, modifying the regional distribution of freshwater resources (UN-Water/FAO, 2007).

According to the United Nations (2006), during the last century, irrigation water use has increased twice as fast as population, allowing the global food system to respond to the

increasing growth in population. However, expanding irrigated areas might not be sufficient to ensure future food security and meet the increasing demand for water in populous but water-scarce regions (Kamara and Sally, 2004). Therefore, one way to address the problem is to reduce the inefficiencies in irrigation. Seckler et al. (1998) estimated that around 50% of the future increase (by 2025) in the demand for water can be met by increasing irrigation efficiency.

Currently, irrigation efficiency in most of the developing countries is performing poorly (Fig. 1), 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 and 40% in the Philippines, Thailand, India, Pakistan, and Mexico; between 40 and 45% in Malaysia and Morocco; and between 50 and 60% 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% of the total global water used for irrigation purposes.

This article studies potential global water savings and its economic implications. Higher levels of irrigation efficiency imply that the same production could be achieved with less water (generating water savings) or, alternatively, that more hectares could be irrigated by the same available water resources (implying higher production). Consequently, regional use of freshwater resources and comparative advantages change, modifying regional trade patterns and welfare. The net effect on water use, therefore, depends on a complex interplay between sectors and regions implying adjustments in supply and demand in all sectors affected.

Improving irrigation efficiency worldwide generates new opportunity costs, which could reverse regional comparative advantages in food production. Regions with relatively poor irrigation performance may experience positive impacts in food production and exports when improving irrigation efficiency. At the same time, food-exporting regions may be vulnerable to positive impacts induced by enhanced irrigation efficiency elsewhere.

International trade of food products is not only the main channel through which welfare impacts spread across regions, it is also seen as a key variable in agricultural water management. As water becomes scarce, importing goods that require abundant water for their production may save water in water-scarce regions.

Most of the existing literature related to irrigation water use investigates irrigation management, water productivity, and water use efficiency. One strand of literature compares the performance of irrigation systems and irrigation strategies in general (e.g., Pereira, 1999; Pereira et al., 2002). Others have a clear regional focus and concentrate on specific crop types. To provide a few examples from this extensive literature: Deng et al. (2006) investigate improvements in agricultural water use efficiency in arid and semiarid areas of China. Bluemling et al. (2007) study wheat-maize cropping pattern in the North China plain. Mailhol et al. (2004) analyze strategies for durum wheat production in Tunisia. Lilienfeld and Asmild (2007) estimate excess water use in irrigated agriculture in western Kansas.

As the above examples indicate, water problems related to irrigation management are typically studied at the farm level, the river-catchment level or the country level. These studies omit the international dimension of water use. A full understanding of water use and the effect of improved irrigation management is impossible without understanding the international market for food and related products, such as textiles. In this article, we present a new version of the GTAP-W model to analyze the economy-wide impacts of enhanced irrigation efficiency. 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. The new GTAP-W model differentiates between rainfed and irrigated crops, which allows a better understanding of the use of water resources in agricultural sectors. The model allows us to calculate the initial water savings (when world markets would not adjust) that could be achieved by improving irrigation efficiency. This is what has been mostly done in the previous literature although not at the global level. We extend this approach by comparing the initial water savings with the final water savings taking into account adjustment processes in food and other markets. This is more interesting since it is very likely that regions will adjust differently to the initial water savings.

The remainder of the article is organized as follows. The next section describes potential impacts on trade and welfare from improvements in irrigation efficiency based on the comparative advantage theory. Section 3 briefly reviews the literature on economic models of water use. Section 4 presents the new GTAP-W model and the data on water resources and water use. Section 5 lays down the three simulation scenarios with no constraints on water availability. Section 6 discusses the results and section 7 concludes.

2. Water scarcity and comparative advantages

One common suggestion to achieve water security in a water-scarce country is to import goods that require water for their production, rather than producing them domestically (Allan, 2001; Hoekstra and Hung, 2005; Zimmer and Renault, 2003). This would reduce pressure on water resources and would result in domestic water savings that can be used for other purposes. Wichelns (2004) showed that this is not always true when only resource endowments are considered ignoring production technologies or opportunity costs of water and other limiting factors.

Technological differences were the first source of comparative advantage to be identified by David Ricardo (1817). The Ricardian model assumes two countries (A and B), two goods (X and Y), and one single factor of production (labor). Differences in technology are modeled by differences in the amount

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

Fig. 1. Average irrigation efficiency, 2001 baseline data.

of output that can be obtained from one unit of labor. Under these assumptions, country A has a comparative advantage in the production of good X if it is relatively more productive in the production of this good, that is, if the opportunity cost of good X in terms of good Y is lower in country A than in country B.[1] Compared to autarky, world output increases and both countries gain from trade if they export the good in which they have a comparative advantage.

Differences in technology or factor productivity are not the only source of comparative advantage. Differences in resource endowments also play a role as demonstrated by the Heckscher–Ohlin model. The standard version of this model assumes two countries, two goods, and two production factors. It also assumes similar technologies and preferences in both countries; different factor endowments; and mobility of factors between industries but not between countries. Four central theorems can be derived based on these assumptions: (1) The Heckscher–Ohlin theorem states that a country tends to export the good, which intensively uses the abundant factor in that country. (2) The Stopler–Samuelson theorem states that an increase in the relative price of one good increases the real return of the factor used intensively in the production of that good and decreases the real return of the other factor. (3) The Rybczynski theorem states that an increase in the endowment of one factor raises more than proportionally the production of the good which uses that factor relatively more intensively and decreases the production of the other good. (4) The factor price equalization theorem states that free trade in final goods is sufficient to bring equalization of factor prices.

Placing our article in the context of comparative advantage, we follow Wichelns (2004) to describe the potential impacts on trade and welfare from improvements in irrigation efficiency. Under the basic assumption of two countries (A and B), two goods (rice and cotton), and two factors (land and water), let us consider first that both countries are water-scarce (available water resources are 180,000 m^3 and 90,000 m^3 in country A and B, respectively) and have different production technologies. Country A has a technology level to produce 6 t/ha of rice or 2 t/ha of cotton. The available technology in country B is lower; it allows producing 4 t/ha of rice or 1 t/ha of cotton. The irrigation water requirements for rice and cotton in both countries are 18,000 m^3/ha and 6,000 m^3/ha, respectively. Under these assumptions, country A could choose to irrigate 10 ha of rice to produce a maximum of 60 t of rice or irrigate 30 ha of cotton to produce a maximum of 60 t of cotton or any linear combination of areas for the production of rice or cotton consistent with its production technology and factor endowments. Similarly, country B could irrigate 5 ha of rice to produce 20 t of rice or 15 ha of cotton to produce 15 t of cotton.

Note that the irrigation water endowment limits production in both countries. Country A is relatively water abundant, it has twice as much water as country B and has an absolute advantage in the production of both goods (higher yields per hectare). This may suggest that country A would have an advantage in the production of rice, the water-intensive crop. However, this is not the case. The opportunity cost of producing 1 t of rice in country A, in terms of cotton production, is higher than in country B (1 t of cotton compared to 0.75 t of cotton, respectively).[2]

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[1] A double comparison across goods and countries is essential. By definition, a difference in relative autarky prices implies the presence of comparative advantages, and every country will have a comparative advantage in the production of one good, even when one of the two countries has an absolute advantage in the production of both goods. Thus, the Ricardian model suggests that what matters is not absolute advantage but comparative advantage.

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[2] Opportunity costs are expressed in terms of foregone production alternatives and defined per unit of output of rice or cotton, rather than per unit of land or water. Thus, the opportunity cost of producing 1 t of rice in country B can be expressed as 0.75 t of cotton (15 t/ha of cotton divided by 20 t/ha of rice).

Therefore, country B (the water-scarce country) has a comparative advantage in the production of rice (the water-intensive crop) and country A has a comparative advantage in the production of cotton, where the opportunity cost of producing 1 t of cotton is lower. Both countries would gain from trade if they export the good in which they have a comparative advantage. The terms of trade, expressed as a ratio, describe how much rice will be required to obtain 1 t of cotton and will lie between the opportunity costs of producing cotton in both countries (between 1 and 1.33).

Wichelns (2004) extended this example to show that as long as water is the limiting factor, country B will have a comparative advantage in rice production, whether or not it has a larger water endowment than country A. He also shows the presence of comparative advantage even when both countries have the same production technology (crop yields are 6 t/ha of rice and 2 t/ha of cotton) but different resource constraints. Water is the limiting factor in country A ($180,000 \text{ m}^3$ compared to $600,000 \text{ m}^3$) and land is the limiting factor in country B (30 ha compared to 40 ha). Under these assumptions, the water-abundant country (country B) will have a comparative advantage in the production of the water-intensive crop (rice). Therefore, the opportunity costs are determined by the production coefficients, the water requirements, and the scarcity conditions.

Within this context, let us now consider an improvement in irrigation efficiency, which is translated into lower irrigation water requirements. Suppose a decrease in the irrigation water requirements for rice in country A from 18,000 to $12,000 \text{ m}^3$ (all other assumptions remain the same). As water is the limiting factor in country A, the new technology allows irrigating more hectares with the same amount of water resources. Country A could irrigate 15 ha of rice to produce 90 t of rice. As a result, the opportunity costs change in country A. The opportunity cost of producing 1 t of rice is 0.66 t of cotton (lower than before) and the opportunity cost of producing 1 t of cotton is 1.5 t of rice (higher than before).

Considering the new opportunity costs in country A, the comparative advantages are reversed when both countries face water scarcity. Country A has a comparative advantage in rice production and country B in cotton production. When both countries have the same production technology but different resource constraints the reduction in the irrigation water requirement is not strong enough to lower the opportunity cost of producing rice. Therefore, country B (water-abundant country) still has a comparative advantage in rice production (water-intensive crop) and country A (water-scarce country) in cotton production (nonwater-intensive crop).

While many of the propositions of these theoretical models are lost by generalization or when considering more realistic assumptions (WTO, 2008), comparative advantage continues to predict and explain the gains of trade. Trade-focused computable general equilibrium models (CGE) are, to some extent, empirical applications of these theories. They are based on the neoclassical (Walrasian) general equilibrium theory and incorporate a theoretical and coherent framework.

3. Economic models of water use

Economic studies of water use based on CGE models have generally been applied to look at the direct effects of water policies, such as water pricing or quantity regulations, on the allocation of water resources (for an overview of this literature see Johansson et al., 2002). These studies are generally based on data for a single country or region assuming no effects for the rest of the world of the implemented policy (e.g., Decaluwé et al., 1999; Diao and Roe, 2003; Diao et al., 2008; Feng et al., 2007; Seung et al., 2000). All of these CGE studies have a limited geographical scope.

Berrittella et al. (2007) are an exception. They use a global CGE model including water resources (GTAP-W, version 1) to analyze the economic impact of restricted water supply for water-short regions. They contrast a market solution, where water owners can capitalize their water rent, to a nonmarket solution, where supply restrictions imply productivity losses only. They show that water supply constraints could actually improve allocative efficiency, as agricultural markets are heavily distorted. The welfare gain from curbing inefficient production may more than offset the welfare losses due to the resource constraint. Berrittella, Rehdanz, Roson, et al. (2008) use the same model to investigate the economic implications of water pricing policies. They find that water taxes reduce water use, and lead to shifts in production, consumption, and international trade patterns. Countries that do not levy water taxes are nonetheless affected by other countries' taxes. Like Feng et al. (2007), Berrittella et al. (2006) analyze the economic effects of the Chinese SNWT project. Their analysis offers less regional detail but focuses in particular on the international implications of the project. Berrittella, Rehdanz, Tol, et al. (2008) extend the previous papers by looking at the impact of trade liberalization on water use.

In this article we present a new version of the GTAP-W model to analyze the economy-wide impacts of enhanced irrigation management through higher levels of irrigation efficiency. Two crucial features differentiate version 2 of GTAP-W, used here, and version 1, used by Berrittella et al. 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.

In the first version of the model, water is combined, at the top level nest of the production structure, with value-added and intermediate inputs using a Leontief production function. That is, water, value-added, and intermediate inputs are used in fixed proportions, there are no substitution possibilities between them (Appendix I, upper diagram Fig. A1). The second version of GTAP-W, used here, remedies this deficiency by incorporating water into the value added nest of the production structure. Indeed, water is combined with irrigated 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 (CES) (Appendix I, lower

diagram Fig. A1). 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 us to discriminate between rainfed and irrigated crop production and the representative farmer to substitute one for the other. The next section introduces a detailed description of the new version of the model.

4. The new GTAP-W model

In order to assess the systemic, general equilibrium effects of improved irrigation management, we use a multi-region world CGE model, called GTAP-W. The model is a further refinement of the GTAP model[3] (Hertel, 1997), and is based on the version modified by Burniaux and Truong (2002)[4] as well as on the previous GTAP-W model introduced by Berrittella et al. (2007).

The new GTAP-W model is based on the GTAP version 6 database, which represents the global economy in 2001. The model has 16 regions and 22 sectors, 7 of which are in agriculture.[5] 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. Pasture land is basically the land used in the production of animals and animal products. The last two types of land differ as rainfall is free but irrigation development is costly. As a result, land equipped for irrigation is generally more valuable because yields per hectare are higher. 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. The lower tree diagram in Fig. A1 (Appendix I) represents the new production structure.

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). To accomplish this, we 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 using its proportionate contribution to total production (see Appendix I, Table A2).[6] The value of pasture land is derived from the value of land in the livestock breeding sector. Regional information on rainfed and irrigated production by crop is based on IMPACT baseline data (Rosegrant et al., 2002).[7]

In the next step, we split the value of irrigated land into the value of land and the value of irrigation using the ratio of irrigated yield to rainfed yield. These ratios are based on IMPACT data (see Appendix I, Table A3).[8] The numbers indicate the relative value of irrigated agriculture compared to rainfed agriculture for particular land parcels. Irrigated and rainfed yields differ between crops as well as regions (not shown). For example, on average, irrigation water is better applied to rice than to oil seeds. At the regional level, more crops are grown under irrigation in South America compared to North Africa or Sub-Saharan Africa.

The procedure we described above to introduce the four new endowments (pasture land, rainfed land, irrigated land, and irrigation) allows us to avoid problems related to model calibration. In fact, since the original database is only split and not altered, the original regions' SAMs are balanced and can be used by the GTAP-W model to assign values to the share parameters of the mathematical equations. Furthermore, the information supplied by the IMPACT model (demand and supply of water, demand and supply of food, rainfed, and irrigated production and rainfed and irrigated area) provides detailed information for a robust calibration of a new baseline. For detailed information about the SAM representation of the GTAP database see McDonald et al. (2005).

The GTAP-W model accounts only for water resources used in the agricultural sector, which consumes globally about 70% of the total freshwater resources. Domestic, industrial, and environmental water uses are not considered by the model, because the necessary data are missing at a global scale. Therefore, the model does not account for alternative uses of water outside the agricultural sector, even though the value of water is generally much higher for domestic and industrial uses. The water industry in GTAP-W accounts only for the collection, purification, and distribution of water to the industrial sector and provides no information on the amount of water used or its value.

As in all CGE models, the GTAP-W model makes use of the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modeled through a representative firm, which maximizes profits in perfectly competitive markets. The

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[3] The GTAP model is a standard CGE static model distributed with the GTAP database of the world economy (www.gtap.org). For detailed information see Hertel (1997) and the technical references and papers available on the GTAP website.

[4] Burniaux and Truong (2002) developed a special variant of the model, called GTAP-E. The model is best suited for the analysis of energy markets and environmental policies. There are 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.

[5] See Appendix II for the regional, sectoral, and factoral aggregation used in GTAP-W.

[6] 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 100 million USD. Thus, we have for region r that irrigated land rents in rice production are 60 million USD and rainfed land rents in rice production are 40 million USD.

[7] The IMPACT model is a global partial equilibrium agricultural sector model that allows for the combined analysis of water and food supply and demand.

[8] 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 60 million USD. Thus, we have for irrigated agriculture in region r that irrigation rents are 20 million USD and land rents are 40 million USD.

production functions are specified via a series of nested CES functions (Appendix I, lower diagram Fig. A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called ''Armington assumption,'' which accounts for product heterogeneity between regions.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, pasture land, rainfed land, irrigated land, irrigation, labor, and capital). Capital and labor are perfectly mobile domestically, but immobile internationally. Pasture land, rainfed land, irrigated 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 nonhomothetic function, which is used to account for possible differences in income elasticities for the various consumption goods. A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.

In the GTAP model and its variants, two industries are not related 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 world bank collects savings from all regions and allocates investments to achieve equality of expected rates of return (macroeconomic closure).

In the original GTAP model, land is combined with natural resources, labor, and the capital-energy composite in a value-added nest. In our modeling framework, we incorporate the possibility of substitution between land and irrigation in irrigated agricultural production by using a nested CES function (Appendix I, lower diagram Fig. A1). The procedure for obtaining the elasticity of factor substitution between land and irrigation (σLW) is explained in more detail in Appendix III.[9] Next, the irrigated land-water composite is combined with pasture land, rainfed land, natural resources, labor, and the capital-energy composite in a value-added nest through a CES structure. The original elasticity of substitution between primary factors (σVAE) is used for the new set of endowments.

In the benchmark equilibrium, water used for irrigation is supposed to be identical to the volume of water used for irrigated agriculture in the IMPACT model. An initial sector and region specific shadow price for irrigation water can be obtained by combining the SAM information about payments to factors and the volume of water used in irrigation from IMPACT. In our analysis, improved irrigation management (particularly, more efficient use of irrigation water use) is introduced in the model through higher levels of productivity in irrigated production.

5. Design of simulation scenarios

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 this article, no distinction is made between conveyance and field application efficiency. Any improvement in irrigation efficiency refers to an improvement in the overall irrigation efficiency.

Global projections of water supply and demand (World Bank, 2003) show that efforts towards improving irrigation efficiency would mostly take place in water-scarce developing areas. Four factors contribute to this: population growth, rapid urbanization, high per-capita water consumption, and climate change (UN-Water/FAO, 2007). Most of these drivers will have a strong influence in developing countries. In fact, almost all of the future population growth will take place in developing countries (with large regional differences).

We evaluate the effects of enhanced irrigation efficiency on global production and income through three different scenarios. The scenarios are designed 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 in *water-scarce developing regions* improves. We consider a region as water-scarce if, for at least one country within the region, water availability is less than 1,500 cubic meters per person per year.[10] 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), 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%, 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% (World Bank, 2003);

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[9] A sensitivity analysis was performed and revealed that the model results are not sensitive to changes in the value of the elasticity of substitution between land and irrigation.

[10] The water-stressed countries were identified using the current AQUASTAT database.

Table 1
Annual irrigation costs for different irrigation systems and suitability of irrigation systems according to the crop type (USD per hectare)

Description	Irrigation system				Additional cost (USD per ha)
	Basin	Furrow	Sprinkler	Drip	
Irrigation cost (USD per ha)	94	97	141	202	
Aggregated crops in GTAP-W					
Rice	←——————→				3
Wheat	←————————————→				47
Cereal grains	←————————————→				47
Vegetable, fruits, nuts			←————————————→		105
Oil seeds	←——————————————————→				108
Sugar cane	←————————————→				47
Other agricultural products			←————————————→		105

Source: Sauer et al. (2010).

see Fig. 1. Therefore, our analysis attempts to study potential global water savings and its economic implications, improving irrigation efficiency to the maximum attainable level.

Our modeling framework does not allow us to directly include investments or costs associated with the improvements in irrigation efficiency. Therefore, we use global estimates on irrigation costs from Sauer et al. (2010) to adjust the resulting welfare gains. Table 1 shows the annual irrigation cost for different irrigation systems as well as the suitability of irrigation systems by crop type. Sauer et al.'s estimates include capital costs as well as operation and maintenance costs. Operation costs include energy and labor, while maintenance costs are set to 3% of the capital costs for basin irrigation and 5% for other irrigation systems. Irrigation costs are associated to efficiency levels; higher costs mean higher efficiency. Field application efficiency for surface irrigation systems is about 60%, for sprinkler irrigation systems around 75%, and for drip irrigation systems around 90%.

To compute regional irrigation costs associated with each of our scenarios, we use the difference in costs (i.e., efficiency) between the most expensive and least expensive irrigation systems suitable for each crop (reported in the last column of Table 1). That is to say, to achieve higher levels of irrigation efficiency, a region pays for the new and more efficient irrigation system. The additional costs are also related to the current irrigation efficiency in the region. For regions where irrigation efficiency is close to the maximum achievable level, the marginal costs of improving irrigation efficiency should be higher than for regions with low performance of irrigation systems. That is, the lower the performance of irrigation systems, the lower the marginal cost of enhancing irrigation efficiency. Combining this infor-

Table 2
Regional irrigation costs of improving irrigation efficiency to its maximum attainable level and average irrigation efficiency

Regions	Total additional irrigation costs (million USD)	Average irrigation efficiency (%)
United States	208	70
Canada	11	55
Western Europe*	167	55
Japan and South Korea*	49	58
Australia and New Zealand	0	73
Eastern Europe*	62	60
Former Soviet Union	250	57
Middle East*	112	68
Central America	186	50
South America	235	41
South Asia*	1,619	55
Southeast Asia*	319	47
China	1,737	56
North Africa*	23	70
Sub-Saharan Africa*	138	45
Rest of the World*	35	41
World	**5,151**	**57**

Note: Water-stressed regions are indicated by an asterisk (*).
Source: Own calculations based on Sauer et al. (2010).

mation with the initially irrigated areas (Appendix I, Table A1), Table 2 shows the irrigation costs of improving irrigation efficiency to its maximum attainable level.

Regional irrigation costs vary according to regional irrigation efficiency, irrigated areas, and type of crop production. Irrigation costs are the largest for China and South Asia, where irrigation efficiency is close to the world average (57%). In South
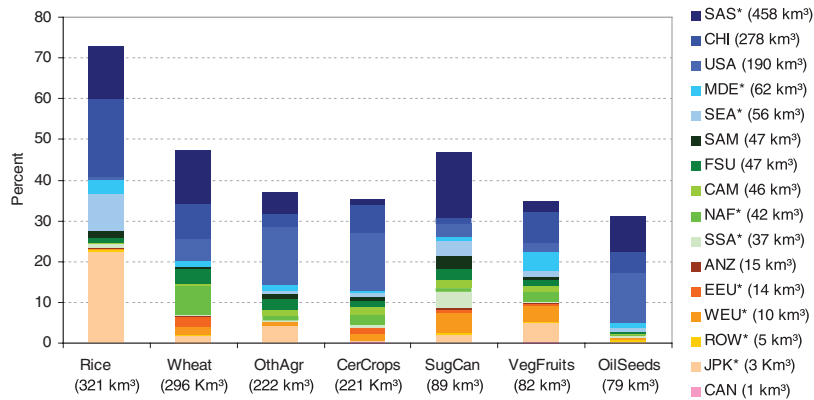
Note: Irrigation water used in km^3 by crop and region is shown in parentheses. Water-stressed regions are indicated by an asterisk (*).

Fig. 2. Share of irrigated production in total production by crop and region, 2001 baseline data.

America, Sub-Saharan Africa, and Southeast Asia efficiency levels are lowest. Improving irrigation efficiency worldwide to the maximum attainable efficiency level is expected to cost more than 5 billion USD (Table 2).[11]

6. Results

Fig. 2 shows irrigated production as the share of total agricultural production in the GTAP-W baseline data. Irrigated rice production accounts for 73% of the total rice production; the major producers are Japan and South Korea, China, South Asia, and Southeast Asia. Around 47% of wheat and sugar cane is produced using irrigation. However, the volume of irrigation water used in sugar cane production is less than one-third of what is used in wheat production. South Asia, China, North Africa, and the United States are major producers of irrigated wheat, and South Asia and Western Europe of sugarcane. The share of irrigated production in total production of the other four crops in GTAP-W (cereal grains, oil seeds, vegetables and fruits, and other agricultural products) varies from 31 to 37%. The United States and China are major producers of cereal grains; the United States, South Asia, and China of oil seeds; China, the Middle East, and Japan and South Korea of vegetables and fruits; and the United States and South Asia of other agricultural products.

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%. There are three major irrigation water users (South Asia (35%), China (21%) and United States (15%)). These regions use more than 70% of the global freshwater water used for irrigation.

Table 3 presents percentage changes in the use of irrigated land and irrigation for four of our seven agricultural sectors (rice, wheat, cereal grains, and vegetables and fruits).[12] See also the irrigated land-water composite in Appendix Fig. A1. These two factors indicate changes in irrigated production. Table 4 displays the percentage changes in total agricultural 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, as discussed below.

Turning to rice production first, the four major rice producers (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 (Table 5) 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.

There are seven major wheat-producing regions in the world (South Asia, China, North Africa, United States, Western Europe, Eastern Europe, and the former Soviet Union). The first four regions are the major producers of irrigated wheat. Comparing the results of Table 3 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

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[11] Some degree of efficiency gains are also 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.

[12] Results for the other three agricultural sectors including oil seeds, sugar cane, and sugar beet as well as other agricultural products are excluded for brevity but can be obtained from the authors on request.

Table 3

Percentage change in irrigated land-water composite as an indicator for changes in irrigated production, results for all scenarios and for four agricultural sectors

Region	Rice (%)			Wheat (%)			Cereal grains (%)			Vegetables and fruits (%)		
	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3
USA	−5.70	−6.97	−7.57	−1.57	−2.13	3.19	0.63	0.86	4.96	0.55	0.35	3.78
CAN	0.00	0.00	0.00	−2.56	−3.45	25.54	1.11	1.50	34.67	−0.01	−0.06	33.20
WEU*	−22.87	4.13	2.36	−0.52	31.91	31.30	0.83	33.17	33.86	0.67	33.76	33.67
JPK*	−0.62	22.99	23.05	−0.12	42.78	42.00	0.67	31.75	28.97	0.64	25.93	26.43
ANZ	−6.10	−7.51	−8.11	−1.86	−1.98	−1.32	1.35	2.02	1.38	0.50	0.47	0.89
EEU*	−1.04	18.89	17.67	−0.17	21.69	21.61	0.06	21.45	21.53	0.10	21.90	21.93
FSU	−0.05	0.01	26.51	−0.17	−0.28	26.42	0.08	0.11	27.08	0.21	0.23	25.96
MDE*	7.97	8.16	8.57	6.63	6.03	4.66	8.80	8.76	8.26	10.01	10.02	10.18
CAM	−1.21	−1.33	54.40	−0.43	−0.65	54.57	0.39	0.59	42.76	0.09	−0.08	48.62
SAM	−0.79	−0.59	73.99	−0.72	−0.64	76.81	0.38	0.55	76.81	0.45	0.29	78.26
SAS*	30.54	30.47	30.55	36.36	36.25	36.15	34.59	34.71	34.93	36.08	36.11	36.20
SEA*	53.32	52.37	52.91	68.47	69.19	69.06	53.70	54.63	53.92	53.00	53.56	53.86
CHI	0.14	0.20	29.92	0.17	0.24	29.28	−0.03	0.07	30.15	0.22	0.30	34.35
NAF*	−5.78	−8.35	−13.23	4.81	4.64	4.54	4.82	4.97	5.00	4.83	4.85	5.07
SSA*	61.45	63.37	63.07	57.50	58.33	56.00	61.68	63.80	63.37	63.02	64.07	63.15
ROW*	76.82	76.86	71.33	98.25	95.31	94.05	77.03	72.35	72.63	71.47	69.38	73.69

Note: Water-stressed regions are indicated by an asterisk (*). *Water-scarce developing regions* (Scen. 1), *water-scarce regions* (Scen. 2), and *all regions* (Scen. 3).

Table 4

Percentage change in total agricultural production, results for all scenarios and for four agricultural sectors

Region	Rice (%)			Wheat (%)			Cereal grains (%)			Vegetables and fruits (%)		
	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3
USA	−7.62	−9.38	−12.97	−2.83	−3.79	−1.18	−0.26	−0.30	−0.51	−0.36	−0.91	−2.17
CAN	−13.89	−14.27	−16.73	−4.64	−6.30	−9.56	−0.30	−0.48	−1.36	−1.65	−2.33	−2.07
WEU*	−28.14	−25.86	−28.34	−1.95	−1.26	−3.03	−0.33	−0.19	−0.81	−0.53	0.69	−0.67
JPK*	−1.50	1.80	1.10	−0.92	18.97	17.35	0.00	10.88	7.38	−0.08	2.38	2.11
ANZ	−8.53	−10.75	−12.44	−3.56	−4.31	−4.59	0.21	0.37	−1.47	−0.83	−1.51	−2.13
EEU*	−1.44	−1.16	−2.65	−0.39	1.09	0.76	−0.13	0.27	0.11	−0.08	0.74	0.52
FSU	−0.38	−0.42	0.04	−0.54	−0.77	−0.30	−0.25	−0.33	−0.13	−0.08	−0.17	0.53
MDE*	−0.10	−0.12	−0.13	−2.12	−3.02	−5.00	−0.10	−0.38	−1.40	0.47	0.24	−0.05
CAM	−1.89	−2.24	6.03	−0.99	−1.47	14.11	−0.03	−0.01	3.26	−0.37	−0.79	6.17
SAM	−1.62	−1.68	0.52	−1.47	−1.67	−0.30	−0.22	−0.32	0.07	−0.12	−0.58	1.40
SAS*	3.71	3.53	3.30	7.16	6.92	6.47	1.37	1.37	1.29	2.61	2.53	2.34
SEA*	6.08	4.79	4.75	14.56	14.54	13.93	5.63	5.82	4.84	2.79	2.71	2.53
CHI	−0.23	−0.35	1.41	−0.21	−0.31	2.16	−0.45	−0.52	2.74	−0.17	−0.28	0.75
NAF*	−11.77	−14.90	−20.78	0.17	−0.27	−0.88	0.33	0.26	−0.21	0.12	−0.10	−0.35
SSA*	−0.22	−0.35	−0.44	1.98	0.99	−0.68	0.07	0.06	−0.08	−0.09	−0.88	−1.40
ROW*	5.92	5.61	2.13	20.56	19.50	18.07	0.71	0.68	0.03	3.14	2.66	2.07

Note: Water-stressed regions are indicated by an asterisk (*). *Water-scarce developing regions* (Scen. 1), *water-scarce regions* (Scen. 2), and *all regions* (Scen. 3).

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 United States 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.

The picture is similar for cereal grains. Major producers (United States, Eastern Europe, former Soviet Union, South America, China, and Sub-Saharan Africa) increase their irrigated production with higher levels of irrigation efficiency—indeed, all regions do. In the developing regions as well as the former Soviet Union irrigation water demand is increasing with higher levels of irrigation efficiency while water demand is decreasing in the United States and Eastern Europe. Total agricultural production increases in only three of the six regions (Eastern Europe, South America, and China).

A relatively large number of regions are major vegetable and fruit producers (United States, Western Europe, Japan and South Korea, former Soviet Union, Middle East, South Asia,

Table 5
Percentage change in water demand in irrigated agriculture, results for all scenarios and for four agricultural sectors

Region	Rice (%)			Wheat (%)			Cereal grains (%)			Vegetables and fruits (%)		
	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3	Scen. 1	Scen. 2	Scen. 3
USA	−5.68	−6.94	−8.70	−1.55	−2.10	0.64	0.65	0.89	−0.92	0.57	0.38	−2.03
CAN	0.00	0.00	0.00	−2.56	−3.45	−5.43	1.11	1.50	1.45	−0.02	−0.06	0.34
WEU*	−22.86	−21.51	−22.84	−0.50	−0.48	−0.94	0.86	0.47	0.98	0.69	0.91	0.84
JPK*	−0.63	−1.45	−1.43	−0.13	9.83	9.20	0.66	9.51	7.18	0.63	−0.38	−0.01
ANZ	−6.11	−7.53	−8.16	−1.88	−2.00	−1.38	1.34	2.00	1.32	0.49	0.45	0.83
EEU*	−1.04	−2.30	−3.31	−0.17	−0.01	−0.07	0.06	−0.21	−0.14	0.10	0.17	0.19
FSU	−0.06	0.00	−2.91	−0.18	−0.29	−0.22	0.07	0.09	0.38	0.20	0.21	1.34
MDE*	1.60	1.78	2.15	−0.50	−1.07	−2.36	0.86	0.82	0.34	−0.23	−0.23	−0.10
CAM	−1.23	−1.34	−7.25	−0.45	−0.66	8.10	0.37	0.58	−0.57	0.07	−0.09	−0.84
SAM	−0.78	−0.59	−2.12	−0.71	−0.64	−0.09	0.38	0.54	0.65	0.46	0.29	0.67
SAS*	−0.18	−0.24	−0.18	2.78	2.70	2.61	−1.60	−1.51	−1.36	−1.23	−1.21	−1.15
SEA*	−2.07	−2.65	−2.33	−0.15	0.31	0.20	2.98	3.64	3.12	−1.19	−0.80	−0.65
CHI	0.12	0.17	−3.28	0.15	0.22	2.17	−0.05	0.05	3.51	0.21	0.27	−0.86
NAF*	−9.67	−12.13	−16.81	0.10	−0.06	−0.15	0.30	0.45	0.47	0.03	0.05	0.25
SSA*	−1.91	−0.62	−0.92	6.42	7.13	5.42	−0.56	0.88	0.48	−2.15	−1.39	−2.07
ROW*	−1.14	−0.04	−3.40	10.64	9.90	9.11	−0.67	−2.89	−2.72	−4.56	−4.92	−1.96

Note: Water-stressed regions are indicated by an asterisk (*). *Water-scarce developing regions* (Scen. 1), *water-scarce regions* (Scen. 2), and *all regions* (Scen. 3).

Southeast Asia and China). However, irrigated production amounts to a significant share of total production only in China, the Middle East, and Japan and South Korea. As with rice, irrigated production of vegetables and fruits increases with higher irrigation efficiency. Irrigated production increases even further when more regions reach higher efficiency levels, except in Western Europe. Irrigation water demand decreases for most regions; exceptions are Western Europe and the former Soviet Union. Comparing the scenarios *water-scarce regions* and *all regions*, water demand falls further if fewer regions increase irrigation efficiency. The results for total production are mixed. Production levels in the United States, Western Europe, and the Middle East decrease, whereas other regions see an increase.

If markets would not adjust, improved irrigation efficiency would lead to water savings. With adjustments in other markets, the effect is ambiguous. Fig. 3 compares how much water used in irrigated agriculture could be saved by the different scenarios. The initial water saving shows the reduction in the irrigation water requirements under improved irrigation efficiency, without considering any adjustment process in food and other markets. Globally, water savings are 158 km² (*water-scarce developing regions*), 163 km³ (*water-scarce regions*), and 282 km³ (*all regions*). This is between 12 and 21% of the total amount of irrigation water used in agriculture (see Fig. 2).

Final water savings are a combination of 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 United States 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 5–10% of the total amount of irrigation water used in agriculture could be saved.

Saved water can be used for other purposes depending on what happens to the drainage water and the return flow of water (Jensen, 2007; Molden and de Fraiture, 2000). This is not considered here.

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%. This comprises an increase in irrigated production of 24.6% and a decline in rainfed production of 15.0%. For individual agricultural products, the shift from rainfed to irrigated production varies widely.

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%), for an increase in total production of 1.7%. The
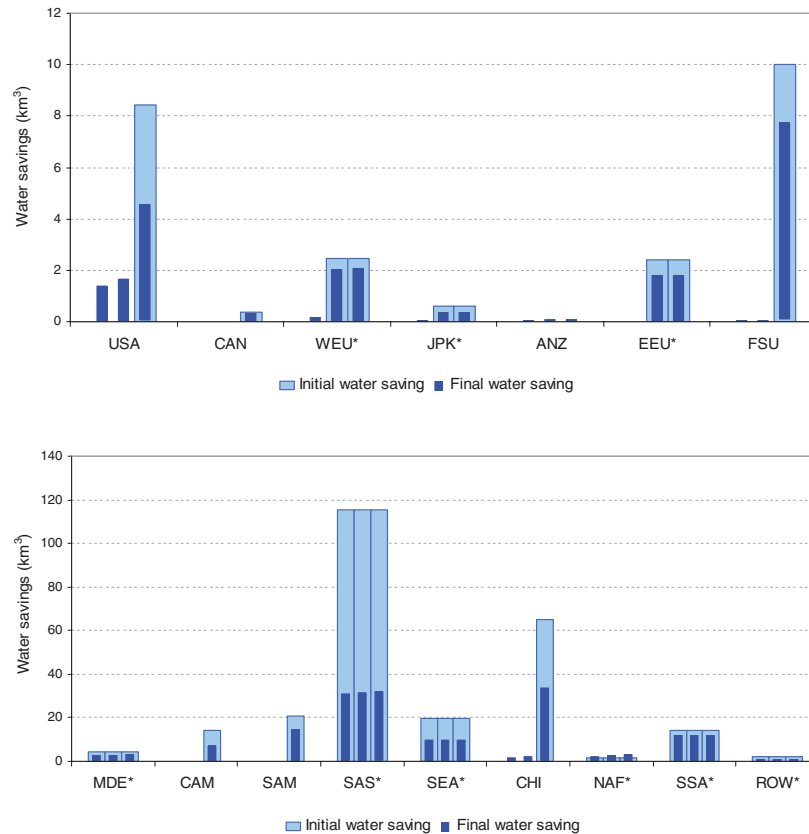
Note: Developed regions (top panel) and developing regions (bottom panel). Water-stressed regions are indicated by an asterisk (*). The three bars refer to the three scenarios (*water-scarce developing regions*, *water-scarce regions*, and *all regions*, respectively).

Fig. 3. Initial and final water savings by scenario, 2001.

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

Agricultural products	Water-scarce developing regions scenario				Water-scarce regions scenario				All regions scenario			
	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**	

fall in the world market price is smallest for cereals (3.4%); total production rises by 0.4%.

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. Fig. 4 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. The
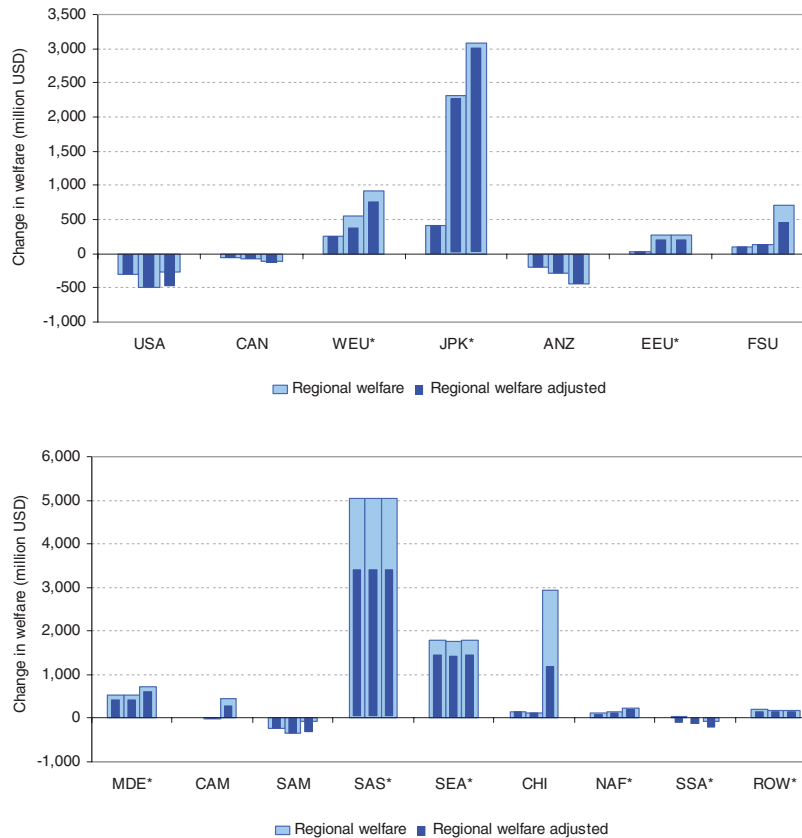
Note: Developed regions (top panel) and developing regions (bottom panel). Water-stressed regions are indicated by an asterisk (*). The three bars refer to the three scenarios (*water-scarce developing regions*, *water-scarce regions*, and *all regions*, respectively).

Fig. 4. Changes in regional welfare with and without the adjustment of irrigation costs by scenario (million USD).

Table 7
Decomposition of welfare changes, all regions scenario (million USD)

	USA	CAN	WEU*	JPK*	ANZ	EEU*	FSU	MDE*	CAM	SAM	SAS*	SEA*	CHI	NAF*	SSA*	ROW*	Total
Regional welfare	−275	−109	925	3,083	−442	268	710	719	458	−76	5,045	1,777	2,926	233	−60	184	**15,365**
Contribution to regional welfare by changes in																	
Outputs	128	11	41	286	17	3	6	36	−119	37	−286	273	261	7	11	6	**720**
Factors	22	10	88	22	5	13	−9	4	−6	6	1	−5	3	1	−1	0	**153**
Imported inputs	1	0	−86	2	−11	2	9	−8	−2	−5	26	4	0	0	−3	3	**−67**
Domestic inputs	42	−8	−244	−23	14	7	106	−11	−27	10	22	6	0	1	1	1	**−104**
Imported goods	−6	−3	−8	−4	−14	4	18	13	1	−10	13	2	0	−4	−3	2	**0**
Domestic goods	−24	−4	−46	128	−7	12	−1	16	6	55	121	22	0	8	4	27	**314**
Exports	2	0	110	−3	6	1	−30	10	1	1	−53	−17	−35	2	−2	0	**−7**
Imports	−119	−21	337	−265	−24	2	40	18	−45	−23	216	−71	−28	7	−8	−1	**14**
Terms of trade	−1,229	−117	305	1,157	−445	46	257	443	−213	−712	134	13	353	140	−136	4	**−1**
Price of capital goods	312	8	89	−44	16	27	−48	7	1	16	47	−228	−235	3	5	25	**0**
Factor productivity	597	16	339	1,826	0	152	363	191	861	549	4,805	1,777	2,606	70	73	119	**14,345**

Note: Water-stressed regions are indicated by an asterisk (*).

decomposition of welfare changes (Table 7) shows that the terms of trade improve in all water-stressed developing regions, except for Sub-Saharan Africa.

For nonwater stressed developing regions, there are mostly welfare gains, which are marked for China in the *all regions* scenario. South America is the exception. As other regions are able to grow more food, South America loses part of its

valuable exports. Table 7 shows a deterioration of the terms of trade for South America, which contributes negatively to regional welfare.

The upper panel of Fig. 4 indicates that water-stressed developed regions benefit from higher levels of irrigation efficiency, and even more so as efficiency improvement occurs in more regions. This is also true for the nonwater stressed former

Soviet Union. For food-exporters (United States, Canada, Australia and New Zealand) an opposite effect occurs; the larger the number of regions implementing more efficient irrigation management the greater the loss. This is reversed for the United States in the *all regions* scenario, in which the United States itself also benefits from improved irrigation efficiency. Food-exporting regions lose their comparative advantage when other regions are more efficient in crop production and experience a deterioration of their terms of trade (Table 7).

Fig. 5 shows, for the *all regions* scenario, changes in welfare as a function of the additional irrigation water used in irrigated production, that is, the difference between the initial water savings and the actual water savings (cf Fig. 3). There is a clear positive relationship for the major users (Central America, Southeast Asia, China, and South Asia). Japan and South Korea are outliers: high levels of welfare improvements are achieved with small increases in water demand for irrigated agriculture. This is due to a combination of water scarcity and a strong preference for locally produced rice. Welfare gains in Japan and South Korea are mostly associated with improvements in its terms of trade and irrigation efficiency (Table 7). Japan and South Korea are in line with the rest of the world when changes in welfare are plotted as a function of changes in total agricultural production (Fig. 6). Changes in welfare are not always associated with higher levels of irrigated production: Western Europe, the Middle East, and the former Soviet Union experience welfare increases with an absolute reduction in domestic agricultural production. Fig. 6 also shows welfare losses for food-exporting regions that lose their comparative advantage as other regions increase their irrigation efficiency.

The costs of improving irrigation efficiency reduce global and regional welfare (Fig. 4). Global welfare decreases between 26 and 34%, depending on the scenario. Regional impacts vary widely, depending on irrigation costs. Welfare decreases more in regions with low irrigation efficiency levels like Central America, South America, China, and Sub-Saharan Africa. In none of the regions the inclusion of irrigation costs reverses the welfare gains of improved irrigation but the impact is more negative in some (United States, South America, and Sub-Saharan Africa). In the *all regions* scenario, irrigation costs take away one-third of the global welfare gains.

Changes in agricultural production modify international trade patterns and generate changes in international flows of virtual water. Virtual water is defined as the volume of water used to produce a commodity (Allan, 1992, 1993). We use the production-site definition, that is, we measure it at the place where the product was actually produced.[13] The water used in the agricultural sector has two components: effective rainfall (green water) and irrigation water (blue water). Table 8 shows the international flows of irrigation water used associated with the additional agricultural production (blue virtual water).

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[13] The virtual water content of a product can also be defined as the volume of water that would have been required to produce the product at the place where the product is consumed (consumption-site definition).

Table 8
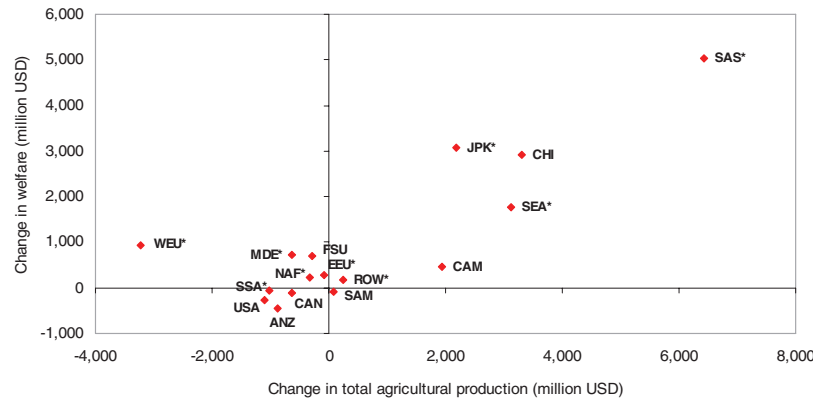Changes in blue virtual water flows related to the additional agricultural production by scenario, in cubic kilometres (km^3)

	Water-scarce developing regions scenario						Water-scarce regions scenario						All regions scenario					
	Virtual water	Virtual water	Destination market			Net	Virtual water	Virtual water	Destination market			Net	Virtual water	Virtual water	Destination market			Net
			Domestic	Exports	Imports				Domestic	Exports	Imports				Domestic	Exports	Imports	
Region	(Pre-Sim)	(a = b + c)	(b)	(c)	(d)	(e = b + d − c)	(Pre-Sim)	(a = b + c)	(b)	(c)	(d)	(e = b + d − c)	(Pre-Sim)	(a = b + c)	(b)	(c)	(d)	(e = b + d − c)
USA	−1.38	−1.38	−0.34	−1.05	0.44	1.16	−1.68	−1.68	−0.39	−1.29	0.43	1.33	−0.47	−0.46	−0.13	−0.33	0.71	0.91
CAN	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.07	0.07
WEU*	−0.19	−0.19	−0.11	−0.07	1.48	1.44	−0.12	−0.09	−0.05	−0.03	1.37	1.35	−0.16	−0.12	−0.08	−0.05	2.57	2.54
JPK*	−0.04	−0.04	−0.01	−0.03	0.41	0.42	0.07	0.06	0.06	0.00	−0.34	−0.29	0.05	0.04	0.04	0.00	1.13	1.17
ANZ	−0.06	−0.06	−0.02	−0.04	0.03	0.05	−0.08	−0.08	−0.02	−0.05	0.02	0.05	−0.08	−0.08	−0.01	−0.07	0.04	0.10
EEU*	−0.01	−0.01	0.00	0.00	0.17	0.17	0.10	0.08	0.04	0.04	0.07	0.08	0.06	0.05	0.03	0.02	−0.24	−0.23
FSU	−0.05	−0.05	−0.03	−0.02	0.19	0.18	−0.07	−0.07	−0.04	−0.03	0.20	0.19	0.04	0.03	0.04	0.00	0.31	0.35
MDE*	0.04	0.04	0.03	0.01	1.41	1.43	0.02	0.02	0.03	−0.01	1.36	1.40	−0.07	−0.07	−0.06	−0.01	1.41	1.37
CAM	−0.06	−0.06	−0.03	−0.03	0.06	0.06	−0.08	−0.08	−0.03	−0.05	0.07	0.09	1.88	1.29	0.87	0.42	−0.14	0.31
SAM	−0.15	−0.15	−0.03	−0.12	0.07	0.16	−0.16	−0.16	−0.03	−0.13	0.07	0.18	0.20	0.11	0.08	0.03	0.06	0.11
SAS*	21.94	16.41	8.70	7.72	−0.08	0.90	21.24	15.89	8.62	7.27	−0.08	1.27	19.85	14.85	8.43	6.42	0.39	2.41
SEA*	3.43	2.21	1.81	0.40	0.83	2.24	3.01	1.95	1.57	0.37	0.66	1.86	2.85	1.84	1.54	0.30	1.44	2.68
CHI	−1.38	−1.38	−0.63	−0.74	0.10	0.21	−1.97	−1.97	−0.81	−1.16	0.10	0.46	9.48	7.28	4.14	3.14	0.29	1.30
NAF*	−1.01	−0.97	−0.04	−0.93	0.16	1.06	−1.32	−1.27	−0.08	−1.19	0.16	1.28	−1.86	−1.79	−0.13	−1.66	0.37	1.90
SSA*	0.06	0.04	0.03	0.01	−0.12	−0.09	0.03	0.02	0.02	0.00	−0.31	−0.29	0.00	0.00	0.00	0.00	−0.20	−0.20
ROW*	0.08	0.04	0.03	0.01	−0.08	−0.06	0.07	0.04	0.03	0.01	−0.08	−0.06	0.05	0.03	0.02	0.01	−0.01	0.01
Total	21.21	14.45	9.36	5.10	5.10	9.36	19.06	12.66	8.92	3.73	3.73	8.92	31.82	23.00	14.79	8.21	8.21	14.79

Note: Virtual water (pre-sim) refers to the blue virtual water needed for the additional agricultural production under the observed regional irrigation efficiency (pre-simulation), while virtual water considers the increase in irrigation efficiency (post-simulation). Water-stressed regions are indicated by an asterisk (*).
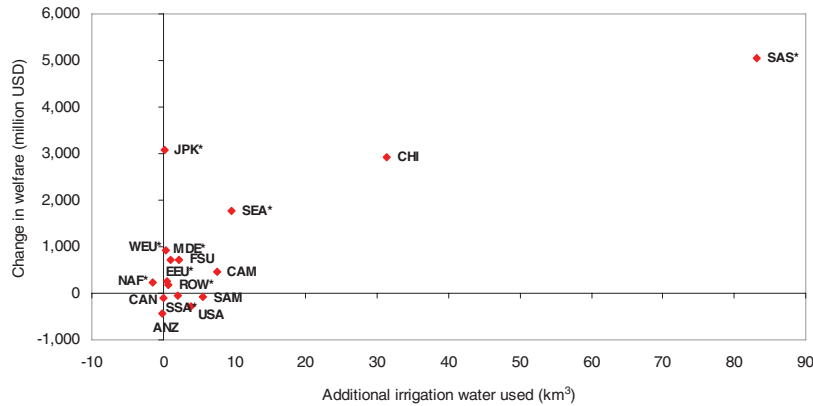
Note: Water-stressed regions are indicated by an asterisk (*).

Fig. 5. Changes in welfare as a function of the additional irrigation water used, *all regions* scenario.

Note: Water-stressed regions are indicated by an asterisk (*).

Fig. 6. Changes in welfare as a function of the additional agricultural production, *all regions* scenario (million USD).

Improving irrigation efficiency leads to a decrease in blue virtual water. At the global level, between 28 and 34% of blue virtual water is saved (compare virtual water pre- and postsimulation, Table 8). The blue virtual water savings are higher when more regions increase irrigation efficiency. Under the *all regions* scenario, blue virtual savings reach almost 9 km³.

In most water-scarce developing regions, the amount of blue virtual water increases with higher levels of irrigation efficiency (Table 8, column a). However, it increases less if more regions have higher levels of irrigation efficiency. The only exception is North Africa with a negative change in blue virtual water, mainly caused by a reduction in agricultural exports. In the water-scarce developed regions, initial savings of blue virtual water (*water-scarce developing regions* scenario) disappear when they experience higher levels of irrigation efficiency (*water-scarce regions* and *all regions* scenarios). An exception is Western Europe where savings of blue virtual water are observed under all three scenarios.

The largest absolute changes in blue virtual water are in South Asia and Southeast Asia; both are water-stressed regions. South Asia exports almost half of its additional blue virtual water; in

Southeast Asia virtual water exports are modest. Reductions in the agricultural production for exports imply savings of blue virtual water for China, North Africa, and the United States. Under the *all regions* scenario, China and the United States achieve higher levels of irrigation efficiency; China substantially increases its blue virtual water use, 43% of which is exported.

These results confirm the initial suggestion: regional resource endowments alone are not enough to determine comparative advantages, opportunity costs and production technologies have to be taken into consideration as well. Patterns of international trade reflect the interaction of several different causes. For instance, opportunity costs are determined by the production coefficients, the water requirements, and the scarcity conditions.

Western Europe, the Middle East, the United States, Southeast Asia as well as Japan and South Korea substantially increase their blue virtual water imports. Higher levels of irrigation efficiency correspond to higher levels of total use of blue virtual water (Table 8, column e). Sub-Saharan Africa is the main exception: the pronounced reduction in the imports of blue virtual water causes a decrease in the total consumption of blue virtual water.

7. Discussions and conclusions

In this article, we present the first CGE model of the world economy with water as an explicit factor of production. The production structure used in this model allows for substitution between irrigation water, irrigated land, rainfed land, labor, 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 a nonmarket good, not reported in national economic accounts. Earlier studies included water resources at the national or smaller scale. These studies necessarily lack the international dimension,[14] which is important as water is implicitly traded in international markets for agricultural products.

Water is increasingly scarce as food demand rises and hence the demand for water for irrigation. However, in many regions, there are no markets for water. Water is free or even subsidized, creating little incentives to save water and to improve irrigation management. While several studies analyze price mechanisms that would lead to the adoption of improved irrigation technology and water savings (e.g., Dinar and Yaron, 1992; Easter and Liu, 2005; Tsur et al., 2004), we explore the potential global water savings and its economic implications by improving irrigation efficiency world-wide to the maximum attainable level.

We find that higher levels of irrigation efficiency have, depending on the scenario and the region, a significant effect on crop production, water use, and welfare. At the global level, water savings are achieved and the magnitude increases when more regions achieve higher levels of irrigation efficiency. The same tendency is observed at the regional level (with a few exceptions). Regions with higher irrigation efficiency changes save water, and this pushes other regions to reduce irrigation water use as well, mainly because of lower agricultural production.

Unlike earlier studies we compare the initial water savings (if markets would not adjust) to final water savings (taking into account adjustment processes in food and related markets). Initial water savings are 12–21% of the total amount of irrigation water currently used. Final water savings are much lower: 5–10%. Therefore, ignoring adjustments in production patterns and food markets would overstate the amount of water that could be saved by improved irrigation.

Improving irrigation efficiency promotes irrigated production, which partially offset rainfed production. When all regions improve irrigation efficiency, global agricultural production increases by 0.7%. While global irrigated production increases by around 25%, global rainfed production declines by around 15%. Consequently, world market prices fall for all agricultural products; and prices fall further if more regions improve irrigation efficiency.

Welfare tends to increase with the additional irrigation water used in irrigated production. However, increased water efficiency also affects competitiveness, particularly hurting rainfed agriculture, so that there are welfare losses as well. Such losses are more than offset, however, by the gains from increased irrigated production and lower food prices. Global and regional welfare gains exceed the costs for more efficient irrigation equipment. When all regions improve irrigation efficiency to the maximum level, irrigation costs account for one-third of the global welfare gains.

Enhanced irrigation efficiency changes regional comparative advantages and modifies regional trade patterns and welfare. Improvements in irrigation efficiency improve the terms of trade and generate welfare gains in all water-scarce regions, with the possible exception of Sub-Saharan Africa.

When all regions increase irrigation efficiency, two-thirds of the water-scarce regions use more blue virtual water. The largest absolute changes in blue virtual water are in South Asia and Southeast Asia. While South Asia exports almost half of its additional blue virtual water, virtual water exports in Southeast Asia are modest. Exports of virtual water are not exclusive of water abundant regions.

Several limitations apply to the above results. First, water-scarce regions are here defined based on country averages. We ignore differences between river basins within countries. For example, although on average water is not short in China, it is a problem in Northern China. In fact, we implicitly assume a perfect water market in each region, including costless transport. Second, we do not consider individual options for irrigation management. Instead, we use water productivity as a proxy for irrigation efficiency. Third, our analysis does not account for alternative uses of water resources outside the agricultural sector. The necessary data on a global basis are missing. Fourth, in our analysis we investigate potential global water savings and its economic implications by increasing irrigation efficiency to its maximum attainable level. We do not take into account that countries and regions differ with respect to environmental circumstances, sources of water supply, and economic opportunities and may therefore prefer different levels of irrigation efficiency. Fifth, we do not investigate the effect of different mechanisms that would lead to the adoption of improved irrigation technology and water savings including an increase in water prices by a tax or the implementation of markets for water. These issues should be addressed in future research. Future work will also study other issues, such as changes in water policy, and the effects of climate change on water resources.

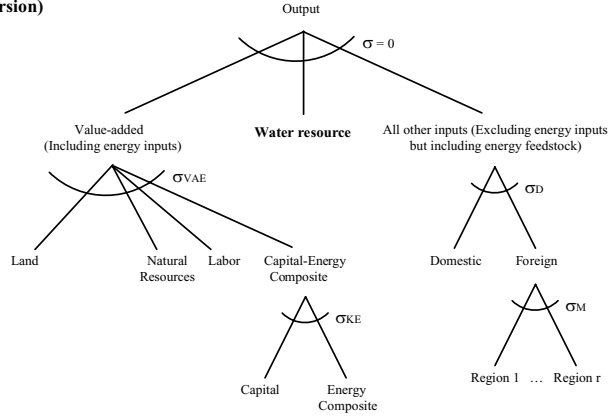[14] Although, in a single country CGE, there is either an explicit "Rest of the World" region or the rest of the world is implicitly included in the closure rules.

Appendix I

Appendix I:

GTAP-W (FIRST Version)

GTAP-W (SECOND Version)
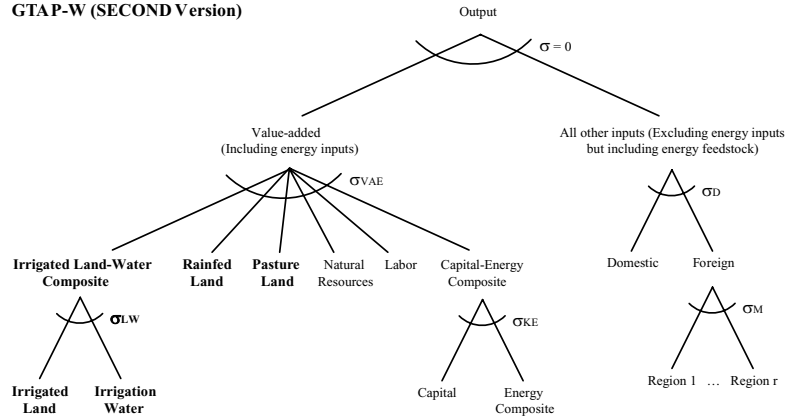
Note: The first version of GTAP-W model introduces water resources at the top level of the production structure, combining with value-added and intermediate inputs. Note that there is no substitution possibilities at the top level of the production structure (Leontief production function). In the second version, the original land endowment has been split into pasture land, rainfed land, irrigated land, and irrigation (bold letters). Irrigation water is inside the value-added nest, implying substitution possibilities with irrigated land and all other factors of production.

Fig. A1. Nested tree structure for industrial production process in the two versions of the GTAP-W model (truncated).

Table A1
2000 Baseline data: Crop harvested area and production by region and crop

	Rainfed agriculture			Irrigated agriculture				Total			
Regions	Area (Thousand ha)	Production (Thousand mt)	Green water (km³)	Area (Thousand ha)	Production (Thousand mt)	Green water (km³)	Blue water (km³)	Area (Thousand ha)	Production (Thousand mt)	Green water (km³)	Blue water (km³)
United States	35,391	209,833	89	67,112	440,470	159	190	102,503	650,303	248	190
Canada	27,267	65,253	61	717	6,065	2	1	27,984	71,318	62	1
Western Europe*	59,494	462,341	100	10,130	146,768	19	10	69,624	609,108	118	10
Japan and South Korea*	1,553	23,080	6	4,909	71,056	21	3	6,462	94,136	27	3
Australia and New Zealand	21,196	67,204	45	2,237	27,353	5	15	23,433	94,557	50	15
Eastern Europe*	37,977	187,468	95	5,958	40,470	16	14	43,935	227,939	111	14
Former Soviet Union	85,794	235,095	182	16,793	74,762	25	47	102,587	309,857	208	47
Middle East*	29,839	135,151	40	21,450	118,989	25	62	51,289	254,140	65	62
Central America	12,970	111,615	47	8,745	89,637	28	46	21,715	201,252	76	46
South America	79,244	649,419	335	9,897	184,304	40	47	89,141	833,723	375	47
South Asia*	137,533	491,527	313	114,425	560,349	321	458	251,958	1,051,877	634	458
Southeast Asia*	69,135	331,698	300	27,336	191,846	134	56	96,471	523,543	434	56
China	64,236	615,196	185	123,018	907,302	419	278	187,254	1,522,498	604	278
North Africa*	15,587	51,056	19	7,352	78,787	4	42	22,938	129,843	23	42
Sub-Saharan Africa*	171,356	439,492	588	5,994	43,283	19	37	177,349	482,775	608	37
Rest of the World*	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											
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. Water-stressed regions are indicated by an asterisk (*). Green water (effective rainfall) and blue water (irrigation water).
Source: IMPACT, 2000 baseline data.

Table A2
Share of irrigated production in total production by region and crop (percentages)

Region	Rice	Wheat	CerCrops	VegFruits	OilSeeds	Sug_Can	Oth_Agr	Total
USA	51.01	78.93	70.25	34.20	68.45	48.00	100.00	**67.73**
CAN	0.00	1.92	10.36	34.72	3.33	44.08	0.00	**8.50**
WEU	48.77	19.56	16.28	35.32	5.69	40.28	5.03	**24.10**
JPK	93.71	79.66	65.26	66.26	32.10	56.64	81.50	**75.48**
ANZ	48.10	12.82	17.94	33.66	11.66	48.34	9.30	**28.93**
CEE	48.50	30.30	18.81	19.01	5.82	28.97	0.00	**17.75**
FSU	49.40	20.76	9.67	28.31	6.18	40.22	24.57	**24.13**
MDE	55.82	45.36	29.59	51.77	47.07	49.60	44.45	**46.82**
CAM	46.82	55.43	49.03	47.34	56.54	41.98	43.73	**44.54**
SAM	63.32	9.71	12.39	20.53	0.66	27.80	17.57	**22.11**
SAS	70.32	75.46	31.05	33.55	31.53	62.55	41.47	**53.27**
SEA	48.59	49.43	30.67	25.16	45.26	51.96	24.62	**36.64**
CHI	100.00	85.91	73.32	26.99	46.83	41.74	82.65	**59.59**
NAF	82.09	63.92	76.49	56.02	46.76	49.65	65.34	**60.68**
SSA	20.80	28.95	4.75	4.20	5.92	42.06	1.07	**8.97**
SIS	49.46	49.75	10.78	25.41	56.09	39.33	22.38	**33.52**
Total	**73.16**	**48.42**	**42.30**	**28.13**	**37.06**	**43.97**	**47.53**	**42.16**

Source: Own calculations based on IMPACT baseline data.

Table A3
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
CEE	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
SIS	1.39	1.41	1.34	1.34	1.33	1.39	1.31

Source: Own calculations based on IMPACT baseline data.
*World average.

Appendix II: Aggregations in GTAP-W

A. Regional Aggregation
1. **USA** - United States
2. **CAN** - Canada
3. **WEU** - Western Europe
4. **JPK** - Japan and South Korea
5. **ANZ** - Australia and New Zealand
6. **EEU** - Eastern Europe
7. **FSU** - Former Soviet Union
8. **MDE** - Middle East
9. **CAM** - Central America
10. **SAM** - South America
11. **SAS** - South Asia
12. **SEA** - Southeast Asia
13. **CHI** - China
14. **NAF** - North Africa
15. **SSA** - Sub-Saharan Africa
16. **ROW** - Rest of the World

C. Endowments
Wtr - Irrigation
Lnd - Irrigated land
RfLand - Rainfed land
PsLand - Pasture land
Lab - Labor
Capital - Capital
NatlRes - Natural resources

B. Sectoral Aggregation
1. **Rice** - Rice
2. **Wheat** - Wheat
3. **CerCrops** - Cereal grains (maize, millet, sorghum, and other grains)
4. **VegFruits** - Vegetable, fruits, nuts
5. **OilSeeds** - Oil seeds
6. **Sug_Can** - Sugar cane, sugar beet
7. **Oth_Agr** - Other agricultural products
8. **Animals** - Animals
9. **Meat** - Meat
10. **Food_Prod** - Food products
11. **Forestry** - Forestry
12. **Fishing** - Fishing
13. **Coal** - Coal
14. **Oil** - Oil
15. **Gas** - Gas
16. **Oil_Pcts** - Oil products
17. **Electricity** - Electricity
18. **Water** - Water
19. **En_Int_Ind** - Energy intensive industries
20. **Oth_Ind** - Other industry and services
21. **Mserv** - Market services
22. **NMServ** - Nonmarket services

Appendix III: The substitution elasticity of water

Let us assume that there is a production function

$$Y = f(X, W), \tag{1}$$

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

$$C = pX + tW, \tag{2}$$

where t is the price of water and p is the composite price of other inputs. Production efficiency implies

$$\frac{f_X}{f_W} = \frac{p}{t}. \tag{3}$$

Let us assume that (1) is CES

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

This implies

$$\frac{f_X}{f_W} = \frac{W^{\rho+1}}{X^{\rho+1}} = \frac{p}{t}. \tag{3'}$$

From Rosegrant et al. (2002), we know the price elasticity of water use, η (estimates for 15 regions). Thus, we have

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

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

$$W_1 = W_2(1 + \eta\delta). \tag{4}$$

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

$$\rho = \frac{\ln(1+\delta)}{\ln(1+\eta\delta)} - 1. \tag{5}$$

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