# WATER, AGRICULTURE AND CLIMATE CHANGE
# A GLOBAL COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS

Dissertation

Zur Erlangung des Grades eines Doktors der
Wirtschafts- und Sozialwissenschaften (Dr. rer. pol.) des

Fachbereichs Wirtschaftswissenschaften
der
Universität Hamburg

vorgelegt von

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Hamburg 2011

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Datum der Disputation: 24. November 2011

*“A l'alta fantasia qui mancò possa;*
*ma già volgeva il mio disio e ‘l velle,*
*sì come rota ch'igualmente è mossa,*
*l'amor che move il sole e l'altre stelle.”*

*Dante Alighieri*
*(Paradiso XXXIII, 142-145)*

*A mi pequeño Ignacio*

# PREFACE

This cumulative thesis contains five papers that address the role of water resources in agriculture and within the context of international trade.

1. *The GTAP-W model: Accounting for water use in agriculture*
   This paper is going to be submitted for peer review at *GTAP Technical Paper Series*.

2. *Water Scarcity and the Impact of Improved Irrigation Management*
   (with Katrin Rehdanz and Richard S.J. Tol)
   This paper is published in *Agricultural Economics 42(3): 305-323*.
   It was presented at the FNU PhD seminar, University of Hamburg (26.05.2008); Eleventh annual conference on Global Economic Analysis, Helsinki (14.07.2008); PhD workshop on Environmental and Natural Resource Economics, University of Birmingham (3.12.2008).

3. *The Economic Impact of more Sustainable Water Use in Agriculture*
   (with Katrin Rehdanz and Richard S.J. Tol)
   This paper is published in the *Journal of Hydrology* 384: 292-305.

4. *Climate Change Impacts on Global Agriculture*
   (with Katrin Rehdanz, Richard Betts, Pete Falloon, Andy Wiltshire and Richard S.J. Tol)
   This paper is currently under peer review in *Climatic Change*.
   It was presented at Thirteenth annual conference on Global Economic Analysis, Penang (10.06.2010).

5. *Economywide Impacts of Climate Change on Agriculture in Sub-Saharan Africa*
   (with Tingju Zhu, Katrin Rehdanz, Richard S.J. Tol and Claudia Ringler)
   This paper is currently under peer review in *Ecological Economics*. It is published as IFPRI Discussion Paper 873. It is going to be part of the Handbook on Climate Change and Agriculture, edited by Robert Mendelsohn and Ariel Dinar.
   It was presented at the workshop on How can African Agriculture Adapt to Climate Change? Insights for South Africa, University of Pretoria (10.11.2008); workshop on How can African Agriculture Adapt to Climate Change? Results and Conclusions for Ethiopia and Beyond, Nazareth (11.12.2008); Twelfth annual conference on Global Economic Analysis, ECLAC-Santiago (10.06.2009); 17th annual conference of the European Association of Environmental and Resource Economists, Amsterdam (27.06.2009); Staff Seminar, Kiel Institute for the World Economy (24.08.2009).

## ACKNOWLEDGEMENTS

I would like to express my deepest gratitude towards my principal advisor Prof. Dr. Richard Tol and my co-advisor Prof. Dr. Katrin Rehdanz. They provided invaluable guidance and mentoring in each step of this thesis. I very much appreciate their continuous support, patience and helpful comments on various drafts of the articles.

Being part of the International Max Planck Research School on Earth System Modelling has been a very enriching experience. I thank Prof. Dr. Michael Funke for taking his time to be my advisory panel chair and for his useful comments on the thesis. I am especially indebted to Antje Weitz, the coordinator of the research school, for her kind assistance and continuous support and patience.

This thesis was supported by the Federal Ministry for Economic Cooperation and Development, Germany, under the project “Food and Water Security under Global Change: Developing Adaptive Capacity with a Focus on Rural Africa.” I am particularly grateful to Claudia Ringler, the project coordinator, for her kind guidance and continuous support. I would also like to thank her colleagues at the International Food Policy Research Institute (IFPRI): Tingju Zhu, Siwa Msangi, Mark Rosegrant, Timothy Sulser and James Thurlow. This thesis would not have been possible without the wonderful data provided by IFPRI.

I also want to thank Richard Betts, Pete Falloon and Andy Wiltshire from the Met Office Hadley Centre for providing the data and useful comments for the climate change analysis. I am especially thankful to Nele Leiner and Daniel Hernandez for helping arranging the dataset.

I am sincerely grateful to Uwe Schneider for his continuous support, helpful comments and insights. I greatly appreciate and wish to thank all the members of my research unit. They made my days enjoyable: Anne Katrin, Christine, Harshi, Ivie, Jacqueline, Jennifer, Kerstin, Marie-Françoise, Nikolinka, Dritan, Ingo, Korbinian, Michael, Thomas and Timm. Once again, I would like to thank Katrin. I learned from her a lot of things, not only scientific research. I am grateful to Sonja Peterson and Gernot Klepper for supporting me in the final completion of this thesis.

I thank my parents, Marina and Iver, for giving me confidence and encouragement during all these years. All my family was exceptional. Finally, I am forever indebted to my wife Leslye for her understanding, patience, encouragement and overall for her endless love. Thanks.

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# I

# GENERAL INTRODUCTION

## 1. Water, agriculture and climate change

Agriculture is by far the largest consumer of freshwater resources. Globally, around 70 percent of all freshwater withdrawals are used for food production. 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). However, the overall performance of irrigation systems is low. Most of the world's major surface irrigation systems lose between half to two thirds of the water in transit from the source to the crop (Tsur et al. 2004).

Although there are enough freshwater resources on the planet to meet everyone's need, they are unevenly distributed. Currently, forty percent of world's population face water shortages (CA 2007). This situation is expected to aggravate in the future as a consequence of population growth, urbanization, an increasing consumption of water per capita and climate change. To ensure food security in populous but water-scarce regions, expanding irrigated areas might no be sufficient, agriculture has to improve the performance of both rainfed and irrigated production (Kamara and Sally 2004).

Irrigation development is positive for food security, economic growth and poverty alleviation, but in many cases negative for the environment. In several regions and river basins, surface and groundwater resources are, or will be, overexploited, damaging ecosystems by reducing water flows to rivers, lakes and wetlands (Rosegrant et al. 2002). In other regions the situation is different. For instance, the large untapped water resources in Sub-Saharan Africa are expected to generate economic opportunities from its intensive use in agriculture (Villholth and Giordano 2007). Therefore, one of the main challenges for the future development of agriculture is the sustainable management of water resources (Shah et al. 2000).

Future climate change may present an additional challenge for global agriculture. In fact, one of the most significant impacts of climate change is likely to be on the hydrological system and hence on regional water resources (Bates et al. 2008). While irrigated agriculture focuses on withdrawals of water from surface and groundwater sources, rainfed agriculture relies on soil moisture generated from rainfall. Climate model simulations suggest that global average precipitation will increase as global temperature rise. As a result, global water availability is expected to increase with climate change. However, large regional differences are expected. At high latitudes and in some wet tropical areas, water availability is projected to increase. An opposite trend is expected in some dry regions at mid-latitudes and in the dry tropics (Falloon and Betts 2006; Bates et al. 2008). In many regions, the positive effects of higher annual runoff and total water supply are likely to be offset by the negative effects of changes in precipitation patterns, intensity and extremes, as well as shifts in seasonal runoff. Therefore, the overall global impacts of climate change on freshwater systems are expected to be negative (Bates et al. 2008).

Although the climate risk is reduced by the use of irrigation, irrigated farming systems are dependent on reliable water resources, therefore they may be exposed to changes in the spatial and temporal distribution of river flow. Additionally, changes in temperature and $CO_2$ fertilization caused by climate change are expected to affect both rainfed and irrigated crop production.

Climate change will not only influence the supply of water, modifying the regional distribution of freshwater resources, it will also influence the demand for water. Higher temperatures and changes in precipitation patterns are expected to increase irrigation water demand for crops (Fischer et al. 2007). In addition, future socio-economic pressures will increase the competition for water between irrigation needs and non-agricultural users due to population and economic growth.

The human response is crucial. While adaptation could potentially limit the severity of impacts, maladaptation may exacerbate the situation. Adaptations on-farm and via market mechanisms are going to be crucially important, they might alleviate any negative impact caused by climate change (e.g. Darwin 1995; Fischer et al. 2007). Similarly, mitigation efforts could potentially reduce the global cost of climate change and decline the number of people at risk of hunger (IPCC 2007).

Computable General Equilibrium (CGE) models have been used to analyze the above water-related problems in agriculture. Most of these studies focus at the farm, the country and the regional level (e.g. Abler et al. 1998; Darwin et al. 1995; Verburg et al. 2008). These studies omit the international dimension. A full understanding of the water use in the agricultural sector is impossible without understanding the international market for food and related products, such as textiles.

For instance, climate change is expected to modify the regional distribution of freshwater water resources, which could generate new opportunity costs and reverse regional comparative advantages in food production. As a result, regional trade patterns and welfare are expected to change. Regions with reliable water resources may experience positive impacts in food production and exports. At the same time, food-exporting regions may be vulnerable not only to direct climate-induced agricultural damages, but also to positive impacts elsewhere. However, regional resource endowments alone are not enough to determine comparative advantages, opportunity costs and production technologies have to be taken into consideration as well.

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, giving rise to the concept of virtual water.

Global CGE models avoid this limitation. However, only a few global CGE models have been used to analyze the role of water resources in the agricultural sector (e.g. Parry et al. 1999; Darwin 2004; Berrittella et al. 2007; Fischer 2007; Tubiello and Fischer 2007). Moreover, none of these studies has water as an explicit factor of production and distinguishes rainfed and irrigated crops as does the GTAP-W model.

## 2. Accounting for water use in agriculture: the GTAP-W model

GTAP-W, the model developed in this thesis, is a multi-region world CGE model. The model is a further refinement of the GTAP model (Hertel 1997), and 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).

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.

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. 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. Therefore, water is an explicit factor of production for irrigated agriculture.

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. This distinction is crucial because allows us to model rainfall and irrigation water used in crop production.

The new GTAP-W model is based on the GTAP version 6 database, which represents the global economy in 2001, and on the IMPACT 2000 baseline data. The IMPACT model, a partial equilibrium agricultural sector model combined with a water simulation model (Rosegrant et al. 2002), provides detailed information (demand and supply of water, demand and supply of food, rainfed and irrigated production and rainfed and irrigated area) to the GTAP-W model for a robust calibration of the baseline year and future benchmark equilibriums.

The distinction between rainfed and irrigated agriculture within the production structure of the GTAP-W model allows us to study expected physical constraints on water supply due to, for example, climate change. In fact, changes in rainfall patterns can be exogenously modelled in GTAP-W by changes in the productivity of rainfed and irrigated land. In the same way, water excess or shortages in irrigated agriculture can be modelled by exogenous changes to the initial irrigation water endowment.

## 3. Objectives and contributions of this thesis

Based on the global general equilibrium model GTAP-W, this thesis aims to study the role of water resources in agriculture and within the context of international trade. The first paper of the thesis introduces the GTAP-W model. In the next four papers different water management policies dealing with water scarcity, sustainability and climate change are analyzed.

The first paper *The GTAP-W Model: Accounting for Water Use in Agriculture* is a technical description of the new data and features of the model. After surveying some existing CGE models that account for water use, this paper introduces the GTAP-W model, describing in detail the new data on production, area and water use in rainfed and irrigated crops and the corresponding land and irrigation rents. The new production structure of the model is described, giving special emphasis on its implementation and changes to the code. Before implementing concrete policy analysis, a comprehensive validation of the model is performed, concluding to a satisfactory robustness of the model.

The second paper *Water Scarcity and the Impact of Improved Irrigation Management* analyzes if improvements in irrigation efficiency worldwide would be economically beneficial for the world as a whole as well as for individual countries and whether and to what extent water savings could be achieved. Currently, less than 60 percent of all the water used for irrigation is effectively consumed by crops. Therefore, we evaluate three scenarios showing a gradual convergence to higher levels of irrigation efficiency. We attempt to study potential global water savings, improving irrigation efficiency to the maximum attainable level.

In *The Economic Impact of more Sustainable Water Use in Agriculture,* we analyze potential impacts on trade and welfare of future projections of allowable water withdrawals for surface and groundwater based on two alternative water management scenarios in 2025. The first scenario explores a deterioration of current trends and policies in the water sector (water crisis scenario), while the second scenario assumes an improvement in policies and trends in the water sector and eliminates groundwater overdraft worldwide, increasing water allocation for the environment (sustainable water use scenario). This paper focuses on the role of green (effective rainfall) and blue (irrigation) water resources in agriculture.

In the fourth paper *Climate Change Impacts on Global Agriculture* we use predicted changes in the magnitude and distribution of global precipitation, temperature and river flow to assess potential impacts of climate change and $CO_2$ fertilization on global agriculture. The analysis is carried out at two time periods (medium-term 2020s and long-term 2050s) and under two IPCC SRES scenarios (A1B and A2). The paper emphasizes the importance of differentiate between rainfed and irrigated agriculture, because both face different climate risk levels.

While the fourth paper focuses on climate change impacts, the fifth paper *Economywide Impacts of Climate Change on Agriculture in Sub-Saharan Africa* evaluates the efficacy of two scenarios as adaptation measures to cope with climate change in Sub-Saharan Africa. In the first adaptation scenario, irrigated areas in Sub-Saharan Africa are doubled by 2050, but total crop area remains constant. In the second adaptation scenario, both rainfed and irrigated crop yields are increased by 25 percent. Both adaptation scenarios are analyzed with IMPACT and GTAP-W, combining in this way the advantages of a partial equilibrium approach, which considers detailed water-agriculture linkages, with a general equilibrium approach, which takes into account linkages between agriculture and non-agricultural sectors and includes a full treatment of factor markets.

The thesis ends with concluding remarks and several policy recommendations.

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# II

## THE GTAP-W MODEL: ACCOUNTING FOR WATER USE IN AGRICULTURE

**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

## 1. Introduction

Most economic activities require water as an input of production. In many regions, there are no markets for water. Water is underpriced, free or even subsidized, creating little incentives to conserve water and limiting the scope for efficient allocation of water resources. Because there is 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 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, 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. Despite distortions of international agricultural markets, the volume of world agricultural trade has grown more rapidly than the volume of world agricultural production (Tangermann 2010). Agriculture 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 focus on the validation of the GTAP-W model. 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 II-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 the CGE model water is a factor of production used by farmers and the water supply firms, which owns some concessional water rights. Crop production is modelled by using a nested CES structure (see Figure II-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 II-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 II-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 II-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 II-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 II-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 II-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 II-1 shows that irrigated areas are concentrated in the

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

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 II-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 water used for irrigation (blue water). 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.

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

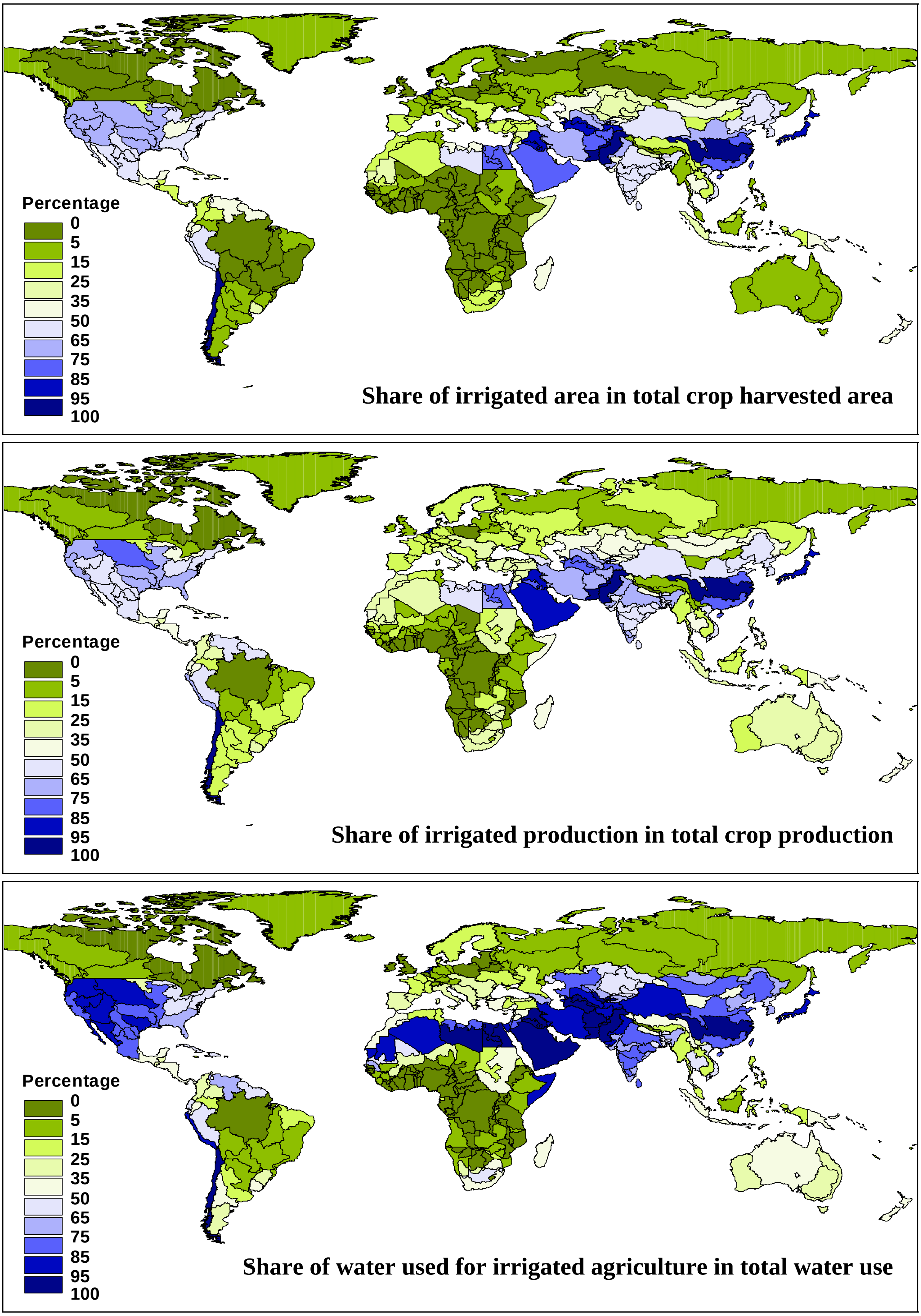


**Figure II–1. 2000 baseline data: Share of irrigated agriculture in total harvested area, production and water use by food producing units (FPUs)**

Source: IMPACT 2000 baseline data (April 2008).

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

| Description | Rainfed Agriculture | | | Irrigated Agriculture | | | | Total | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Area | Production | Green water | Area | Production | Green water | Blue water | Area | Production | Green water | Blue water |
| | (thousand ha) | (thousand mt) | ($km^3$) | (thousand ha) | (thousand mt) | ($km^3$) | ($km^3$) | (thousand ha) | (thousand mt) | ($km^3$) | ($km^3$) |
| **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 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 II-2).

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

**Table II–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).

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 II-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 II–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:

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

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

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

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

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

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 II-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 II–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 II-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$^3$. These prices are consistent with the high land rents observed in this region (see Figure II-4 below).

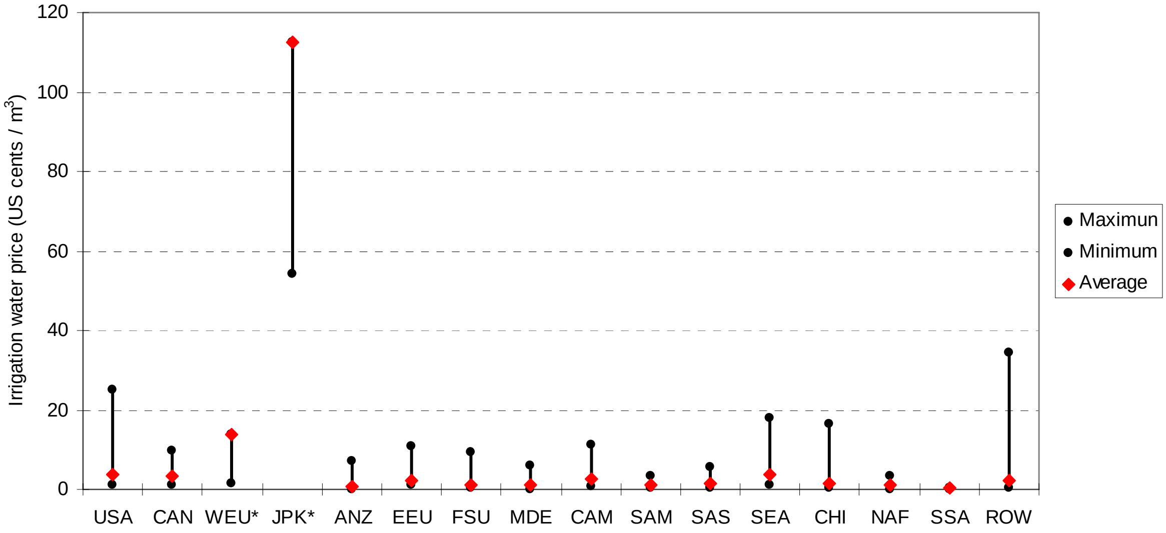


**Figure II–2. Regional ranges and averages (over all crops) of irrigation water prices per cubic metre**

Source: Based on GTAP-W database.
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), South Africa (SAF) and Rest of the World (ROW).
* The maximum value has been deleted for illustrative purposes. Maximum values are: JPK (668) and WEU (237).

Regional ranges and averages of irrigation water prices in GTAP-W are consistent with those observed in the literature. Cornish et al. (2004) summarize the findings of an extended literature review on irrigation water prices (Figure II-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.

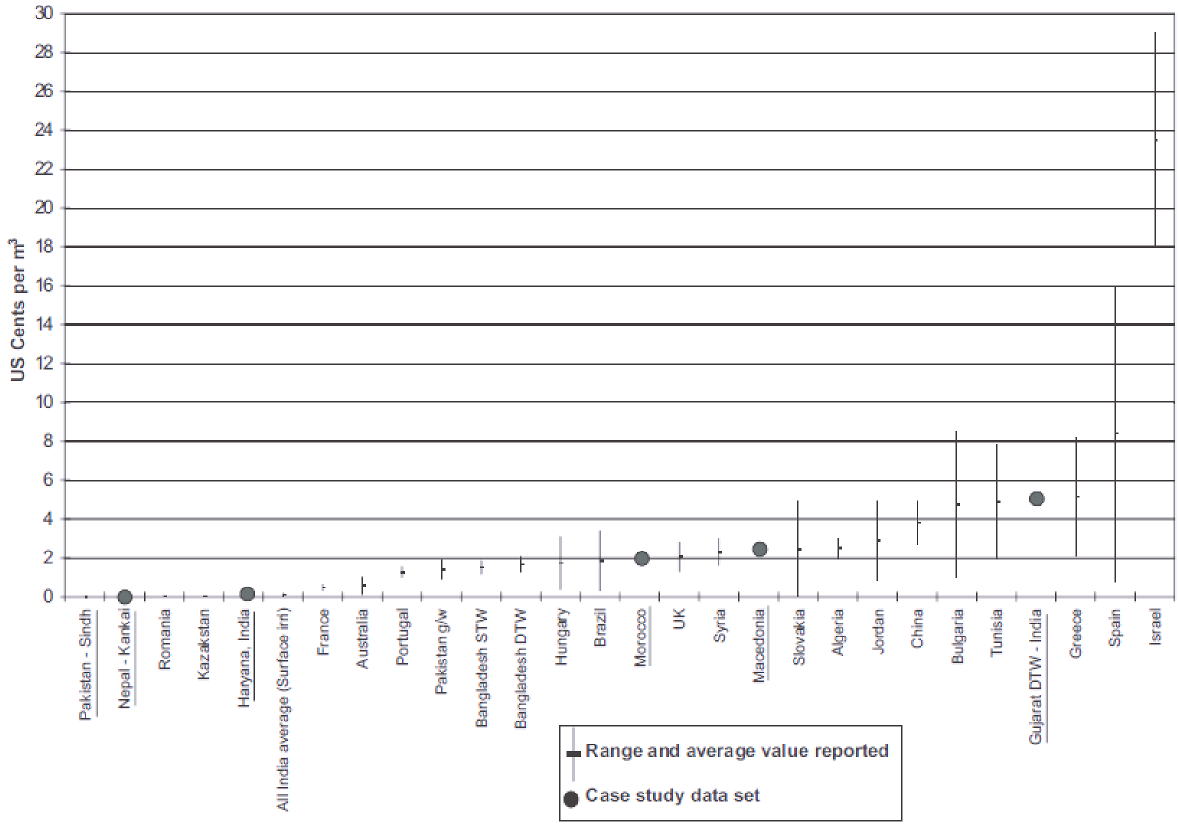


**Figure II–3. Global range of irrigation water prices per cubic metre**

Source: Cornish et al. (2004).

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 II-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 375 US$/ha and 459 US$/ha for rainfed and irrigable land, respectively.

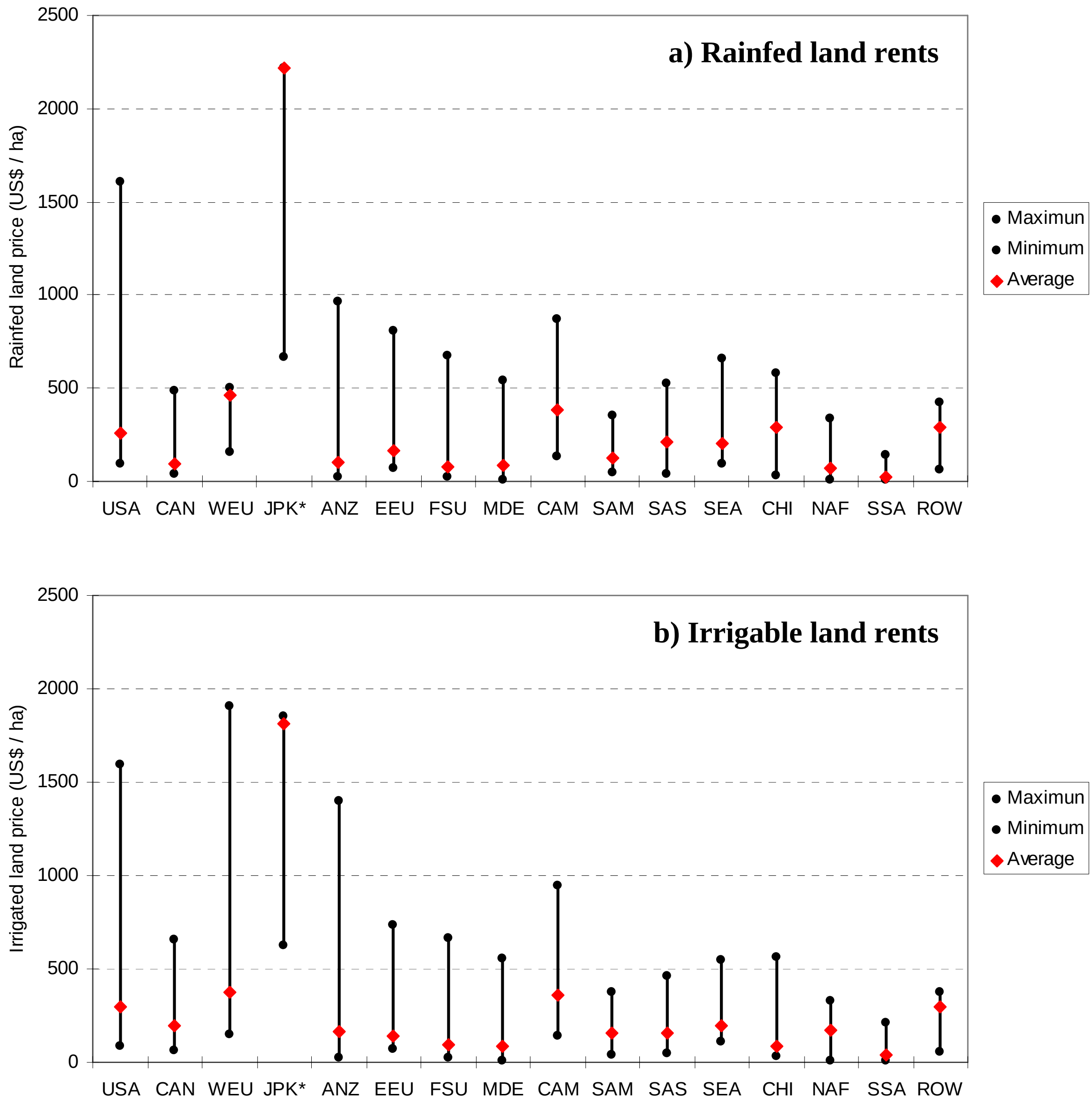


**Figure II–4. Regional range and average (over all crops) of rainfed and irrigable land rents per hectare**

Source: Based on GTAP-W database.

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), South Africa (SAF) and Rest of the World (ROW).

* The maximum value has been deleted for illustrative purposes. Maximum values are: rainfed land rents (3503) and irrigated land rents (3617)

While 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 higher (92 US$/ha and 193 US$/ha, respectively). The lowest 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

[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.

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 II-5). The procedure for obtaining the elasticity of factor substitution between land and irrigation ($\sigma_{LW}$) is explained in section 3.6. Next, the irrigable land-water composite is combined with pasture land, rainfed land, natural resources, labour and the capital-energy composite in a value-added nest through a CES structure. The original elasticity of substitution between primary factors ($\sigma_{VAE}$) 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 II-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, irrigable land and irrigation, the new version of the GTAP-W model allows for discriminating and substituting rainfed and irrigated crop production.

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

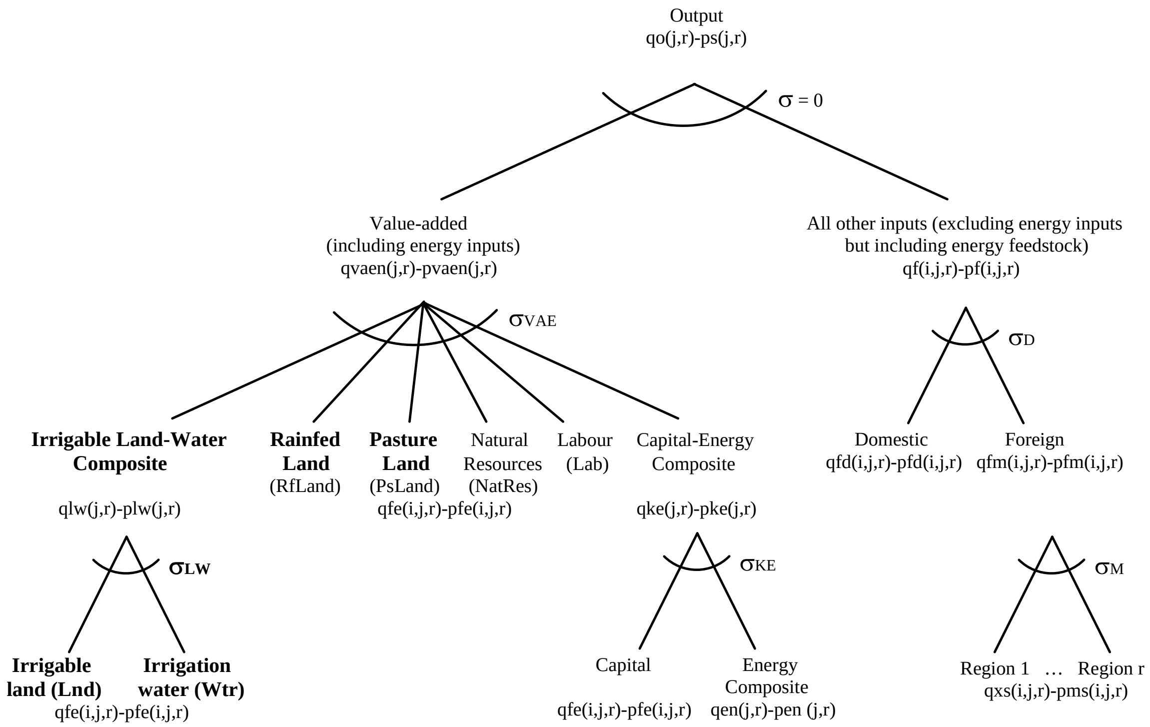


**Figure II–5. Nested tree structure for industrial production process in the GTAP-W model (truncated)**

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. $\sigma$ is the elasticity of substitution between value added and intermediate inputs, $\sigma_{VAE}$ is the elasticity of substitution between primary factors, $\sigma_{LW}$ is the elasticity of substitution between irrigable land and irrigation, $\sigma_{KE}$ is the elasticity of substitution between capital and the energy composite, $\sigma_D$ is the elasticity of substitution between domestic and imported inputs and $\sigma_M$ is the elasticity of substitution between imported inputs. The production structure links quantities and prices.

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 II-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 II-A6 in Annex A).

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] Annex C provides a complete documentation of the core structure of the GTAP-W model, the basic notation, equations and intuition behind the model. As shown in Figure II-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

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

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:

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

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 $\rho$ > -1), $\delta_i$ are the distribution parameters and $\alpha$ is the efficiency parameter (with $\alpha$ > 0).

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 II-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 $ELLW_{j,r}$ ($\sigma_{LW}$). At this stage, only biased technical change is specified.

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

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

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 $ELKE_{j,r}$ ($\sigma_{KE}$). At this stage, only biased technical change is specified.

Demand for capital (Capital) and the energy composite:

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

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

Unit cost of the capital-energy composite:

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

*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 $ESUBVA_j$ ($\sigma_{VAE}$). At this stage, only biased technical change is specified.

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

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

$i$=RfLand, PsLand, NatRes, Lab

Demand for the irrigable land-water composite:

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

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):

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

*Upper level:* Producers combine the value-added composite with all other inputs according to a CES function with elasticity of substitution $ESUBT_j$ ($\sigma$). 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 ($\sigma_{LW}$ in Figure II-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+δ)*:

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

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

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 $\eta$ implies the substitution elasticity $\rho$, for any price change $\delta$.

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

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

| Regions | Price elasticity ($\eta$) | Substitution elasticity ($\rho$) |
|---|---|---|
| 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 II-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.

## 4. Validation of the GTAP-W model

Before exploring concrete policies, a comprehensive validation of the model should be performed 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. Dixon and Rimmer (2010a) point out that the major challenge in CGE modelling is validation. They suggest four forms of validation: checking the code and data, plausibility checks on results, fitting history and forecasting performance.

*Checking the code and data* for errors is often done by performing a homogeneity test. That is, run a simulation for which the solution has a simple structure which is known *a priori* from the theory of the model. *Checking for plausible results* and contrasting them with theory is another form of validation. Dixon and Rimmer (2010a) suggest that once the macro results from detailed models are understood by means of equations that are familiar from simple models, the justification of the results in a multi-sector, multi-region model becomes straight-forward.

The third form of validation of the model proposed by Dixon and Rimmer (2010a) is checking its consistency (or otherwise) with history (*fitting history*). This implies forcing models to track observed movements in outputs, inputs and final demands and allowing them to generate implied changes in technologies, consumer preferences, world trading condition and other naturally exogenous but unobservable variables. In this way, results from historical simulations are used to refine parameter estimates.

CGE forecasts are part of policy analyses that require, before exploring the effects of a particular shock, projecting the evolution of the economy without the shock (a business-as-usual or basecase simulation). Furthermore, *analyzing the forecast performance* of the model

[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).

is also another form of validation of the model results. Dixon and Rimmer (2010b), for example, use the USAGE model to forecast growth in outputs of 500 US industries between 1998 and 2005. They found that forecasts that include trends in technologies, consumer preferences and trade conditions derived from an historical simulation for 1992 to 1998 together with expert macro and energy forecasts available in 1998 are 42 percent better that those that could be derived by simply extrapolating output trends from the period 1992 to 1998.

To validate the GTAP-W model, we apply two homogeneity tests to check the code and data, as well as we check the forecast performance 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.

*Analyzing the forecast performance*:

The inclusion of water resources in GTAP-W and the distinction between rainfed and irrigated agriculture, makes the model suitable for the analysis of future climate change impacts on agriculture. However, the long-term nature of climate change impacts requires first projecting the evolution of the world economy towards 2050 and beyond. To obtain a future benchmark equilibrium database for the GTAP-W model, we use the methodology described by Dixon and Rimmer (2002). This methodology allows us to find a hypothetical general equilibrium state in the future by imposing forecasted values for some key economic variables in the initial calibration database. That is, we impose a forecast closure exogenizing macroeconomic variables for which forecasts are available.

In this way, we impose forecasted changes in regional endowments (labour, capital, rainfed land, irrigated land and irrigation), in regional factor-specific and multifactor productivity, and in regional population. We use estimates of regional labour productivity, labour stock, and capital stock from the G-Cubed model (McKibbin and Wilcoxen 1998). Changes in the allocation of rainfed and irrigated land within a world region, as well as irrigation and agricultural land productivity, are implemented according to the values obtained from IMPACT. Finally, we use the medium-variant population estimates from the Population Division of the United Nations (United Nations 2004).

Table II-6 shows the forecast changes imposed to exogenous variables in the GTAP-W model to project the global economy for the baseline simulation (without a policy shock). These values are used to obtain a benchmark equilibrium for 2010; however, they are derived from forecasts made for 2050. Therefore, the 2010 GTAP-W baseline may underestimate some results when comparing to current observations. In fact, Figure II-6 shows for most of the regions that the average annual GDP growth rate implicit in the 2010 baseline simulation is lower than that observed for the period 2000-2008. The rapid economic growth over the past years in the former Soviet Union, South Asia, Southeast Asia and China are not captured by the 2010 GTAP-W baseline simulation mainly because the shocks imposed to the model are more appropriated for long-run simulations where GDP growth rates are expected to be lower.

**Table II–6. Forecast changes in exogenous variables to obtain a 2010 baseline simulation (percentage change with respect to 2001)**

| | Popula- | Capital | Labour | Labour productivity | | | | | Land Productivity[1] | | Land Expansion[2] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | tion | Stock | Stock | Agricul- | Energy | Electricity | Services | Energy | Rainfed | Irrigated | Rainfed | Irrigated |
| Regions | | | | ture | | | | Int. Inds. | Crops | Crops | Area | Area[3] |
| USA | 7.7 | 27.6 | 23.6 | 15.5 | 0.0 | 10.1 | 19.6 | 15.5 | 13.8 | 13.9 | -2.1 | 0.6 |
| CAN | 6.8 | 21.5 | 26.7 | 17.5 | 1.6 | 19.3 | 19.3 | 17.5 | 13.3 | 12.9 | -4.4 | -2.9 |
| WEU | 0.8 | 15.3 | 26.2 | 18.4 | 2.5 | 12.9 | 21.3 | 18.4 | 7.9 | 9.5 | -7.7 | -3.9 |
| JPK | -0.6 | 34.6 | 13.6 | 17.4 | 0.0 | 11.9 | 19.8 | 17.4 | 10.7 | 5.8 | -6.6 | -5.1 |
| ANZ | 7.1 | 21.3 | 26.7 | 17.3 | 1.6 | 19.2 | 19.2 | 17.3 | 11.6 | 13.4 | -1.3 | -0.9 |
| EEU | -1.6 | 21.9 | 23.0 | 29.6 | 12.4 | 23.6 | 29.6 | 32.6 | 10.0 | 16.1 | -5.1 | -3.9 |
| FSU | -1.6 | 23.1 | 23.0 | 31.2 | 13.2 | 24.9 | 31.2 | 34.5 | 13.4 | 13.5 | -1.3 | 0.3 |
| MDE | 21.1 | 33.5 | 45.8 | 36.2 | 17.9 | 29.8 | 33.4 | 30.2 | 8.7 | 15.9 | 0.6 | 2.3 |
| CAM | 14.6 | 24.7 | 46.8 | 37.1 | 18.4 | 30.6 | 40.9 | 37.1 | 17.6 | 15.8 | 0.7 | 3.5 |
| SAM | 12.6 | 26.9 | 46.8 | 40.4 | 20.0 | 33.4 | 44.6 | 40.4 | 22.1 | 21.8 | 4.8 | 6.4 |
| SAS | 15.3 | 33.8 | 27.7 | 39.9 | 19.8 | 32.9 | 43.8 | 39.9 | 13.2 | 12.7 | -6.7 | 4.8 |
| SEA | 13.6 | 22.2 | 46.8 | 33.5 | 16.5 | 27.6 | 37.0 | 33.5 | 10.2 | 18.4 | 2.3 | 0.2 |
| CHI | 8.1 | 29.6 | 27.7 | 35.0 | 17.2 | 28.8 | 38.4 | 35.0 | 7.6 | 6.3 | -1.7 | -0.7 |
| NAF | 20.3 | 18.7 | 46.8 | 28.3 | 13.9 | 23.3 | 31.2 | 28.3 | 15.8 | 12.4 | 1.4 | 2.4 |
| SSA | 23.9 | 24.7 | 46.8 | 37.2 | 18.4 | 30.6 | 41.0 | 37.2 | 12.7 | 17.7 | 6.0 | 12.4 |
| ROW | 11.6 | 27.6 | 46.8 | 41.4 | 20.5 | 34.2 | 45.6 | 41.4 | 16.2 | 20.1 | 3.1 | 5.5 |

Source: Based on United Nations (2004), McKibbin and Wilcoxen (1998) and Rosegrant et al. (2002).
Note: Energy Int. Inds. (energy intensive industries).
[1] Average for different crops
[2] Regional numbers
[3] We assume that irrigable land and irrigation change by the same proportion

Studies analyzing long-term projections are close to our estimates for those regions. For example, Valenzuela and Anderson (2011) use the GTAP model to provide a consistent baseline projection of the world economy to 2030 and 2050. They calibrate the model to ensure that real prices of primary products remain broadly unchanged compared to their base year database (2004). Their implicit assumption on annual GDP growth for the period 2030-2050 is 5.1 percent for China, 4.9 for India and 3.1 for Russia. Similarly, for a baseline projection of the world economy to 2050, Hawksworth (2006) assume an annual GDP growth of 3.9 percent for China, 5.1 percent for India and 2.7 percent for Russia.

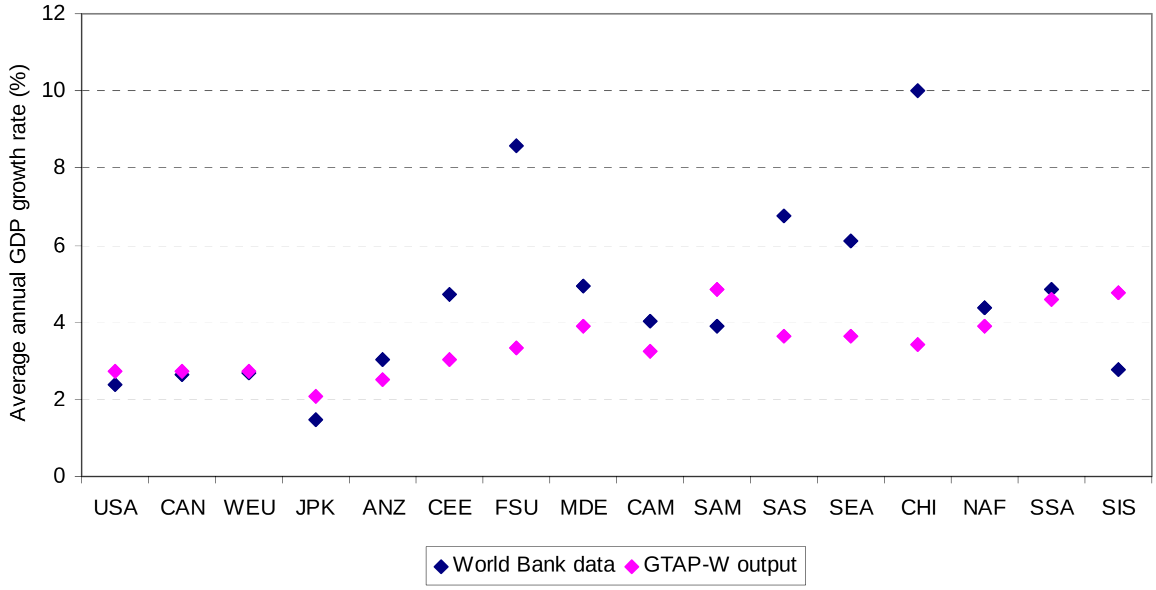


**Figure II–6. Average annual GDP growth rate, World Bank data (average for the period 2000-2008) and 2010 GTAP-W baseline simulation (average for the period 2001-2010)**

Source: Based on World Bank (2009) and 2010 GTAP-W baseline simulation.

Dixon and Rimmer (2010a) point out that policy simulations conducted in comparative static models or models without realistic baseline forecasts may generate misleading results. We overcome this problem by using consistent forecast data from specialized models like the G-Cubed model that combine in a unified framework macroeconometric and CGE models, and the IMPACT model that combined a partial equilibrium agricultural sector model with a water simulation model.

## 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 a non-market 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, 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 including: irrigation efficiency (Chapter 3), sustainable water use (Chapter 4), climate change (Chapter5) and adaptation options to climate change (Chapter 6).

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.

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## Annex A: Production structure in selected CGE models

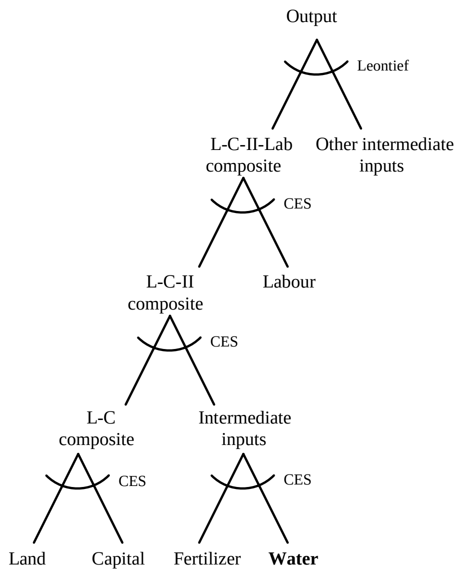



**Figure II–A1. Decaluwé et al. (1999)**

Source: Based on Decaluwé et al. (1999)

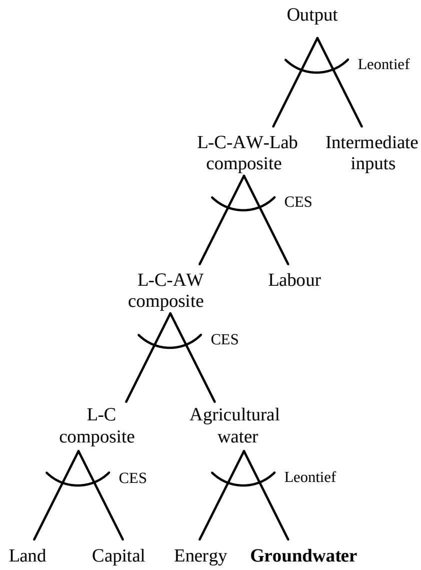



**Figure II–A2. Gómez et al. (2004)**

Source: Based on Gómez et al. (2004)

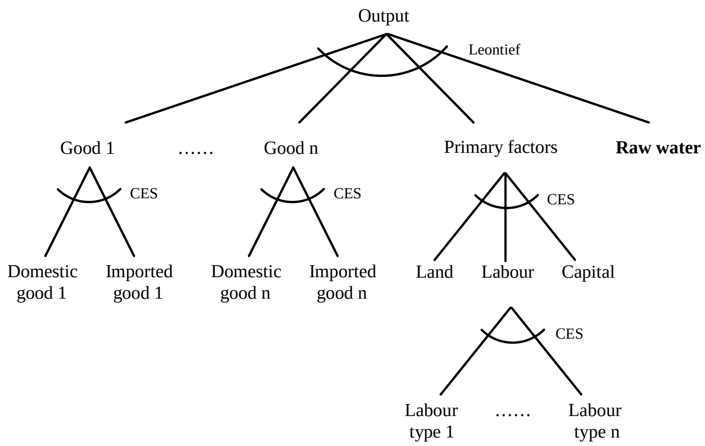



**Figure II–A3. van Heerden et al. (2008)**

Source: Based on van Heerden et al. (2008)

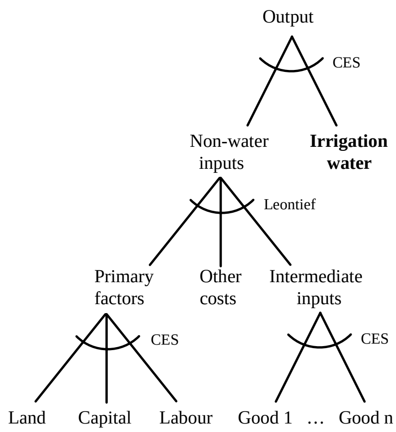



**Figure II–A4. Peterson et al. (2004)**

Source: Based on Peterson et al. (2004)

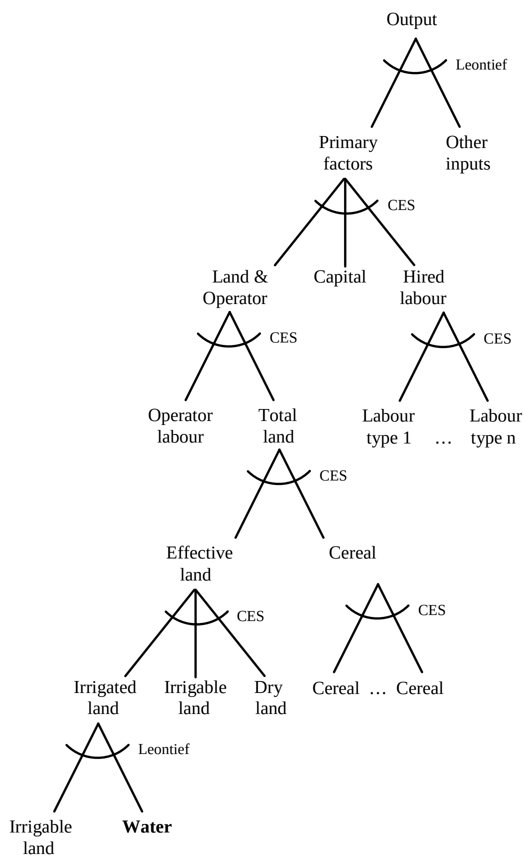



**Figure II–A5. Dixon et al. (2010)**

Source: Based on Dixon et al. (2010)

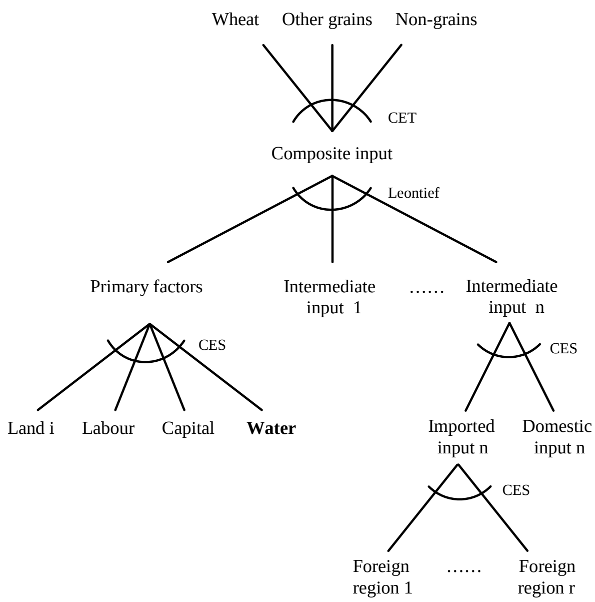



**Figure II–A6. Darwin (2004)**

Source: Based on Darwin et al. (1995)

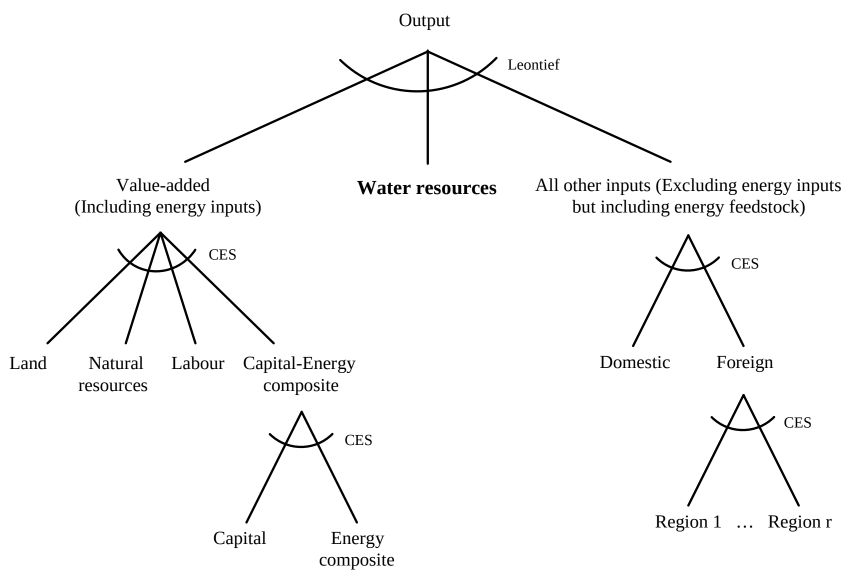
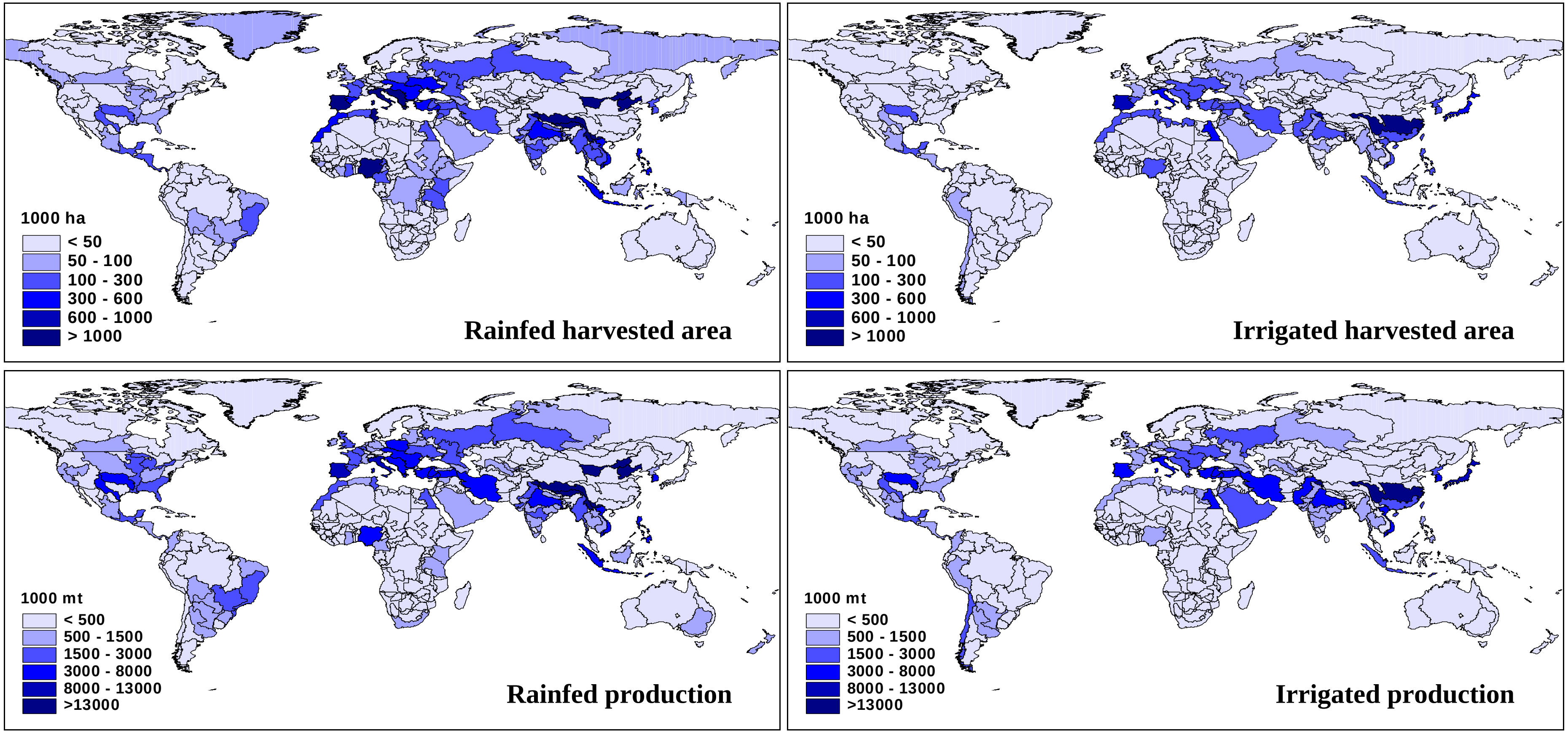



**Figure II–A7. Berrittella et al. (2007)**

Source: Based on Berrittella et al. (2007). Truncated.

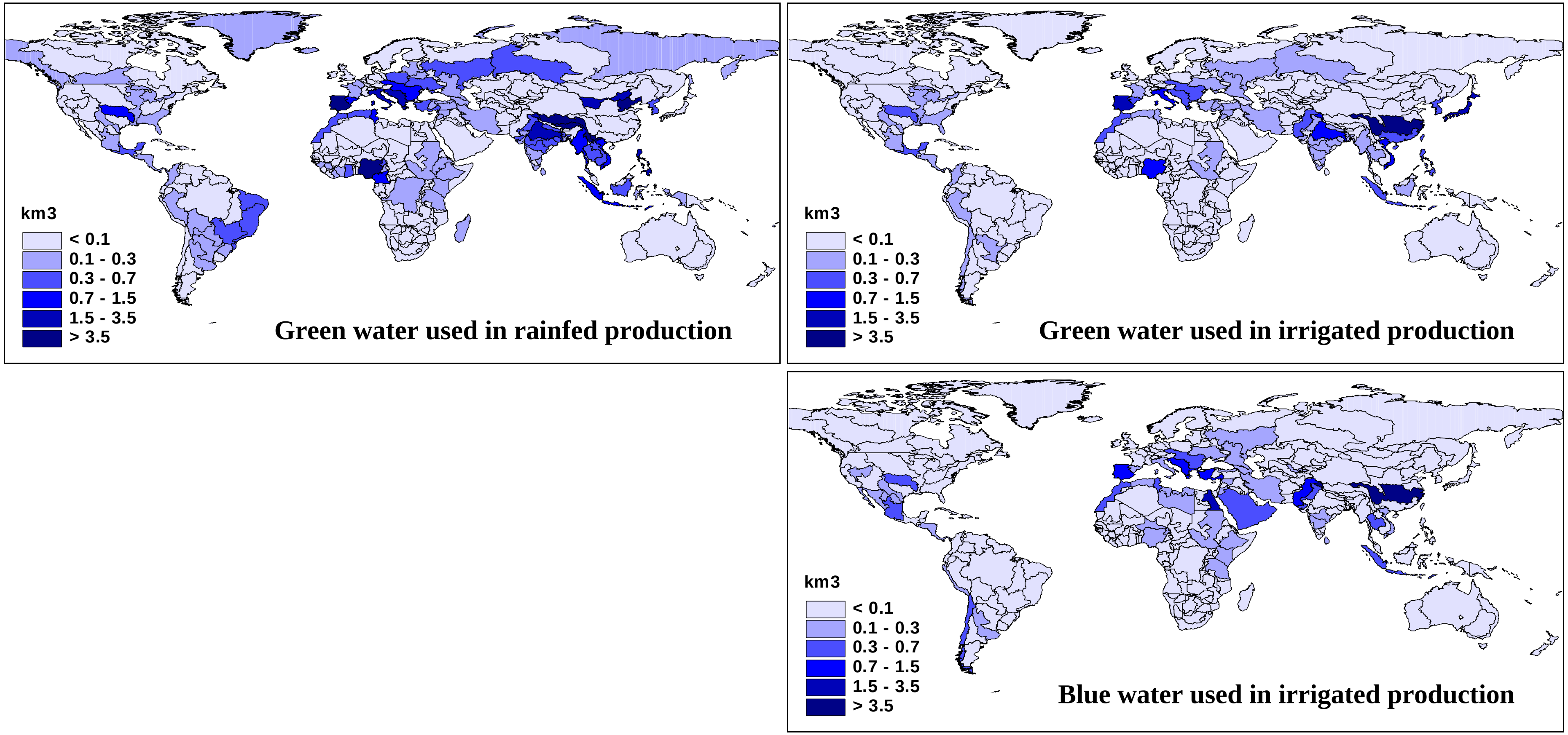
## Annex B: Baseline data and aggregation used in GTAP-W

**Figure II–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 II–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).

**Table II–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) | |

**Annex C: The core structure of the GTAP-W model**

This annex provides a complete documentation of the core structure of the GTAP-W model. It shows the basic notation, equations and intuition behind the model. The GTAP-W model is a further refinement of the GTAP model (Hertel 1997) and is based on the GTAP-E model (Burniaux and Truong 2002). For simplicity, we omit the equations showing the derivation of parameters from the database and the equations related to $CO_2$ emissions. The equations are expressed in linearized form, where uppercase variables denotes "levels" (*Y*) and lowercase variables denotes the "linearized form of variables" ($y = [dY / Y] * 100$).

**Summary:**


A - Sets, Subsets and Elements

B - Parameters from the Database and Derivatives of the Database

- B.1 Value Flows
- B.2 Technology, Preference and Mobility Parameters
- B.3 Shares, Dummy Variables and Distribution Parameters
- B.4 Tax Parameters
- B.5 Utility and Welfare Parameters

C - Variables

- C.1 Quantity Variables
- C.2 Price Variables
- C.3 Policy Variables
- C.4 Technical Change Variables
- C.5 Slack Variables
- C.6 Value and Income Variables
- C.7 Utility Variables
- C.8 Welfare Variables
- C.9 Trade Balance Variables
- C.10 List of Exogenous Variables (All the Rest Endogenous)

D - Equations

- D.1 Government Consumption
  - D.1.1 Demands for Composite Goods
  - D.1.2 Composite Tradeables
- D.2 Private Consumption
  - D.2.1 Utility from Private Consumption
  - D.2.2 Composite Demand
  - D.2.3 Composite Tradeables
- D.3 Firms
  - D.3.1 Total Output Nest
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D.3.4 Zero Profits Equations
D.4 Investment, Global Bank and Savings
D.4.1 Equations of Notational Convenience
D.4.2 Rate of Return Equations
D.4.3 Capital Accumulation Equations
D.4.4 Global Bank
D.4.5 Price Index of Aggregate Global Composite Capital Goods
D.4.6 Price of Saving
D.5 International Trade
D.5.1 International Price Transmission
D.5.2 Demand for imports
D.6 International Transport Services
D.6.1 Demand for Global Transport Services
D.6.2 Supply of Transport Services
D.7 Regional Household
D.7.1 Supply of Sluggish Endowments by the Regional Household
D.7.2 Computation of Regional Income
D.7.3 Regional Household Demand System
D.7.4 Aggregate Utility
D.8 Equilibrium Conditions
D.8.1 Market Clearing Conditions
D.8.2 Walras Law
D.9 Summary Indices
D.9.1 Factor Price Indices
D.9.2 Regional Terms of Trade
D.9.3 Equivalent Variation
D.9.4 GDP Indices (Value, Price and Quantity)
D.9.5 Aggregate Trade Indices (Value, Price and Quantity)
D.9.6 Trade Balance Indices

## A - SETS, SUBSETS AND ELEMENTS

| | |
|---|---|
| REG | Regions in the model<br>= {USA,CAN,WEU,JPK,ANZ,EEU,FSU,MDE,CAM,SAM,SAS,SEA,CHI,NAF,SSA,ROW} |
| TRAD | Traded commodities<br>={Rice,Wheat,CerCrops,VegFruits,OilSeeds,Sug_Can,Oth_Agr,Animals,Meat,Food_Prod, Forestry,Fishing,Coal,Oil,Gas,Oil_Pcts,Electricity,Water,En_Int_Ind,Oth_Ind,MServ,NMServ} |
| ENDW | Endowment commodities<br>= {Wtr,Lnd,RfLand,PsLand,Lab,Capital,NatlRes} |
| CGDS | Capital goods commodities<br>= {cgds} |
| MARG | Margin commodities ($\subset$ TRAD) |

| | |
|---|---|
| | = {MServ} |
| NMRG | Non-margin commodities<br>= TRAD – MARG |
| PROD | Produced commodities (⊂ NSAV)<br>= TRAD ∪ CGDS |
| DEMD | Demanded commodities<br>= ENDW ∪ TRAD |
| NSAV | Non-savings commodities<br>= DEMD ∪ CGDS |
| ENDWS | Sluggish endowment commodities<br>= {Wtr,Lnd,RfLand,PsLand,NatlRes} |
| ENDWM | Mobile endowment commodities<br>= ENDW – ENDWS |
| ENDWC | Capital endowment commodity (⊂ ENDW)<br>= {Capital} |
| ENDWLW | Lnd and Wtr endowment commodities (⊂ ENDW)<br>= {Lnd,Wtr} |
| ENDWCLW | Capital, Lnd and Wtr endowment commodities (⊂ ENDW)<br>= ENDWLW ∪ ENDWC) |
| ENDWNAL | Non Capital, Lnd and Wtr endowment commodities<br>= ENDW – ENDWCLW |
| EGYCOM | Energy commodities (⊂ TRAD)<br>= {Coal,Oil,Gas,Oil_Pcts,Electricity} |
| ELYS | Electricity (⊂ EGYCOM)<br>={Electricity} |
| COALS | Coal (⊂ EGYCOM) (⊂ PROD)<br>={Coal} |
| LEVEL1 | First level composite primary factors + energy goods (⊂ DEMD)<br>= ENDW ∪ EGYCOM |
| LEVEL2 | Second level composite capital + energy goods (⊂ DEMD)<br>= ENDWC ∪ EGYCOM |
| LEVEL3 | Third level composite non-electric good<br>= EGYCOM – ELYS |
| LEVEL4 | Fourth level of composite non-coal energy good<br>= LEVEL3 – COALS |

## B - Parameters from the Database and Derivatives of the Database

### B.1 Value Flows

| | | |
|---|---|---|
| $FY_r$ | primary factor income in *r* net of depreciation | ∀r∈REG |
| $GDP_r$ | Gross Domestic Product in region *r* | ∀r∈REG |
| GLOBINV | global expenditures on net investment | |
| $GOVEXP_r$ | government expenditure in region *r* | ∀r∈REG |
| $GRNETRATIO_r$ | ratio of GROSS/NET rates of return on capital in *r* | ∀r∈REG |
| $INCOME_r$ | level of expenditure, which equals NET income in region *r* | ∀r∈REG |

| | | |
|---|---|---|
| $INVKERATIO_r$ | ratio of gross investment to end-of-period capital stock in *r* | ∀r∈REG |
| $NETINV_r$ | regional NET investment in region *r* | ∀r∈REG |
| $REGINV_r$ | regional GROSS investment in *r* (value of "cgds" output) | ∀r∈REG |
| $SAVE_r$ | expenditure on NET savings in region *r* valued at agent's prices | ∀r∈REG |
| $TBAL_r$ | trade balance for region *r* | ∀r∈REG |
| $VDEP_r$ | value of capital depreciation in *r* (exogenous) | ∀r∈REG |
| $VDFA_{i,j,r}$ | purchases of domestic *i* for use by *j* in region *r* | ∀i∈TRAD ∀j∈PROD ∀r∈REG |
| $VDGA_{i,r}$ | government consumption expenditure on domestic *i* in *r* | ∀i∈TRAD ∀r∈REG |
| $VDPA_{i,r}$ | private consumption expenditure on domestic *i* in *r* | ∀i∈TRAD ∀r∈REG |
| $VENDWREG_r$ | value of primary factors, at market prices, by region | ∀r∈REG |
| VENDWWLD | value of primary factors, at market prices, worldwide | |
| $VFA_{i,j,r}$ | producer expenditure on *i* by *j* in *r* valued at agents' prices | ∀i∈DEMD ∀j∈PROD ∀r∈REG |
| $VGA_{i,r}$ | government consumption expenditure on *i* in *r* at agent's prices | ∀i∈TRAD ∀r∈REG |
| $VIFA_{i,j,r}$ | purchases of imported *i* for use by *j* in region *r* | ∀i∈TRAD ∀j∈PROD ∀r∈REG |
| $VIGA_{i,r}$ | government consumption expenditure on imported *i* | ∀i∈TRAD ∀r∈REG |
| $VIMS_{i,r,s}$ | imports of *i* from *r* to *s* valued at domestic market prices | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $VIPA_{i,r}$ | private consumption expenditure on imported *i* in *r* | ∀i∈TRAD ∀r∈REG |
| $VIWCOMMOD_i$ | global value of commodity imports, cif, by commodity | ∀i∈TRAD |
| $VIW_{i,s}$ | value of commodity imports *i* into *s* at cif prices | ∀i∈TRAD ∀s∈REG |
| $VIWREGION_r$ | value of commodity imports by region *r* at cif prices | ∀r∈REG |
| $VIWS_{i,r,s}$ | imports of *i* from *r* to *s* valued cif (tradeables only) | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $VOA_{i,r}$ | value of commodity *i* output in region *r* at agents' prices | ∀i∈NSAV ∀r∈REG |
| $VOM_{i,r}$ | value of commodity *i* output in region *r* at market prices | ∀i∈NSAV ∀r∈REG |
| $VOW_{i,r}$ | value of output in *r* at fob including transportation services | ∀i∈TRAD ∀r∈REG |
| $VPA_{i,r}$ | private household expenditure on *i* in *r* valued at agent's prices | ∀i∈TRAD ∀r∈REG |
| $VST_{m,r}$ | exports of *m* from *r* for international transport valued at market prices (tradeables only) | ∀m∈MARG ∀r∈REG |
| $VWOU_i$ | value of world output of *i* at user prices | ∀i∈TRAD |
| $VWOW_i$ | value of world supply at world prices for *i* | ∀i∈TRAD |
| $VXMD_{i,r,s}$ | exports of *i* from *r* to *s* valued at market prices (tradeables only) | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $VXWCOMMOD_i$ | value of world exports by commodity *i* at fob prices | ∀i∈TRAD |
| $VXWD_{i,r,s}$ | exports of *i* from *r* to *s* valued fob (tradeables only) | ∀i∈TRAD |

| | | |
|---|---|---|
| | | ∀r∈REG<br>∀s∈REG |
| $VXW_{i,r}$ | value of exports by commodity *i* and region *r* at fob prices | ∀i∈TRAD<br>∀r∈REG |
| VXWLD | value of commodity exports, fob, globally | |
| $VXWREGION_r$ | value of exports by region *r* at fob prices | ∀r∈REG |

**B.2 Technology, Preference and Mobility Parameters**

| | | |
|---|---|---|
| $ELCO_{j,r}$ | elasticity of substitution between coal and the composite | ∀j∈PROD<br>∀r∈REG |
| $ELELY_{j,r}$ | elasticity of subs. between electricity and the composite non-electric good in *j* | ∀j∈PROD<br>∀r∈REG |
| $ELFU_{j,r}$ | elasticity of substitution between remaining fossil fuels in *j* | ∀j∈PROD<br>∀r∈REG |
| $ELKE_{j,r}$ | elasticity of subs. between capital and the composite energy good in *j* | ∀j∈PROD<br>∀r∈REG |
| $ELLW_{j,r}$ | elasticity of substitution between irrigable land and water in *j* | ∀j∈PROD<br>∀r∈REG |
| $EP_{i,k,r}$ | uncompensated cross-price elasticity private household demand for *i* with respect to *k* in *r* | ∀i∈TRAD<br>∀k∈TRAD<br>∀r∈REG |
| $ESUBD_i$ | region-generic elasticity of substitution dom./imp. in Armington for all agents | ∀i∈TRAD |
| $ESUBM_i$ | region-generic elasticity of subs. among imports of *i* in Armington structure | ∀i∈PROD |
| $ESUBT_j$ | elasticity of substitution among composite intermediate inputs in production | ∀j∈PROD |
| $ESUBVA_j$ | elasticity of substitution in production of value-added in *j* | ∀j∈PROD |
| $ETRAE_i$ | elasticity of transformation for sluggish primary factor endowments | ∀i∈ENDW |
| $EY_{i,r}$ | income elasticity of private household demand for *i* in *r* | ∀i∈TRAD<br>∀r∈REG |
| RORDELTA | binary coefficient to switch mechanism of allocating investment funds | |
| $RORFLEX_r$ | flexibility of expected net ROR on capital stock in *r* wrt investment | ∀r∈REG |
| $UELASPRIV_r$ | elasticity of cost with respect to utility from private consumption | ∀r∈REG |
| $UTILELAS_r$ | elasticity of cost of utility with respect to utility | ∀r∈REG |

**B.3 Shares, Dummy Variables and Distribution Parameters**

| | | |
|---|---|---|
| $CONSHR_{i,r}$ | share of private household consumption devoted to good *i* in *r* | ∀i∈TRAD<br>∀r∈REG |
| $D\_COAL_{i,j,r}$ | dummy variable for intermediate demand : 1 = coal; others = 0 | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $D\_ELY_{i,j,r}$ | dummy variable for intermediate demand : 1 = electricity; others = 0 | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $D\_NEGY_{i,j,r}$ | dummy variable for intermediate demand : 1 = non-energy; energy = 0 | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $D\_OFF_{i,j,r}$ | dummy variable for intermediate demand : 1 = oil, gas, petr. Products; others = 0 | ∀i∈ TRAD<br>∀j∈PROD<br>∀r∈REG |
| $D\_VFA_{i,j,r}$ | 0, 1 variable for identifying zero expenditures in VFA | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $DPARGOV_r$ | government consumption distribution parameter | ∀r∈REG |
| $DPARPRIV_r$ | private consumption distribution parameter | ∀r∈REG |

| | | |
|---|---|---|
| $DPARSAVE_r$ | saving distribution parameter | $\forall r \in REG$ |
| $DPARSUM_r$ | sum of distribution parameters | $\forall r \in REG$ |
| $FMSHR_{i,j,s}$ | share of firms' imports in domestic composite, agents' prices | $\forall i \in TRAD$<br>$\forall j \in PROD$<br>$\forall s \in REG$ |
| $FOBSHR_{i,r,s}$ | fob share in VIW | $\forall i \in TRAD$<br>$\forall r \in REG$<br>$\forall s \in REG$ |
| $GMSHR_{i,s}$ | share of imports for government household at agent's prices | $\forall i \in TRAD$<br>$\forall s \in REG$ |
| $MSHRS_{i,r,s}$ | share of imports from *r* in import bill of *s* at market prices | $\forall i \in TRAD$<br>$\forall r \in REG$<br>$\forall s \in REG$ |
| $PMSHR_{i,s}$ | share of imports for private household at agent's prices | $\forall i \in TRAD$<br>$\forall s \in REG$ |
| $REVSHR_{i,j,r}$ | share of endowment commodity | $\forall i \in ENDW$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SEN_{i,j,r}$ | share of *i* in third level composite energy good (elec.+ non-elec.) | $\forall i \in EGYCOM$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SHRDFM_{i,j,r}$ | share of domestic production *i* used by sector *j* in *r* at market prices | $\forall i \in TRAD$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SHRDGM_{i,r}$ | share of imports of *i* used by government households in *r* | $\forall i \in TRAD$<br>$\forall r \in REG$ |
| $SHRDM_{i,r}$ | share of domestic sales of *i* in *r* | $\forall i \in TRAD$<br>$\forall r \in REG$ |
| $SHRDPM_{i,r}$ | share of domestic production of *i* used by private households in *r* | $\forall i \in TRAD$<br>$\forall r \in REG$ |
| $SHREM_{i,j,r}$ | share of mobile endowments *i* used by sector *j* at market prices | $\forall i \in ENDWM$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SHRIFM_{i,j,r}$ | share of import *i* used by sector *j* in *r* | $\forall i \in TRAD$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SHRIGM_{i,r}$ | share of import *i* used by government households in *r* | $\forall i \in TRAD$<br>$\forall r \in REG$ |
| $SHRIPM_{i,r}$ | share of import *i* used by private households in *r* | $\forall i \in TRAD$<br>$\forall r \in REG$ |
| $SHRST_{m,r}$ | share of sales of *m* to global transport services in *r* | $\forall m \in MARG$<br>$\forall r \in REG$ |
| $SHRXMD_{i,r,s}$ | share of export sales of *i* to *s* in *r* | $\forall i \in TRAD$<br>$\forall r \in REG$<br>$\forall s \in REG$ |
| $SKE_{i,j,r}$ | share of *i* in second level composite good "capital+energy" | $\forall i \in LEVEL2$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SLW_{i,j,r}$ | share of *i* in the composite good "irrigable land+water" | $\forall i \in ENDWLW$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SNCOAL_{i,j,r}$ | share of *i* in fifth level composite non-coal good | $\forall i \in EGYCOM$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $SNELY_{i,j,r}$ | share of *i* in third level composite non-electric good | $\forall i \in EGYCOM$<br>$\forall j \in PROD$<br>$\forall r \in REG$ |
| $STC_{i,j,r}$ | share of *i* in total costs of *j* in *r* | $\forall i \in DEMD$<br>$\forall j \in PROD$ |

| | | |
|---|---|---|
| | | ∀r∈REG |
| $SVAEN_{i,j,r}$ | share of *i* in first level composite good "value added+energy" | ∀i∈LEVEL1<br>∀j∈PROD<br>∀r∈REG |
| $TRNSHR_{i,r,s}$ | transport share in VIW | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| VTFSD $\_MSH_{m,i,r,s}$ | share of margin *m* in cost of getting *i* from *r* to *s* | ∀m∈MARG<br>∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| VTM $USESHR_{m,i,r,s}$ | share of *i,r,s* usage in global demand for *m* | ∀m∈MARG<br>∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| $VTSUPPSHR_{m,r}$ | share of region *r* in global supply of margin *m* | ∀m∈MARG<br>∀r∈REG |
| $XSHRGOV_r$ | government expenditure share in regional income | ∀r∈REG |
| $XSHRPRIV_r$ | private expenditure share in regional income | ∀r∈REG |
| $XSHRSAVE_r$ | saving share in regional income | ∀r∈REG |
| $XWCONSHR_{i,r}$ | expansion-parameter-weighted consumption share | ∀i∈TRAD<br>∀r∈REG |

**B.4 Tax Parameters**

| | | |
|---|---|---|
| $DFTAX_{i,j,r}$ | tax on use of domestic intermediate good *i* by *j* in *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $DGTAX_{i,r}$ | tax on government consumption of domestic good *i* in region *r* | ∀i∈TRAD<br>∀r∈REG |
| $DPTAX_{i,r}$ | tax on private consumption of domestic good *i* in region *r* | ∀i∈TRAD<br>∀r∈REG |
| $ETAX_{i,j,r}$ | tax on use of endowment good *i* by industry *j* in region *r* | ∀i∈ENDW<br>∀j∈PROD<br>∀r∈REG |
| $IFTAX_{i,j,r}$ | tax on use of imported intermediate good *i* by *j* in *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $IGTAX_{i,r}$ | tax on government consumption of imported good *i* in region *r* | ∀i∈TRAD<br>∀r∈REG |
| $INDTAX_r$ | indirect tax receipts in *r* | ∀r∈REG |
| $IPTAX_{i,r}$ | tax on private consumption of imported good *i* in region *r* | ∀i∈TRAD<br>∀r∈REG |
| $MTAX_{i,r,s}$ | tax on imports of good *i* from source *r* in destination *s* | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| $PTAX_{i,r}$ | output tax on good *i* in region *r* | ∀i∈NSAV<br>∀r∈REG |
| $TEX_r$ | export tax payments in *r* | ∀r∈REG |
| $TFU_r$ | firms' tax payments on primary factor usage in *r* | ∀r∈REG |
| $TGC_r$ | government consumption tax payments in *r* | ∀r∈REG |
| $TIM_r$ | import tax payments in *r* | ∀r∈REG |
| $TINC_r$ | income tax payments in *r* | ∀r∈REG |
| $TIU_r$ | firms' tax payments on intermediate goods usage in *r* | ∀r∈REG |
| $TOUT_r$ | production tax payments in *r* | ∀r∈REG |
| $TPC_r$ | private consumption tax payments in *r* | ∀r∈REG |

| | | |
|---|---|---|
| $XTAXD_{i,r,s}$ | tax on exports of good *i* from source *r* to destination *s* | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |

**B.5 Utility and Welfare Parameters**

| | | |
|---|---|---|
| $EYEV_{i,r}$ | expenditure elasticity of private household demand for *i* in *r*, for EV calc. | ∀i∈TRAD<br>∀r∈REG |
| $INCOMEEV_r$ | regional income, for EV calculation | ∀r∈REG |
| $UELASPRIVEV_r$ | elasticity of cost wrt utility from private consumption, for EV calculation | ∀r∈REG |
| $UTILELASEV_r$ | elasticity of cost of utility with respect to utility, for EV calculation | ∀r∈REG |
| $UTILGOVEV_r$ | utility from government consumption, for EV calculation | ∀r∈REG |
| $UTILGOV_r$ | utility from government consumption | ∀r∈REG |
| $UTILPRIVEV_r$ | utility from private consumption, for EV calculation | ∀r∈REG |
| $UTILPRIV_r$ | utility from private consumption | ∀r∈REG |
| $UTILSAVEEV_r$ | utility from saving, for EV calculation | ∀r∈REG |
| $UTILSAVE_r$ | utility from saving | ∀r∈REG |
| $XSHRGOVEV_r$ | government expenditure share in regional income, for EV calculation | ∀r∈REG |
| $XSHRPRIVEV_r$ | private expenditure share in regional income, for EV calculation | ∀r∈REG |
| $XSHRSAVEEV_r$ | saving share in regional income, for EV calculation | ∀r∈REG |
| $XWCONSHREV_{i,r}$ | expansion-parameter-weighted consumption share, for EV calculation | ∀i∈TRAD<br>∀r∈REG |

## C - VARIABLES

**C.1 Quantity Variables**

| | | |
|---|---|---|
| globalcgds | global supply of capital goods for NET investment | |
| $kb_r$ | beginning-of-period capital stock, in *r* | ∀r∈REG |
| $ke_r$ | end-of-period capital stock, in *r* | ∀r∈REG |
| $ksvces_r$ | capital services = qo("capital",r) | ∀r∈REG |
| $pop_r$ | regional population | ∀r∈REG |
| $qcgds_r$ | output of capital goods sector = qo("cgds",r) | ∀r∈REG |
| $qds_{i,r}$ | domestic sales of commodity *i* in *r* | ∀i∈TRAD<br>∀r∈REG |
| $qen_{j,r}$ | composite energy (elec.+ non-elec.) in industry *j* of region *r* | ∀j∈PROD<br>∀r∈REG |
| $qfd_{i,j,s}$ | domestic good *i* demanded by industry *j* in region *s* | ∀i∈TRAD<br>∀j∈PROD<br>∀s∈REG |
| $qfe_{i,j,r}$ | demand for endowment *i* for use in industry *j* in region *r* | ∀i∈ENDW<br>∀j∈PROD<br>∀r∈REG |
| $qf_{i,j,r}$ | demand for commodity *i* for use by *j* in region *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $qfm_{i,j,s}$ | demand for *i* by industry *j* in region *s* | ∀i∈TRAD<br>∀j∈PROD<br>∀s∈REG |
| $qgd_{i,s}$ | government household demand for domestic *i* in region *s* | ∀i∈TRAD<br>∀s∈REG |
| $qgdp_r$ | GDP quantity index | ∀r∈REG |

| | | |
|---|---|---|
| $qg_{i,r}$ | government household demand for commodity *i* in region *r* | ∀i∈TRAD ∀r∈REG |
| $qgm_{i,s}$ | government household demand for imports of *i* in region *s* | ∀i∈TRAD ∀s∈REG |
| $qim_{i,s}$ | aggregate imports of *i* in region *s*, market price weights | ∀i∈TRAD ∀s∈REG |
| $qiwcom_{i}$ | volume of global merchandise imports by commodity | ∀i∈TRAD |
| $qiw_{i,s}$ | aggregate imports of *i* into region *s*, cif weights | ∀i∈TRAD ∀s∈REG |
| $qiwreg_{r}$ | volume of merchandise imports, by region | ∀r∈REG |
| $qke_{j,r}$ | composite "capital+energy" in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $qlw_{j,r}$ | composite "irrigable land+water" in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $qncoal_{j,r}$ | composite non-coal energy good in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $qnel_{j,r}$ | composite non-electric good in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $qoes_{i,j,r}$ | supply of sluggish endowment *i* used by *j*, in *r* | ∀i∈ENDWS ∀j∈PROD ∀r∈REG |
| $qo_{i,r}$ | industry output of commodity *i* in region *r* | ∀i∈NSAV ∀r∈REG |
| $qow_{i}$ | change in index of world production of *i* | ∀i∈TRAD |
| $qowu_{i}$ | quantity index for world supply of good *i* at user prices | ∀i∈TRAD |
| $qpd_{i,s}$ | private household demand for domestic *i* in region *s* | ∀i∈TRAD ∀s∈REG |
| $qpev_{i,r}$ | private household demand for commodity *i* in region *r*, for EV calc. | ∀i∈TRAD ∀r∈REG |
| $qp_{i,r}$ | private household demand for commodity *i* in region *r* | ∀i∈TRAD ∀r∈REG |
| $qpm_{i,s}$ | private household demand for imports of *i* in region *s* | ∀i∈TRAD ∀s∈REG |
| $qsaveev_{r}$ | total quantity of savings demanded, for EV calculation | ∀r∈REG |
| $qsave_{r}$ | regional demand for NET savings | ∀r∈REG |
| $qst_{m,r}$ | sales of m from *r* to international transport | ∀m∈MARG ∀r∈REG |
| $qtmfsd_{m,i,r,s}$ | international usage margin *m* on *i* from *r* to *s* | ∀m∈MARG ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $qtm_{m}$ | global margin usage | ∀m∈MARG |
| $qvaen_{j,r}$ | value-added in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $qxs_{i,r,s}$ | export sales of commodity *i* from *r* to region *s* | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $qxwcom_{i}$ | volume of global merchandise exports by commodity | ∀i∈TRAD |
| $qxw_{i,r}$ | aggregate exports of *i* from region *r*, fob weights | ∀i∈TRAD ∀r∈REG |
| $qxwreg_{r}$ | volume of merchandise exports, by region | ∀r∈REG |
| qxwwld | computes percentage change in quantity index of global exports | |
| walras_dem | demand in the omitted market--global demand for savings | |
| walras_sup | supply in omitted market--global supply of cgds composite | |

**C.2 Price Variables**

| | | |
|---|---|---|
| $pcgds_r$ | price of investment goods = ps("cgds",r) | ∀r∈REG |
| pcgdswld | world average price of capital goods (net investment weights) | |
| $pcif_{i,r,s}$ | cif world price of commodity *i* supplied from *r* to *s* | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $pdw_r$ | index of prices paid for tradeables used in region *r* | ∀r∈REG |
| $pen_{j,r}$ | price of energy (elec.+ non-elec.) composite in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $pfactor_r$ | market price index of primary factors, by region | ∀r∈REG |
| $pfactreal_{i,r}$ | ratio of return to primary factor *i* to cpi in *r* | ∀i∈ENDW ∀r∈REG |
| pfactwld | world price index of primary factors | |
| $pfd_{i,j,s}$ | price index for domestic purchases of *i* by *j* in region *s* | ∀i∈TRAD ∀j∈PROD ∀s∈REG |
| $pfe_{i,j,r}$ | firms' price for endowment commodity *i* in industry *j*, region r | ∀i∈ENDW ∀j∈PROD ∀r∈REG |
| $pf_{i,j,r}$ | firms' price for commodity *i* for use by *j*, in *r* | ∀i∈TRAD ∀j∈PROD ∀r∈REG |
| $pfm_{i,j,s}$ | price index for imports of *i* by *j* in region *s* | ∀i∈TRAD ∀j∈PROD ∀s∈REG |
| $pfob_{i,r,s}$ | fob world price of commodity *i* supplied from *r* to *s* | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $pgd_{i,s}$ | price of domestic *i* in government consumption in *s* | ∀i∈TRAD ∀s∈REG |
| $pgdp_r$ | GDP price index | ∀r∈REG |
| $pg_{i,r}$ | government consumption price for commodity *i* in region *r* | ∀i∈TRAD ∀r∈REG |
| $pgm_{i,s}$ | price of imports of *i* in government consumption in *s* | ∀i∈TRAD ∀s∈REG |
| $pgov_r$ | price index for government household expenditures in region *r* | ∀r∈REG |
| $pim_{i,r}$ | market price of composite import *i* in region *r* | ∀i∈TRAD ∀r∈REG |
| $piwcom_i$ | price index of global merchandise imports by commodity | ∀i∈TRAD |
| $piw_{i,r}$ | world price of composite import *i* in region *r* | ∀i∈TRAD ∀r∈REG |
| $piwreg_r$ | price index of merchandise imports, by region | ∀r∈REG |
| $pke_{j,r}$ | firms' price of "capital+energy" composite in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $plw_{j,r}$ | firms' price of "irrigable land+water" composite in industry *j* of region *r* | ∀j∈PROD ∀r∈REG |
| $pmes_{i,j,r}$ | market price of sluggish endowment *i* used by *j*, in *r* | ∀i∈ENDWS ∀j∈PROD ∀r∈REG |
| $pm_{i,r}$ | market price of commodity *i* in region *r* | ∀i∈NSAV ∀r∈REG |
| $pms_{i,r,s}$ | domestic price for good *i* supplied from *r* to region *s* | ∀i∈TRAD ∀r∈REG ∀s∈REG |

| | | |
|---|---|---|
| $pncoal_{j,r}$ | price of non-coal composite in industry *j* of region *r* | ∀j∈PROD<br>∀r∈REG |
| $pnel_{j,r}$ | price of non-electric composite in industry *j* of region *r* | ∀j∈PROD<br>∀r∈REG |
| $ppd_{i,s}$ | price of domestic *i* to private households in *s* | ∀i∈TRAD<br>∀s∈REG |
| $pp_{i,r}$ | private consumption price for commodity *i* in region *r* | ∀i∈TRAD<br>∀r∈REG |
| $ppm_{i,s}$ | price of imports of *i* by private households in *s* | ∀i∈TRAD<br>∀s∈REG |
| $ppriv_r$ | price index for private consumption expenditure in region *r* | ∀r∈REG |
| $p_r$ | price index for disposition of income by regional household | ∀r∈REG |
| $pr_{i,r}$ | ratio of domestic to imported prices in *r* | ∀i∈TRAD<br>∀r∈REG |
| $psave_r$ | price of savings in region *r* | ∀r∈REG |
| $ps_{i,r}$ | supply price of commodity *i* in region *r* | ∀i∈NSAV<br>∀r∈REG |
| $psw_r$ | index of prices received for tradeables produced in *r* | ∀r∈REG |
| $pt_m$ | price of composite margins services, type | ∀m∈MARG |
| $ptrans_{i,r,s}$ | cost index for international transport of *i* from *r* to *s* | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| $pvaen_{j,r}$ | firms' price of value-added in industry *j* of region *r* | ∀j∈PROD<br>∀r∈REG |
| $pw_i$ | world price index for total good *i* supplies | ∀i∈TRAD |
| $pwu_i$ | world price index for total good *i* supplies at user prices | ∀i∈TRAD |
| $pxwcom_i$ | price index of global merchandise exports by commodity | ∀i∈TRAD |
| $pxw_{i,r}$ | aggregate exports price index of *i* from region *r* | ∀i∈TRAD<br>∀r∈REG |
| $pxwreg_r$ | price index of merchandise exports, by region | ∀r∈REG |
| pxwwld | price index of world trade | |
| $rental_r$ | rental rate on capital = ps("capital",r) | ∀r∈REG |
| $rorc_r$ | current net rate of return on capital stock, in *r* | ∀r∈REG |
| $rore_r$ | expected net rate of return on capital stock, in *r* | ∀r∈REG |
| rorg | global net rate of return on capital stock | |
| $tot_r$ | terms of trade for region *r* | ∀r∈REG |

**C.3 Policy Variables**

| | | |
|---|---|---|
| $atpd_{i,r}$ | actual tax on domestic *i* purchased by private household in *r* | ∀i∈TRAD<br>∀r∈REG |
| $atpm_{i,r}$ | actual tax on imported *i* purchased by private households in *r* | ∀i∈TRAD<br>∀r∈REG |
| $tfd_{i,j,r}$ | tax on domestic *i* purchased by *j* in *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $tf_{i,j,r}$ | tax on primary factor *i* used by *j* in region *r* | ∀i∈ENDW<br>∀j∈PROD<br>∀r∈REG |
| $tfm_{i,j,r}$ | tax on imported *i* purchased by *j* in *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $tgd_{i,r}$ | tax on domestic *i* purchased by government households in *r* | ∀i∈TRAD<br>∀r∈REG |

| | | |
|---|---|---|
| $tgm_{i,r}$ | tax on imported *i* purchased by government household in *r* | ∀i∈TRAD<br>∀r∈REG |
| $tm_{i,s}$ | variable import levy good *i* into region *s* -- source generic | ∀i∈TRAD<br>∀s∈REG |
| $tms_{i,r,s}$ | import tax on good *i* imported from region *r* to *s* | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| $to_{i,r}$ | output (or income) tax in region *r* | ∀i∈NSAV<br>∀r∈REG |
| $tpd_{i,r}$ | shock to tax on domestic *i* purchased by private household in *r* | ∀i∈TRAD<br>∀r∈REG |
| $tpm_{i,r}$ | shock to tax on imported *i* purchased by private household in *r* | ∀i∈TRAD<br>∀r∈REG |
| $tp_r$ | region-wide shock to tax on purchases by private household in *r* | ∀r∈REG |
| $tx_{i,r}$ | variable export tax (subsidy) good *i* from *r*, destination generic | ∀i∈TRAD<br>∀r∈REG |
| $txs_{i,r,s}$ | combined tax on good *i* from region *r* bound for region *s* | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |

**C.4 Technical Change Variables**

| | | |
|---|---|---|
| $afall_{i,j,r}$ | intermediate input *i* augmenting technical change by *j* in *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $afcom_i$ | intermediate technical change of input *i*, worldwide | ∀i∈TRAD |
| $afeall_{i,j,r}$ | primary factor *i* augmenting technical change sector *j* in *r* | ∀i∈ENDW<br>∀j∈PROD<br>∀r∈REG |
| $afecom_i$ | factor input technical change of input *i*, worldwide | ∀i∈ENDW |
| $afe_{i,j,r}$ | primary factor *i* augmenting technical change by *j* of *r* | ∀i∈ENDW<br>∀j∈PROD<br>∀r∈REG |
| $afereg_r$ | factor input technical change in region *r* | ∀r∈REG |
| $afesec_j$ | factor input technical change of sector *j*, worldwide | ∀j∈PROD |
| $af_{i,j,r}$ | composite intermediate input *i* augmenting technical change by *j* of *r* | ∀i∈TRAD<br>∀j∈PROD<br>∀r∈REG |
| $afreg_r$ | intermediate technical change in region *r* | ∀r∈REG |
| $afsec_j$ | intermediate technical change of sector *j*, worldwide | ∀j∈PROD |
| $ams_{i,r,s}$ | import *i* from region *r* augmenting technical change in region *s* | ∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| $aoall_{j,r}$ | output augmenting technical change in sector *j* of *r* | ∀j∈PROD<br>∀r∈REG |
| $ao_{j,r}$ | output augmenting technical change in sector *j* of *r* | ∀j∈PROD<br>∀r∈REG |
| $aoreg_r$ | output technical change in region *r* | ∀r∈REG |
| $aosec_j$ | output technical change of sector *j*, worldwide | ∀j∈PROD |
| $atall_{m,i,r,s}$ | technical change in *m*'s shipping of *i* from region *r* to *s* | ∀m∈MARG<br>∀i∈TRAD<br>∀r∈REG<br>∀s∈REG |
| $atd_s$ | technical change shipping to *s* | ∀s∈REG |
| $atf_i$ | technical change shipping of *i*, worldwide | ∀i∈TRAD |

| | | |
|---|---|---|
| $atmfsd_{m,i,r,s}$ | technical change in *m*'s shipping of *i* from region *r* to *s* | ∀m∈MARG ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $atm_m$ | technical change in mode *m*, worldwide | ∀m∈TRAD |
| $ats_r$ | technical change shipping from region *r* | ∀r∈REG |
| $avaall_{j,r}$ | value added augmenting technical change in sector *j* of *r* | ∀j∈PROD ∀r∈REG |
| $ava_{i,r}$ | value added augmenting technical change in sector *i* of *r* | ∀i∈PROD ∀r∈REG |
| $avareg_r$ | value-added technical change in region *r* | ∀r∈REG |
| $avasec_j$ | value-added technical change of sector *j*, worldwide | ∀j∈PROD |

**C.5 Slack Variables**

| | | |
|---|---|---|
| $cgdslack_r$ | slack variable for $qcgds_r$ | ∀r∈REG |
| $endwslack_{i,r}$ | slack variable in endowment market clearing condition | ∀i∈ENDW ∀r∈REG |
| $incomeslack_r$ | slack variable in the expression for regional income | ∀r∈REG |
| $profitslack_{j,r}$ | slack variable in the zero profit equation | ∀j∈PROD ∀r∈REG |
| $psaveslack_r$ | slack variable for the savings price equation | ∀r∈REG |
| $tradslack_{i,r}$ | slack variable in tradeables market clearing condition | ∀i∈TRAD ∀r∈REG |
| walraslack | slack variable in the omitted market | |

**C.6 Value and Income Variables**

| | | |
|---|---|---|
| $compvalad_{i,r}$ | composition of value added for good *i* and region *r* | ∀i∈PROD ∀r∈REG |
| $del\_indtaxr_r$ | change in ratio of indirect taxes to INCOME in *r* | ∀r∈REG |
| $del\_taxrexp_r$ | change in ratio of export tax to INCOME | ∀r∈REG |
| $del\_taxrfu_r$ | change in ratio of tax on primary factor usage to INCOME | ∀r∈REG |
| $del\_taxrgc_r$ | change in ratio of government consumption tax to INCOME | ∀r∈REG |
| $del\_taxrimp_r$ | change in ratio of import tax to INCOME | ∀r∈REG |
| $del\_taxrinc_r$ | change in ratio of income tax to INCOME | ∀r∈REG |
| $del\_taxriu_r$ | change in ratio of tax on intermediate usage to INCOME | ∀r∈REG |
| $del\_taxrout_r$ | change in ratio of output tax to INCOME | ∀r∈REG |
| $del\_taxrpc_r$ | change in ratio of private consumption tax to INCOME | ∀r∈REG |
| $del\_ttaxr_r$ | change in ratio of taxes to INCOME in *r* | ∀r∈REG |
| $dpgov_r$ | government consumption distribution parameter | ∀r∈REG |
| $dppriv_r$ | private consumption distribution parameter | ∀r∈REG |
| $dpsave_r$ | saving distribution parameter | ∀r∈REG |
| $dpsum_r$ | sum of the distribution parameters | ∀r∈REG |
| $EXPAND_{i,r}$ | change in investment levels relative to endowment stock | ∀i∈ENDWC ∀r∈REG |
| $fincome_r$ | factor income at market prices net of depreciation | ∀r∈REG |
| $valuew_i$ | value of world supply of good *i* | ∀i∈TRAD |
| $valuewu_i$ | value of world supply of good *i* at user prices | ∀i∈TRAD |

| | | |
|---|---|---|
| $vgdp_r$ | change in value of GDP | ∀r∈REG |
| $viwcif_{i,s}$ | value of merchandise regional imports, by commodity, cif | ∀i∈TRAD ∀s∈REG |
| $viwcom_i$ | value of global merchandise imports *i*, at world prices | ∀i∈TRAD |
| $viwreg_r$ | value of merchandise imports, by region, at world prices | ∀r∈REG |
| $vxwcom_i$ | value of global merchandise exports by commodity | ∀i∈TRAD |
| $vxwfob_{i,s}$ | value of merchandise regional exports, by commodity, fob | ∀i∈TRAD ∀s∈REG |
| $vxwreg_r$ | value of merchandise exports, by region | ∀r∈REG |
| vxwwld | value of world trade | |
| $yg_r$ | regional government consumption expenditure, in region *r* | ∀r∈REG |
| $yp_r$ | regional private consumption expenditure, in region *r* | ∀r∈REG |
| $y_r$ | regional household income, in region *r* | ∀r∈REG |

## C.7 Utility Variables

| | | |
|---|---|---|
| $au_r$ | input-neutral shift in utility function | ∀r∈REG |
| $uelas_r$ | elasticity of cost of utility with respect to utility | ∀r∈REG |
| $uepriv_r$ | elasticity of cost with respect to utility from private consumption | ∀r∈REG |
| $ugev_r$ | per capita utility from government expenditure, for EV calculation | ∀r∈REG |
| $ug_r$ | per capita utility from government expenditure, in region *r* | ∀r∈REG |
| $upev_r$ | per capita utility from private expend., for EV calculation | ∀r∈REG |
| $up_r$ | per capita utility from private expenditure, in region *r* | ∀r∈REG |
| $u_r$ | per capita utility from aggregate household expenditure, in region *r* | ∀r∈REG |

## C.8 Welfare Variables

| | | |
|---|---|---|
| $dpavev_r$ | average distribution parameter shift, for EV calculation | ∀r∈REG |
| $dpav_r$ | average distribution parameter shift, for EV calculation | ∀r∈REG |
| $EV_r$ | equivalent variation, $ US million | ∀r∈REG |
| $uelasev_r$ | elasticity of cost of utility with respect to utility, for EV calculation | ∀r∈REG |
| $ueprivev_r$ | utility elasticity of private consumption expenditure, for EV calculation | ∀r∈REG |
| WEV | equivalent variation for the world | |
| $yev_r$ | regional household income, in region *r*, for EV calculation | ∀r∈REG |
| $ygev_r$ | government consumption expenditure, in region *r*, for EV calculation | ∀r∈REG |
| $ypev_r$ | private consumption expenditure, in region *r*, for EV calculation | ∀r∈REG |
| $ysaveev_r$ | NET savings expenditure, for EV calculation | ∀r∈REG |

## C.9 Trade Balance Variables

| | | |
|---|---|---|
| $DTBALi_{i,r}$ | change in trade balance by *i* and by *r*, $ US million | ∀i∈TRAD ∀r∈REG |
| $DTBAL_r$ | change in trade balance X - M, $ US million | ∀r∈REG |
| $DTBALR_r$ | change in ratio of trade balance to regional income | ∀r∈REG |

## C.10 List of Exogenous Variables (All the Rest Endogenous)

| | | |
|---|---|---|
| $afall_{i,j,r}$ | intermediate input *i* augmenting technical change by *j* in *r* | ∀i∈TRAD ∀j∈PROD ∀r∈REG |

| | | |
|---|---|---|
| $afcom_i$ | intermediate technical change of input *i*, worldwide | ∀i∈TRAD |
| $afeall_{i,j,r}$ | primary factor *i* augmenting technical change sector *j* in *r* | ∀i∈ENDW ∀j∈PROD ∀r∈REG |
| $afecom_i$ | factor input technical change of input *i*, worldwide | ∀i∈ENDW |
| $afereg_r$ | factor input technical change in region *r* | ∀r∈REG |
| $afereg_r$ | factor input technical change in region *r* | ∀r∈REG |
| $afesec_j$ | factor input technical change of sector *j*, worldwide | ∀j∈PROD |
| $afesec_j$ | factor input technical change of sector *j*, worldwide | ∀j∈PROD |
| $ams_{i,r,s}$ | import *i* from region *r* augmenting technical change in region *s* | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $aoall_{j,r}$ | output augmenting technical change in sector *j* of *r* | ∀j∈PROD ∀r∈REG |
| $aoreg_r$ | output technical change in region *r* | ∀r∈REG |
| $aosec_j$ | output technical change of sector *j*, worldwide | ∀j∈PROD |
| $atd_s$ | technical change shipping to *s* | ∀s∈REG |
| $atf_i$ | technical change shipping of *i*, worldwide | ∀i∈TRAD |
| $atm_m$ | technical change in mode *m*, worldwide | ∀m∈TRAD |
| $ats_r$ | technical change shipping from region *r* | ∀r∈REG |
| $au_r$ | input-neutral shift in utility function | ∀r∈REG |
| $avareg_r$ | value-added technical change in region *r* | ∀r∈REG |
| $avasec_j$ | value-added technical change of sector *j*, worldwide | ∀j∈PROD |
| $cgdslack_r$ | slack variable for $qcgds_r$ | ∀r∈REG |
| $dpgov_r$ | government consumption distribution parameter | ∀r∈REG |
| $dppriv_r$ | private consumption distribution parameter | ∀r∈REG |
| $dpsave_r$ | saving distribution parameter | ∀r∈REG |
| $endwslack_{i,r}$ | slack variable in endowment market clearing condition | ∀i∈ENDW ∀r∈REG |
| $incomeslack_r$ | slack variable in the expression for regional income | ∀r∈REG |
| pfactwld | world price index of primary factors | |
| $pop_r$ | regional population | ∀r∈REG |
| $profitslack_{j,r}$ | slack variable in the zero profit equation | ∀j∈PROD ∀r∈REG |
| $psaveslack_r$ | slack variable for the savings price equation | ∀r∈REG |
| $qo_{i,r}$ | industry output of commodity *i* in region *r* | ∀i∈ENDW ∀r∈REG |
| $tm_{i,s}$ | variable import levy good *i* into region *s* -- source generic | ∀i∈TRAD ∀s∈REG |
| $tms_{i,r,s}$ | import tax on good *i* imported from region *r* to *s* | ∀i∈TRAD ∀r∈REG ∀s∈REG |
| $to_{i,r}$ | output (or income) tax in region *r* | ∀i∈NSAV ∀r∈REG |
| $tp_r$ | region-wide shock to tax on purchases by private household in *r* | ∀r∈REG |
| $tradslack_{i,r}$ | slack variable in tradeables market clearing condition | ∀i∈TRAD ∀r∈REG |
| $tx_{i,r}$ | variable export tax (subsidy) good *i* from *r*, destination generic | ∀i∈TRAD |

| | | |
|---|---|---|
| $txs_{i,r,s}$ | combined tax on good *i* from region *r* bound for region *s* | $\forall r \in REG$ $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ |

## D - EQUATIONS

### D.1 Government Consumption

*D.1.1 Demands for Composite Goods:*

Price index for aggregate government purchases: $\forall r \in REG$ C-1

$pgov_r = \sum_{i \in TRAD} [VGA_{i,r} / GOVEXP_r] * pg_{i,r}$

Government consumption demands for composite commodities: $\forall i \in TRAD$ $\forall r \in REG$ C-2

$qg_{i,r} - pop_r = ug_r - [pg_{i,r} - pgov_r]$

Utility from government consumption in region *r*: $\forall r \in REG$ C-3

$yg_r - pop_r = pgov_r + ug_r$

*D.1.2 Composite Tradeables:*

Equation that links domestic market and government consumption prices: $\forall i \in TRAD$ $\forall r \in REG$ C-4

$pgd_{i,r} = tgd_{i,r} + pm_{i,r}$

Equation that links domestic market and government consumption prices: $\forall i \in TRAD$ $\forall r \in REG$ C-5

$pgm_{i,r} = tgm_{i,r} + pim_{i,r}$

Government consumption price for composite commodities: $\forall i \in TRAD$ $\forall s \in REG$ C-6

$pg_{i,s} = GMSHR_{i,s} * pgm_{i,s} + [1 - GMSHR_{i,s}] * pgd_{i,s}$

Government consumption demand for aggregate imports: $\forall i \in TRAD$ $\forall s \in REG$ C-7

$qgm_{i,s} = qg_{i,s} + ESUBD_i * [pg_{i,s} - pgm_{i,s}]$

Government consumption demand for domestic goods: $\forall i \in TRAD$ $\forall s \in REG$ C-8

$qgd_{i,s} = qg_{i,s} + ESUBD_i * (pg_{i,s} - pgd_{i,s})$

Change in ratio of government consumption tax payments to regional income: $\forall r \in REG$ C-9

$100.0 * INCOME_r * del\_taxrgc_r = \sum_{i \in TRAD} VDGA_{i,r} * tgd_{i,r}$
$+ \sum_{i \in TRAD} DGTAX_{i,r} * [pm_{i,r} + qgd_{i,r}] + \sum_{i \in TRAD} VIGA_{i,r} * tgm_{i,r}$
$+ \sum_{i \in TRAD} IGTAX_{i,r} * [pim_{i,r} + qgm_{i,r}] - TGC_r * y_r$

### D.2 Private Consumption

*D.2.1 Utility from Private Consumption:*

Price index for private consumption expenditure: $\forall r \in REG$ C-10

$ppriv_r = \sum_{i \in TRAD} CONSHR_{i,r} * pp_{i,r}$

Computation of utility from private consumption in *r*: $\forall r \in REG$ C-11

$yp_r - pop_r = ppriv_r + UELASPRIV_r * up_r$

Elasticity of expenditure with respect to utility from private consumption: $\forall r \in REG$ C-12

$uepriv_r = \sum_{i \in TRAD} XWCONSHR_{i,r} * [pp_{i,r} + qp_{i,r} - yp_r]$

*D.2.2 Composite Demand:*

Private consumption demands for composite commodities: $\forall i \in TRAD$ $\forall r \in REG$ C-13

$qp_{i,r} - pop_r = \sum_{k \in TRAD} EP_{i,k,r} * pp_{k,r} + EY_{i,r} * [yp_r - pop_r]$

*D.2.3 Composite Tradeables:*

Equation that links domestic market and private consumption prices: $\forall i \in TRAD$ $\forall s \in REG$ C-14

$ppd_{i,r} = atpd_{i,r} + pm_{i,r}$

Equation that permits implementation of a uniform consumption tax change: $\forall i \in TRAD$ C-15

$atpd_{i,r} = tpd_{i,r} + tp_r$ ∀s∈REG

Equation that links domestic market and private consumption prices: ∀i∈TRAD ∀r∈REG C-16

$ppm_{i,r} = atpm_{i,r} + pim_{i,r}$

Equation that permits implementation of a uniform consumption tax change: ∀i∈TRAD ∀r∈REG C-17

$atpm_{i,r} = tpm_{i,r} + tp_r$

Change in ratio of private consumption tax payments to regional income: ∀r∈REG C-18

$100.0 * INCOME_r * del\_taxrpc_r = \sum_{i\in TRAD} VDPA_{i,r} * atpd_{i,r}$
$+ \sum_{i\in TRAD} DPTAX_{i,r} * [pm_{i,r} + qpd_{i,r}] + \sum_{i\in TRAD} VIPA_{i,r} * atpm_{i,r}$
$+ \sum_{i\in TRAD} IPTAX_{i,r} * [pim_{i,r} + qpm_{i,r}] - TPC_r * y_r$

Private consumption price for composite commodities: ∀i∈TRAD ∀s∈REG C-19

$pp_{i,s} = PMSHR_{i,s} * ppm_{i,s} + [1 - PMSHR_{i,s}] * ppd_{i,s}$

Private consumption demand for domestic goods: ∀i∈TRAD ∀s∈REG C-20

$qpd_{i,s} = qp_{i,s} + ESUBD_i * [pp_{i,s} - ppd_{i,s}]$

Private consumption demand for aggregate imports: ∀i∈TRAD ∀s∈REG C-21

$qpm_{i,s} = qp_{i,s} + ESUBD_i * [pp_{i,s} - ppm_{i,s}]$

## D.3 Firms

*D.3.1 Total Output Nest:*

Sector / region specific average rate of output augmenting technical change: ∀j∈PROD ∀r∈REG C-22

$ao_{j,r} = aosec_j + aoreg_r + aoall_{j,r}$

Sector / region specific average rate of value added augmenting technical change: ∀j∈PROD ∀r∈REG C-23

$ava_{j,r} = avasec_j + avareg_r + avaall_{j,r}$

Sector demands for primary factor + energy composite: ∀j∈PROD ∀r∈REG C-24

$qvaen_{j,r} = -ava_{j,r} + qo_{j,r} - ao_{j,r} - ESUBT_j * [pvaen_{j,r} - ava_{j,r} - ps_{j,r} - ao_{j,r}]$

Sector / region specific average rate of intermediates augmenting technical change: ∀i∈TRAD ∀j∈PROD ∀r∈REG C-25

$af_{i,j,r} = afcom_i + afsec_j + afreg_r + afall_{i,j,r}$

*D.3.2 Composite Intermediates Nest:*

Equation that links domestic market and firm prices: ∀i∈TRAD ∀j∈PROD ∀r∈REG C-26

$pfd_{i,j,r} = tfd_{i,j,r} + pm_{i,r}$

Equation that links domestic market and firm prices: ∀i∈TRAD ∀j∈PROD ∀r∈REG C-27

$pfm_{i,j,r} = tfm_{i,j,r} + pim_{i,r}$

Change in ratio of tax payments on intermediate goods to regional income: ∀r∈REG C-28

$100.0 * INCOME_r * del\_taxriu_r = \sum_{i\in TRAD} \sum_{j\in PROD} VDFA_{i,j,r} * tfd_{i,j,r}$
$+ \sum_{i\in TRAD} \sum_{j\in PROD} DFTAX_{i,j,r} * [pm_{i,r} + qfd_{i,j,r}] + \sum_{i\in TRAD} \sum_{j\in PROD} VIFA_{i,j,r} * tfm_{i,j,r}$
$+ \sum_{i\in TRAD} \sum_{j\in PROD} IFTAX_{i,j,r} * [pim_{i,r} + qfm_{i,j,r}] - TIU_r * y_r$

Industry price for composite commodities: ∀i∈TRAD ∀j∈PROD ∀r∈REG C-29

$pf_{i,j,r} = FMSHR_{i,j,r} * pfm_{i,j,r} + [1 - FMSHR_{i,j,r}] * pfd_{i,j,r}$

Industry *j* demands for composite import *i*: ∀i∈TRAD ∀j∈PROD ∀s∈REG C-30

$qfm_{i,j,s} = qf_{i,j,s} - ESUBD_i * [pfm_{i,j,s} - pf_{i,j,s}]$

Industry *j* demands for domestic good *i*: ∀i∈TRAD ∀j∈PROD ∀s∈REG C-31

$qfd_{i,j,s} = qf_{i,j,s} - ESUBD_i * [pfd_{i,j,s} - pf_{i,j,s}]$

*D.3.3 Value-added Nest:*

Equation that links domestic and firm demand prices: ∀i∈ENDWM ∀j∈PROD ∀r∈REG C-32

$pfe_{i,j,r} = tf_{i,j,r} + pm_{i,r}$

Equation that links domestic and firm demand prices: ∀i∈ENDWS ∀j∈PROD ∀r∈REG C-33

$pfe_{i,j,r} = tf_{i,j,r} + pmes_{i,j,r}$

Sector / region specific average rate of prim. factor *i* augmenting technical change: ∀i∈ENDW ∀j∈PROD ∀r∈REG C-34

$afe_{i,j,r} = afecom_{i} + afesec_{j} + afereg_{r} + afeall_{i,j,r}$

Effective price of "value added+energy" composite in each sector / region: ∀j∈PROD ∀r∈REG C-35

$pvaen_{j,r} = \sum_{k\in ENDW} SVAEN_{k,j,r} * [pfe_{k,j,r} - afe_{k,j,r}] + \sum_{k\in EGYCOM} SVAEN_{k,j,r} * [pf_{k,j,r} - af_{k,j,r}]$

Effective price of composite "capital+energy" sectors in each sector / region: ∀j∈PROD ∀r∈REG C-36

$pke_{j,r} = \sum_{k\in ENDWC} SKE_{k,j,r} * [pfe_{k,j,r} - afe_{k,j,r}] + \sum_{k\in EGYCOM} SKE_{k,j,r} * [pf_{k,j,r} - af_{k,j,r}]$

Effective price of composite "irrigable land+water" in each sector / region: ∀j∈PROD ∀r∈REG C-37

$plw_{j,r} = \sum_{k\in ENDWLW} SLW_{k,j,r} * [pfe_{k,j,r} - afe_{k,j,r}]$

Effective price of composite energy goods in each sector / region: ∀j∈PROD ∀r∈REG C-38

$pen_{j,r} = \sum_{k\in EGYCOM} SEN_{k,j,r} * [pf_{k,j,r} - af_{k,j,r}]$

Effective price of composite non-electric goods in each sector / region: ∀j∈PROD ∀r∈REG C-39

$pnel_{j,r} = \sum_{k\in LEVEL3} SNELY_{k,j,r} * [pf_{k,j,r} - af_{k,j,r}]$

Effective price of composite non-coal energy goods in each sector / region: ∀j∈PROD ∀r∈REG C-40

$pncoal_{j,r} = \sum_{k\in LEVEL4} SNCOAL_{k,j,r} * [pf_{k,j,r} - af_{k,j,r}]$

Change in ratio of tax payments on factor usage to regional income: ∀r∈REG C-41

$100.0 * INCOME_{r} * del\_taxrfu_{r} = \sum_{i\in ENDWM} \sum_{j\in PROD} VFA_{i,j,r} * tf_{i,j,r} + \sum_{i\in ENDWM} \sum_{j\in PROD} ETAX_{i,j,r} * [pm_{i,r} + qfe_{i,j,r}] + \sum_{i\in ENDWS} \sum_{j\in PROD} VFA_{i,j,r} * tf_{i,j,r} + \sum_{i\in ENDWS} \sum_{j\in PROD} ETAX_{i,j,r} * [pmes_{i,j,r}+qfe_{i,j,r}] - TFU_{r} * y_{r}$

Demands for endowment commodities: ∀i∈ENDWNAL ∀j∈PROD ∀r∈REG C-42

$qfe_{i,j,r}= - afe_{i,j,r} + qvaen_{j,r} - ESUBVA_{j} * [pfe_{i,j,r} - afe_{i,j,r} - pvaen_{j,r}]$

Demands for the composite capital+energy: ∀j∈PROD ∀r∈REG C-43

$qke_{j,r} = qvaen_{j,r} - ESUBVA_{j} * [pke_{j,r} - pvaen_{j,r}]$

Demands for endowment commodities: ∀i∈ENDWC ∀j∈PROD ∀r∈REG C-44

$qfe_{i,j,r} = - afe_{i,j,r} + qke_{j,r} - ELKE_{j,r} * [pfe_{i,j,r} - afe_{i,j,r} - pke_{j,r}]$

Demands for the composite irrigable land+water: ∀j∈PROD ∀r∈REG C-45

$qlw_{j,r} = qvaen_{j,r} - ESUBVA_{j} * [plw_{j,r} - pvaen_{j,r}]$

Demands for endowment commodities: ∀i∈ENDWLW ∀j∈PROD ∀r∈REG C-46

$qfe_{i,j,r} = - afe_{i,j,r} + qlw_{j,r} - ELLW_{j,r} * [pfe_{i,j,r} - afe_{i,j,r} - plw_{j,r}]$

Demands for composite energy goods: ∀j∈PROD ∀r∈REG C-47

$qen_{j,r} = qke_{j,r} - ELKE_{j,r} * [pen_{j,r} - pke_{j,r}]$

Demands for composite non-electric goods: ∀j∈PROD ∀r∈REG C-48

$qnel_{j,r} = qen_{j,r} - ELELY_{j,r} * [pnel_{j,r} - pen_{j,r}]$

Demands for composite non-coal energy goods: ∀j∈PROD ∀r∈REG C-49

$qncoal_{j,r} = qnel_{j,r} - ELCO_{j,r} * [pncoal_{j,r} - pnel_{j,r}]$

Industry demands for intermediate inputs, including cgds: ∀i∈TRAD ∀j∈PROD ∀r∈REG C-50

$$qf_{i,j,r} = D\_NEGY_{i,j,r} * D\_VFA_{i,j,r} * [ - af_{i,j,r} + qo_{j,r} - ao_{j,r} - ESUBT_{j} * [pf_{i,j,r} - af_{i,j,r} - ps_{j,r}]] + D\_ELY_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qen_{j,r} - ELELY_{j,r} * [pf_{i,j,r} - af_{i,j,r} - pen_{j,r}]] + D\_COAL_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qnel_{j,r} - ELCO_{j,r} * [pf_{i,j,r} - af_{i,j,r} - pnel_{j,r}]] + D\_OFF_{i,j,r} * D\_VFA_{i,j,r} * [- af_{i,j,r} + qncoal_{j,r} - ELFU_{j,r} * [pf_{i,j,r} - af_{i,j,r} - pncoal_{j,r}]]$$

*D.3.4 Zero Profits Equations:*

Equation that links pre- and post-tax supply prices for all industries: $\forall j \in PROD$ $\forall r \in REG$ C-51

$ps_{i,r} = to_{i,r} + pm_{i,r}$

Change in ratio of output tax payments to regional income: $\forall r \in REG$ C-52

$100.0 * INCOME_r * del\_taxrout_r = \sum_{i \in PROD} VOA_{i,r} * [-to_{i,r}] + \sum_{i \in PROD} PTAX_{i,r} * [pm_{i,r} + qo_{i,r}] - TOUT_r * y_r$

Industry zero pure profits condition: $\forall j \in PROD$ $\forall r \in REG$ C-53

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

## D.4 Investment, Global Bank and Savings

*D.4.1 Equations of Notational Convenience:*

Equation that defines a variable for capital services: $\forall r \in REG$ C-54

$ksvces_r = \sum_{h \in ENDWC} [VOA_{h,r} / \sum_{k \in ENDWC} VOA_{k,r})] * qo_{h,r}$

Equation that defines a variable for capital rental rate: $\forall r \in REG$ C-55

$rental_r = \sum_{h \in ENDWC} [VOA_{h,r} / \sum_{k \in ENDWC} VOA_{k,r})] * ps_{h,r}$

Equation that defines a variable for gross investment: $\forall r \in REG$ C-56

$qcgds_r = \sum_{h \in CGDS} [VOA_{h,r} / REGINV_r] * qo_{h,r}$

Equation that defines the price of cgds: $\forall r \in REG$ C-57

$pcgds_r = \sum_{h \in CGDS} [VOA_{h,r} / REGINV_r] * ps_{h,r}$

Associates change in capital services with respect to change in capital stock: $\forall r \in REG$ C-58

$kb_r = ksvces_r$

Ending capital stock equals beginning stock plus net investment: $\forall r \in REG$ C-59

$ke_r = INVKERATIO_r * qcgds_r + [1.0 - INVKERATIO_r] * kb_r$

*D.4.2 Rate of Return Equations:*

Current rate of return on capital in region *r*: $\forall r \in REG$ C-60

$rorc_r = GRNETRATIO_r * [rental_r - pcgds_r]$

Expected rate of return depends on the current return and investment: $\forall r \in REG$ C-61

$rore_r = rorc_r - RORFLEX_r * [ke_r - kb_r]$

*D.4.3 Capital Accumulation Equations:*

Change in investment levels relative to endowment stock: $\forall i \in ENDWC$ $\forall r \in REG$ C-62

$EXPAND_{i,r} = qcgds_r - qo_{i,r}$

*D.4.4 Global Bank:*

Global supply of capital goods, or global rental rate on investment: $\forall r \in REG$ C-63

$RORDELTA * rore_r + [1 - RORDELTA] * \{[REGINV_r / NETINV_r] * qcgds_r - [VDEP_r / NETINV_r] * kb_r\} = RORDELTA * rorg + [1 - RORDELTA] * globalcgds + cgdslack_r$

Change in global investment, or change in expected global rate of return: C-64

$RORDELTA * globalcgds + [1 - RORDELTA] * rorg = RORDELTA * [\sum_{r \in REG} \{[REGINV_r / GLOBINV] * qcgds_r - [VDEP_r / GLOBINV] * kb_r\}] + [1 - RORDELTA] * \sum_{r \in REG} [NETINV_r / GLOBINV] * rore_r$

*D.4.5 Price Index of Aggregate Global Composite Capital Goods:*

Equation that generates a price index for the aggregate global cgds composite: C-65

$pcgdswld = \sum_{r \in REG} [ NETINV_r / GLOBINV] * pcgds_r$

*D.4.6 Price of Saving:*

Savings price: $\forall r \in REG$ C-66

$psave_r = pcgds_r + \sum_{s \in REG} [[NETINV_s - SAVE_s] / GLOBINV] * pcgds_s$
$+ psaveslack_r$

## D.5 International Trade

*D.5.1 International Price Transmission:*

Equation that links agent's and world prices: $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-67

$pfob_{i,r,s} = pm_{i,r} - tx_{i,r} - txs_{i,r,s}$

Equation that links domestic and world prices: $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-68

$pms_{i,r,s} = tm_{i,s} + tms_{i,r,s} + pcif_{i,r,s}$

Equation that defines target price ratio to be attained via the variable levy: $\forall i \in TRAD$ $\forall s \in REG$ C-69

$pr_{i,s} = pm_{i,s} - pim_{i,s}$

*D.5.2 Demand for Imports:*

Price for aggregate imports: $\forall i \in TRAD$ $\forall r \in REG$ C-70

$pim_{i,s} = \sum_{k \in REG} MSHRS_{i,k,s} * [pms_{i,k,s}-ams_{i,k,s}]$

Regional demand for disaggregated imported commodities by source: $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-71

$qxs_{i,r,s} = -ams_{i,r,s} + qim_{i,s} - ESUBM_i * [pms_{i,r,s} - ams_{i,r,s} - pim_{i,s}]$

Change in ratio of import tax payments to regional income: $\forall r \in REG$ C-72

$100.0 * INCOME_r * del\_taxrimp_r = \sum_{i \in TRAD} \sum_{s \in REG} VIMS_{i,s,r} * [tm_{i,r} + tms_{i,s,r}]$
$+ \sum_{i \in TRAD} \sum_{s \in REG} MTAX_{i,s,r} * [pcif_{i,s,r} + qxs_{i,s,r}] - TIM_r * y_r$

Change in ratio of export tax payments to regional income: $\forall r \in REG$ C-73

$100.0 * INCOME_r * del\_taxrexp_r = \sum_{i \in TRAD} \sum_{s \in REG} VXMD_{i,r,s} * [-tx_{i,r} - txs_{i,r,s}]$
$+ \sum_{i \in TRAD} \sum_{s \in REG} XTAXD_{i,r,s} * [pfob_{i,r,s} + qxs_{i,r,s}] - TEX_r * y_r$

## D.6 International Transport Services

*D.6.1 Demand for Global Transport Services:*

Bilateral demand for transport services: $\forall m \in MARG$ $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-74

$qtmfsd_{m,i,r,s} = qxs_{i,r,s} - atmfsd_{m,i,r,s}$

Equation that computes global demand for margin *m*: $\forall m \in MARG$ C-75

$qtm_m = \sum_{i \in TRAD} \sum_{r \in REG} \sum_{s \in REG} VTMUSESHR_{m,i,r,s} * qtmfsd_{m,i,r,s}$

*D.6.2 Supply of Transport Services:*

Generate price index for composite transportation services: $\forall m \in MARG$ C-76

$pt_m = \sum_{r \in REG} VTSUPPSHR_{m,r} * pm_{m,r}$

Generates flow-specific modal average cost of transport index: $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-77

$ptrans_{i,r,s} = \sum_{m \in MARG} VTFSD\_MSH_{m,i,r,s} * [pt_m - atmfsd_{m,i,r,s}]$

Generates flow-specific average rate of technical change: $\forall m \in MARG$ $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-78

$atmfsd_{m,i,r,s} = atm_m + atf_i + ats_r + atd_s + atall_{m,i,r,s}$

Generate demand for regional supply of global transportation service: $\forall m \in MARG$ $\forall r \in REG$ C-79

$qst_{m,r} = qtm_m + [pt_m - pm_{m,r}]$

Equation that links fob and cif prices for good *i* shipped from region *r* to *s*: $\forall i \in TRAD$ $\forall r \in REG$ $\forall s \in REG$ C-80

$pcif_{i,r,s} = FOBSHR_{i,r,s} * pfob_{i,r,s} + TRNSHR_{i,r,s} * ptrans_{i,r,s};$

## D.7 Regional Household

*D.7.1 Supply of Endowments by the Regional Household:*

Equation that links pre- and post-tax endowment supply prices: $\forall i \in ENDW$ $\forall r \in REG$ C-81

$ps_{i,r} = to_{i,r} + pm_{i,r}$

Change in ratio of income tax payments to regional income: $\forall s \in REG$ C-82

$100.0 * INCOME_r * del\_taxrinc_r = \sum_{i \in ENDW} VOA_{i,r} * [-to_{i,r}] + \sum_{i \in ENDW} PTAX_{i,r} * [pm_{i,r} + qo_{i,r}] - TINC_r * y_r$

Equation that generates the composite price for sluggish endowments: $\forall i \in ENDWS$ $\forall r \in REG$ C-83

$pm_{i,r} = \sum_{k \in PROD} REVSHR_{i,k,r} * pmes_{i,k,r}$

Equation that distributes the sluggish endowments across sectors: $\forall i \in ENDWS$ $\forall j \in PROD$ $\forall r \in REG$ C-84

$qoes_{i,j,r} = qo_{i,r} - endwslack_{i,r} + ETRAE_i * [pm_{i,r} - pmes_{i,j,r}]$

*D.7.2 Computation of Regional Income:*

Factor income at market prices net of depreciation: $\forall r \in REG$ C-85

$FY_r * fincome_r = \sum_{i \in ENDW} VOM_{i,r} * [pm_{i,r} + qo_{i,r}] - VDEP_r * [pcgds_r + kb_r]$

Change in ratio of indirect taxes to INCOME in *r*: $\forall r \in REG$ C-86

$del\_indtaxr_r = del\_taxrpc_r + del\_taxrgc_r + del\_taxriu_r + del\_taxrfu_r + del\_taxrout_r + del\_taxrexp_r + del\_taxrimp_r$

Change in ratio of taxes to INCOME in *r*: $\forall r \in REG$ C-87

$del\_ttaxr_r = del\_taxrpc_r + del\_taxrgc_r + del\_taxriu_r + del\_taxrfu_r + del\_taxrout_r + del\_taxrexp_r + del\_taxrimp_r + del\_taxrinc_r$

Regional income = sum of primary factor income and indirect tax receipts: $\forall r \in REG$ C-88

$INCOME_r * y_r = FY_r * fincome_r + 100.0 * INCOME_r * del\_indtaxr_r + INDTAX_r * y_r + INCOME_r * incomeslack_r$

*D.7.3 Regional Household Demand System:*

Average distribution parameter shift: $\forall r \in REG$ C-89

$dpav_r = XSHRPRIV_r * dppriv_r + XSHRGOV_r * dpgov_r + XSHRSAVE_r * dpsave_r$

Elasticity of cost of utility with respect to utility: $\forall r \in REG$ C-90

$uelas_r = XSHRPRIV_r * uepriv_r - dpav_r$

Private consumption expenditure: $\forall r \in REG$ C-91

$yp_r - y_r = -[uepriv_r - uelas_r] + dppriv_r$

Government consumption expenditure: $\forall r \in REG$ C-92

$yg_r - y_r = uelas_r + dpgov_r$

Saving: $\forall r \in REG$ C-93

$psave_r + qsave_r - y_r = uelas_r + dpsave_r$

*D.7.4 Aggregate Utility:*

Price index for disposition of income by regional household: $\forall r \in REG$ C-94

$p_r = XSHRPRIV_r * ppriv_r + XSHRGOV_r * pgov_r + XSHRSAVE_r * psave_r$

Regional household utility: $\forall r \in REG$ C-95

$u_r = au_r + DPARPRIV_r * loge(UTILPRIV_r) * dppriv_r + DPARGOV_r * loge(UTILGOV_r) * dpgov_r + DPARSAVE_r * loge(UTILSAVE_r) * dpsave_r + [1.0 / UTILELAS_r] * [y_r - pop_r - p_r]$

Sum of the distribution parameters: $\forall r \in REG$ C-96

$DPARSUM_r * dpsum_r = DPARPRIV_r * dppriv_r + DPARGOV_r * dpgov_r + DPARSAVE_r * dpsave_r$

## D.8 Equilibrium Conditions

*D.8.1 Market Clearing Conditions:*

Equation that assures market clearing for margins commodities: $\forall m \in MARG$ $\forall r \in REG$ C-97

$qo_{m,r} = SHRDM_{m,r} * qds_{m,r} + SHRST_{m,r} * qst_{m,r} + \sum_{s \in REG} SHRXMD_{m,r,s} * qxs_{m,r,s} + tradslack_{m,r}$

Equation that assures market clearing for the non-margins commodities: $\forall m \in NMRG$ $\forall r \in REG$ C-98

$qo_{i,r} = SHRDM_{i,r} * qds_{i,r} + \sum_{s \in REG} SHRXMD_{i,r,s} * qxs_{i,r,s} + tradslack_{i,r}$

Equation that assures market clearing for imported goods entering each region: $\forall i \in TRAD$ $\forall r \in REG$ C-99

$qim_{i,r} = \sum_{j \in PROD} SHRIFM_{i,j,r} * qfm_{i,j,r} + SHRIPM_{i,r} * qpm_{i,r} + SHRIGM_{i,r} * qgm_{i,r}$

Equation that assures market clearing for domestic sales: $\forall i \in TRAD$ $\forall r \in REG$ C-100

$qds_{i,r} = \sum_{j \in PROD} SHRDFM_{i,j,r} * qfd_{i,j,r} + SHRDPM_{i,r} * qpd_{i,r} + SHRDGM_{i,r} * qgd_{i,r}$

Equation that assures market clearing for perfectly mobile endowments in region *r*: $\forall i \in ENDWM$ $\forall r \in REG$ C-101

$qo_{i,r} = \sum_{j \in PROD} SHREM_{i,j,r} * qfe_{i,j,r} + endwslack_{i,r}$

Equation that assures market clearing for imperfectly mobile endowments in *r*: $\forall i \in ENDWS$ $\forall j \in PROD$ $\forall r \in REG$ C-102

$qoes_{i,j,r} = qfe_{i,j,r}$

*D.8.2 Walras Law:*

Extra equation that computes change in supply in the omitted market: C-103

$walras\_sup = pcgdswld + globalcgds$

Extra equation that computes change in demand in the omitted market: C-104

$GLOBINV * walras\_dem = \sum_{r \in REG} SAVE_r * [psave_r + qsave_r]$

Walras: C-105

$walras\_sup = walras\_dem + walraslack$

## D.9 Summary Indices

*D.9.1 Factor Price Indices:*

Equation that defines the real rate of return to primary factor i in region r: $\forall i \in ENDW$ $\forall s \in REG$ C-106

$pfactreal_{i,s} = pm_{i,s} - ppriv_s$

Computes the percentage change in the price index of primary factors, by region: $\forall r \in REG$ C-107

$VENDWREG_r * pfactor_r = \sum_{i \in ENDW} VOM_{i,r} * pm_{i,r}$

Computes the percentage change in the global price index of primary factors: C-108

$VENDWWLD * pfactwld = \sum_{r \in REG} VENDWREG_r * pfactor_r$

*D.9.2 Regional Terms of Trade:*

Estimate change in index of prices received for tradeables *i* produced in *r*: $\forall r \in REG$ C-109

$VXWREGION_r * psw_r = \sum_{i \in TRAD} \sum_{s \in REG} VXWD_{i,r,s} * pfob_{i,r,s} + \sum_{m \in MARG} VST_{m,r} * pm_{m,r}$

Estimate change in index of prices paid for tradeable products used in *r*: $\forall r \in REG$ C-110

$VIWREGION_r * pdw_r = \sum_{i \in TRAD} \sum_{k \in REG} VIWS_{i,k,r} * pcif_{i,k,r}$

Terms of trade equation computed as difference in psw and pdw: $\forall i \in ENDWS$ $\forall r \in REG$ C-111

$tot_r = psw_r - pdw_r$

*D.9.3 Equivalent Variation*

Utility from government consumption in *r*: $\forall r \in REG$ C-112

$ygev_r - pop_r = ugev_r$

Private household demands for composite commodities, for EV calculation: $\forall i \in TRAD$ $\forall r \in REG$ C-113

$qpev_{i,r} - pop_r = EYEV_{i,r} * [ypev_r - pop_r]$

Computation of utility from private consumption in r: $\forall r \in REG$ C-114

$ypev_r - pop_r = UELASPRIVEV_r * upev_r$

Elasticity of cost wrt utility from private consumption, for EV calculation: ∀r∈REG C-115

$ueprivev_r = \sum_{i\in TRAD} XWCONSHREV_{i,r} * [qpev_{i,r} - ypev_r]$

Average distribution parameter shift, for EV calculation: ∀r∈REG C-116

$dpavev_r = XSHRPRIVEV_r * dppriv_r + XSHRGOVEV_r * dpgov_r + XSHRSAVEEV_r * dpsave_r$

Elasticity of cost of utility with respect to utility, for EV calculation: ∀r∈REG C-117

$uelasev_r = XSHRPRIV_r * ueprivev_r - dpavev_r$

Private consumption expenditure, for EV calculation: ∀r∈REG C-118

$ypev_r - yev_r = -[ueprivev_r - uelasev_r] + dppriv_r$

Government consumption expenditure, for EV calculation: ∀r∈REG C-119

$ygev_r - yev_r = uelasev_r + dpgov_r$

Saving: ∀r∈REG C-120

$ysaveev_r - yev_r = uelasev_r + dpsave_r$

Saving: ∀r∈REG C-121

$qsaveev_r = ysaveev_r$

Equivalent income ∀r∈REG C-122

$u_r = au_r + DPARPRIV_r * loge(UTILPRIVEV_r) * dppriv_r + DPARGOV_r * loge(UTILGOVEV_r) * dpgov_r + DPARSAVE_r * loge(UTILSAVEEV_r) * dpsave_r + [1.0 / UTILELASEV_r] * [yev_r - pop_r]$

Regional EV: ∀r∈REG C-123

$EV_r = [INCOMEEV_r / 100] * yev_r$

EV for the world: C-124

$WEV = \sum_{r\in REG} EV_r$

*D.9.4 GDP Indices (Value, Price and Quantity):*

Change in value of GDP: ∀r∈REG C-125

$GDP_r * vgdp_r = \sum_{i\in TRAD} VGA_{i,r} * [qg_{i,r} + pg_{i,r}] + \sum_{i\in TRAD} VPA_{i,r} * [qp_{i,r} + pp_{i,r})$
$+ REGINV_r * [qcgds_r + pcgds_r] + \sum_{i\in TRAD} \sum_{s\in REG} VXWD_{i,r,s} * [qxs_{i,r,s} + pfob_{i,r,s}]$
$+ \sum_{m\in MARG} VST_{m,r} * [qst_{m,r} + pm_{m,r}] - \sum_{i\in TRAD} \sum_{s\in REG} VIWS_{i,s,r} * [qxs_{i,s,r} + pcif_{i,s,r}]$

GDP price index: ∀r∈REG C-126

$GDP_r * pgdp_r = \sum_{i\in TRAD} VGA_{i,r} * pg_{i,r} + \sum_{i\in TRAD} VPA_{i,r} * pp_{i,r}$
$+ REGINV_r * pcgds_r + \sum_{i\in TRAD} \sum_{s\in REG} VXWD_{i,r,s} * pfob_{i,r,s}$
$+ \sum_{m\in MARG} VST_{m,r} * pm_{m,r} - \sum_{i\in TRAD} \sum_{s\in REG} VIWS_{i,s,r} * pcif_{i,s,r}$

GDP quantity index: ∀r∈REG C-127

$qgdp_r = vgdp_r - pgdp_r$

Track change in composition of value added: ∀i∈PROD ∀r∈REG C-128

$compvalad_{i,r} = qo_{i,r} - qgdp_r$

*D.9.5 Aggregate Trade Indices (Value, Price and Quantity):*

Change in fob value of exports of *m* from *r*: ∀m∈MARG ∀r∈REG C-129

$VXW_{m,r} * vxwfob_{m,r} = \sum_{s\in REG} VXWD_{m,r,s} * [qxs_{m,r,s} + pfob_{m,r,s}] + VST_{m,r} * [qst_{m,r} + pm_{m,r}]$

Change in fob value of exports of commodity *i* from *r*: ∀i∈NMRG ∀r∈REG C-130

$VXW_{i,r} * vxwfob_{i,r} = \sum_{s\in REG} VXWD_{i,r,s} * [qxs_{i,r,s} + pfob_{i,r,s}]$

Change in cif value of imports of commodity *i* into *s*: ∀i∈TRAD ∀s∈REG C-131

$VIW_{i,s} * viwcif_{i,s} = \sum_{r\in REG} VIWS_{i,r,s} * [pcif_{i,r,s} + qxs_{i,r,s}]$

Computes the percentage change in value of merchandise exports, by region: $\forall r \in REG$ C-132
$VXWREGION_r * vxwreg_r = \sum_{i \in TRAD} VXW_{i,r} * vxwfob_{i,r}$

Computes the percentage change in value of imports, cif basis, by region: $\forall s \in REG$ C-133
$VIWREGION_s * viwreg_s = \sum_{i \in TRAD} VIW_{i,s} * viwcif_{i,s}$

Computes the percentage change in fob value of global exports, by commodity: $\forall i \in TRAD$ C-134
$VXWCOMMOD_i * vxwcom_i = \sum_{r \in REG} VXW_{i,r} * vxwfob_{i,r}$

Computes the percentage change in value of global imports, by commodity: $\forall i \in TRAD$ C-135
$VIWCOMMOD_i * viwcom_i = \sum_{s \in REG} VIW_{i,s} * viwcif_{i,s}$

Computes the percentage change in value of global exports: C-136
$VXWLD * vxwwld = \sum_{r \in REG} VXWREGION_r * vxwreg_r$

Change in value of world output of commodity *i* at fob prices: $\forall i \in TRAD$ C-137
$VWOW_i * valuew_i = \sum_{r \in REG} VOW_{i,r} * [pxw_{i,r} + qo_{i,r}]$

Change in value of world output of commodity *i* at user prices: $\forall i \in TRAD$ C-138
$VWOU_i * valuewu_i = \sum_{s \in REG} \{VPA_{i,s} * [pp_{i,s} + qp_{i,s}]$
$+ VGA_{i,s} * [pg_{i,s} + qg_{i,s}] + \sum_{j \in PROD} VFA_{i,j,s} * [pf_{i,j,s} + qf_{i,j,s}]\}$

Change in fob price index of exports of *m* from *r*: $\forall m \in MARG$ $\forall r \in REG$ C-139
$VXW_{m,r} * pxw_{m,r} = \sum_{s \in REG} VXWD_{m,r,s} * pfob_{m,r,s} + VST_{m,r} * pm_{m,r}$

Change in fob price index of exports of commodity *i* from *r*: $\forall i \in NMRG$ $\forall r \in REG$ C-140
$VXW_{i,r} * pxw_{i,r} = \sum_{s \in REG} VXWD_{i,r,s} * pfob_{i,r,s}$

Change in cif price index of imports of commodity *i* into *s*: $\forall i \in TRAD$ $\forall s \in REG$ C-141
$VIW_{i,s} * piw_{i,s} = \sum_{r \in REG} VIWS_{i,r,s} * pcif_{i,r,s}$

Computes the percentage change in price index of exports, by region: $\forall r \in REG$ C-142
$VXWREGION_r * pxwreg_r = \sum_{i \in TRAD} VXW_{i,r} * pxw_{i,r}$

Computes the percentage change in price index of imports, by region: $\forall s \in REG$ C-143
$VIWREGION_s * piwreg_s = \sum_{i \in TRAD} VIW_{i,s} * piw_{i,s}$

Computes the percentage change in price index of exports, by commodity: $\forall i \in TRAD$ C-144
$VXWCOMMOD_i * pxwcom_i = \sum_{r \in REG} VXW_{i,r} * pxw_{i,r}$

Computes the percentage change in price index of imports, by commodity $\forall i \in TRAD$ C-145
$VIWCOMMOD_i * piwcom_i = \sum_{s \in REG} VIW_{i,s} * piw_{i,s}$

Computes the percentage change in price index of global exports: C-146
$VXWLD * pxwwld = \sum_{r \in REG} VXWREGION_r * pxwreg_r$

Change in index of world prices, fob, for total production of *i*: $\forall i \in TRAD$ C-147
$VWOW_i * pw_i = \sum_{r \in REG} VOW_{i,r} * pxw_{i,r}$

Change in index of user prices for deflating world production of *i*: $\forall i \in TRAD$ C-148
$VWOU_i * pwu_i = \sum_{s \in REG} \{VPA_{i,s} * pp_{i,s} + VGA_{i,s} * pg_{i,s} + \sum_{j \in PROD} VFA_{i,j,s} * pf_{i,j,s}\}$

Change in volume of exports of commodity *i* from *r*: $\forall i \in TRAD$ $\forall r \in REG$ C-149
$qxw_{i,r} = vxwfob_{i,r} - pxw_{i,r}$

Change in volume of imports of commodity *i* into *s*: $\forall i \in TRAD$ $\forall r \in REG$ C-150
$qiw_{i,s} = viwcif_{i,s} - piw_{i,s}$

Computes the percentage change in quantity index of exports, by region: $\forall r \in REG$ C-151
$qxwreg_r = vxwreg_r - pxwreg_r$

Computes the percentage change in quantity index of imports, by region: $\forall s \in REG$ C-152
$qiwreg_s = viwreg_s - piwreg_s$

Computes the percentage change in quantity index of exports, by commodity: $\forall i \in TRAD$ C-153
$qxwcom_i = vxwcom_i - pxwcom_i$

| | | |
|---|---|---|
| Computes the percentage change in quantity index of imports, by commodity:<br>$qiwcom_i = viwcom_i - piwcom_i$ | ∀i∈TRAD | C-154 |
| Computes the percentage change in quantity index of global exports:<br>$qxwwld = vxwwld - pxwwld$ | | C-155 |
| Change in index of world production of *i*:<br>$qow_i = valuew_i - pw_i$ | ∀i∈TRAD | C-156 |
| Change in index of world production of *i* evaluated at user prices:<br>$qowu_i = valuewu_i - pwu_i$ | ∀i∈TRAD | C-157 |
| *D.9.6 Trade Balance Indices:* | | |
| Computes change in trade balance by commodity and by region:<br>$DTBALi_{i,r} = [VXW_{i,r} / 100] * vxwfob_{i,r} - [VIW_{i,r} / 100] * viwcif_{i,r}$ | ∀i∈TRAD<br>∀r∈REG | C-158 |
| Computes change in trade balance (X - M), by region:<br>$DTBAL_r = [VXWREGION_r / 100] * vxwreg_r - [VIWREGION_r / 100] * viwreg_r$ | ∀r∈REG | C-159 |
| Change in ratio of trade balance to regional income:<br>$100 * INCOME_r * DTBALR_r = 100 * DTBAL_r - TBAL_r * y_r$ | | C-160 |

# III

## WATER SCARCITY AND THE IMPACT OF IMPROVED IRRIGATION MANAGEMENT

**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 percent 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 world-wide. The results show that a water policy directed to improve irrigation efficiency lead 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 non-water 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.

**Keywords:** Computable General Equilibrium, Irrigation, Water Policy, Water Scarcity, Irrigation Efficiency

**JEL Classification:** D58, Q17, Q25

## 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 percent of all freshwater withdrawals are used for food production. However, less than 60 percent of all the water used for irrigation is effectively consumed by crops. This paper therefore analyzes the extent to which improvements in 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 as a result 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 percent will live in developing countries and 58 percent in rapidly growing urban areas (Rosegrant et al. 2002). As a consequence, 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 percent 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 (Figure III-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 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.

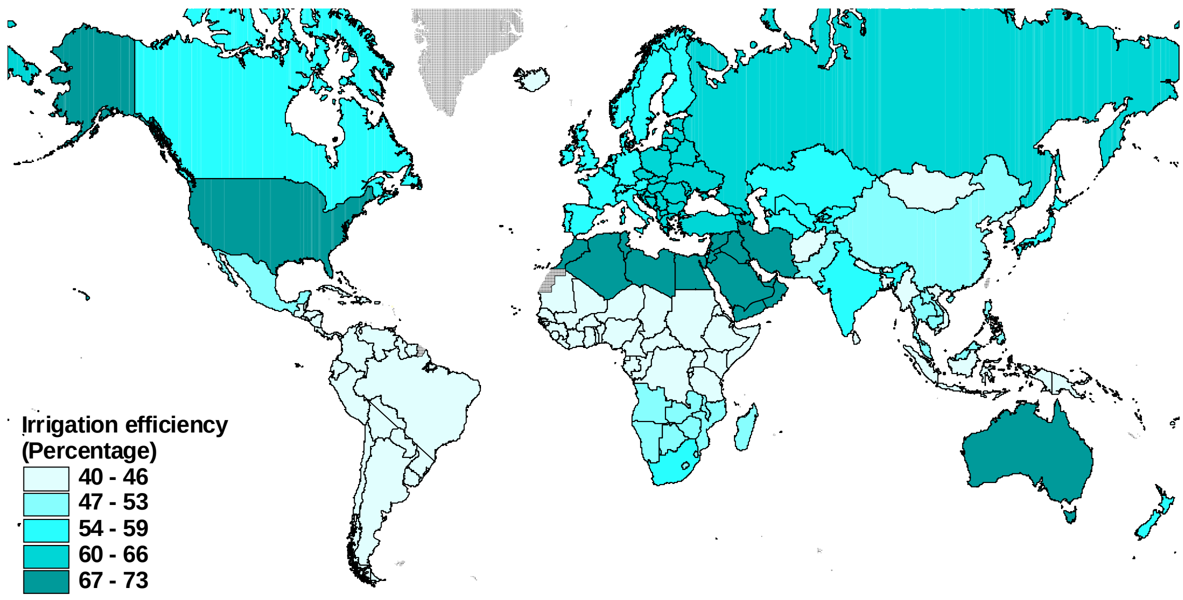


**Figure III–1. Average irrigation efficiency, 2001 baseline data**

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

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). As a consequence, 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 world-wide 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 paper 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 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 adjustments 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 (labour). Differences in technology are modelled by differences in the amount of output that can be obtained from one unit of labour. 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.[9] 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: i) The Heckscher-Ohlin theorem states that a country tends to export the good which intensively uses the abundant factor in that country. ii) 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. iii) 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. iv) The factor price equalization theorem states that free trade in final goods is sufficient to bring equalization of factor prices.

Placing our paper 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 to produce 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.

[9] 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.

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).[10] 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 $m^3$ compared to 600,000 $m^3$) 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 $m^3$ to 12,000 $m^3$ (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 1t 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 (non water-intensive crop).

[10] 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).

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 Johannson 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; Seung et al. 2000; Diao and Roe 2003; Feng et al. 2007; Diao et al. 2008). 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 non-market 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 et al. (2008a) 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 et al. (2008b) 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 (Annex A, upper diagram Figure III-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) (Annex A, lower diagram Figure III-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[11] (Hertel, 1997), and is based on the version modified by Burniaux and Truong[12] (2002) 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.[13] 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 Figure III-A1 (Annex A) 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

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[11] 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.

[12] 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.

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

the value of land included in the GTAP social accounting matrix into the value of rainfed land and the value of irrigated land using its proportionate contribution to total production (see Annex A, Table III-A2).[14] 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).[15]

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 Annex A, Table III-A3).[16] 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 wells 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' 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. 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 social accounting matrix (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 percent 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 modelled through a representative firm, which maximizes profits in perfectly competitive markets. The

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[14] 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.

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

[16] 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 constant elasticity of substitution (CES) functions (Annex A, lower diagram Figure III-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, labour and capital). Capital and labour 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 non-homothetic 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 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 (Annex A, lower diagram Figure III-A1). The procedure for obtaining the elasticity of factor substitution between land and irrigation ($\sigma_{LW}$) is explained in more detail in Annex C.[17] Next, the irrigated land-water composite is combined with pasture land, rainfed land, natural resources, labour and the capital-energy composite in a value-added nest through a CES structure. The original elasticity of substitution between primary factors ($\sigma_{VAE}$) 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

[17] 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.

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 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 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.[18] 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); see Figure III-1. Therefore, our analysis attempts to study potential global water savings and its economic implications, improving irrigation efficiency to the maximum attainable level.

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

Our modelling 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. (forthcoming) to adjust the resulting welfare gains. Table III-1 shows the annual irrigation cost for different irrigation systems as well as the suitability of irrigation systems by crop type. Sauer's estimates include capital costs as well as operation and maintenance costs. Operation costs include energy and labour, while maintenance costs are set to 3 percent of the capital costs for basin irrigation and 5 percent 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 percent, for sprinkler irrigation systems around 75 percent and for drip irrigation systems around 90 percent.

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

| | Irrigation system | | | | Additional cost |
|---|---|---|---|---|---|
| **Description** | **Basin** | **Furrow** | **Sprinkler** | **Drip** | **(USD per ha)** |
| 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. (forthcoming).

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 III-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 information with the initially irrigated areas (Annex A, Table III-A1), Table III-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 percent). In South America, Sub-Saharan Africa and Southeast Asia efficiency levels are lowest. Improving irrigation efficiency world-wide to the maximum attainable efficiency level is expected to cost more than 5 billion USD (Table III-2).[19]

**Table III–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 (*).

## 6. Results

Figure III-2 shows irrigated production as the share of total agricultural production in the GTAP-W baseline data. Irrigated rice production accounts for 73 percent of the total rice production; the major producers are Japan and South Korea, China, South Asia and Southeast Asia. Around 47 percent 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 USA 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 percent. The USA and China are major producers of cereal grains; the USA, South Asia and China of oil seeds; China, the Middle East and Japan and South Korea of vegetables and fruits; and the USA and South Asia of other agricultural products.

[19] Some degree of efficiency gains is 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.

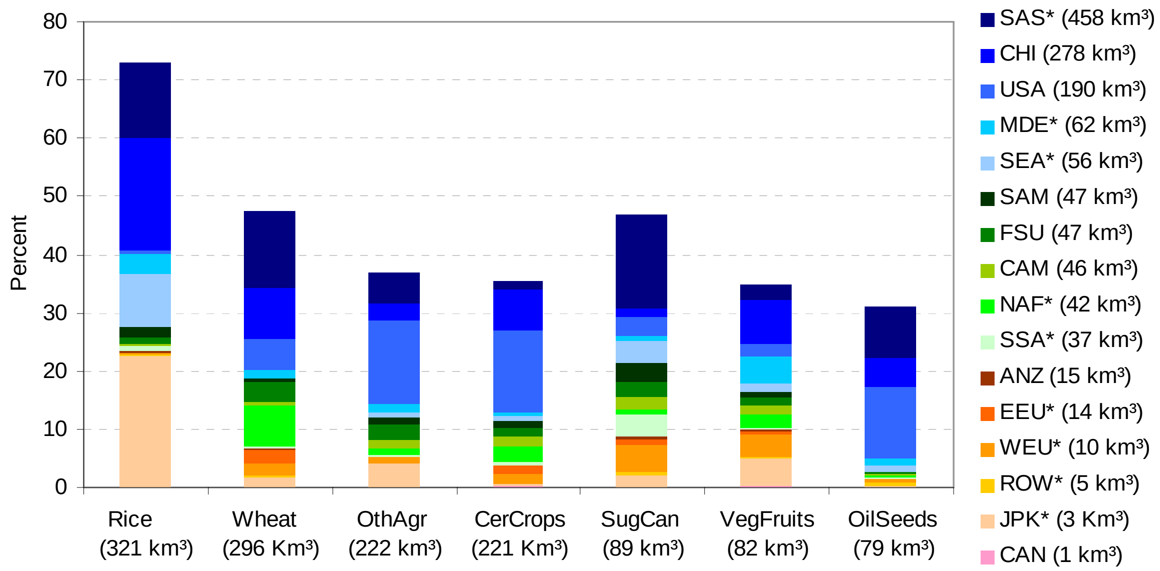


**Figure III–2. Share of irrigated production in total production by crop and region, 2001 baseline data**

Note: Irrigation water used in $km^3$ by crop and region is shown in parenthesis. Water-stressed regions are indicated by an asterisk (*).

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

**Table III–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**

| | 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** | -5.7 | -7.0 | -7.6 | -1.6 | -2.1 | 3.2 | 0.6 | 0.9 | 5.0 | 0.6 | 0.3 | 3.8 |
| **CAN** | 0.0 | 0.0 | 0.0 | -2.6 | -3.5 | 25.5 | 1.1 | 1.5 | 34.7 | 0.0 | -0.1 | 33.2 |
| **WEU*** | -22.9 | 4.1 | 2.4 | -0.5 | 31.9 | 31.3 | 0.8 | 33.2 | 33.9 | 0.7 | 33.8 | 33.7 |
| **JPK*** | -0.6 | 23.0 | 23.1 | -0.1 | 42.8 | 42.0 | 0.7 | 31.7 | 29.0 | 0.6 | 25.9 | 26.4 |
| **ANZ** | -6.1 | -7.5 | -8.1 | -1.9 | -2.0 | -1.3 | 1.3 | 2.0 | 1.4 | 0.5 | 0.5 | 0.9 |
| **CEE*** | -1.0 | 18.9 | 17.7 | -0.2 | 21.7 | 21.6 | 0.1 | 21.4 | 21.5 | 0.1 | 21.9 | 21.9 |
| **FSU** | 0.0 | 0.0 | 26.5 | -0.2 | -0.3 | 26.4 | 0.1 | 0.1 | 27.1 | 0.2 | 0.2 | 26.0 |
| **MDE*** | 8.0 | 8.2 | 8.6 | 6.6 | 6.0 | 4.7 | 8.8 | 8.8 | 8.3 | 10.0 | 10.0 | 10.2 |
| **CAM** | -1.2 | -1.3 | 54.4 | -0.4 | -0.6 | 54.6 | 0.4 | 0.6 | 42.8 | 0.1 | -0.1 | 48.6 |
| **SAM** | -0.8 | -0.6 | 74.0 | -0.7 | -0.6 | 76.8 | 0.4 | 0.5 | 76.8 | 0.4 | 0.3 | 78.3 |
| **SAS*** | 30.5 | 30.5 | 30.6 | 36.4 | 36.3 | 36.1 | 34.6 | 34.7 | 34.9 | 36.1 | 36.1 | 36.2 |
| **SEA*** | 53.3 | 52.4 | 52.9 | 68.5 | 69.2 | 69.1 | 53.7 | 54.6 | 53.9 | 53.0 | 53.6 | 53.9 |
| **CHI** | 0.1 | 0.2 | 29.9 | 0.2 | 0.2 | 29.3 | 0.0 | 0.1 | 30.1 | 0.2 | 0.3 | 34.4 |
| **NAF*** | -5.8 | -8.3 | -13.2 | 4.8 | 4.6 | 4.5 | 4.8 | 5.0 | 5.0 | 4.8 | 4.9 | 5.1 |
| **SSA*** | 61.4 | 63.4 | 63.1 | 57.5 | 58.3 | 56.0 | 61.7 | 63.8 | 63.4 | 63.0 | 64.1 | 63.2 |
| **ROW*** | 76.8 | 76.9 | 71.3 | 98.2 | 95.3 | 94.0 | 77.0 | 72.4 | 72.6 | 71.5 | 69.4 | 73.7 |

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 III-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).[20] See also the irrigated land-water composite in the Figure III-A1. These two factors indicate changes in irrigated production. Table III-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.

**Table III–4. Percentage change in total agricultural production, results for all scenarios and for four agricultural sectors**

| | 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 | -7.6 | -9.4 | -13.0 | -2.8 | -3.8 | -1.2 | -0.3 | -0.3 | -0.5 | -0.4 | -0.9 | -2.2 |
| CAN | -13.9 | -14.3 | -16.7 | -4.6 | -6.3 | -9.6 | -0.3 | -0.5 | -1.4 | -1.7 | -2.3 | -2.1 |
| WEU* | -28.1 | -25.9 | -28.3 | -2.0 | -1.3 | -3.0 | -0.3 | -0.2 | -0.8 | -0.5 | 0.7 | -0.7 |
| JPK* | -1.5 | 1.8 | 1.1 | -0.9 | 19.0 | 17.4 | 0.0 | 10.9 | 7.4 | -0.1 | 2.4 | 2.1 |
| ANZ | -8.5 | -10.8 | -12.4 | -3.6 | -4.3 | -4.6 | 0.2 | 0.4 | -1.5 | -0.8 | -1.5 | -2.1 |
| CEE* | -1.4 | -1.2 | -2.6 | -0.4 | 1.1 | 0.8 | -0.1 | 0.3 | 0.1 | -0.1 | 0.7 | 0.5 |
| FSU | -0.4 | -0.4 | 0.0 | -0.5 | -0.8 | -0.3 | -0.2 | -0.3 | -0.1 | -0.1 | -0.2 | 0.5 |
| MDE* | -0.1 | -0.1 | -0.1 | -2.1 | -3.0 | -5.0 | -0.1 | -0.4 | -1.4 | 0.5 | 0.2 | 0.0 |
| CAM | -1.9 | -2.2 | 6.0 | -1.0 | -1.5 | 14.1 | 0.0 | 0.0 | 3.3 | -0.4 | -0.8 | 6.2 |
| SAM | -1.6 | -1.7 | 0.5 | -1.5 | -1.7 | -0.3 | -0.2 | -0.3 | 0.1 | -0.1 | -0.6 | 1.4 |
| SAS* | 3.7 | 3.5 | 3.3 | 7.2 | 6.9 | 6.5 | 1.4 | 1.4 | 1.3 | 2.6 | 2.5 | 2.3 |
| SEA* | 6.1 | 4.8 | 4.8 | 14.6 | 14.5 | 13.9 | 5.6 | 5.8 | 4.8 | 2.8 | 2.7 | 2.5 |
| CHI | -0.2 | -0.3 | 1.4 | -0.2 | -0.3 | 2.2 | -0.4 | -0.5 | 2.7 | -0.2 | -0.3 | 0.7 |
| NAF* | -11.8 | -14.9 | -20.8 | 0.2 | -0.3 | -0.9 | 0.3 | 0.3 | -0.2 | 0.1 | -0.1 | -0.4 |
| SSA* | -0.2 | -0.4 | -0.4 | 2.0 | 1.0 | -0.7 | 0.1 | 0.1 | -0.1 | -0.1 | -0.9 | -1.4 |
| ROW* | 5.9 | 5.6 | 2.1 | 20.6 | 19.5 | 18.1 | 0.7 | 0.7 | 0.0 | 3.1 | 2.7 | 2.1 |

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).

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 III-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.

[20] 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 III–5. Percentage change in water demand in irrigated agriculture, results for all scenarios and for four agricultural sectors**

| | 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** | -5.7 | -6.9 | -8.7 | -1.6 | -2.1 | 0.6 | 0.6 | 0.9 | -0.9 | 0.6 | 0.4 | -2.0 |
| **CAN** | 0.0 | 0.0 | 0.0 | -2.6 | -3.5 | -5.4 | 1.1 | 1.5 | 1.4 | 0.0 | -0.1 | 0.3 |
| **WEU*** | -22.9 | -21.5 | -22.8 | -0.5 | -0.5 | -0.9 | 0.9 | 0.5 | 1.0 | 0.7 | 0.9 | 0.8 |
| **JPK*** | -0.6 | -1.5 | -1.4 | -0.1 | 9.8 | 9.2 | 0.7 | 9.5 | 7.2 | 0.6 | -0.4 | 0.0 |
| **ANZ** | -6.1 | -7.5 | -8.2 | -1.9 | -2.0 | -1.4 | 1.3 | 2.0 | 1.3 | 0.5 | 0.5 | 0.8 |
| **CEE*** | -1.0 | -2.3 | -3.3 | -0.2 | 0.0 | -0.1 | 0.1 | -0.2 | -0.1 | 0.1 | 0.2 | 0.2 |
| **FSU** | -0.1 | 0.0 | -2.9 | -0.2 | -0.3 | -0.2 | 0.1 | 0.1 | 0.4 | 0.2 | 0.2 | 1.3 |
| **MDE*** | 1.6 | 1.8 | 2.1 | -0.5 | -1.1 | -2.4 | 0.9 | 0.8 | 0.3 | -0.2 | -0.2 | -0.1 |
| **CAM** | -1.2 | -1.3 | -7.3 | -0.4 | -0.7 | 8.1 | 0.4 | 0.6 | -0.6 | 0.1 | -0.1 | -0.8 |
| **SAM** | -0.8 | -0.6 | -2.1 | -0.7 | -0.6 | -0.1 | 0.4 | 0.5 | 0.7 | 0.5 | 0.3 | 0.7 |
| **SAS*** | -0.2 | -0.2 | -0.2 | 2.8 | 2.7 | 2.6 | -1.6 | -1.5 | -1.4 | -1.2 | -1.2 | -1.1 |
| **SEA*** | -2.1 | -2.6 | -2.3 | -0.2 | 0.3 | 0.2 | 3.0 | 3.6 | 3.1 | -1.2 | -0.8 | -0.6 |
| **CHI** | 0.1 | 0.2 | -3.3 | 0.2 | 0.2 | 2.2 | 0.0 | 0.0 | 3.5 | 0.2 | 0.3 | -0.9 |
| **NAF*** | -9.7 | -12.1 | -16.8 | 0.1 | -0.1 | -0.2 | 0.3 | 0.5 | 0.5 | 0.0 | 0.1 | 0.3 |
| **SSA*** | -1.9 | -0.6 | -0.9 | 6.4 | 7.1 | 5.4 | -0.6 | 0.9 | 0.5 | -2.1 | -1.4 | -2.1 |
| **ROW*** | -1.1 | 0.0 | -3.4 | 10.6 | 9.9 | 9.1 | -0.7 | -2.9 | -2.7 | -4.6 | -4.9 | -2.0 |

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).

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 Table III-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 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.

The picture is similar for cereal grains. Major producers (USA, 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 USA 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 (USA, Western Europe, Japan and South Korea, former Soviet Union, Middle East, South Asia, 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 vegetable and fruit 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 USA, 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. Figure III-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 the improved irrigation efficiency, without considering any adjustment process in food and other markets. Globally, water savings are 158 $km^3$ (*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 (see Figure III-2).

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.

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

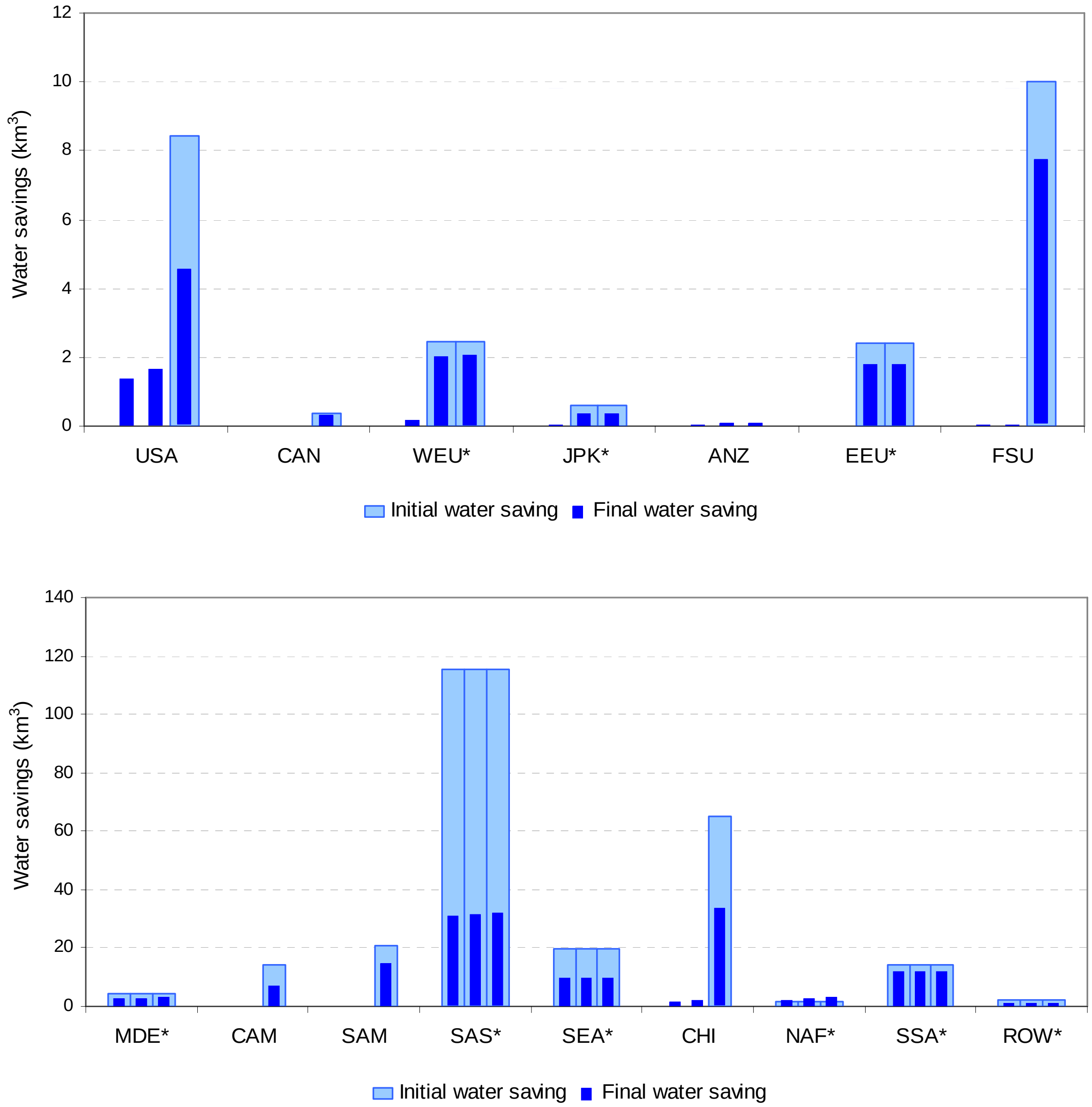


**Figure III–3. Initial and final water savings by scenario, 2001**

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).

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 III-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.

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.

**Table III–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** | |

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

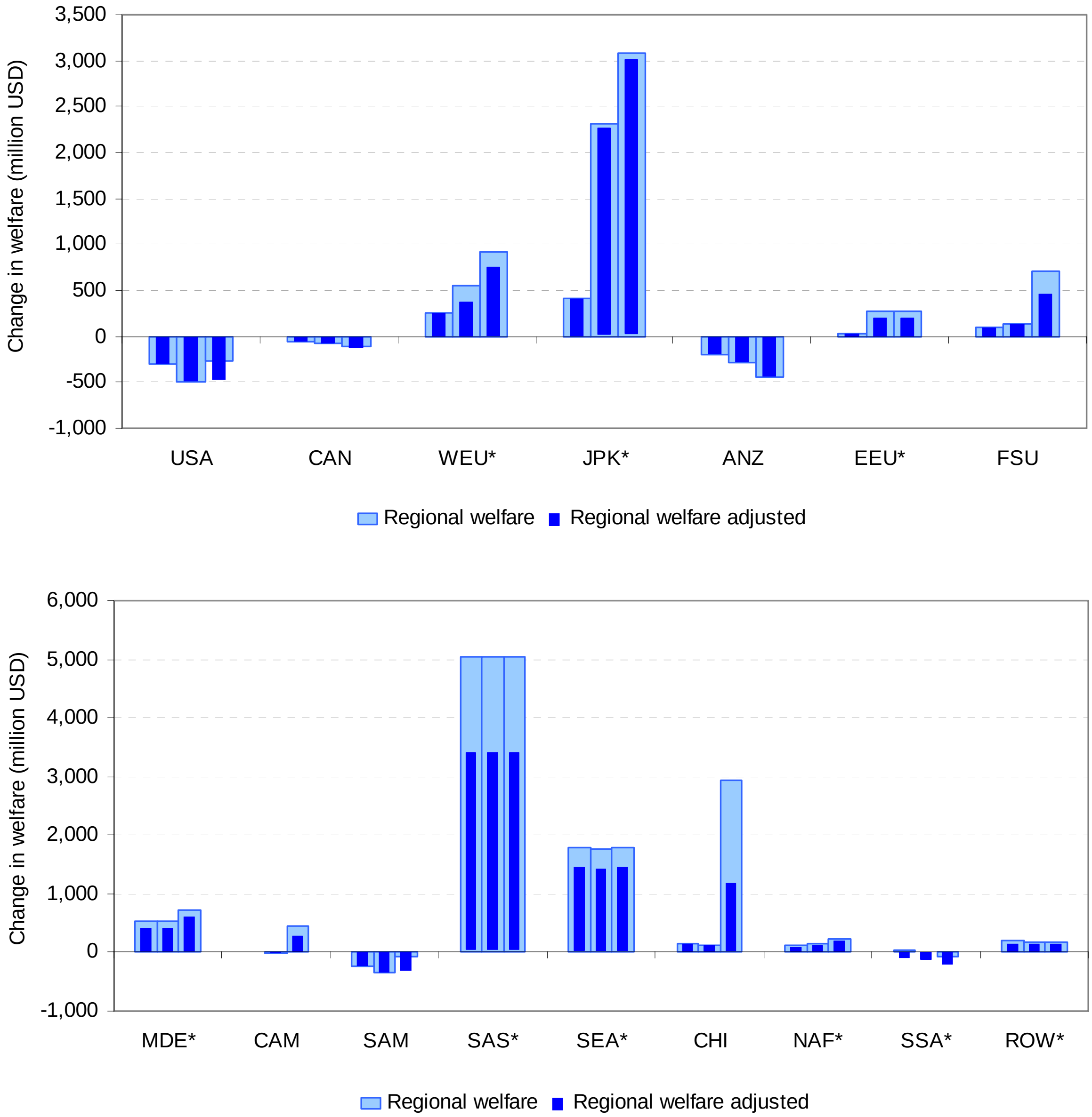


**Figure III–4. Changes in regional welfare with and without the adjustment of irrigation costs by scenario (million USD)**

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).

For non-water stressed developing regions, there are mostly welfare gains, which are marked for China (in absolute terms) 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 III-7 shows a deterioration of the terms of trade for South America which contributes negatively to regional welfare.

**Table III–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 (*).

The upper panel of Figure III-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 non-water stressed former Soviet Union. For food-exporters (USA, 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 USA in the *all regions* scenario, in which the USA 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 III-7).

Figure III-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. Figure III-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 III-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 (Figure III-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. Figure III-6 also shows welfare losses for food-exporting regions that lose their comparative advantage as other regions increase their irrigation efficiency.

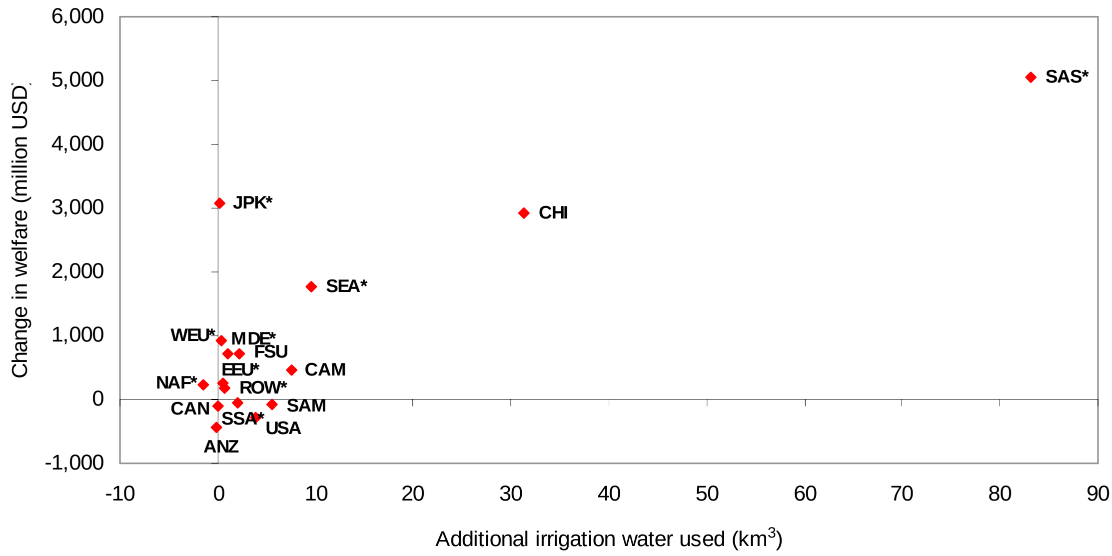


**Figure III–5. Changes in welfare as a function of the additional irrigation water used, *all regions* scenario**

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

The costs of improving irrigation efficiency reduce global and regional welfare (Figure III-4). Global welfare decreases between 26 to 34 percent, 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 (USA, South America and Sub-Saharan Africa). In the *all regions* scenario, irrigation costs take away one-third of the global welfare gains.

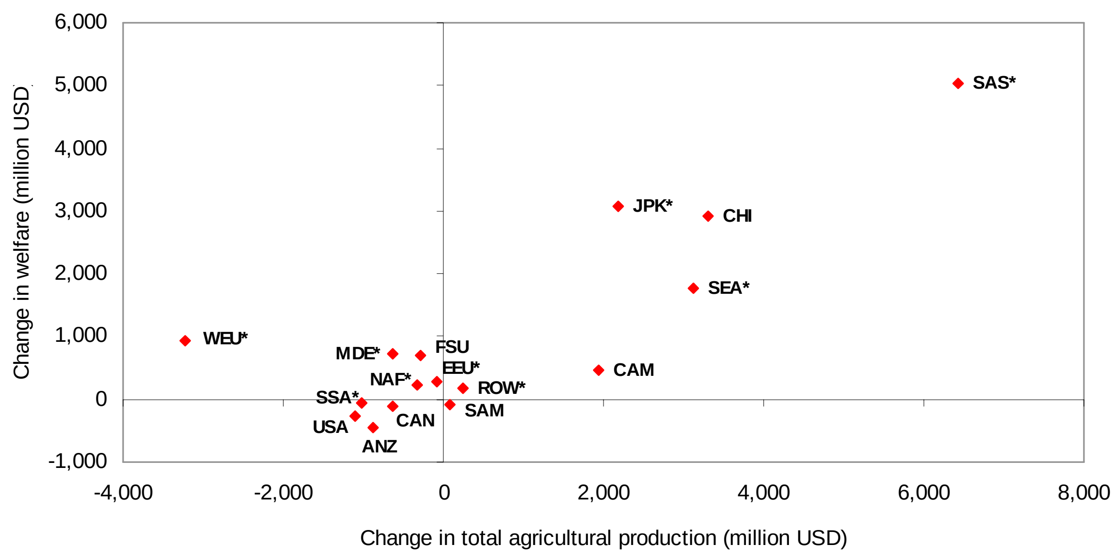


**Figure III–6. Changes in welfare as a function of the additional agricultural production, *all regions* scenario (million USD)**

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

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 and 1993). We use the production-site definition, that is, we measure it at the place where the product was actually produced.[21] The water used in the agricultural sector has two components: effective rainfall (green water) and irrigation water (blue water). Table III-8 shows the international flows of irrigation water used associated with the additional agricultural production (blue virtual water).

Improving irrigation efficiency leads to a decrease in blue virtual water. At the global level, between 28 to 34 percent of blue virtual water is saved (compare virtual water pre and post simulation, Table III-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 cubic kilometres.

In most water-scarce developing regions, the amount of blue virtual water increases with higher levels of irrigation efficiency (Table III-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 USA. Under the *all regions* scenario, China and the USA achieve higher levels of irrigation efficiency; China substantially increases its blue virtual water use, 43 percent 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.

[21] 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 III–8. Changes in blue virtual water flows related to the additional agricultural production by scenario, in cubic kilometres (km$^3$)**

| Region | ***Water-scarce developing regions*** **scenario** | | | | | | ***Water-scarce regions*** **scenario** | | | | | | ***All regions*** **scenario** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Virtual** | **Virtual** | **Destination Market** | | | | **Virtual** | **Virtual** | **Destination Market** | | | | **Virtual** | **Virtual** | **Destination Market** | | | |
| | **Water** | **Water** | **Domestic** | **Exports** | **Imports** | **Net** | **Water** | **Water** | **Domestic** | **Exports** | **Imports** | **Net** | **Water** | **Water** | **Domestic** | **Exports** | **Imports** | **Net** |
| | (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 (*).

Western Europe, the Middle East, the USA, 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 III-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 computable general equilibrium 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, 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 a non-market 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,[22] 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; Tsur et al. 2004; Easter and Liu 2005), 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 and water use. 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 percent of the total amount of irrigation water currently used. Final water savings are much lower: 5-10 percent. Therefore, ignoring adjustments in production patterns and food markets would overstate the amount of water that could be saved by improved irrigation.

[22] 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.

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

Welfare tends to increases 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 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.

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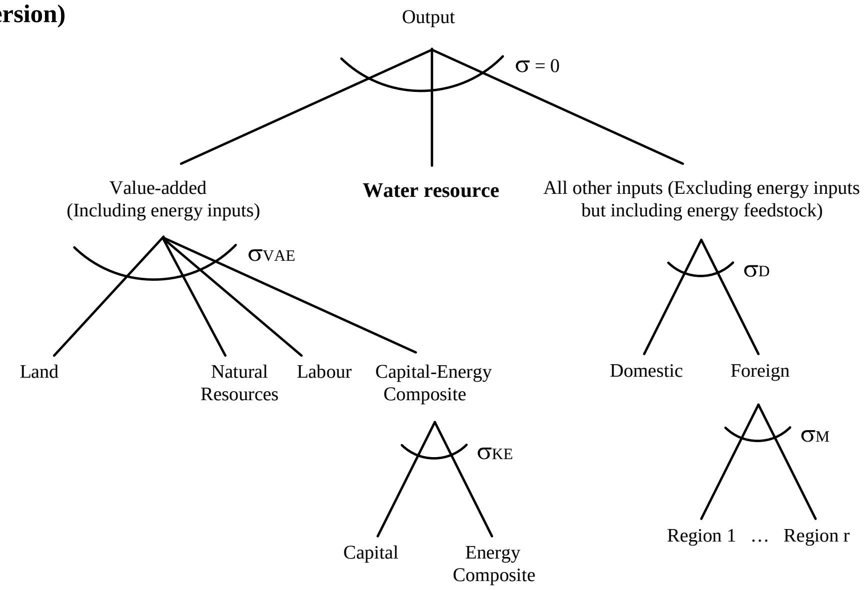
# Annex A

**GTAP-W (FIRST Version)**




**GTAP-W (SECOND Version)**

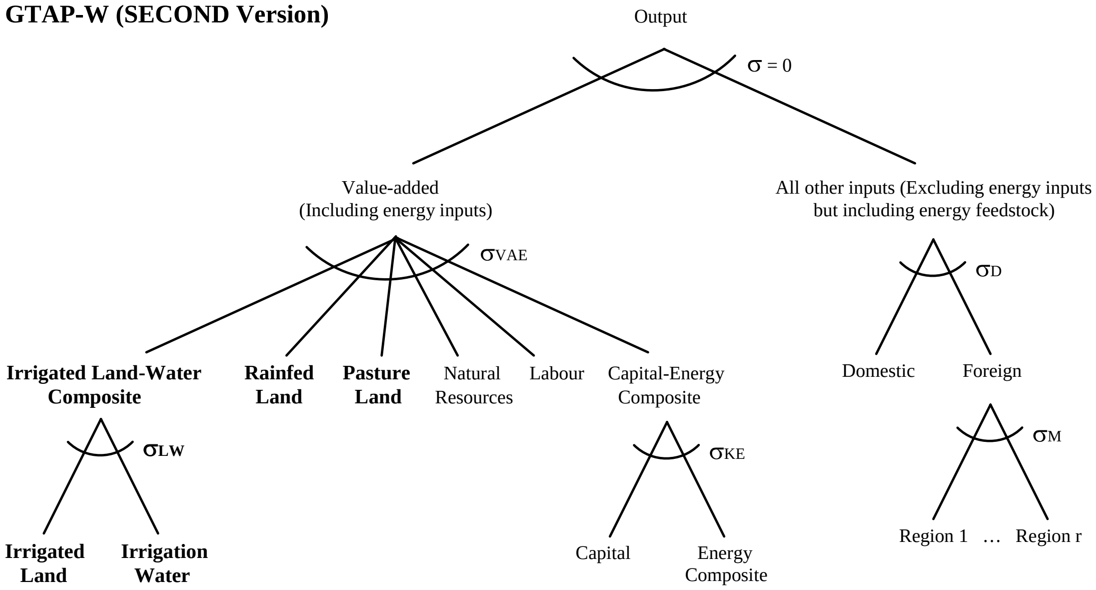



**Figure III–A1. Nested tree structure for industrial production process in the two versions of the GTAP-W model (truncated)**

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.

**Table III–A1. 2000 Baseline data: Crop harvested area and production by region and crop**

| Regions | 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 ($km^3$) |
| 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 III–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** | 51.0 | 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** |
| **CEE** | 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** |
| **SIS** | 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 baseline data.

**Table III–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.

## Annex B: 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

### *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 -** Non-market services

### *C. Endowments*

**Wtr -** Irrigation
**Lnd -** Irrigated land
**RfLand -** Rainfed land
**PsLand -** Pasture land
**Lab -** Labour
**Capital -** Capital
**NatlRes -** Natural resources

**Annex C: 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

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

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, $\eta$ (estimates for 15 regions). Thus, we have

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

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

That is, the price elasticity $\eta$ implies the substitution elasticity $\rho$, for any price change $\delta$:

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

# IV

## THE ECONOMIC IMPACT OF MORE SUSTAINABLE WATER USE IN AGRICULTURE

**Abstract**

Agriculture is the largest consumer of freshwater resources – around 70 percent of all freshwater withdrawals are used for food production. These agricultural products are traded internationally. A full understanding of water use is, therefore, impossible without understanding the international market for food and related products, such as textiles. Based on the global general equilibrium model GTAP-W, we offer a method for investigating the role of green (rain) and blue (irrigation) water resources in agriculture and within the context of international trade. We use future projections of allowable water withdrawals for surface water and groundwater to define two alternative water management scenarios. The first scenario explores a deterioration of current trends and policies in the water sector (water crisis scenario). The second scenario assumes an improvement in policies and trends in the water sector and eliminates groundwater overdraft worldwide, increasing water allocation for the environment (sustainable water use scenario). In both scenarios, welfare gains or losses are not only associated with changes in agricultural water consumption. Under the water crisis scenario, welfare not only rises for regions where water consumption increases (China, South East Asia and the USA). Welfare gains are observed in Japan, South Korea, Southeast Asia and Western Europe as well. These regions benefit from higher levels of irrigated production and lower food prices. Alternatively, under the sustainable water use scenario, welfare losses not only affect regions where overdrafting is occurring. Welfare decreases in other regions as well. These results indicate that, for water use, there is a clear trade-off between economic welfare and environmental sustainability.

**Keywords:** Agricultural Water Use, Computable General Equilibrium, Irrigation, Sustainable Water Use

**JEL Classification:** Q17, D58, Q15, Q25

## 1. Introduction

Water is one of our basic resources, but it is often in short supply. Surface water and groundwater are both important sources not only for human use but also for ecological systems. While in some countries groundwater resources still are abundant and readily available for development, in others depletion due to overdrafting, water-logging, salination as well as pollution cause severe problems. Similarly, overexploitation of surface water resources in some regions is damaging ecosystems by reducing water flows to rivers, lakes and wetlands. Since world-wide use of surface water has remained constant or increased at a slower rate, the increase in global water use in recent years has been based on groundwater (Villholth and Giordano, 2007; Zektser and Everett, 2004). In addition, the uneven distribution of water (and population) among regions has made the adequate supply critical for a growing number of countries. Rapid population growth and an increasing consumption of water per capita have aggravated the problem. This tendency is likely to continue as water consumption for most uses is projected to increase by at least 50% by 2025 compared to 1995 level (Rosegrant et al., 2002). One additional reason for concern is (anthropogenic) climate change, which may lead to increased drought in many places (IPCC, 2001).

The agricultural sector is the largest consumer of water. While rainfed agriculture relies on soil moisture generated from rainfall, irrigated agriculture focuses on withdrawals of water from surface and groundwater sources. In many arid and semi-arid regions such as India, Northern China as well as Pakistan groundwater is critical for development and food security. A similar situation is observed in developed arid regions of the world including the USA, Australia and Mexico. In the arid Southern and Eastern rims of the Mediterranean basin, agriculture accounts for 82 percent of the water withdrawals in the region (Plan Bleu, 2009). In other regions of the world the situation is different. Countries in Sub-Saharan Africa, for example, could benefit from more intensive groundwater use for agricultural as well as other uses but are limited in their development due to among others a lack of infrastructure, poor energy access and low investment (Villholth and Giordano, 2007). However, taken together, the more serious problem today is not the development of groundwater but the sustainable management of water (Shah et al., 2000). According to Tsur et al. (2004) the world's major surface irrigation systems lose between half and two thirds of the water in transit between source and crops.

To ensure a more sustainable management of water resources and groundwater resources in particular, water-use policies need to be established or improved. These could include, for example, incentives to use more water-saving irrigation techniques. Water problems related to water-use management are typically studied at the farm-level, the river-catchment-level or the country-level. About 70 percent of all freshwater withdrawals is used for agriculture (United Nations, 2003), and agricultural products are traded internationally. A full understanding of water use and the effect of more sustainable management of surface and groundwater resources is impossible without understanding the international market for food and related products, such as textiles.

We use the new version of the GTAP-W model to analyze the economy-wide impacts of more sustainable water use in the agricultural sector. The GTAP-W model (Calzadilla et al., 2008) is a global computable general equilibrium (CGE) model that allows for a rich set of economic feedbacks and for a complete assessment of the welfare implications of alternative development pathways. The GTAP-W model is based on the GTAP 6 database and has been calibrated to 2000 and 2025 using information from the IMPACT model (a partial equilibrium agricultural sector model combined with a water simulation model, see Rosegrant et al., 2002). Unlike the predecessor GTAP-W (Berrittella et al., 2007), the new production structure of the model, which introduces a differentiation between rainfed and irrigated crops, allows a better understanding of the use of water resources in agricultural sectors. In fact, the distinction between rainfed and irrigated agriculture in GTAP-W, allows us to model green (rain) and blue (irrigation) water used in crop production.

Efforts towards improving groundwater development as well as the management of water resources, e.g. through more efficient irrigation methods, benefit societies by saving large amounts of water. These would be available for other uses. The aim of our paper is to analyze if improvements in agricultural water management would be economically beneficial for the world as a whole as well as for individual countries and whether and to what extent water savings could be achieved. Problems related to surface and groundwater use, as discussed above, are present today. Since problems related to water availability are becoming more severe in the future, it is important to analyze the impact of different water use options for the future. We use scenario data for 2025 taken from Rosegrant et al. (2002).

Economic models of water use 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. In order to obtain insights from alternative water policy scenarios on the allocation of water resources, partial and general equilibrium models have been used. While partial equilibrium analysis focuses 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 the economy-wide effect; partial equilibrium models tend to have more detail. Most of the studies using either of the two approaches analyze pricing of irrigation water only (for an overview of this literature see Johannson et al., 2002). Rosegrant, et al. (2002) use the IMPACT model to estimate demand and supply of food and water to 2025. 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, other sectors are excluded; it is a partial equilibrium model. Studies using general equilibrium approaches are generally based on data for a single country or region assuming no interlinkages with the rest of the world regarding policy changes and shocks (e.g. Diao and Roe, 2003; Gómez et al., 2004; Letsoalo et al., 2007).

The remainder of the paper is organized as follows: the next section describes the new GTAP-W model. Section 3 lays down two simulation scenarios for future agricultural water use in 2025. Section 4 presents the results and section 5 discusses the findings and concludes.

## 2. The GTAP-W model

In order to assess the systemic general equilibrium effects of more sustainable water use in agriculture, we use a multi-region world CGE model, called GTAP-W. The model is a further refinement of the GTAP model[1] (Hertel, 1997), and is based on the version modified by Burniaux and Truong[2] (2002) 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.[3] 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 as yields per hectare are higher. To account for this difference, we split irrigated agriculture further into the value for land and the value for irrigation. The value of irrigation includes the equipment but also the water necessary for agricultural production. In the short-run irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability. The tree diagram in Figure IV-A1 in Annex A 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 into the value of rainfed land and the value of irrigated land using its proportionate contribution to total production.[4] The value of pasture land is derived from the value of land in the livestock breeding sector.

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[1] 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.

[2] 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 in a nested level of substitution with capital. This allows for more substitution possibilities. Second, database and model are extended to account for $CO_2$ emissions related to energy consumption.

[3] See Table IV-A1 in Annex A for the regional, sectoral and factoral aggregation used in GTAP-W.

[4] Let us assume, for example, 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.

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.[5] The numbers indicate how relatively more valuable irrigated agriculture is compared to rainfed agriculture. The magnitude of additional yield differs not only with respect to the region but also to the crop. On average, producing rice using irrigation is relatively more productive than using irrigation for growing oil seeds, for example.

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

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 (CES) (Figure IV-A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called ''Armington assumption'', which accounts for product heterogeneity.[6]

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, labour and capital). Capital and labour are perfectly mobile domestically, but immobile internationally. Pasture land, rainfed land, irrigated land, irrigation and natural resources are imperfectly mobile. 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. The expenditure shares are generally fixed, which amounts to saying that the top level utility function has a Cobb-Douglas specification. 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

[5] 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.

[6] 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.

elasticities for the various consumption goods.[7] A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.[8]

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 countries, in variable proportions. In a similar way, a hypothetical world bank collects savings from all regions and allocates investments so as to achieve equality of expected future rates of return (macroeconomic closure).

In the original GTAP-E 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 constant elasticity of substitution function (Figure IV-A1). The procedure how the elasticity of factor substitution between land and irrigation ($\sigma_{LW}$) was obtained is explained in more detail in Calzadilla et al. (2008). Next, the irrigated land-water composite is combined with pasture land, rainfed land, natural resources, labour and the capital-energy composite in a value-added nest through a CES structure.

The IMPACT model provides detailed information on green water use in rainfed production (defined as effective rainfall); and both green and blue water use in irrigated production (blue water or irrigation is defined as the water diverted from water systems).[9] In the GTAP-W benchmark equilibrium, water used for irrigation is supposed to be identical to the volume of blue 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 social accounting matrix information about payments to factors and the volume of water used in irrigation from IMPACT. Contrary to blue water, green water used in rainfed and irrigated crop production has no price. It is modelled exogenously in the GTAP-W model using information from IMPACT.

## 3. Simulation scenarios

To model water supply and demand at the basin scale, Rosegrant et al. (2002) introduced the concept of maximum allowable water withdrawal (MAWW), which is the water withdrawal capacity available for agricultural, municipal and industrial water uses. The MAWW

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

[8] The equivalent variation measures the welfare impact of a policy change in monetary terms. It is defined as the change in regional household income at constant prices that is equivalent to the proposed change.

[9] 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 the 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).

constrains the actual water withdrawals and depends on the availability of surface and groundwater; the physical capacity of water withdrawal; instream flow requirements for navigation; hydropower generation; environmental constrains; recreation purposes; and water demand.

Future projections of allowable water withdrawals are presented by Rosegrant et al. (2002) under three alternative scenarios: business as usual, water crisis and sustainable water use. In the business as usual scenario (BAU), MAWW projections are according to current conditions of water withdrawal capacity and physical constrains on pumping; and consider projected growth in water demand and investments in infrastructure. In the water crisis scenario (CRI), MAWW projections reflect a deterioration (from an environmental perspective) of current trends and policies in the water sector. In contrast to the previous scenario, the sustainable water use scenario (SUS) projects improvements in policies and trends in the water sector, with greater environmental water reservation.

Table IV-1 shows the annual MAWW for surface and groundwater for BAU, CRI and SUS for 1995 and 2025. Compared to 1995 levels, the business as usual projection for 2025 considers a small decline in extraction rates for those countries or regions pumping in excess. Overexploitation of groundwater aquifers is observable particularly in northern India, northern China, West Asia and North Africa, and in the western United States, where extraction rates substantially exceed recharge rates. Alternatively, for those countries or regions underutilizing groundwater relative to the water withdrawal capacity, they assume a gradual increase in the extraction rates (e.g. Sub-Saharan Africa and Southeast Asia).

**Table IV–1. Annual maximum allowable water withdrawal for surface and groundwater under business as usual, water crisis and sustainable water use scenario, 1995 and 2025 (km$^3$)**

| Country/Region | **Surface** (km$^3$) | | | | **Groundwater** (km$^3$) | | | | **Total** (km$^3$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1995** | **2025 projection** | | | **1995** | **2025 projection** | | | **1995** | **2025 projection** | | |
| | **Baseline** | **BAU** | **CRI** | **SUS** | **Baseline** | **BAU** | **CRI** | **SUS** | **Baseline** | **BAU** | **CRI** | **SUS** |
| Asia | 1,919 | 2,464 | 2,926 | 2,464 | 478 | 542 | 519 | 389 | 2,397 | 3,006 | 3,445 | 2,853 |
| China | 584 | 764 | 916 | 764 | 138 | 171 | 176 | 137 | 722 | 935 | 1,092 | 901 |
| India | 573 | 735 | 872 | 735 | 237 | 255 | 235 | 163 | 810 | 990 | 1,107 | 898 |
| Southeast Asia | 194 | 286 | 375 | 286 | 22 | 32 | 41 | 32 | 216 | 318 | 416 | 318 |
| South Asia India | 318 | 390 | 444 | 390 | 57 | 58 | 41 | 32 | 375 | 448 | 485 | 422 |
| Latin America | 251 | 358 | 452 | 358 | 65 | 79 | 90 | 79 | 316 | 437 | 542 | 437 |
| Sub-Saharan Africa | 73 | 141 | 222 | 141 | 63 | 87 | 109 | 90 | 136 | 228 | 331 | 231 |
| West Asia / North Africa | 246 | 302 | 348 | 302 | 72 | 74 | 60 | 45 | 318 | 376 | 408 | 347 |
| Developed countries | 976 | 1,131 | 1,247 | 1,131 | 255 | 278 | 293 | 267 | 1,231 | 1,409 | 1,540 | 1,398 |
| Developing countries | 2,425 | 3,197 | 3,875 | 3,197 | 670 | 773 | 769 | 594 | 3,095 | 3,970 | 4,644 | 3,791 |
| **World** | **3,401** | **4,328** | **5,122** | **4,328** | **925** | **1,051** | **1,062** | **861** | **4,326** | **5,379** | **6,184** | **5,189** |

Note: Business as usual (BAU), water crisis (CRI) and sustainable water use (SUS).
Source: Rosegrant et al. (2002).

The water crisis scenario assumes, for countries pumping in excess, the same growth in extraction rates as the business as usual scenario until 2010, followed by a rapid decline in MAWW for groundwater until 2025. The decline in groundwater is more than compensated by additional use of surface water (see e.g. South Asia including India and West Asia as well as North Africa). For regions where overdrafting is not a problem, extraction rates and MAWW for surface and groundwater are higher compared to the business as usual scenario (see e.g. Sub-Saharan Africa and Southeast Asia). Under the water crisis scenario, the world's annual MAWW for surface water increases by 794 cubic kilometres compared to the business as usual scenario. MAWW for groundwater increases only slightly (11 cubic kilometres). Since more water is available for agriculture, the crisis is therefore not a crisis for agriculture, but rather a crisis for the natural environment which would have to make do with less water.

In the sustainable water use scenario, groundwater overdrafting is eliminated gradually until 2025 through a reduction in the extraction rates. Compared to the business as usual scenario, the MAWW for groundwater decreases substantially in all regions except for Sub-Saharan Africa and South Asia where overdrafting is not occurring. The MAWW for surface remains unchanged. Under this scenario the world's annual MAWW for groundwater decreases by 190 cubic kilometres compared to the business as usual scenario. This constrains agriculture, but leaves more water for the natural environment.

Based on the three scenario projections of maximum allowable water withdrawals for surface and groundwater presented by Rosegrant et al. (2002), we evaluate the effects of the water crisis and sustainable water use scenarios on production and income. Both scenarios are compared with the business as usual scenario; assuming that the BAU scenario generates a future baseline with current policies and trends in the water sector (i.e. 2025 baseline).[10]

Table IV-2 shows for 2025 the percentage change in the total (surface plus groundwater) maximum allowable water withdrawal used in the agricultural sector for the water crisis and sustainable water use scenarios.[11] Under the water crisis scenario, all regions increase the maximum water withdrawal capacity for agriculture compared to the business as usual scenario. In developing regions increases are higher than in developed regions. Under the sustainable water use scenario, water constraints occur in all regions except for those where groundwater is underutilized (Central and South America, Southeast Asia and Sub-Saharan Africa).

[10] Regional mapping between GTAP-W and Rosegrant et al. (2002) is as follows: United States, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Eastern Europe and the former Soviet Union correspond to developed countries; Middle East corresponds to West Asia / North Africa; Central America and South America correspond to Latin America; South Asia corresponds to South Asia including India; Southeast Asia corresponds to Southeast Asia; China corresponds to China; North Africa corresponds to West Asia / North Africa; Sub-Saharan Africa corresponds to Sub-Saharan Africa; and the Rest of the World corresponds to developing countries.

[11] The maximum allowable water withdrawal for surface and groundwater from Rosegrant et al. (2002) presented in Table IV-1 was updated with information regarding groundwater used by the agricultural sector (AQUASTAT database).

**Table IV–2. Percentage change in total (surface plus groundwater) maximum allowable water withdrawal used in the agricultural sector, 2025 (percentage change with respect to the business as usual scenario)**

| **Regions** (according to GTAP-W) | **CRI** (%) | **SUS** (%) |
|---|---|---|
| United States | 3.84 | -0.32 |
| Canada | 1.09 | -0.09 |
| Western Europe | 2.33 | -0.20 |
| Japan and South Korea | 5.13 | -0.43 |
| Australia and New Zealand | 5.46 | -0.46 |
| Eastern Europe | 2.80 | -0.23 |
| Former Soviet Union | 5.11 | -0.43 |
| Middle East | 6.21 | -5.63 |
| Central America | 14.46 | 0.00 |
| South America | 17.91 | 0.00 |
| South Asia | 7.82 | -5.49 |
| Southeast Asia | 22.08 | 0.00 |
| China | 11.37 | -2.46 |
| North Africa | 6.87 | -6.22 |
| Sub-Saharan Africa | 29.85 | 0.87 |
| Rest of the World | 7.53 | -2.00 |

Note: Water crisis (CRI) and sustainable water use (SUS).
Source: Authors' estimates based on Rosegrant et al. (2002) and the AQUASTAT database.

Projections of future surface and groundwater use in agriculture, according to the water crisis and sustainable water use scenarios, are introduced in the 2025 GTAP-W baseline simulation based on information in Table IV-2. The baseline dataset and projections out to 2025 on agricultural production as well as green and blue water use are present in Annex B. While changes in surface and groundwater use in agriculture modify the use of blue water or irrigation endowment in GTAP-W, changes in green water use driven by changes in rainfed and irrigated crop production is modelled exogenously in the GTAP-W model using information from IMPACT.

Under the water crisis scenario, higher levels of surface and groundwater withdrawal are assumed to expand irrigated agriculture. Irrigated crop area and irrigation are increased in GTAP-W according to Table IV-2. Under the sustainable water use scenario, constraints in surface and groundwater capacity are assumed to reduce irrigated agriculture (first stage). As a consequence of the decline in agricultural production and income, farmers react and expand rainfed crop areas to offset the initial losses (second stage). In the first stage, irrigated crop area and irrigation are reduced in GTAP-W according to Table IV-2. In the second stage, rainfed crop area is increased according to the initial reduction in irrigated crop area. That is, total harvested area stays the same, but crop production falls as rainfed agriculture is less productive than irrigated agriculture.

## 4. Results

### Water crisis scenario: Deterioration of current trends and policies in the water sector

Higher surface and groundwater withdrawal capacity increases irrigation water supply, which promotes irrigated crop production and relegates rainfed production. Table IV-3 shows the percentage changes, with respect to the baseline simulation, in crop production and green and blue water use by region and crop type in 2025. At the global level, global irrigated production increases by 9.9 percent while global rainfed production decreases by 6.7 percent; as a result, total production increases slightly by 0.4 percent.

**Table IV–3. Water crisis scenario: Percentage change in crop production, green and blue water use and world market price by region and crop type, compared to the 2025 baseline simulation**

| Description | Rainfed Agriculture | | Irrigated Agriculture | | | Total | | | | World Market price |
|---|---|---|---|---|---|---|---|---|---|---|
| | Produc-tion | Green water | Produc-tion | Green water | Blue water | Produc-tion | Green water | Blue water | Total water | |
| **Regions** | | | | | | | | | | |
| United States | -5.33 | -6.92 | 3.09 | 3.44 | 3.18 | 0.54 | -0.15 | 3.18 | 1.50 | |
| Canada | -3.21 | -3.09 | 1.35 | 0.96 | 0.81 | -2.83 | -2.99 | 0.81 | -2.88 | |
| Western Europe | -1.81 | -1.75 | 2.56 | 2.24 | 1.60 | -0.65 | -1.07 | 1.60 | -0.77 | |
| Japan and South Korea | -12.56 | -10.73 | 4.60 | 2.04 | -0.35 | 0.13 | -0.67 | -0.35 | -0.65 | |
| Australia and New Zealand | -3.74 | -2.66 | 5.88 | 5.70 | 5.72 | -0.85 | -1.81 | 5.72 | 0.41 | |
| Eastern Europe | -0.81 | -0.79 | 2.79 | 2.76 | 2.77 | -0.06 | -0.28 | 2.77 | 0.32 | |
| Former Soviet Union | -1.82 | -1.59 | 5.12 | 5.08 | 5.09 | -0.11 | -0.76 | 5.09 | 0.52 | |
| Middle East | -8.10 | -8.71 | 5.91 | 5.28 | 5.43 | -0.67 | -3.07 | 5.43 | 1.61 | |
| Central America | -9.07 | -10.75 | 13.33 | 13.44 | 13.60 | 1.16 | -1.41 | 13.60 | 4.29 | |
| South America | -5.54 | -4.56 | 18.21 | 17.98 | 17.98 | -0.06 | -1.98 | 17.98 | 0.63 | |
| South Asia | -10.55 | -11.70 | 7.65 | 7.55 | 7.74 | 0.58 | -0.70 | 7.74 | 2.66 | |
| Southeast Asia | -12.43 | -13.79 | 21.74 | 21.90 | 21.88 | 1.31 | -2.99 | 21.88 | -0.16 | |
| China | -11.29 | -16.02 | 11.04 | 9.65 | 8.94 | 1.98 | 1.91 | 8.94 | 3.99 | |
| North Africa | -10.57 | -12.94 | 6.75 | 6.83 | 5.98 | -0.34 | -9.18 | 5.98 | 1.60 | |
| Sub-Saharan Africa | -4.73 | -3.30 | 30.00 | 30.00 | 30.03 | -0.59 | -1.95 | 30.03 | 0.10 | |
| Rest of the World | -4.51 | -3.69 | 7.43 | 7.35 | 7.39 | -0.02 | -0.37 | 7.39 | 1.63 | |
| **Total** | **-6.69** | **-7.05** | **9.93** | **10.05** | **8.93** | **0.44** | **-1.05** | **8.93** | **1.62** | |
| | | | | | | | | | | |
| **Crops** | | | | | | | | | | |
| Rice | -21.63 | -21.89 | 7.75 | 9.31 | 7.91 | 0.64 | -2.22 | 7.91 | 0.80 | -5.08 |
| Wheat | -7.94 | -7.30 | 7.49 | 7.31 | 8.05 | 0.04 | -1.96 | 8.05 | 2.69 | -1.99 |
| Cereal grains | -5.36 | -4.77 | 7.09 | 9.63 | 9.18 | 0.28 | -1.36 | 9.18 | 1.15 | -1.72 |
| Vegetables, fruits, nuts | -4.06 | -3.91 | 9.79 | 11.61 | 10.17 | 0.16 | -0.73 | 10.17 | 1.26 | -1.60 |
| Oil seeds | -3.97 | -3.72 | 6.39 | 8.91 | 6.61 | 0.37 | -0.63 | 6.61 | 1.05 | -1.83 |
| Sugar cane, sugar beet | -8.70 | -10.02 | 12.66 | 14.40 | 12.41 | 0.26 | -2.07 | 12.41 | 3.14 | -2.38 |
| Other agricultural products | -7.44 | -5.81 | 10.46 | 11.04 | 9.44 | 1.33 | 0.28 | 9.44 | 2.17 | -1.90 |
| **Total** | **-6.69** | **-7.05** | **9.93** | **10.05** | **8.93** | **0.44** | **-1.05** | **8.93** | **1.62** | |

At the regional level, the tendency is similar. Irrigated crop production increases in all regions, particularly in developing regions where overdrafting in not occurring (Sub-Saharan Africa, Southeast Asia and South America). Contrary to irrigated production, rainfed crop production declines in all regions. The combined effect of changes in irrigated and rainfed agriculture on total crop production is mixed; but total crop production increases mostly in developing regions (China, Southeast Asia and Central America). Reductions in total crop production are considerable in Canada, followed by Australia and New Zealand; the Middle East; and Western Europe.

Green and blue water use changes accordingly. At the global level, total agricultural water consumption increases by 105 cubic kilometres. While blue water use increases by 155 cubic kilometres, green water use decreases by 50 cubic kilometres. At the regional level, total agricultural water consumption decreases only in four regions (Canada; Western Europe; Japan and South Korea; and Southeast Asia) (Figure IV-1). Regional blue water use increases more in developing regions where groundwater is underutilized (Sub-Saharan Africa, Southeast Asia, and South and Central America). In developing regions, pumping groundwater in excess, including China, South Asia, North Africa and the Middle East, blue water use increases. Regional green water use in rainfed and irrigated production changes according to the additional crop production.

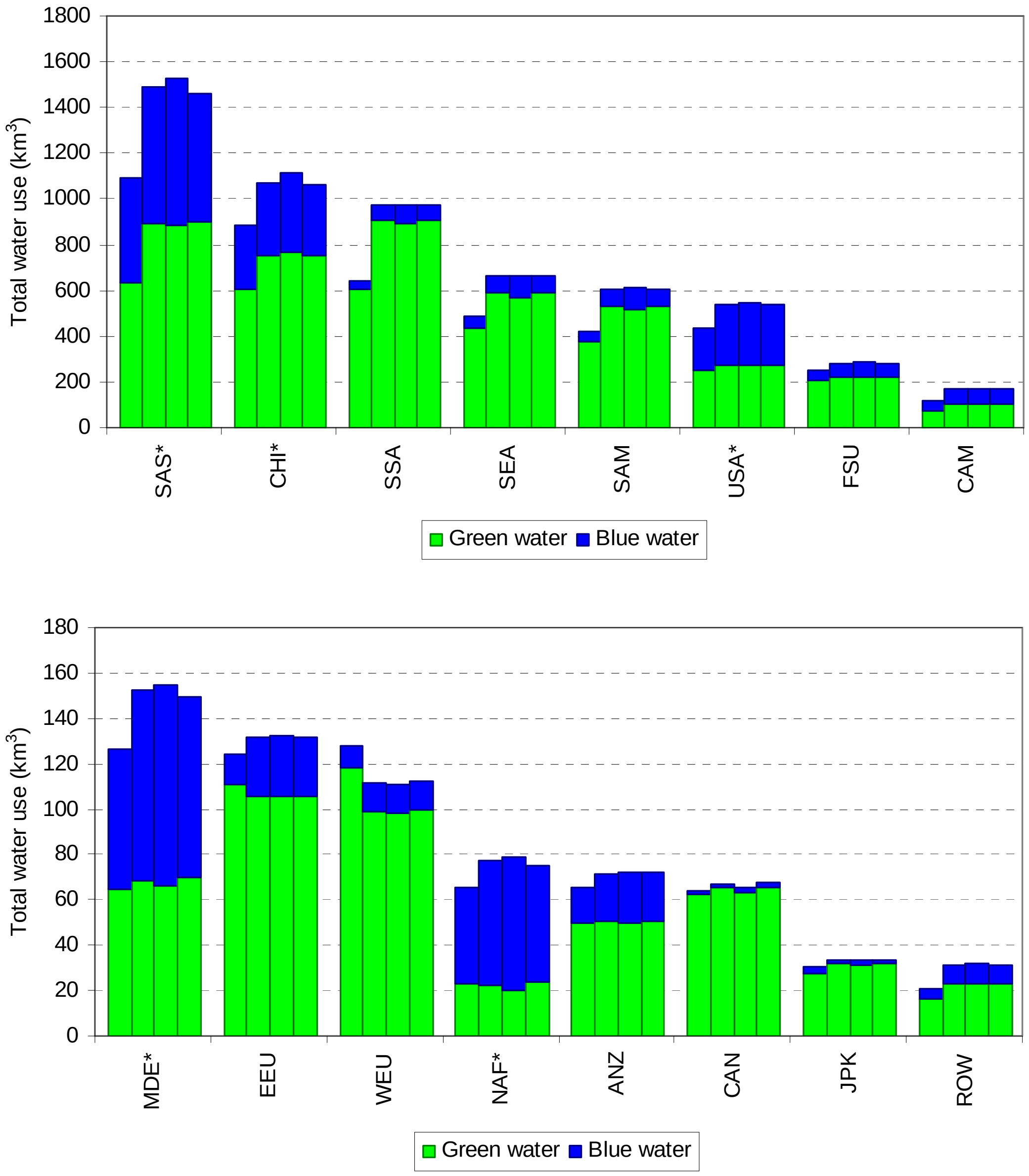


**Figure IV–1. Green and blue water use by region and scenario ($km^3$)**

Note: The four bars refer to the 2000 baseline data, the 2025 baseline scenario, the water crisis scenario and the sustainable water use scenario (final result), respectively. Regions where overdrafting of groundwater aquifers occurs are denoted by an asterisk (*).

Changes in green and blue water use by crop type are shown in the bottom of Table IV-3 and in Figure IV-2. For most crops, total agricultural water use increases as a consequence of higher crop production. Total green water use decreases while blue water use increases for all crops. An exception is “other agricultural products”, the crop category with the highest increase in production, for which both green and blue water consumption increases.

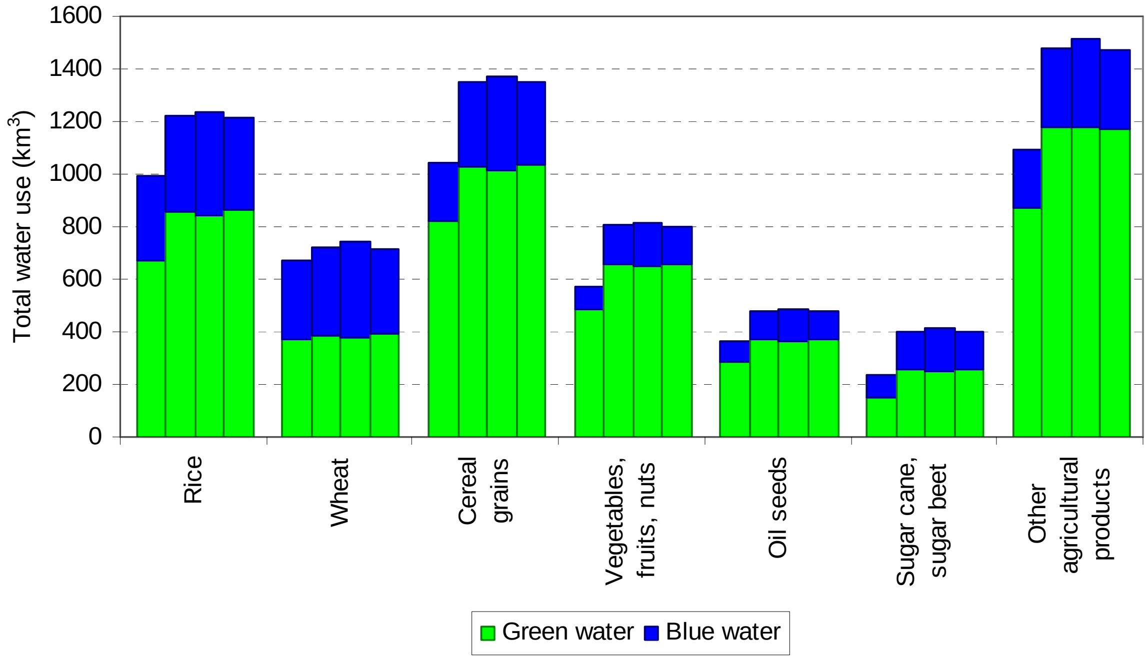


**Figure IV–2. Green and blue water use by crop and scenario (km$^3$)**

Note: The four bars refer to the 2000 baseline data, the 2025 baseline scenario, the water crisis scenario and the sustainable water use scenario (final result), respectively.

Higher surface and groundwater extraction promotes irrigation and improves agricultural yields, which in turn leads to a decrease in the production costs of agricultural products.[12] The last column in Table IV-3 reports the percentage change in world market prices. For all agricultural products, world market prices decrease as a consequence of lower production costs. Reductions in world market prices are considerable for rice, sugar cane and sugar beet. Lower market prices stimulate consumption and total production of all agricultural products increases. Total production increases particularly for “other agricultural products” as well as for rice and oil seeds production. Lower prices and higher supply of crops promotes non-agricultural activities as well. Market prices for food related products, animal production and meat decline.

[12] Higher levels of irrigation usually imply an increase of production costs related to the variable costs of crops. In our analysis we are not able to take that into account.

Changes in water withdrawal capacity alter competitiveness and induce changes in welfare. At the global level, welfare increase when more water is used in agriculture. However, at the regional level, the results are more mixed. Welfare decreases mainly in food-exporting regions (356 million USD in South America; 326 million USD in Australia and New Zealand; and 234 in Sub-Saharan Africa) (Figure IV-3). The competitive advantage of those regions decreases as other regions increase irrigated agriculture. Welfare changes are positive in all other regions, with the exception of Canada (welfare decreases by 85 million USD). Compared to other regions, welfare gains are larger in China and South Asia, developing regions where overdrafting of groundwater is high (welfare increases by 2,241 and 2,044 million USD, respectively). In Japan and South Korea, Southeast Asia and Western Europe welfare gains are lower (1,397; 1.104 and 1101 million USD, respectively).

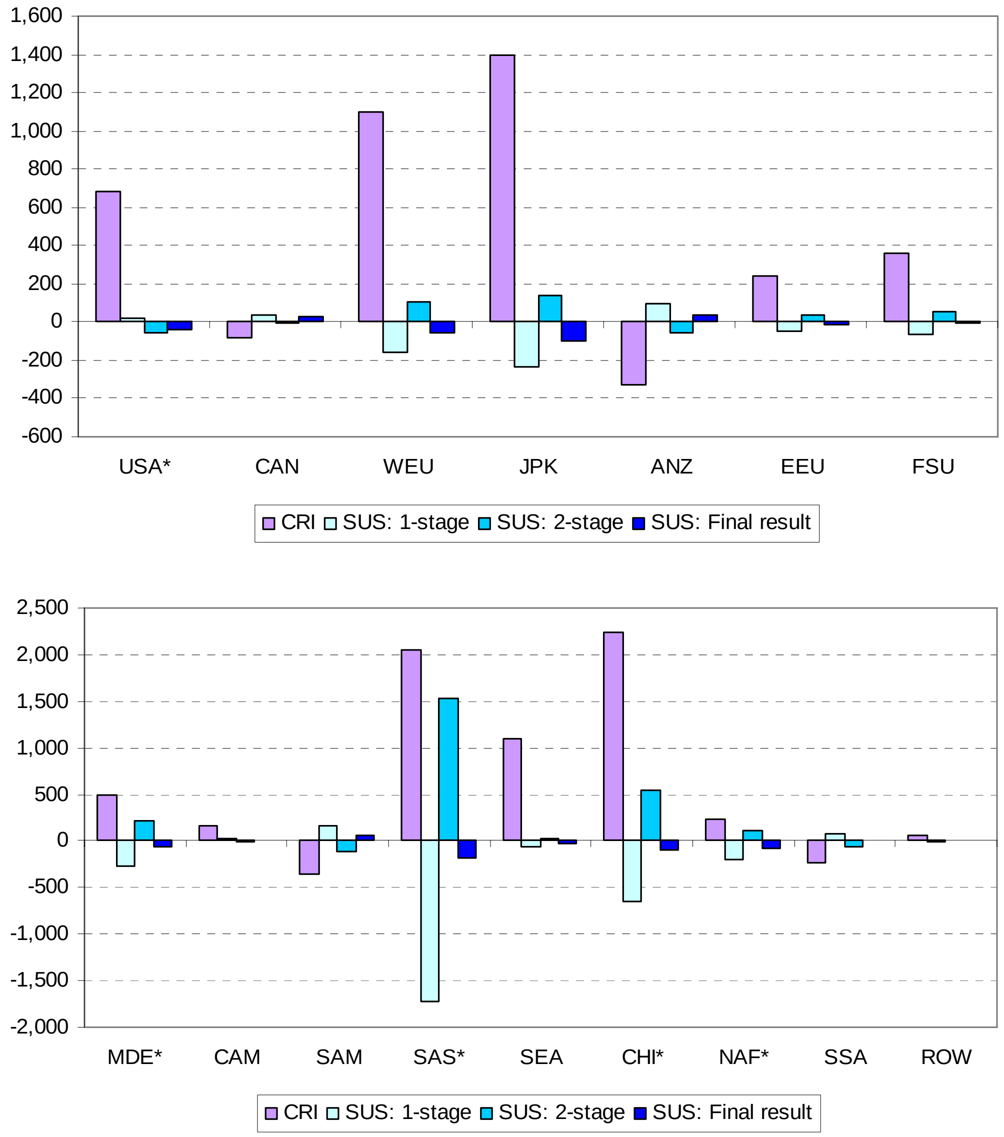


**Figure IV–3. Changes in regional welfare, water crisis and sustainable water use scenarios (million USD)**

Note: Developed regions (top panel) and developing regions (bottom panel). Regions where overdrafting of groundwater aquifers occurs are denoted by an asterisk (*).

**Sustainable water use scenario: Improvements in policies and trends in the water sector**
Unlike the water crisis scenario, the sustainable water use scenario focuses on the sustainable exploitation of groundwater resources. Under this scenario, no restriction is imposed upon surface water withdrawal; however, groundwater overdrafting is eliminated gradually until 2025. The scenario is divided into two stages, in the first stage restrictions in irrigation water withdrawal constrain irrigated agriculture, which in turn reduce total production and income. In the second stage, farmers react and increase rainfed harvested areas in order to compensate the initial losses in income. Table IV-4 shows the percentage changes in crop production as well as green and blue water use by region in 2025, compared to the baseline simulation. Displayed are the results for both stages as well as the final result. At the global level, total production decreases by 0.13 percent in the first stage and increases by 0.06 percent in the second stage. The final result is a small decrease in total production by 0.07 percent.

At regional level, results vary widely. For developing regions where overdrafting is a problem, the results of the first stage show a decrease in irrigated and total crop production (see e.g. South Asia, China, North Africa and the Middle East). In the second stage, rainfed and total crop production increases. However, this increase is insufficient to offset the initial reduction in total production. As a final result, total production declines in these regions. The only exception is the Middle East, where total production increases by 0.14 percent. For the USA, a developed country pumping in excess, total production in both stages increases slightly; as a final result total crop production increases by 0.1 percent.

For regions where overdrafting is not occurring, irrigated production decreases and total production increases in the first stage. An exception is Sub-Saharan Africa, where groundwater is underutilized and irrigated production increases. In the second stage, rainfed and total production decreases. As a final result, total production increases in all these regions, particularly in Canada as well as Australia and New Zealand.

Changes in rainfed and irrigated production have an effect on the demand for green and blue water resources. At the global level, water savings are expected since groundwater is constrained. Total water use decreases by 0.65 percent (42 cubic kilometres) in the first stage and increases slightly by 0.04 percent (3 cubic kilometres) in the second stage. The final result is a decrease in total water use by 0.61 percent (40 cubic kilometres). While blue water use decreases, total green water use increases in both stages.

At the regional level, green and blue water use varies widely. For regions where overdrafting is a problem, blue and total water use decrease in the first stage, particularly in North Africa, the Middle East and South Asia. In the second stage blue as well as total water use increases (exceptions are the USA and South Asia). However, the final result, taken the results of stages 1 and 2 together, blue and total water use decrease (Table IV-4 and Figure IV-1). Together total water savings in all these regions reach 42 cubic kilometres. South Asia accounts for more than two-thirds of the total water savings in these regions. For regions where overdrafting is not occurring, results are less pronounced.

**Table IV–4. Sustainable water use scenario: Percentage change in crop production and green and blue water use by region, compared to the 2025 baseline simulation**

| Regions | Rainfed Agriculture | | Irrigated Agriculture | | | Total | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Production | Green water | Production | Green water | Blue water | Production | Green water | Blue water | Total water |
| **First stage** | | | | | | | | | |
| United States | 0.77 | 1.08 | -0.25 | -0.25 | -0.27 | 0.06 | 0.21 | -0.27 | -0.03 |
| Canada | 0.93 | 0.88 | -0.14 | 0.01 | 0.07 | 0.84 | 0.86 | 0.07 | 0.84 |
| Western Europe | 0.33 | 0.37 | -0.27 | -0.14 | 0.37 | 0.17 | 0.28 | 0.37 | 0.29 |
| Japan and South Korea | 1.61 | 2.96 | -0.44 | -0.41 | -0.40 | 0.09 | 0.31 | -0.40 | 0.27 |
| Australia and New Zealand | 0.78 | 0.79 | -0.62 | -0.36 | -0.43 | 0.36 | 0.67 | -0.43 | 0.35 |
| Eastern Europe | 0.10 | 0.11 | -0.23 | -0.22 | -0.22 | 0.03 | 0.06 | -0.22 | 0.01 |
| Former Soviet Union | 0.24 | 0.25 | -0.44 | -0.41 | -0.41 | 0.07 | 0.16 | -0.41 | 0.04 |
| Middle East | 6.17 | 6.21 | -5.58 | -5.49 | -5.50 | -0.05 | 1.50 | -5.50 | -2.36 |
| Central America | 0.21 | 0.27 | -0.10 | -0.08 | -0.07 | 0.07 | 0.13 | -0.07 | 0.06 |
| South America | 0.14 | 0.26 | -0.17 | -0.08 | -0.06 | 0.07 | 0.22 | -0.06 | 0.18 |
| South Asia | 6.68 | 7.36 | -5.33 | -5.32 | -5.47 | -0.67 | 0.12 | -5.47 | -2.11 |
| Southeast Asia | 0.15 | 0.19 | -0.03 | 0.00 | 0.00 | 0.08 | 0.13 | 0.00 | 0.12 |
| China | 2.20 | 3.10 | -2.41 | -2.12 | -1.96 | -0.54 | -0.55 | -1.96 | -0.96 |
| North Africa | 8.17 | 9.93 | -6.23 | -6.27 | -6.62 | -0.34 | 6.86 | -6.62 | -2.73 |
| Sub-Saharan Africa | 0.09 | 0.17 | 0.78 | 0.81 | 0.82 | 0.17 | 0.19 | 0.82 | 0.23 |
| Rest of the World | 1.12 | 0.88 | -1.92 | -1.92 | -1.93 | -0.02 | 0.04 | -1.93 | -0.47 |
| **Total** | **1.41** | **1.51** | **-2.19** | **-2.46** | **-2.76** | **-0.13** | **0.12** | **-2.76** | **-0.65** |
| **Second stage** | | | | | | | | | |
| United States | 0.15 | 0.12 | -0.01 | 0.00 | -0.01 | 0.04 | 0.04 | -0.01 | 0.02 |
| Canada | -0.43 | -0.35 | 0.09 | 0.18 | 0.13 | -0.39 | -0.34 | 0.13 | -0.32 |
| Western Europe | -0.18 | -0.18 | 0.01 | -0.02 | -0.10 | -0.13 | -0.15 | -0.10 | -0.15 |
| Japan and South Korea | -0.03 | 0.08 | -0.03 | 0.01 | 0.02 | -0.03 | 0.03 | 0.02 | 0.03 |
| Australia and New Zealand | -0.22 | -0.18 | 0.17 | 0.18 | 0.18 | -0.10 | -0.15 | 0.18 | -0.05 |
| Eastern Europe | -0.02 | -0.03 | 0.00 | 0.00 | 0.00 | -0.02 | -0.02 | 0.00 | -0.02 |
| Former Soviet Union | -0.06 | -0.07 | 0.01 | 0.00 | 0.00 | -0.04 | -0.06 | 0.00 | -0.05 |
| Middle East | 0.34 | 0.55 | 0.04 | 0.19 | 0.17 | 0.19 | 0.39 | 0.17 | 0.26 |
| Central America | -0.18 | -0.22 | 0.07 | 0.06 | 0.06 | -0.07 | -0.11 | 0.06 | -0.05 |
| South America | -0.10 | -0.21 | 0.10 | 0.07 | 0.05 | -0.06 | -0.18 | 0.05 | -0.15 |
| South Asia | 1.16 | 1.28 | -0.10 | -0.03 | -0.07 | 0.43 | 0.49 | -0.07 | 0.26 |
| Southeast Asia | -0.08 | -0.07 | 0.01 | 0.03 | 0.02 | -0.04 | -0.04 | 0.02 | -0.03 |
| China | 0.42 | 0.52 | -0.04 | 0.01 | 0.02 | 0.15 | 0.16 | 0.02 | 0.11 |
| North Africa | 0.41 | 0.48 | -0.04 | 0.02 | 0.07 | 0.16 | 0.38 | 0.07 | 0.16 |
| Sub-Saharan Africa | -0.18 | -0.17 | 0.02 | 0.00 | 0.01 | -0.15 | -0.17 | 0.01 | -0.16 |
| Rest of the World | 0.07 | 0.09 | -0.02 | -0.01 | -0.02 | 0.04 | 0.06 | -0.02 | 0.04 |
| **Total** | **0.11** | **0.08** | **-0.02** | **0.00** | **-0.01** | **0.06** | **0.06** | **-0.01** | **0.04** |
| **Final result** | | | | | | | | | |
| United States | 0.93 | 1.20 | -0.27 | -0.25 | -0.28 | 0.10 | 0.26 | -0.28 | -0.01 |
| Canada | 0.50 | 0.53 | -0.05 | 0.19 | 0.20 | 0.45 | 0.52 | 0.20 | 0.51 |
| Western Europe | 0.15 | 0.19 | -0.26 | -0.16 | 0.27 | 0.04 | 0.13 | 0.27 | 0.14 |
| Japan and South Korea | 1.58 | 3.04 | -0.47 | -0.40 | -0.38 | 0.06 | 0.33 | -0.38 | 0.29 |
| Australia and New Zealand | 0.56 | 0.60 | -0.45 | -0.18 | -0.25 | 0.25 | 0.52 | -0.25 | 0.30 |
| Eastern Europe | 0.08 | 0.08 | -0.23 | -0.22 | -0.22 | 0.01 | 0.04 | -0.22 | -0.01 |
| Former Soviet Union | 0.18 | 0.17 | -0.43 | -0.41 | -0.42 | 0.03 | 0.10 | -0.42 | -0.01 |
| Middle East | 6.53 | 6.72 | -5.54 | -5.29 | -5.32 | 0.14 | 1.88 | -5.32 | -2.09 |
| Central America | 0.03 | 0.05 | -0.04 | -0.02 | -0.01 | 0.00 | 0.02 | -0.01 | 0.01 |
| South America | 0.04 | 0.05 | -0.07 | -0.02 | -0.01 | 0.01 | 0.05 | -0.01 | 0.04 |
| South Asia | 7.92 | 8.55 | -5.42 | -5.36 | -5.54 | -0.24 | 0.60 | -5.54 | -1.85 |
| Southeast Asia | 0.06 | 0.12 | -0.02 | 0.02 | 0.02 | 0.03 | 0.09 | 0.02 | 0.08 |
| China | 2.64 | 3.61 | -2.46 | -2.11 | -1.94 | -0.39 | -0.39 | -1.94 | -0.85 |
| North Africa | 8.61 | 10.37 | -6.26 | -6.25 | -6.54 | -0.18 | 7.21 | -6.54 | -2.57 |
| Sub-Saharan Africa | -0.09 | -0.01 | 0.80 | 0.81 | 0.83 | 0.01 | 0.02 | 0.83 | 0.08 |
| Rest of the World | 1.19 | 0.97 | -1.94 | -1.93 | -1.95 | 0.01 | 0.10 | -1.95 | -0.43 |
| **Total** | **1.53** | **1.59** | **-2.21** | **-2.45** | **-2.76** | **-0.07** | **0.17** | **-2.76** | **-0.61** |

Changes in green and blue water use by crop type are reported in Table IV-5. In the first stage, when groundwater withdrawal is limited, there is a shift in production from irrigated to rainfed agriculture. Global irrigated production decreases, which implies a reduction in green and blue water use. By contrast, global rainfed production and green water use increases. Rainfed production increases considerably for rice and wheat (5.1 and 3.2 percent, respectively). As a result, global production decreases by 0.1 percent and water savings reach 42 cubic kilometres.

**Table IV–5. Sustainable water use scenario: Percentage change in crop production, green and blue water use and world market price by crop type, compared to the 2025 baseline simulation**

| Crops | Rainfed Agriculture | | Irrigated Agriculture | | | Total | | | | World Market price |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Green water | Production | Green water | Blue water | Production | Green water | Blue water | Total water | |
| **First stage** | | | | | | | | | | |
| Rice | 5.11 | 4.49 | -1.95 | -2.35 | -2.85 | -0.24 | 0.18 | -2.85 | -0.72 | 1.50 |
| Wheat | 3.19 | 2.91 | -3.15 | -2.56 | -4.30 | -0.09 | 0.91 | -4.30 | -1.51 | 0.84 |
| Cereal grains | 0.94 | 0.84 | -1.22 | -1.51 | -1.38 | -0.04 | 0.28 | -1.38 | -0.11 | 0.41 |
| Vegetables, fruits, nuts | 0.99 | 0.75 | -2.47 | -2.30 | -2.91 | -0.07 | 0.13 | -2.91 | -0.43 | 0.49 |
| Oil seeds | 0.69 | 0.71 | -1.04 | -1.63 | -1.24 | -0.04 | 0.13 | -1.24 | -0.18 | 0.64 |
| Sugar cane, sugar beet | 1.24 | 0.81 | -1.93 | -1.43 | -2.52 | -0.09 | 0.08 | -2.52 | -0.86 | 0.98 |
| Other agricultural products | 1.88 | 1.48 | -2.67 | -3.52 | -3.00 | -0.35 | -0.33 | -3.00 | -0.88 | 0.65 |
| **Total** | **1.41** | **1.51** | **-2.19** | **-2.46** | **-2.76** | **-0.13** | **0.12** | **-2.76** | **-0.65** | |
| **Second stage** | | | | | | | | | | |
| Rice | 0.43 | 0.27 | 0.02 | 0.00 | 0.00 | 0.13 | 0.10 | 0.00 | 0.07 | -0.25 |
| Wheat | 0.05 | 0.01 | 0.04 | 0.06 | 0.05 | 0.04 | 0.02 | 0.05 | 0.03 | -0.24 |
| Cereal grains | 0.05 | 0.05 | 0.00 | -0.03 | -0.02 | 0.02 | 0.03 | -0.02 | 0.02 | -0.28 |
| Vegetables, fruits, nuts | 0.14 | 0.10 | -0.09 | -0.13 | -0.10 | 0.07 | 0.05 | -0.10 | 0.02 | -0.76 |
| Oil seeds | -0.01 | -0.03 | 0.05 | 0.05 | -0.01 | 0.02 | -0.01 | -0.01 | -0.01 | -0.86 |
| Sugar cane, sugar beet | 0.09 | 0.04 | -0.01 | 0.01 | -0.05 | 0.05 | 0.03 | -0.05 | 0.00 | -0.46 |
| Other agricultural products | 0.15 | 0.10 | -0.02 | 0.04 | 0.01 | 0.07 | 0.08 | 0.01 | 0.06 | -0.49 |
| **Total** | **0.11** | **0.08** | **-0.02** | **0.00** | **-0.01** | **0.06** | **0.06** | **-0.01** | **0.04** | |
| **Final result** | | | | | | | | | | |
| Rice | 5.56 | 4.78 | -1.93 | -2.36 | -2.85 | -0.12 | 0.28 | -2.85 | -0.65 | 1.25 |
| Wheat | 3.24 | 2.92 | -3.11 | -2.51 | -4.25 | -0.05 | 0.94 | -4.25 | -1.48 | 0.60 |
| Cereal grains | 0.99 | 0.89 | -1.22 | -1.54 | -1.39 | -0.02 | 0.31 | -1.39 | -0.09 | 0.12 |
| Vegetables, fruits, nuts | 1.12 | 0.85 | -2.55 | -2.43 | -3.00 | 0.00 | 0.18 | -3.00 | -0.40 | -0.27 |
| Oil seeds | 0.68 | 0.68 | -0.99 | -1.58 | -1.25 | -0.02 | 0.13 | -1.25 | -0.19 | -0.22 |
| Sugar cane, sugar beet | 1.33 | 0.84 | -1.93 | -1.42 | -2.56 | -0.04 | 0.11 | -2.56 | -0.85 | 0.52 |
| Other agricultural products | 2.03 | 1.58 | -2.70 | -3.49 | -2.99 | -0.28 | -0.25 | -2.99 | -0.82 | 0.15 |
| **Total** | **1.53** | **1.59** | **-2.21** | **-2.45** | **-2.76** | **-0.07** | **0.17** | **-2.76** | **-0.61** | |

In the second stage, when rainfed areas expand to neutralize production and income losses, global rainfed and total production increases slightly. Taking the results of both stages together, the final results show, at the bottom of Table IV-5, a decrease in total production for all crops. The sectors “Other agricultural products” and rice have the largest decrease in total production. While blue water use declines for all crops, total green water use increases for all crops except for “other agricultural products” (Figure IV-2). The final water savings reach 40 cubic kilometres. Water savings are marked for the crops “other agricultural products”, wheat and rice.

The last column in Table IV-5 shows the changes in world market prices for all crop types. When groundwater use is constrained (first stage), world market prices increase for all crops and for agricultural related products (food products, animal production and meat production). World market prices increase mainly for rice; sugar cane and sugar beet; and wheat. In the second stage, world market prices decrease for all crops when rainfed areas are increased. World market prices decline mainly for oil seeds and vegetables, fruits and nuts. The combined effect of both stages shows a decrease in price for oil seeds and vegetables, fruits and nuts. For all other crops including agricultural related activities, world market prices increase.

Reducing groundwater overdraft worldwide alters the competitiveness of regions and induces changes in welfare. At the global level, welfare declines in the first stage by 2,993 million USD and increases by 2,490 million USD in the second stage. Taken both results together, welfare declines by 503 million USD (Figure IV-3). At the regional level, welfare effects are diverse depending on the region. In the first stage, welfare decreases for most of the regions, but mainly for developing regions where overdrafting is excessive. In South Asia, China and the Middle East welfare decreases by 1,721; 643 and 274 million USD, respectively. In this stage, welfare gains are observable mainly in developing regions where groundwater use is underutilized. Welfare increases in South America, Sub-Saharan Africa and Central America by 167, 77 and 20 million USD, respectively. In the second stage, welfare changes for all regions have an opposite sign than in the first stage. In South Asia, China and the Middle East welfare increases by 1,537; 546 and 221 million USD, respectively. In South America, Sub-Saharan Africa and Central America welfare declines by 115, 61 and 12 million USD, respectively.

Regional welfare gains in the second stage are more than offset by welfare losses in the first stage. Taken the results of stages 1 and 2 together, final welfare changes are negative for regions with excessive overdraft. Welfare losses are highest for South Asia and China (183 and 96 million USD, respectively). For regions where groundwater use is underutilized, welfare changes are mostly positive. Welfare increases in South America, Sub-Saharan Africa and Central America by 52, 16 and 8 million USD, respectively. The only exception is Southeast Asia, where welfare decreases by 23 million USD. For the rest of the regions where groundwater overdraft is not problematic, welfare changes are mostly negative. The highest decreases in welfare are present in Japan and South Korea; and Western Europe (97 and 59 million USD, respectively). Exceptions are Australia and New Zealand; and Canada, where welfare increases by 40 and 25 million USD, respectively.

## 5. Discussion and conclusions

In our analysis, the water crisis and sustainable water use scenarios lead to different patterns in agricultural water consumption. While the water crisis scenario explores a deterioration in current conditions and policies in the water sector, the sustainable water use scenario assumes an improvement and eliminates groundwater overdraft worldwide.

Irrigation water use is promoted under the water crisis scenario. At the global level, total production increases by 1.6 percent. Irrigated production expands suppressing rainfed production. As a result, total agricultural water consumption increases; irrigation water use increases even more, while the use of rain water falls. Higher levels of irrigation increase agricultural yields and allow farmers to obtain more output per unit of input, which in turn reduces production costs and crop prices. World market prices decrease for all crops and for agricultural related products (food products, animal production and meat production). Global welfare would increase by 9 billion USD.

An opposite picture is obtained under the sustainable use scenario. At the global level, total elimination of groundwater overdraft decreases total production moderately. As groundwater use is limited, irrigated production decreases and rainfed production increases. Total water consumption decreases. World market prices increase, but not for all crops. Global welfare falls by 0.5 billion USD.

At the regional level, results vary widely. Under the water crisis scenario, total production increases mainly in China, Southeast Asia and Central America and decreases principally in Canada and Australia and New Zealand. Under the sustainable water use scenario, total production decreases only in China, South Asia and North Africa and increases in all other regions mainly in Canada and Australia and New Zealand.

Under the water crisis scenario, irrigated production increases in all regions but more in developing regions where overdraft is not a problem. Irrigated production increases less in regions with overdraft. Under the sustainable water use scenario, irrigated production decreases in all regions, but mainly in developing regions with overdraft. Irrigated production increases only in Sub-Saharan Africa, where groundwater is underutilized.

Under the water crisis scenario, irrigated and total production increases for all crops, while rainfed production decreases. The opposite occurs under the sustainable water use scenario.

Regional use of green and blue water resources changes according to the additional rainfed and irrigated crop production. In absolute terms, under the water crisis scenario, most of the total water consumption occurs in regions where overdrafting is a problem, mainly in China, South East Asia and the USA. For most regions, total green water use decreases and blue water use increases. In Japan and South Korea, both green and blue water consumption decreases slightly. In China, both green and blue water consumption increases. Under the sustainable water use scenario, water restrictions affect predominantly regions where groundwater resources are on pressure. Total water consumption decrease mainly in South Asia, China and the Middle East.

In both scenarios, welfare changes go beyond changes in agricultural water consumption. Welfare changes in regions where water use changes, but it spills over to other regions too. Under the sustainable water use scenario, global and regional welfare losses could be larger if farmers do not increase rainfed areas to offset initial losses in production and income due to irrigation constraints.

The results reveal a clear trade-off between agricultural production, and hence human welfare as measurable by consumption of market goods on the one hand and nature conservation on the other hand. There is more water available for agriculture in the water crisis scenario than in business as usual scenario, and welfare is higher. The sustainable water use scenario has less water for agriculture, and lower welfare. However, the amount of water available to the natural environment moves in the opposite direction: More water for agriculture means less water for nature. This paper does not quantify the benefits of water to nature. It does, however, quantify the welfare implications of restricting or increasing the human take of total water. In the water crisis scenario, for instance, the human benefits of taking 105 cubic kilometres of water out of nature are some 9 billion USD – less than $1.3 per person. The welfare costs of the policies presumed in the sustainable water use scenario are also very small.

Several limitations apply to the above results. First, our analysis is based on regional averages. We do not differentiate between different regions within a country. China is an example of such a country. Although on average water is not short, water supply is a problem in Northern China, where groundwater overexploitation occurs. In our sustainable water use scenario we try to account for this effect. Second, under the water crisis scenario, expansion of irrigated areas is driven by the availability of water for irrigation, we do not account for possible environmental effects of land use changes. Third, under the water crisis scenario, we do not consider any cost or investment associated with irrigation expansion. Therefore, our results might overestimate the benefits of this scenario. Forth, we implicitly assume, for the sustainable water crisis scenario, availability and accessibility of green water resources when rainfed agriculture expands. In addition, some areas might be more suitable for rainfed agriculture than others. As a consequence, the initial loss in income might not be compensated as much as indicated in our scenario. Fifth, the GTAP-W model considers water quantity and prices but ignores non-market benefits or costs of water use. For instance, the model is unable to predict the direct ecological impact of limiting groundwater use. Sixth, our analysis does not account for surface and groundwater use apart from agriculture, since the necessary data are missing. These issues should be addressed in future research.

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## Annex A

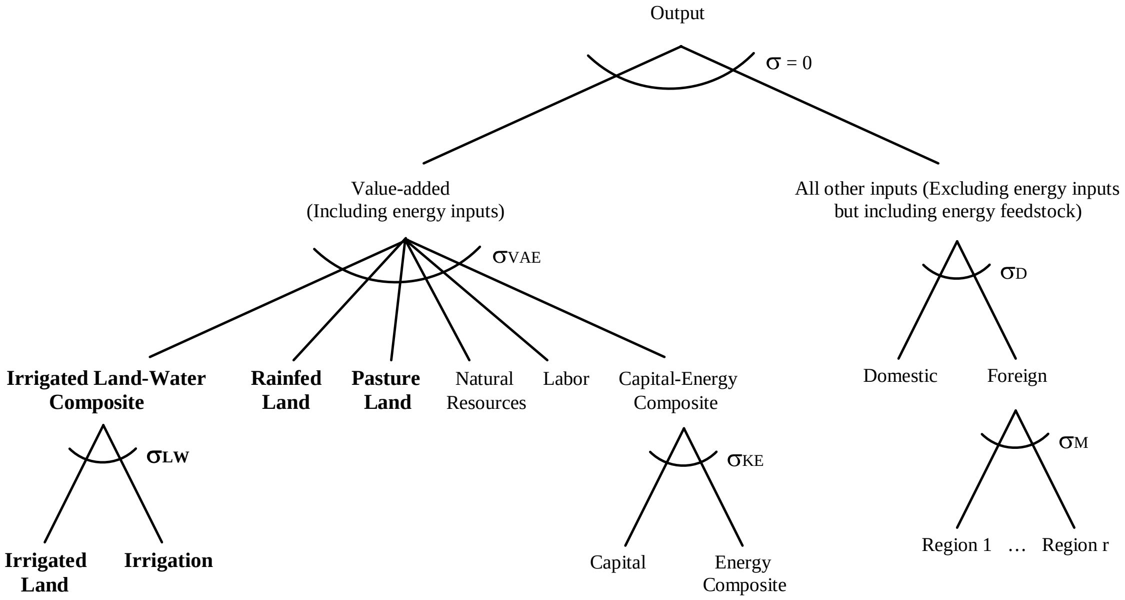


**Figure IV–A1. Nested tree structure for industrial production process in GTAP-W (truncated)**

Note: The original land endowment has been split into pasture land, rainfed land, irrigated land and irrigation (bold letters). σ is the elasticity of substitution between value added and intermediate inputs, σVAE is the elasticity of substitution between primary factors, σLW is the elasticity of substitution between irrigated land and irrigation, σKE is the elasticity of substitution between capital and the energy composite, σD is the elasticity of substitution between domestic and imported inputs and σM is the elasticity of substitution between imported inputs.

**Table IV–A1. Aggregations in GTAP-W**

| ***A. Regional Aggregation*** | ***B. Sectoral Aggregation*** |
|---|---|
| **1. USA -** United States | **1. Rice** - Rice |
| **2. CAN -** Canada | **2. Wheat** - Wheat |
| **3. WEU -** Western Europe | **3. CerCrops** - Cereal grains (maize, millet, sorghum and other grains) |
| **4. JPK -** Japan and South Korea | **4. VegFruits -** Vegetable, fruits, nuts |
| **5. ANZ -** Australia and New Zealand | **5. OilSeeds -** Oil seeds |
| **6. EEU -** Eastern Europe | **6. Sug_Can -** Sugar cane, sugar beet |
| **7. FSU -** Former Soviet Union | **7. Oth_Agr -** Other agricultural products |
| **8. MDE -** Middle East | **8. Animals -** Animals |
| **9. CAM -** Central America | **9. Meat -** Meat |
| **10. SAM -** South America | **10. Food_Prod -** Food products |
| **11. SAS -** South Asia | **11. Forestry -** Forestry |
| **12. SEA -** Southeast Asia | **12. Fishing -** Fishing |
| **13. CHI -** China | **13. Coal -** Coal |
| **14. NAF -** North Africa | **14. Oil -** Oil |
| **15. SSA -** Sub-Saharan Africa | **15. Gas -** Gas |
| **16. ROW -** Rest of the World | **16. Oil_Pcts -** Oil products |
| ***C. Endowments*** | **17. Electricity -** Electricity |
| **Wtr -** Irrigation | **18. Water -** Water |
| **Lnd -** Irrigated land | **19. En_Int_Ind -** Energy intensive industries |
| **RfLand -** Rainfed land | **20. Oth_Ind -** Other industry and services |
| **PsLand -** Pasture land | **21. Mserv -** Market services |
| **Lab -** Labour | **22. NMServ -** Non-market services |
| **Capital -** Capital | |
| **NatlRes -** Natural resources | |

**Annex B: Future baseline simulation**

To obtain a 2025 benchmark equilibrium dataset for the GTAP-W model we use the methodology described by Dixon and Rimmer (2002). This methodology allows us to find a hypothetical general equilibrium state in the future imposing forecasted values for some key economic variables in the initial calibration dataset. In this way, we impose forecasted changes in regional endowments (labour, capital, natural resources, rainfed land, irrigated land and irrigation), in regional factor-specific and multi-factor productivity and in regional population. We use estimates of the regional labour productivity, labour stock and capital stock from the G-Cubed model, a multicountry, multisector intertemporal general equilibrium model of the world economy developed by McKibbin and Wilcoxen (1998). Changes in the allocation of rainfed and irrigated land within a region as well as irrigation and agricultural land productivity are implemented according to the values obtained by the IMPACT model. 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 the GTAP-W model with detailed information for a robust calibration of a new dataset. Finally, we use the medium variant population estimates for 2025 from the Population Division of the United Nations (United Nations, 2004).

Compared to the 2000 baseline data (Table IV-B1), the IMPACT model projects a growth in both harvested crop area as well as crop productivity for 2025 under normal climate conditions (Table IV-B2). The world's crop harvested area is expected to increases by about 1.4 percent between 2000 and 2025. This is equivalent to a total area of 1.3 billion hectares in 2025, 34.4 percent of which is under irrigation. For the same period, green water used (effective rainfall) in rainfed areas is expected to increase by 27.2 percent; and both green and blue water used (water diverted from water systems) in irrigated areas are expected to increase by 33.7 and 32.1 percent, respectively. As a result, total water used in agriculture is expected to rise by 30.4 percent, to 6,466 cubic kilometres in 2025.

Farmers in Sub-Saharan Africa and South Asia use around 37 percent of the world's rainfed area in 2025, which accounts for about 24 percent of the world's crop area (Table IV-B2). Similarly, 62 percent of the world's irrigated area in 2025 is in Asia, which accounts for about 21 percent of the world's crop area. Sub-Saharan Africa, South Asia and China use more than half of total green water used worldwide. Principal users of blue water are South Asia, China and the United States, using almost 70 percent of the total. On the crop level, rainfed production of "cereal grains" and "other agricultural product" consumes about half of the total green water used in dry farms. Similarly, irrigated production of "rice" and "other agricultural products" uses around half of the total green and blue water used in irrigated agriculture.

**Table IV–B1. 2000 Baseline data: Crop harvested area, production and water use by region and crop**

| Regions | 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 ($km^3$) |
| 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.
Source: IMPACT, 2000 baseline data.

## Table IV–B2. 2025 Baseline data: Crop harvested area, production and water use by region and crop

| Regions | 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 ($km^3$) |
| United States | 33,561 | 282,634 | 95 | 68,312 | 649,118 | 178 | 269 | 101,873 | 931,752 | 272 | 269 |
| Canada | 24,547 | 84,579 | 64 | 668 | 7,816 | 2 | 2 | 25,216 | 92,395 | 65 | 2 |
| Western Europe | 49,655 | 471,745 | 82 | 9,206 | 170,610 | 17 | 13 | 58,861 | 642,355 | 99 | 13 |
| Japan and South Korea | 1,330 | 25,507 | 7 | 4,339 | 72,386 | 25 | 2 | 5,669 | 97,893 | 32 | 2 |
| Australia and New Zealand | 20,574 | 87,458 | 45 | 2,211 | 37,586 | 5 | 21 | 22,785 | 125,044 | 50 | 21 |
| Eastern Europe | 33,620 | 214,995 | 91 | 5,411 | 56,306 | 15 | 26 | 39,031 | 271,301 | 106 | 26 |
| Former Soviet Union | 83,041 | 327,597 | 194 | 16,850 | 107,271 | 28 | 62 | 99,890 | 434,868 | 222 | 62 |
| Middle East | 30,330 | 171,058 | 41 | 22,838 | 192,787 | 28 | 84 | 53,169 | 363,844 | 69 | 84 |
| Central America | 13,197 | 177,760 | 63 | 9,543 | 149,400 | 40 | 63 | 22,740 | 327,161 | 103 | 63 |
| South America | 89,653 | 1,305,413 | 468 | 11,725 | 391,766 | 60 | 79 | 101,378 | 1,697,179 | 528 | 79 |
| South Asia | 117,502 | 567,087 | 384 | 129,479 | 893,522 | 511 | 594 | 246,981 | 1,460,609 | 895 | 594 |
| Southeast Asia | 73,223 | 457,800 | 409 | 27,488 | 307,826 | 178 | 76 | 100,711 | 765,626 | 587 | 76 |
| China | 61,143 | 710,893 | 227 | 120,294 | 1,041,731 | 526 | 316 | 181,436 | 1,752,624 | 753 | 316 |
| North Africa | 16,117 | 79,552 | 18 | 7,820 | 114,835 | 4 | 55 | 23,937 | 194,388 | 22 | 55 |
| Sub-Saharan Africa | 200,093 | 727,357 | 873 | 8,311 | 98,412 | 37 | 62 | 208,404 | 825,769 | 910 | 62 |
| Rest of the World | 4,122 | 78,566 | 16 | 1,260 | 47,376 | 7 | 8 | 5,382 | 125,941 | 23 | 8 |
| **Total** | **851,709** | **5,770,002** | **3,075** | **445,754** | **4,338,747** | **1,660** | **1,730** | **1,297,463** | **10,108,749** | **4,736** | **1,730** |
| | | | | | | | | | | | |
| **Crops** | | | | | | | | | | | |
| Rice | 52,329 | 107,187 | 318 | 91,357 | 335,710 | 542.15 | 364.85 | 143,686 | 442,897 | 860 | 365 |
| Wheat | 115,502 | 370,764 | 245 | 88,649 | 397,007 | 141.15 | 335.74 | 204,150 | 767,771 | 387 | 336 |
| Cereal grains | 221,740 | 682,485 | 787 | 74,630 | 566,363 | 244.02 | 321.84 | 296,370 | 1,248,848 | 1,031 | 322 |
| Vegetables, fruits, nuts | 142,260 | 1,838,783 | 523 | 41,014 | 806,515 | 134.72 | 146.85 | 183,274 | 2,645,298 | 658 | 147 |
| Oil seeds | 71,325 | 137,662 | 278 | 30,735 | 99,416 | 90.05 | 111.35 | 102,060 | 237,078 | 368 | 111 |
| Sugar cane, sugar beet | 21,827 | 1,662,782 | 173 | 11,997 | 1,202,418 | 83.59 | 144.46 | 33,823 | 2,865,200 | 257 | 144 |
| Other agricultural products | 226,726 | 970,340 | 751 | 107,373 | 931,317 | 424.58 | 305.38 | 334,099 | 1,901,657 | 1,175 | 305 |
| **Total** | **851,709** | **5,770,002** | **3,075** | **445,754** | **4,338,747** | **1,660** | **1,730** | **1,297,463** | **10,108,749** | **4,736** | **1,730** |

Note: Linear interpolation from IMPACT 2050 simulation with no climate change.
Source: IMPACT.

Figure IV-B1 shows for the 2025 baseline simulation a global map of irrigated harvested area as a share of total crop area by country. Most of the farming land in the Middle East region is nowadays highly irrigated and this situation is projected to persist in the future. Irrigated crop area in Iraq is expected to account for 92 percent of the total crop area. In Saudi Arabia and Iran, the share of irrigated area to total area is projected to be 84 and 73 percent, respectively. In the USA, approximately 67 percent of the total harvested area is expected to be under irrigation in 2025. In Asia, irrigated farming is expected to account for more than half of the total crop area in the region. By contrast, irrigated agriculture in Sub-Saharan Africa is small, only 4 percent of the total crop harvested area is expected to be irrigated by 2025. Most of the countries in Sub-Saharan Africa are expected to continue to use irrigation on less than 5 percent of crop land. Madagascar and Swaziland are exceptions expected to be irrigating around 55 percent of their total crop area. The numbers for Somalia and South Africa are much lower (34 and 22 percent, respectively).

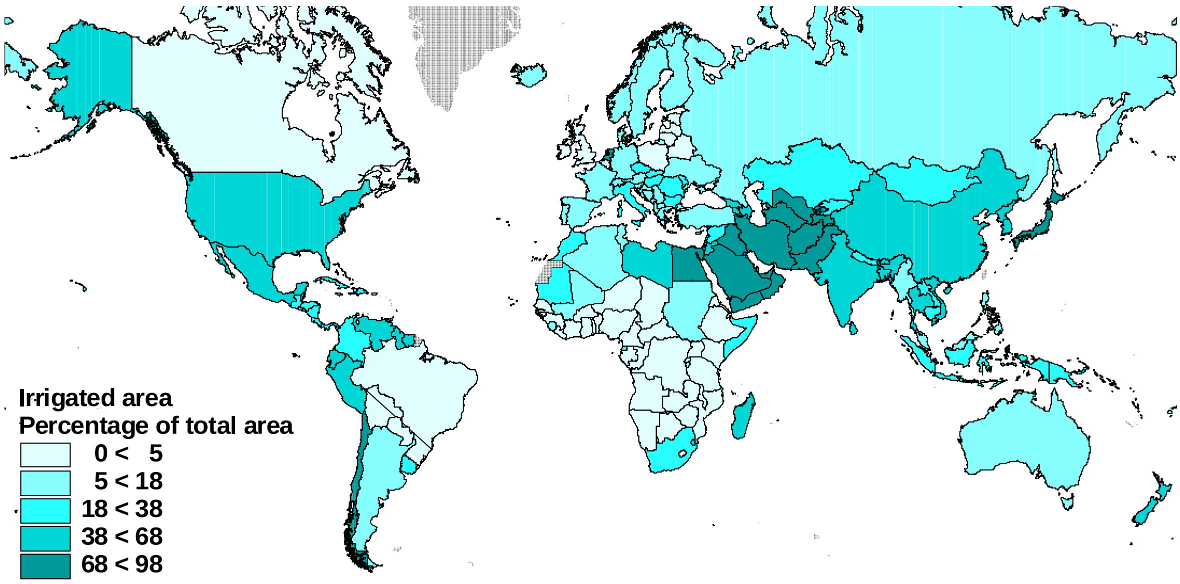


**Figure IV–B1. Irrigated harvested area as a share of total crop harvested area, 2025 baseline simulation**

Source: IMPACT.

# V

## CLIMATE CHANGE IMPACTS ON GLOBAL AGRICULTURE

**Abstract**

Based on predicted changes in the magnitude and distribution of global precipitation, temperature and river flow under the IPCC SRES A1B and A2 scenarios, this study assesses the potential impacts of climate change and $CO_2$ fertilization on global agriculture. The analysis uses the new version of the GTAP-W model, which distinguishes between rainfed and irrigated agriculture and implements water as an explicit factor of production for irrigated agriculture. Future climate change is likely to modify regional water endowments and soil moisture. As a consequence, the distribution of harvested land would change, modifying production and international trade patterns. The results suggest that a partial analysis of the main factors through which climate change will affect agricultural productivity lead to different outcomes. Our results show that global food production, welfare and GDP fall in the two time periods and SRES scenarios. Higher food prices are expected. Independently of the SRES scenario, expected losses in welfare are larger in the long term. They are larger under the SRES A2 scenario for the 2020s and under the SRES A1B scenario for the 2050s. The results show that countries are not only influenced by regional climate change, but also by climate-induced changes in competitiveness.

**Keywords:** Computable General Equilibrium, Climate Change, Agriculture, Water Resources, River Flow

**JEL Classification:** D58, Q54, Q17, Q25

## 1. Introduction

Water is essential. The impact of climate change on water resources is therefore one of the most important reasons for concern about unabated greenhouse gas emissions. However, while many studies have focussed on the natural science aspects of water availability, the human response is crucially important: Adaptation could potentially alleviate the impact of falling water resource but maladaptation may exacerbate the situation. Adaptation, including adaptation to changing water resources, is often studied at the local scale. However, farmers are the biggest global water users and farmers operate, directly or indirectly, at the world market for agricultural products. This paper therefore looks at the impacts of climate-change-induced changes in water resources on agriculture in the context of international trade.

Current observations and climate projections suggest that one of the most significant impacts of climate change is likely to be on the hydrological system, and hence on river flows and regional water resources (Bates et al. 2008; Strzepek and McCluskey 2007). Principal climate variables affecting water availability are precipitation, temperature and potential evaporation. Precipitation is the source of all freshwater resources and determines the level of soil moisture, which is essential in the formation of runoff and hence river flow.[1] Soil moisture is determined not only by the volume and timing of precipitation, but also by a complex interaction and feedbacks with evaporation and temperature (IPCC 2001b).

By itself, an increase in precipitation would increase soil moisture. However, even with higher precipitation, surface runoff may decrease in some river basins due to greater evaporation in a warmer atmosphere (IPCC 2001a). Temperature is particularly important in snow-dominated regions, determining the timing of snowmelt and thus the seasonality of available water. In regions with little or no snowfall, surface runoff is much more dependent on rainfall than on temperature (Bates et al. 2008; Barnett et al. 2005).

Climate model simulations suggest that global average precipitation will increase as global temperature rise. As a result, global water availability is expected to increase with climate change. However, large regional differences are expected. At high latitudes and in some wet tropical areas, river flow and water availability are projected to increase. An opposite trend is projected for some dry regions at mid-latitudes and in the dry tropics (Falloon and Betts 2006; Bates et al. 2008). In many regions, the positive effects of higher annual runoff and total water supply are likely to be offset by the negative effects of changes in precipitation patterns, intensity and extremes, as well as shifts in seasonal runoff. Therefore, the overall global impacts of climate change on freshwater systems are expected to be negative (Bates et al. 2008).

[1] Runoff and river flow are closely related and its distinction can be vague. Runoff is the amount of precipitation which flows into rivers and streams following evaporation and transpiration by plants, usually expressed as units of depth over the area of the catchment. River flow or streamflow is the water flow within a river channel, usually expressed as a rate of flow past a point (IPCC 2001a).

Precipitation intensity and variability are expected to rise under a warmer climate, increasing the risks of flooding and drought in many regions. Alcamo et al. (2007a) estimated an increase in future average water availability in Russia, but also a significant change in the frequency of high and low runoff events; which eventually change the positive effect of more water supply. In many of the main crop areas in Russia, changes in the frequency of extreme climate events could double the frequency of food production shortfalls in the 2020s and triple in the 2070s.

In addition, the projected increase in precipitation intensity is expected to exacerbate water pollution and produce adverse effects on surface and groundwater quality as well as increase the risk of soil erosion (Boxall et al. 2009; Falloon and Betts 2009; Macleod et al. 2010). Similarly, more frequent and intense droughts are expected to spread water stress and increase land degradation, increasing the risk of water and food shortages. Changes in precipitation patterns may also affect groundwater recharge rates (Bates et al. 2008).

Shifts in the amount and seasonality of river flows caused by changes in monthly precipitation and temperature are expected to impact aquatic and riparian ecosystems and modify the availability of water for irrigation, industrial and domestic use. Barnett et al. (2005) projected a decline in the water stored in glaciers and snow cover in the tropical Andes and in many Asian mountain regions, affecting adversely river flow and water supply during the long dry seasons. Changes in river flow would also affect the capacity of hydroelectric power generation.

In addition to affecting water supply systems, climate change will also affect water demand. Higher temperatures and changes in precipitation patterns are expected to increase irrigation water demand for crops. Based on a revised SRES A2 scenario, Fischer et al. (2007) estimated an increase in global irrigation water requirements of 45 percent between 2000 and 2080. Irrigation water requirements were projected to increase by around 50 percent in developing regions and 16 percent in developed regions. Fischer et al. (2007) found that two-thirds of the increases in irrigation water requirements were related to an increase in the average daily requirements caused by warming and changed precipitation patterns; and one-third was related to the extended crop calendars in temperate and sub-tropical zones. In turn, irrigation can also alter local and regional climate (Boucher et al. 2004).

Rosenzweig et al. (2004) pointed out that while changes in the hydrological systems will influence the demand for and supply of water for irrigation, in addition future socio-economic pressures will increase the competition for water between irrigation needs and non-agricultural users due to population and economic growth. Global estimates show an increase in the number of people living in water-stressed regions despite the projected increase in global water availability, suggesting that regional precipitation patterns and demographic and socio-economic factors play an important role on future global water stress (Arnell 2004; Alcamo et al. 2007b).

Agriculture is by far the biggest global user of freshwater resources and consequently highly vulnerable to climate change. Globally, around 70 percent of all available freshwater is used for irrigation, 22 percent is used by industry and 8 percent is used for residential purposes (United Nations 2003). In most developing countries, the agricultural sector provides the main livelihood and employment for most of the population and contributes considerably to national GDP. Therefore, reductions in agricultural production caused by future climate change could seriously weaken food security and worsen the livelihood conditions for the rural poor (Commission for Africa 2005).

The World Bank (2007) identifies five main factors through which climate change will affect the productivity of agricultural crops: changes in precipitation, temperature, carbon dioxide ($CO_2$) fertilization, climate variability, and surface water runoff. Increased climate variability and droughts will affect livestock production as well. Crop production is directly influenced by precipitation and temperature. Precipitation determines the availability of freshwater and the level of soil moisture, which are critical inputs for crop growth. Based on an econometric analysis, Reilly et al. (2003) found that higher precipitation leads to a reduction in yield variability. Therefore, higher precipitation will reduce the yield gap between rainfed and irrigated agriculture, but it may also have a negative impact if extreme precipitation causes flooding (Falloon and Betts 2009).

Temperature and soil moisture determine the length of growing season and control the crop’s development and water requirements. In general, higher temperatures will shorten the freeze periods, promoting cultivation in cool-climate marginal croplands. However, in arid and semi arid areas, higher temperatures will shorten the crop cycle and reduce crop yields (IPCC 2007). A higher atmospheric concentration of carbon dioxide enhances plant growth and increases water use efficiency ($CO_2$ fertilization) and so affects water availability (e.g. Betts et al. 2007; Gedney et al. 2006; Long et al. 2006).

Climate variability, especially changes in rainfall patterns, is particularly important for rainfed agriculture. Soil moisture limitations reduce crop productivity and increase the risk of rainfed farming systems. Although the risk of climate variability is reduced by the use of irrigation, irrigated farming systems are dependent on reliable water resources, therefore they may be exposed to changes in the spatial and temporal distribution of river flow (CA 2007).

The aim of our paper is to assess how climate change impacts on water availability influence agricultural production world-wide. As climate variables we use predicted changes in global precipitation, temperature and river flow under the IPCC SRES A1B and A2 scenarios from Falloon and Betts (2006) and Johns et al. (2006) and include the effect of $CO_2$ fertilization as well. All these variables play an important role in determining agricultural outcomes. Temperature and $CO_2$ fertilization affect both rainfed and irrigated crop production. While precipitation is directly related to runoff and soil moisture and hence to rainfed production; river flow is directly related to irrigation water availability and hence to irrigated production. The analysis is carried out using the new version of the GTAP-W model. Unlike earlier studies we are able to take into account changes in river flow since GTAP-W distinguishes between rainfed and irrigated agriculture and implements water as an explicit factor of production for irrigated agriculture. The GTAP-W model (Calzadilla et al.

2008a) is a global computable general equilibrium (CGE) model that allows for a rich set of economic feedbacks and for a complete assessment of the welfare implications of alternative development pathways. Therefore, our methodology allows us to study the impacts of future availability of water resources on agriculture and within the context of international trade taking into account a more complete set of climate change impacts (see section 2 for more details on the literature).

The remainder of the paper is organized as follows: the next section briefly reviews the literature on economic models of water use including studies of climate change impacts. Section 3 describes the revised version of the GTAP-W model. Section 4 focuses on the future baseline simulations. Section 5 describes the data used and lays down the simulation scenarios. Section 6 discusses the principal results and section 7 concludes.

## 2. Economic models of water use

Economic models of water use 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. Partial and general equilibrium models have been used. While partial equilibrium analysis 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 the economy-wide effect; partial equilibrium models tend to have more detail. Most of the studies using either of the two approaches analyze pricing of irrigation water only (for an overview of this literature see Johansson et al. 2002). Rosegrant et al. (2002) used the IMPACT model to estimate demand and supply of food and water to 2025. While the IMPACT model covers a wide range of agricultural products and regions, other sectors are excluded; it is a partial equilibrium model.

Studies of water use using general equilibrium approaches are generally based on data for a single country or region assuming no effects for the rest of the world of the implemented policy (for an overview of this literature see Calzadilla et al. 2008a or Dudu and Chumi 2008). All of these CGE studies have a limited geographical scope. Berittella et al. (2007) and Calzadilla et al. (2008a) are an exception. Calzadilla et al. (2008a) used the global CGE model GTAP-W, which accounts for water resources use in the agricultural sector, to 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. They show mostly positive welfare gains for water-stressed regions; for non-water scarce regions welfare gains are more mixed and mostly negative. Calzadilla et al. (2010) used the same model to investigate the role of green (rainfall) and blue (irrigation) 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. 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.

Using a previous version of the GTAP-W model, Berrittella et al. (2006, 2007, 2008a and 2008b) analyzed the economic impact of various water resource policies. Unlike the predecessor GTAP-W, the revised GTAP-W model, used here, distinguishes between rainfed and irrigated agriculture. 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.

Despite the global scale of climate change and the fact that food products are traded internationally, climate change impacts on agriculture have mostly been studied at the farm (e.g. Abler et al. 1998), the country or the regional level (e.g. Darwin et al. 1995; Verburg et al. 2008; Calzadilla et al 2009). Early studies of climate change impacts on global agriculture analyzed the economic effects of doubling the atmospheric carbon dioxide concentration based on alternative crop response scenarios with and without $CO_2$ effects on plant growth. Results indicate that the inclusion of $CO_2$ fertilization is likely to offset some of the potential welfare losses generated by climate change (Kane et al. 1992; Reilly et al. 1994; Rosenzweig and Parry 1994; Tsigas et al. 1997; Darwin and Kennedy 2000).

While these approaches were unable to analyze adaptation options at farm or regional level, global CGE models that capture regional changes in agricultural inputs and managements options avoid these limitations. Darwin et al. (1995) used 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 global CGE model and a geographic information system that links climate with production possibilities at regional-level. The results suggest that farm-level adaptations might mitigate any negative impacts induced by climate change. In a more recent analysis, Darwin (2004) suggested 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.

Based on the general equilibrium Basic Linked System (BLS) model, Fischer et al. (1994, 1996) studied the potential biophysical responses of major food crops to a doubling of $CO_2$ concentrations as well as the socio-economic consequences for the period 1990-2060. Parry et al. (1999) used the same model to look at the world’s food security, estimating that climate change may increase the number of people at risk of hunger by around 80 million people in 2080. 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. Adaptations on-farm and via market mechanisms are going to be important contributors to limiting the severity of impacts. Mitigation efforts could potentially reduce the global cost of climate change and decline the number of additional people at risk of malnutrition.

None of these studies have water as an explicit factor of production, as does our GTAP-W model. Moreover, most of these studies are based on scenarios related to a doubling of $CO_2$ concentration, not taking into account the timing of the expected change in climate. Despite the considerable uncertainty in future climate projections (IPCC 2007), detailed information on the impacts of changes in precipitation, temperature and $CO_2$ fertilization on crop yields is available, as well as the benefits of adaptation strategies. However, there is a lack of information about potential impacts of changes in river flow on irrigated agriculture. Our approach, based on the global CGE model GTAP-W, allows us to distinguish between rainfed and irrigated agriculture as well as to analyze how economic actors in one region/sector might respond to climate-induced economic changes in another region/sector. We analyze climate change impacts on global and regional agriculture at two time periods (2020s and 2050s). We use projected changes in global precipitation, temperature and river flow under the IPCC SRES A1B and A2 scenarios; as well as $CO_2$ fertilization effects on crop growth.

## 3. The GTAP-W model

In order to assess the systemic general equilibrium effects of climate change impacts on global agriculture, we use a multi-region world CGE model, called GTAP-W. The model is a further refinement of the GTAP model[2] (Hertel 1997), and is based on the version modified by Burniaux and Truong[3] (2002) 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, and on the IMPACT 2000 baseline data. The model has 16 regions and 22 sectors, 7 of which are in agriculture.[4] 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 (grazing land used by livestock) and land for rainfed and for irrigated agriculture. 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 as yields per hectare are higher. To

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[2] The GTAP model is a standard static CGE 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.

[3] 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 in a nested level of substitution with capital. This allows for more substitution possibilities. Second, database and model are extended to account for $CO_2$ emissions related to energy consumption.

[4] See Table V-A1 in Annex A for the regional, sectoral and factoral aggregation used in GTAP-W.

account for this difference, we split irrigated agriculture further into the value for land and the value for 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 tree diagram in Figure V-A1 in Annex A 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 into the value of rainfed land and the value of irrigated land using its proportionate contribution to total production. The value of pasture land is derived from the value of land in the livestock breeding sector.

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. The numbers indicate how relatively more valuable irrigated agriculture is compared to rainfed agriculture for particular land parcels. The magnitude of additional yield differs not only with respect to the region but also to the crop. On average, producing rice using irrigation is relatively more productive than using irrigation for growing oil seeds, for example. Regionally, on average 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’ 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. For detailed information about the social accounting matrix representation of the GTAP database see McDonald et al. (2005).

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 (CES) (Figure V-A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called ‘‘Armington assumption’’, which accounts for product heterogeneity.[5]

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, labour and capital). Capital and labour are perfectly mobile domestically, but

[5] 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.

immobile internationally. Pasture land, rainfed land, irrigated land, irrigation and natural resources are imperfectly mobile. 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. The expenditure shares are generally fixed, which amounts to saying that the top level utility function has a Cobb-Douglas specification. 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.[6] A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.[7]

In the original GTAP-E 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 constant elasticity of substitution function (Figure V-A1). The procedure how the elasticity of factor substitution between land and irrigation ($\sigma_{LW}$) was obtained is explained in more detail in Calzadilla et al. (2008a). Next, the irrigated land-water composite is combined with pasture land, rainfed land, natural resources, labour and the capital-energy composite in a value-added nest through a CES structure.

The IMPACT model provides detailed information on green water use in rainfed production (defined as effective rainfall); and both green and blue water use in irrigated production (blue water or irrigation is defined as the water diverted from water systems).[8] In the GTAP-W benchmark equilibrium, water used for irrigation is supposed to be identical to the volume of blue 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 social accounting matrix information about payments to factors and the volume of water used in irrigation from IMPACT. Contrary to blue water, green water used in rainfed and irrigated crop production has no price. It is modelled exogenously in the GTAP-W model using information from IMPACT.

The distinction between rainfed and irrigated agriculture within the production structure of the GTAP-W model allows us to study expected physical constraints on water supply due to, for example, climate change. In fact, changes in rainfall patterns can be

[6] A non-homothetic utility function implies that with different income levels a households budget shares spent on various commodities changes.
[7] The equivalent variation measures the welfare impact of a policy change in monetary terms. It is defined as the change in regional household income at constant prices that is equivalent to the proposed change.
[8] 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 the 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).

exogenously modelled in GTAP-W by changes in the productivity of rainfed and irrigated land. In the same way, water excess or shortages in irrigated agriculture can be modelled by exogenous changes to the initial irrigation water endowment.

## 4. Future baseline simulations

Future climate change impacts on agriculture are analyzed at two time periods: the 2020s and 2050s. Economy-wide climate change impacts are compared to alternative no climate change benchmarks for each period. To obtain a future benchmark equilibrium dataset for the GTAP-W model we use the methodology described by Dixon and Rimmer (2002). This methodology allows us to find a hypothetical general equilibrium state in the future imposing projected values for some key economic variables in the initial calibration dataset. In this way, we impose projected changes in regional endowments (labour, capital, natural resources, rainfed land, irrigated land and irrigation), in regional factor-specific and multi-factor productivity and in regional population. We use estimates of regional labour productivity, labour stock and capital stock from the G-Cubed model (McKibbin and Wilcoxen 1998). Changes in the allocation of rainfed and irrigated land within a region as well as irrigation and agricultural land productivity are implemented according to estimates from the IMPACT model (Rosegrant et al. 2002). Finally, we use the medium-variant population estimates from the Population Division of the United Nations (United Nations 2004).

The detailed 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) to the GTAP-W model allows for a calibration of the baseline year and future benchmark equilibriums. We use the IMPACT 2050 simulation without climate change to find a hypothetical general equilibrium in 2020 and 2050. The 2020 data is obtained by linear interpolation between the 2000 baseline data and the 2050 simulation without climate change.

Compared to the 2000 baseline data (Table V-B1 in Annex B), the IMPACT model projects a growth in both harvested area and crop productivity for 2020 under normal climate conditions (Table V-B2 in Annex B). The world’s harvested area is expected to increase by about 1.1 percent between 2000 and 2020. This is equivalent to a total area of 1.3 billion hectares in 2020, 34.2 percent of which is under irrigation. For the same period, the world’s crop production is expected to increase by 32.8 percent. Rainfed crop production increases by 31.3 percent, despite a decrease in rainfed area by 0.1 percent. Irrigated crop production and harvested area increase by 34.8 and 3.5 percent, respectively.

A similar tendency is observed in 2050 (Table V-B3 in Annex B). Between 2000 and 2050, the world’s crop production is expected to increase by 91.7 percent. Rainfed and irrigated production increase by 88.0 and 96.8 percent, respectively. For the same period, the world’s crop area is expected to increase by 2.8 percent. While rainfed crop area decreases by 0.2 percent, irrigated crop area increases by 8.7 percent. In 2050, farmers in Sub-Saharan Africa, South Asia and China are expected to use around half of the world’s crop area, accounting for 37.8 percent of the world's crop production. Sub-Saharan Africa and South Asia are expected to use around 38.3 percent of the world's rainfed area and produce around 22.1 percent of the world's rainfed production. Similarly, South Asia and China are expected to use around 56.4 percent of the world's irrigated area and produce around 41.8 percent of the world's irrigated production.

## 5. Data input and design of simulation scenarios

We analyze climate change impacts on global agriculture based on predicted changes in the magnitude and distribution of global precipitation, temperature and river flow from Falloon and Betts (2006) and Stott et al. (2006). They analyzed data from simulations using the Hadley Centre Global Environmental Model including a dynamic river routing model (HadGEM1-TRIP) (Johns et al. 2006; Martin et al. 2006) over the next century and under the IPCC SRES A1B and A2 scenarios. Their results are in agreement with previous studies (e.g. Arnell 2003; Milly et al. 2005). For consistency, we note here that while these HadGEM1 simulations did include the impact of elevated $CO_2$ concentrations on runoff, they did not include explicit representations of crops, irrigation, groundwater or dams.

A relatively optimistic scenario (A1B) is contrasted with a relatively pessimistic scenario (A2), covering in this way part of the uncertainty of future climate change impacts on water availability. As described in the SRES report (IPCC 2000), the A1B group of the A1 storyline and scenario family considers a balance between fossil intensive and non-fossil energy sources. It shows a future world of very rapid economic growth, global population that peaks in mid-century and decline thereafter, as well as rapid and more efficient technology development. It considers convergence among regions, with a substantial reduction in regional differences in per capita income. The SRES A2 scenario describes a very heterogeneous world. It considers self-reliance and preservation of local identities, and continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The analysis is carried out at two time periods: the 2020s (medium-term) and 2050s (long-term). Both time periods represent the average for the 30-year period centred on the given year; the 2020s represents the average for the 2006-2035 period and the 2050s represents the average for the 2036-2065 period. Predicted changes in precipitation, temperature and river flow under the two emission scenarios are compared to a historic-anthropogenic baseline simulation, which represents the natural variability of these variables. It is the 30-year average for the 1961-1990 period. We use annual average precipitation, temperature and river flow data. Therefore, in the current study we do not consider local scale impacts nor changes in seasonality or extremes.

*River Flow*

Compared to the average for the 1961-1990 period (historic-anthropogenic simulation), Falloon and Betts (2006) found large inter-annual and decadal variability of the average global total river flow, with an initial decrease until around 2060. For the 2071-2100 period, the average global total river flow is projected to increase under both SRES scenarios (around 4 percent under the A1B scenario and 8 percent under the A2 scenario). The A2 scenario produced more severe and widespread changes in river flow than the A1B scenario.

Figure V-1 shows for the two time periods (2020s and 2050s) and for the two emission scenarios (A1B and B2) a global map of predicted changes in river flow relative to the 1961-1990 period. Large regional differences are observed. For both emission scenarios and time periods, the number of countries subject to decreasing river flow is projected to be higher than those with increasing river flow. In general, similar regional patterns of changes in river flow are observed under the two emission scenarios and time periods. Significant decreases in river flow are predicted for northern South America, southern Europe, the Middle East, North Africa and southern Africa. In contrast, substantial increases in river flow are predicted for boreal regions of North America and Eurasia, western Africa and southern Asia. Some exceptions are parts of eastern Africa and the Middle East, where changes in river flow vary depending on the scenario and time period. Additionally under the A1B-2050s scenario, river flow changes are positive for China and negative for Australia and Canada, while opposite trends were observed for other scenarios and time periods.

River flow is a useful indicator of freshwater availability for agricultural production. Irrigated agriculture relies on the availability of irrigation water from surface and groundwater sources, which depend on the seasonality and interannual variability of river flow. Therefore, river flow limits a region’s water supply and hence constrains its ability to irrigate crops. Table V-1 shows for the two time periods and emission scenarios regional changes in river flow and water supply according to the 16 regions defined in Table V-A1 (Annex A). Regional changes in river flow are related to regional changes in water supply by the runoff elasticities of water supply estimated by Darwin et al. (1995) (Table V-1). The runoff elasticity of water supply is defined as the proportional change in a region’s water supply divided by the proportional change in a region’s runoff. That is, an elasticity of 0.5 indicates that a 2 percent change in runoff results in a 1 percent change in water supply. Regional differences in elasticities are related to differences in hydropower capacity, because hydropower production depends on dams, which enable a region to store water that could be withdrawn for irrigation or other uses during dry and rainy seasons.

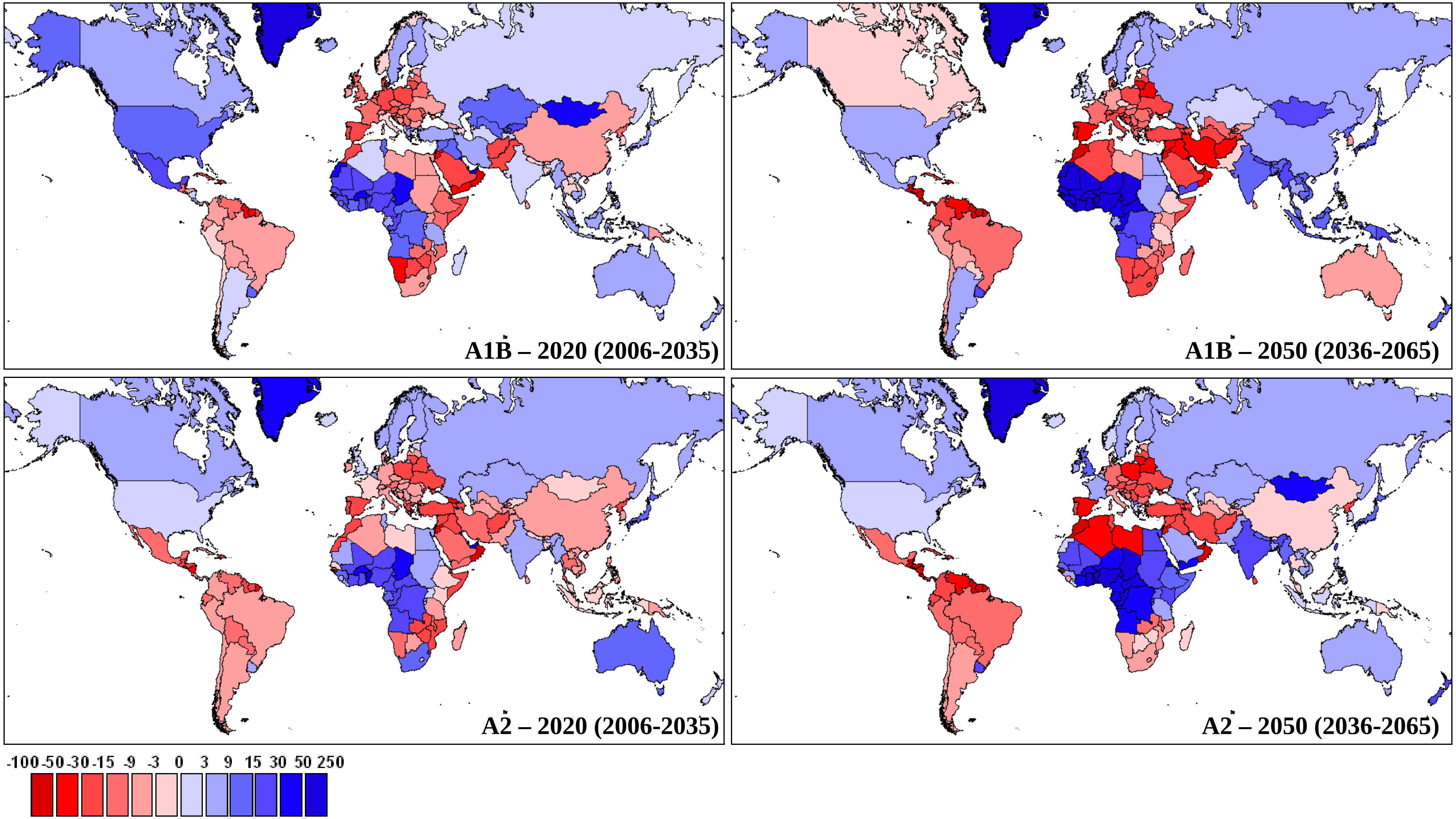


**Figure V–1. Percentage change in annual average river flow under the two emission scenarios and for the two time periods, with respect to the 30-year average for the 1961-1990 period (historic-anthropogenic simulation)**

Own calculations based on Falloon and Betts (2006).

**Table V–1. Percentage change in regional river flow, water supply, precipitation and temperature with respect to the average over the 1961-1990 period**

| Regions | Elasticity of water supply* | Changes in river flow (%) | | | | Changes in water supply (%) | | | | Changes in precipitation (%) | | | | Changes in temperature ( °C ) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020s | | 2050s | | 2020s | | 2050s | | 2020s | | 2050s | | 2020s | | 2050s | |
| | | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 |
| United States | 0.469 | 11.60 | 3.03 | 5.29 | 2.30 | 5.44 | 1.42 | 2.48 | 1.08 | 6.30 | 2.91 | 6.55 | 3.01 | 1.75 | 1.88 | 3.76 | 3.73 |
| Canada | 0.448 | 5.59 | 8.02 | 0.46 | 4.22 | 2.51 | 3.59 | 0.21 | 1.89 | 6.24 | 6.31 | 9.40 | 9.72 | 2.24 | 2.03 | 4.37 | 4.24 |
| Western Europe | 0.342 | -5.81 | -0.77 | -4.21 | -0.46 | -1.99 | -0.26 | -1.44 | -0.16 | 0.68 | 2.07 | 0.25 | 1.48 | 1.82 | 1.78 | 3.24 | 3.17 |
| Japan and South Korea | 0.426 | 7.57 | 7.85 | 11.60 | 10.67 | 3.23 | 3.34 | 4.94 | 4.55 | 4.38 | 4.55 | 6.80 | 5.40 | 1.47 | 1.51 | 2.93 | 2.68 |
| Australia and New Zealand | 0.341 | 6.82 | 11.67 | -5.05 | 6.10 | 2.33 | 3.98 | -1.72 | 2.08 | -0.08 | 4.91 | -8.92 | -6.13 | 1.05 | 1.10 | 2.04 | 2.24 |
| Eastern Europe | 0.299 | -11.60 | -8.03 | -11.92 | -16.52 | -3.47 | -2.40 | -3.57 | -4.94 | 1.22 | 1.70 | 2.52 | -0.32 | 1.49 | 1.64 | 3.19 | 3.14 |
| Former Soviet Union | 0.453 | 2.68 | 3.62 | 7.76 | 8.18 | 1.21 | 1.64 | 3.52 | 3.71 | 7.08 | 8.59 | 13.76 | 12.97 | 2.30 | 2.58 | 4.69 | 4.56 |
| Middle East | 0.223 | 8.31 | -20.18 | -32.61 | -23.84 | 1.85 | -4.50 | -7.27 | -5.32 | -2.18 | -4.13 | -12.84 | -8.93 | 1.40 | 1.42 | 2.87 | 2.91 |
| Central America | 0.318 | 16.17 | -10.28 | -5.85 | -19.85 | 5.14 | -3.27 | -1.86 | -6.31 | 2.83 | -5.49 | -9.35 | -15.39 | 1.23 | 1.19 | 2.38 | 2.36 |
| South America | 0.318 | -3.97 | -6.51 | -9.08 | -12.41 | -1.26 | -2.07 | -2.89 | -3.95 | -3.70 | -4.69 | -7.87 | -8.90 | 1.21 | 1.05 | 2.37 | 2.37 |
| South Asia | 0.279 | -3.91 | -0.33 | 11.16 | 8.99 | -1.09 | -0.09 | 3.11 | 2.51 | -1.78 | 1.60 | 1.56 | 2.62 | 1.26 | 1.08 | 2.60 | 2.45 |
| Southeast Asia | 0.324 | 4.04 | -0.72 | 13.91 | 5.54 | 1.31 | -0.23 | 4.51 | 1.80 | 2.10 | -0.84 | 5.17 | 1.03 | 1.18 | 1.17 | 2.54 | 2.38 |
| China | 0.412 | -6.07 | -7.64 | 8.78 | -0.67 | -2.50 | -3.15 | 3.62 | -0.27 | -1.94 | -3.32 | 6.22 | 1.91 | 1.48 | 1.52 | 3.16 | 2.88 |
| North Africa | 0.223 | -3.16 | 7.66 | 6.99 | 20.07 | -0.70 | 1.71 | 1.56 | 4.48 | -5.61 | -9.24 | -22.56 | -25.27 | 1.44 | 1.50 | 2.66 | 2.81 |
| Sub-Saharan Africa | 0.223 | 4.42 | 9.75 | 17.78 | 25.26 | 0.99 | 2.17 | 3.97 | 5.63 | -3.82 | -2.45 | -2.88 | -1.49 | 1.06 | 0.94 | 2.08 | 2.03 |
| Rest of the World | 0.324 | -4.22 | -4.29 | 15.91 | 0.27 | -1.37 | -1.39 | 5.15 | 0.09 | -1.13 | -0.69 | 8.31 | 0.52 | 1.83 | 1.67 | 3.62 | 3.47 |

Source: Own calculation based on Falloon and Betts (2006).
* Regional elasticities of water supply are based on Darwin et al. (1995).

*Precipitation*

Falloon and Betts (2006) pointed out that predicted changes in river flow were largely driven by changes in precipitation, since the pattern of changes in precipitation were very similar to the pattern of changes in river flow, and the changes in evaporation opposed the changes in river flow in some regions. Figure V-2 shows for the two time periods and for the two emission scenarios a global map of predicted changes in precipitation relative to the 1961-1990 period. Decreases in both river flow and precipitation were predicted for northern South America and southern Europe while evaporation was reduced – hence the reduction in river flow was driven mostly by the reduction in rainfall. In high latitude rivers, increases in river flow and rainfall were predicted along with increases in evaporation, so the river flow changes here were mostly driven by changes in rainfall. In tropical Africa, increases in river flow and rainfall were predicted along with decreases in evaporation, so changes in rainfall and evaporation both contributed to the river flow changes.

The exposure of irrigated agriculture to the risk of changes in climate conditions is more limited compared to rainfed agriculture which depends solely on adequate soil moisture. Therefore, rainfed production is highly vulnerable to changes in precipitation. Regional crop yield responses to changes in precipitation and temperature are based on Rosenzweig and Iglesias (1994) (Table V-B4 in Annex B). They used the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) dynamic crop growth models to estimate climate change impacts on crop yields at 112 sites in 18 countries, representing both major production areas and vulnerable regions at low, mid and high latitudes. The IBSNAT models have been validated over a wide range of environments and are not specific to any particular location or soil type. Rosenzweig and Iglesias (1994) used the IBSNAT crop models CERES (wheat, maize, rice and barley) and SOYGRO (soybeans) to analyze crop yield responses to arbitrary incremental changes in precipitation (+/- 20%) and temperature (+2°C and +4°C).

*Temperature*

The regional patterns of temperature increases were similar for the two emission scenarios and time periods (Figure V-3). Larger temperature increases are expected at high latitudes and under the SRES A1B scenario.

Crop production is directly influenced by precipitation and temperature. Temperature and soil moisture determine the length of growing season and control the crop’s development and water requirements. Crop yield responses to higher temperature levels are based on Rosenzweig and Iglesias (1994) (Table V-B4 in Annex B).

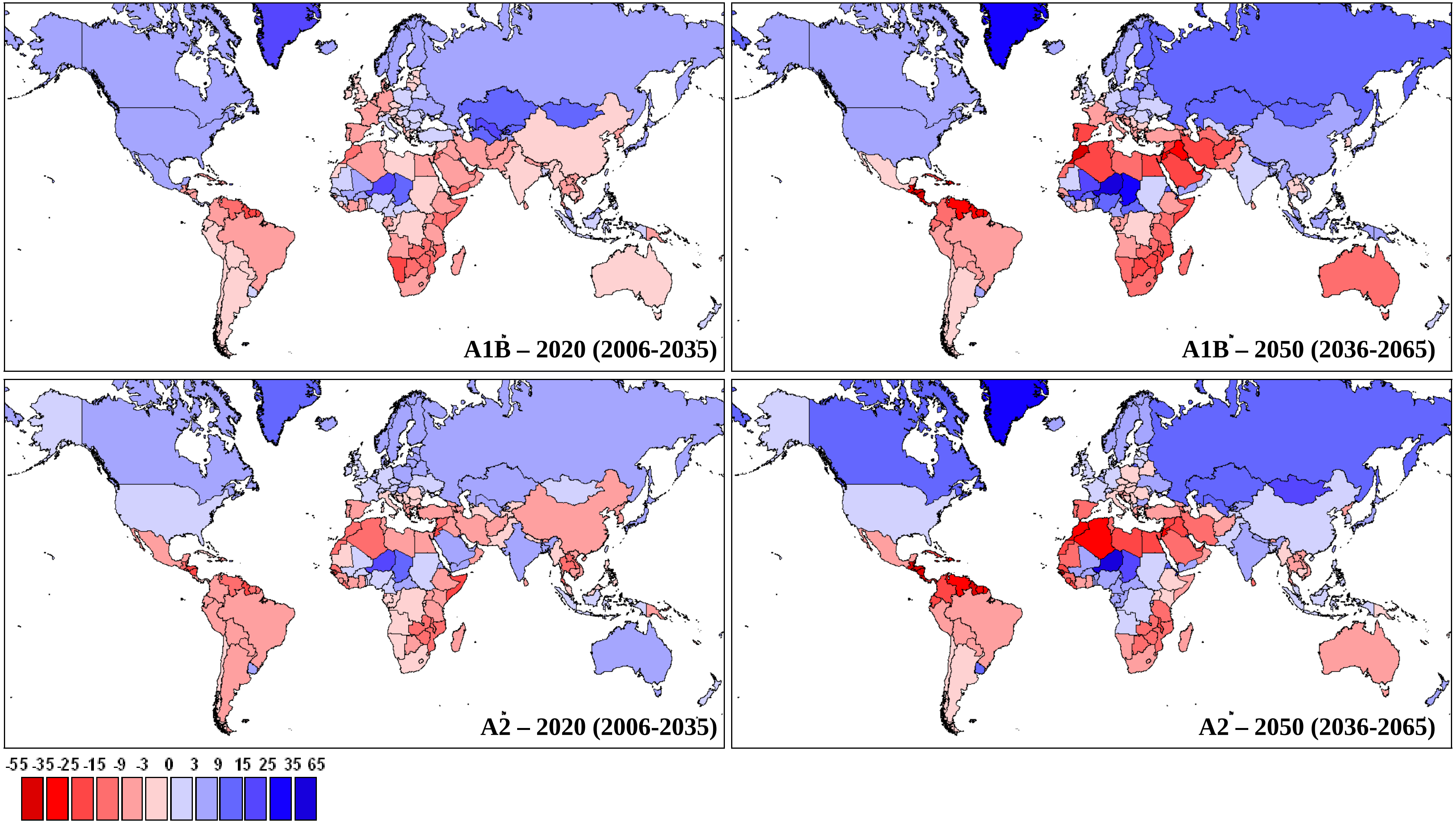


**Figure V–2. Percentage change in annual average precipitation under the two emission scenarios and for the two time periods, with respect to the 30-year average for the 1961-1990 period (historic-anthropogenic simulation)**

Own calculations based on Falloon and Betts (2006).

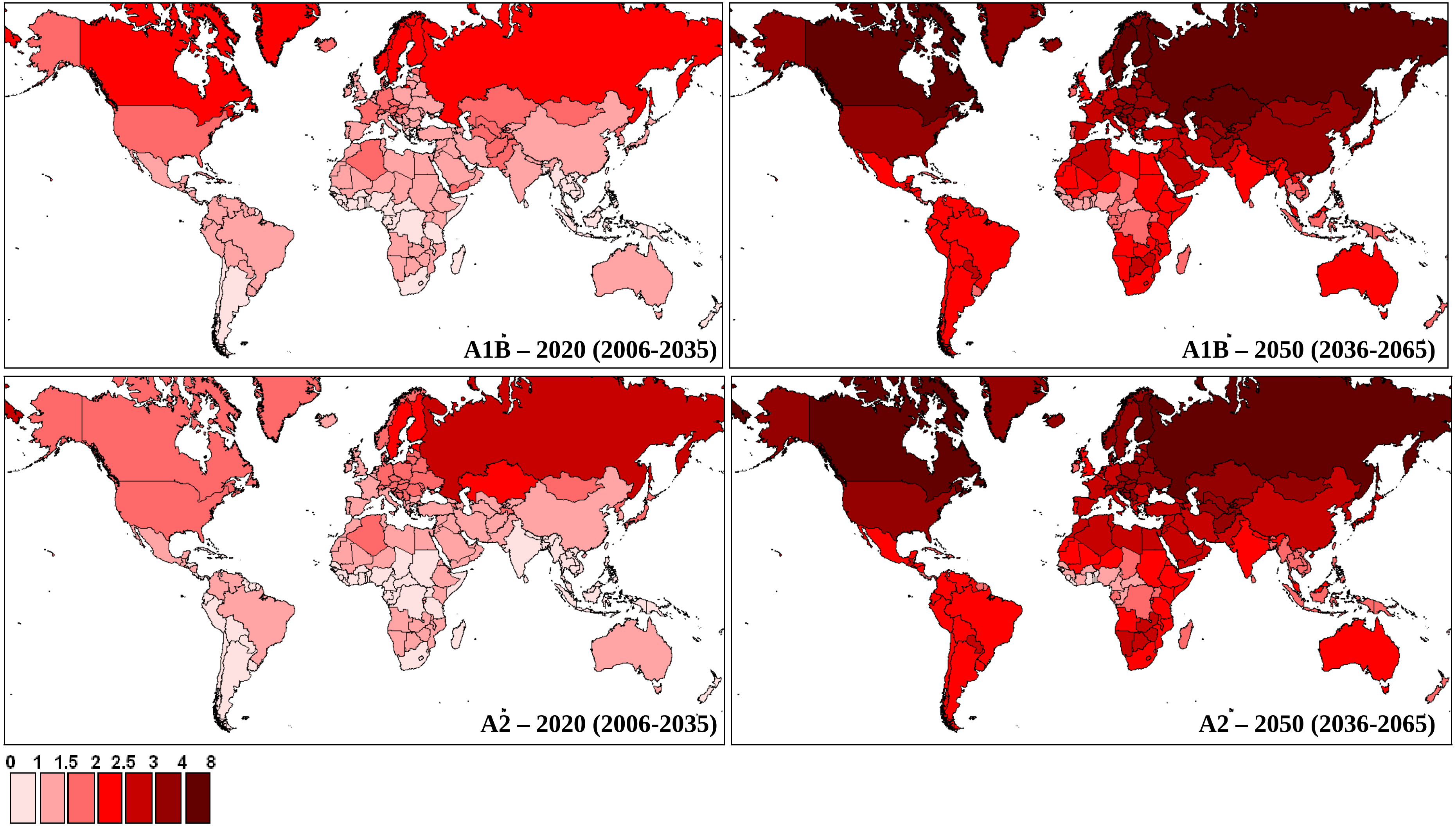


**Figure V–3. Percentage change in annual average temperature under the two emission scenarios and for the two time periods, with respect to the 30-year average for the 1961-1990 period (historic-anthropogenic simulation)**

Own calculations based on Falloon and Betts (2006).

*$CO_2$ Fertilization*

Our estimates of the $CO_2$ fertilization effect on crop yields are based on information presented by Tubiello et al. (2007). They reported yield response ratios for C3 and C4 crops to elevated $CO_2$ concentrations in the three major crop models (CERES, EPIC and AEZ). The yield response ratio of a specific crop is the yield of that crop at elevated $CO_2$ concentration, compared by the yield at a reference scenario. In our analysis, we use the average crop yield response of the three crop models. The $CO_2$ concentrations levels in 2020 and 2050 are consistent with the IPCC SRES A1B and A2 scenarios. Thus, for 2020 and under the SRES A1B scenario crop yield is expected to increase by 5.5 and 2.4 percent at 418 ppm for C3 and C4 crops, respectively. For the same period, crop yield increases under the SRES A2 scenario are expected to be slightly lower, 5.2 and 2.3 percent at 414 ppm for C3 and C4 crops, respectively. $CO_2$ concentration levels in 2050 are expected to be similar for both SRES scenarios (522 ppm), increasing C3 crop yields by 12.6 percent and C4 crop yields by 5.2 percent.

*Simulation Scenarios*

Based on the regional changes in river flow (water supply), precipitation and temperature presented in Table V-1, we evaluate the impact of climate change on global agriculture according to six scenarios. Each scenario is implemented for the two time periods and emission scenarios presented above. Table V-2 presents the main characteristics of the six simulation scenarios.

**Table V–2. Summary of inputs for the simulation scenarios**

| | Changes in | | | | |
|---|---|---|---|---|---|
| | **Precipitation** | **$CO_2$** | **Temperature** | **River flow** | **Land** |
| ***Scenario*** | | | | | |
| Precipitation-only | X | | | | |
| Precipitation-$CO_2$ | X | X | | | |
| Precipitation-temperature-$CO_2$ | X | X | X | | |
| Water-only | X | | | X | |
| Water-land | X | | | X | X |
| All-factors | X | X | X | X | X |

The first three scenarios are directly comparable to previous studies. They show the impacts of changes in precipitation, temperature and $CO_2$ fertilization on crop yields. These scenarios are implemented in such a way that no distinction is made between rainfed and irrigated agriculture, as was common in previous work. The *precipitation-only* scenario analyzes changes in precipitation, the *precipitation-$CO_2$* scenario analyzes changes in precipitation and $CO_2$ fertilization, and the *precipitation-temperature-$CO_2$* scenario analyzes changes in precipitation, temperature and $CO_2$ fertilization.

The last three scenarios distinguish between rainfed and irrigated agriculture –the main feature of the new version of the GTAP-W model. Thus, the *water-only* scenario considers that climate change may bring new problems to irrigated agriculture related to changes in the availability of water for irrigation. Reductions in river flow diminish water supplies for irrigation increasing the climate risk for irrigated agriculture. In addition, climate change is expected to affect rainfed agriculture by changing the level of soil moisture through changes in precipitation. In this scenario, changes in precipitation modify rainfed crop yields, while changes in water supply modify the irrigation water endowment for irrigated crops.

Future climate change would modify regional water endowments and soil moisture, and in response the distribution of harvested land would change. Therefore, the *water-land* scenario explores possible shifts in the geographical distribution of irrigated agriculture. It assumes that irrigated areas could expand in regions with higher water supply. Similarly, irrigated farming can become unsustainable in regions subject to water shortages. In this scenario, in addition to changes in precipitation and water supply, irrigated areas in GTAP-W are adjusted according to the changes in regional water supply presented in Table V-1. That is, the relative change in the supply of irrigated land equals the relative change in water supply.

The last scenario, called *all-factors,* shows the impacts of all climate variables affecting agricultural production. Temperature and $CO_2$ fertilization affect both rainfed and irrigated crop yields, precipitation affects rainfed crop yields and water supply influences both the irrigation water endowment and the distribution of irrigated crop areas.

## 6. Results

Climate change impacts agricultural productivity, modifying agricultural production world-wide. Table V-3 shows for the two time periods (2020s and 2050s) and SRES scenarios (A1B and A2) the percentage changes in total crop production by region and simulation scenario. Let us first consider the three simulation scenarios that do not distinguish between rainfed and irrigated agriculture. For both time periods, changes in *precipitation-only* slightly increase world food production under the SRES A1B scenario and decrease under the SRES A2 scenario. As expected, the addition of $CO_2$ fertilization in the analysis causes an increase in world food production. However, the $CO_2$ fertilization effect is not strong enough to compensate world food losses caused by higher temperatures (compare *precipitation-*$CO_2$ and *precipitation-temperature-*$CO_2$ scenarios). For the 2050s and under the *precipitation-temperature-*$CO_2$ scenario, world food production is expected to decrease by around 2.5 percent under both emission scenarios. Our results are thus comparable to Parry et al. (1999), probably because we used roughly the same input data. Other studies foresee an increase in the world food production due to climate change.

At the regional level, climate change impacts on food production vary widely. Under the *precipitation-temperature-*$CO_2$ scenario, food production decreases particularly in developing regions, with the exception of China and Sub-Saharan Africa, where production increases as other regions lose their comparative advantages. An opposite trend is observed in developed regions, where food production is expected to increase. Exceptions are the former Soviet Union, the United States and Canada, regions with high yield responses to temperature increases.

**Table V–3. Percentage change in total crop production for the two time periods and SRES scenarios by region and simulation scenario, percentage change with respect to the baseline (no climate change) simulations**

| Regions | Baseline | Precipitation-only | | Precipitation-$CO_2$ | | Precip.-Temp.-$CO_2$ | | Water-only | | Water-land | | All-factors | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (thousand mt) | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 |
| ***Results for the 2020s*** | | | | | | | | | | | | | |
| United States | 873,944 | 1.50 | 0.76 | 2.02 | 1.34 | -2.06 | -3.59 | 0.97 | 0.29 | 2.03 | 0.72 | -1.61 | -3.73 |
| Canada | 88,699 | 3.23 | 3.88 | -0.67 | 0.08 | -1.31 | 0.44 | 3.19 | 3.50 | 2.53 | 3.58 | -2.02 | -0.05 |
| Western Europe | 638,485 | -0.06 | 0.23 | -0.22 | 0.04 | 2.39 | 2.81 | -0.12 | 0.13 | -0.33 | 0.18 | 2.09 | 2.72 |
| Japan and South Korea | 97,299 | 0.03 | 0.14 | -0.12 | -0.01 | 0.54 | 0.63 | 0.10 | 0.22 | 0.51 | 0.76 | 1.08 | 1.31 |
| Australia and New Zealand | 118,733 | -0.40 | 3.13 | -0.02 | 3.11 | 7.25 | 11.07 | -0.28 | 2.77 | -0.44 | 2.89 | 7.16 | 10.76 |
| Eastern Europe | 263,636 | 0.08 | 0.16 | 1.77 | 1.77 | 1.59 | 1.50 | 0.04 | 0.11 | -0.09 | 0.05 | 1.41 | 1.38 |
| Former Soviet Union | 410,215 | 0.44 | 0.60 | 0.53 | 0.66 | -4.04 | -4.77 | 0.34 | 0.46 | 0.34 | 0.52 | -4.19 | -4.95 |
| Middle East | 340,539 | -1.64 | -2.92 | -2.01 | -3.05 | -2.19 | -3.93 | -1.31 | -2.47 | -1.36 | -2.69 | -1.83 | -3.62 |
| Central America | 299,744 | -0.05 | -0.33 | 0.49 | 0.23 | -0.18 | -0.42 | 0.16 | -0.29 | 0.50 | -0.64 | 0.42 | -0.75 |
| South America | 1,496,931 | -0.19 | -0.13 | -0.16 | -0.11 | -0.06 | 0.21 | -0.17 | -0.13 | -0.24 | -0.15 | -0.12 | 0.19 |
| South Asia | 1,373,835 | 0.00 | 0.32 | 1.44 | 1.66 | -1.67 | -0.77 | -0.04 | 0.20 | -0.18 | 0.19 | -1.87 | -0.92 |
| Southeast Asia | 713,486 | 0.81 | 0.03 | 3.89 | 3.01 | -5.47 | -6.40 | 0.72 | 0.01 | 0.81 | 0.02 | -5.48 | -6.41 |
| China | 1,705,822 | -0.39 | -0.51 | -0.16 | -0.25 | 2.50 | 2.38 | -0.40 | -0.42 | -0.96 | -1.05 | 1.86 | 1.77 |
| North Africa | 180,359 | -1.53 | -2.68 | -2.11 | -2.97 | -1.67 | -3.42 | -0.46 | -0.67 | -0.54 | -0.52 | -0.29 | -0.42 |
| Sub-Saharan Africa | 751,022 | -0.26 | -0.07 | -0.66 | -0.49 | 0.83 | 1.27 | -0.26 | -0.10 | -0.29 | -0.04 | 0.79 | 1.29 |
| Rest of the World | 113,851 | -0.09 | -0.04 | 0.47 | 0.50 | -1.36 | -1.05 | -0.10 | -0.05 | -0.15 | -0.07 | -1.41 | -1.09 |
| **Total** | **9,466,600** | **0.03** | **-0.04** | **0.54** | **0.46** | **-0.36** | **-0.42** | **0.00** | **-0.06** | **-0.04** | **-0.13** | **-0.45** | **-0.53** |
| ***Results for the 2050s*** | | | | | | | | | | | | | |
| United States | 1,232,174 | 3.02 | 1.80 | 5.88 | 4.86 | -8.04 | -9.36 | 1.33 | 0.75 | 2.06 | 1.16 | -9.20 | -10.12 |
| Canada | 106,975 | 12.56 | 13.23 | 9.11 | 9.75 | -7.48 | -5.87 | 10.37 | 10.62 | 9.96 | 10.69 | -10.04 | -8.53 |
| Western Europe | 640,851 | 1.34 | 1.45 | 4.07 | 4.22 | 4.83 | 5.02 | 0.90 | 1.03 | 0.68 | 1.09 | 4.30 | 4.83 |
| Japan and South Korea | 99,685 | 1.63 | 1.59 | 0.43 | 0.47 | 4.92 | 5.23 | 1.59 | 1.58 | 2.91 | 3.06 | 6.47 | 6.86 |
| Australia and New Zealand | 158,200 | -9.25 | -5.76 | -4.08 | -1.12 | 6.98 | 9.99 | -8.56 | -5.61 | -8.80 | -5.61 | 6.95 | 9.49 |
| Eastern Europe | 302,068 | 0.61 | 0.23 | 6.67 | 6.35 | 2.92 | 2.68 | 0.45 | 0.05 | 0.31 | -0.13 | 2.59 | 2.29 |
| Former Soviet Union | 555,515 | 3.00 | 2.94 | 4.62 | 4.61 | -20.91 | -20.07 | 2.35 | 2.25 | 2.52 | 2.48 | -21.28 | -20.42 |
| Middle East | 490,596 | -17.47 | -11.22 | -12.61 | -7.95 | -24.10 | -17.12 | -16.48 | -10.82 | -16.84 | -11.05 | -23.24 | -16.81 |
| Central America | 481,010 | -0.52 | -0.87 | 1.56 | 1.32 | -1.64 | -2.03 | -0.39 | -0.68 | -0.64 | -1.52 | -1.70 | -2.70 |
| South America | 2,905,101 | -0.24 | -0.26 | 1.21 | 1.23 | -1.84 | -1.82 | -0.24 | -0.26 | -0.28 | -0.34 | -1.77 | -1.81 |
| South Asia | 1,932,186 | 0.82 | 1.20 | 4.98 | 5.24 | -3.14 | -1.96 | 0.70 | 0.93 | 0.82 | 1.08 | -3.16 | -2.17 |
| Southeast Asia | 1,054,256 | 2.60 | 0.69 | 10.68 | 8.89 | -11.86 | -12.54 | 2.39 | 0.62 | 2.75 | 0.83 | -11.63 | -12.28 |
| China | 1,992,463 | 1.67 | 1.02 | 4.11 | 3.64 | 10.07 | 9.89 | 1.51 | 0.40 | 2.50 | 0.27 | 11.18 | 9.04 |
| North Africa | 272,933 | -19.87 | -23.70 | -16.33 | -18.87 | -25.75 | -31.91 | -7.22 | -9.60 | -7.27 | -9.26 | -8.90 | -13.73 |
| Sub-Saharan Africa | 1,245,619 | 0.99 | 1.05 | 0.76 | 0.84 | 3.91 | 4.02 | 0.58 | 0.59 | 0.55 | 0.66 | 3.54 | 3.69 |
| Rest of the World | 195,251 | 0.23 | 0.00 | 2.26 | 2.11 | -3.78 | -3.73 | 0.24 | 0.01 | 0.31 | 0.01 | -3.58 | -3.64 |
| **Total** | **13,664,884** | **0.03** | **-0.09** | **2.85** | **2.74** | **-2.64** | **-2.46** | **0.02** | **-0.13** | **0.24** | **-0.09** | **-2.28** | **-2.38** |

**Table V–4. Percentage change in total water use in agricultural production for the two time periods and SRES scenarios by region and simulation scenario, percentage change with respect to the baseline (no climate change) simulations**

| Regions | Baseline ($km^3$) | Precipitation-only | | Precipitation-$CO_2$ | | Precip.-Temp.-$CO_2$ | | Water-only | | Water-land | | All-factors | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 |
| ***Results for the 2020s*** | | | | | | | | | | | | | |
| United States | 520 | 2.19 | 1.06 | 3.80 | 2.67 | -3.45 | -5.61 | 1.33 | 0.32 | 3.21 | 0.97 | -2.65 | -5.82 |
| Canada | 67 | 3.42 | 4.07 | -0.36 | 0.39 | -1.62 | 0.18 | 3.36 | 3.73 | 2.69 | 3.79 | -2.27 | -0.23 |
| Western Europe | 115 | -0.11 | 0.20 | -0.23 | 0.04 | 3.02 | 3.45 | -0.19 | 0.09 | -0.50 | 0.12 | 2.60 | 3.32 |
| Japan and South Korea | 33 | -0.21 | -0.02 | -0.81 | -0.63 | 1.17 | 1.43 | -0.14 | 0.00 | -0.16 | 0.16 | 1.35 | 1.76 |
| Australia and New Zealand | 70 | -0.56 | 5.62 | 1.40 | 7.10 | 11.27 | 17.91 | -0.21 | 3.85 | -0.08 | 4.59 | 11.76 | 16.85 |
| Eastern Europe | 130 | 0.08 | 0.16 | 2.12 | 2.10 | 1.89 | 1.78 | -0.09 | 0.01 | -0.57 | -0.30 | 1.22 | 1.30 |
| Former Soviet Union | 278 | 0.73 | 0.96 | 1.31 | 1.48 | -5.87 | -6.82 | 0.36 | 0.49 | 0.46 | 0.70 | -6.21 | -7.21 |
| Middle East | 147 | -3.89 | -7.04 | -2.49 | -5.46 | -6.80 | -10.56 | -1.48 | -3.69 | -1.07 | -5.47 | -3.94 | -8.81 |
| Central America | 157 | -0.03 | -0.54 | 1.48 | 0.94 | -0.72 | -1.15 | 0.54 | -0.43 | 1.50 | -1.35 | 0.81 | -1.96 |
| South America | 565 | -0.48 | -0.33 | -0.50 | -0.37 | 0.04 | 0.67 | -0.41 | -0.29 | -0.65 | -0.43 | -0.13 | 0.57 |
| South Asia | 1,410 | 0.03 | 0.50 | 2.64 | 2.96 | -2.74 | -1.47 | -0.13 | 0.12 | -0.49 | 0.10 | -3.26 | -1.88 |
| Southeast Asia | 627 | 0.74 | 0.00 | 3.54 | 2.72 | -5.27 | -6.17 | 0.68 | -0.01 | 0.69 | -0.05 | -5.33 | -6.23 |
| China | 1,031 | -0.50 | -0.69 | 0.66 | 0.44 | 2.96 | 2.71 | -0.49 | -0.53 | -1.36 | -1.55 | 2.00 | 1.75 |
| North Africa | 75 | -5.70 | -9.42 | -5.05 | -8.45 | -8.11 | -12.66 | -0.64 | -0.64 | -0.90 | 0.03 | -2.85 | -2.41 |
| Sub-Saharan Africa | 902 | -0.34 | -0.16 | -0.73 | -0.56 | 0.90 | 1.38 | -0.32 | -0.14 | -0.37 | -0.05 | 0.87 | 1.48 |
| Rest of the World | 29 | -0.12 | -0.05 | 1.40 | 1.40 | -2.73 | -2.26 | -0.12 | -0.07 | -0.44 | -0.35 | -3.03 | -2.55 |
| **Total** | **6,156** | **-0.01** | **-0.10** | **1.27** | **1.13** | **-1.17** | **-1.16** | **0.00** | **-0.08** | **-0.09** | **-0.25** | **-1.27** | **-1.33** |
| ***Results for the 2050s*** | | | | | | | | | | | | | |
| United States | 647 | 2.99 | 1.55 | 8.47 | 7.15 | -10.45 | -11.91 | 1.01 | 0.47 | 2.03 | 0.99 | -11.69 | -12.62 |
| Canada | 69 | 12.24 | 12.94 | 9.92 | 10.56 | -8.19 | -6.62 | 10.74 | 11.06 | 10.31 | 11.05 | -9.70 | -8.25 |
| Western Europe | 97 | 1.33 | 1.50 | 4.84 | 5.00 | 5.58 | 5.86 | 0.81 | 0.97 | 0.48 | 1.03 | 4.83 | 5.53 |
| Japan and South Korea | 35 | 1.29 | 1.47 | -0.33 | -0.17 | 5.59 | 5.93 | 1.20 | 1.32 | 2.39 | 2.73 | 6.69 | 7.28 |
| Australia and New Zealand | 78 | -13.69 | -8.76 | -5.10 | -0.36 | 8.52 | 12.92 | -8.79 | -5.64 | -9.41 | -5.23 | 11.86 | 15.46 |
| Eastern Europe | 137 | 0.71 | 0.30 | 7.32 | 6.96 | 3.98 | 3.72 | 0.25 | -0.14 | -0.52 | -1.16 | 2.69 | 2.17 |
| Former Soviet Union | 312 | 3.65 | 3.60 | 5.74 | 5.69 | -22.76 | -21.88 | 2.37 | 2.29 | 2.85 | 2.89 | -23.52 | -22.55 |
| Middle East | 179 | -26.55 | -17.09 | -19.79 | -11.33 | -34.04 | -24.17 | -16.75 | -11.00 | -19.64 | -13.00 | -26.50 | -19.74 |
| Central America | 214 | -1.00 | -1.47 | 2.94 | 2.55 | -2.06 | -2.54 | -0.55 | -0.99 | -1.19 | -2.88 | -2.20 | -3.93 |
| South America | 837 | -0.27 | -0.12 | 0.06 | 0.19 | -0.09 | -0.03 | -0.40 | -0.37 | -0.87 | -0.74 | -0.65 | -0.67 |
| South Asia | 1,881 | 0.87 | 1.35 | 6.61 | 6.93 | -3.88 | -2.54 | 0.82 | 0.97 | 1.31 | 1.44 | -3.46 | -2.49 |
| Southeast Asia | 843 | 2.71 | 0.72 | 10.59 | 8.78 | -12.22 | -12.96 | 2.55 | 0.60 | 2.49 | 0.55 | -12.42 | -13.13 |
| China | 1,249 | 1.80 | 1.00 | 6.46 | 5.82 | 10.64 | 10.51 | 1.72 | 0.32 | 3.10 | 0.16 | 12.16 | 9.46 |
| North Africa | 89 | -36.40 | -41.38 | -28.32 | -33.10 | -43.60 | -50.38 | -4.77 | -5.64 | -4.19 | -3.70 | -8.76 | -10.89 |
| Sub-Saharan Africa | 1,359 | 0.58 | 0.75 | 1.05 | 1.20 | 3.58 | 3.83 | 0.32 | 0.44 | 0.24 | 0.51 | 3.26 | 3.60 |
| Rest of the World | 43 | 0.36 | -0.02 | 4.65 | 4.39 | -5.97 | -5.86 | 0.45 | 0.00 | 1.32 | 0.05 | -5.09 | -5.78 |
| **Total** | **8,068** | **0.21** | **0.10** | **4.30** | **4.19** | **-2.81** | **-2.44** | **0.50** | **0.22** | **0.77** | **0.26** | **-2.19** | **-2.31** |

Patterns in global and regional water use generally follow those observed in agricultural production. Table V-4 shows the effect of the different scenarios on total agricultural water use. Under the *precipitation-temperature-$CO_2$* scenario, reductions in global water use are more pronounced for the 2050s and under the SRES A1B scenario. For the 2050s, global water use decreases by 2.8 and 2.4 percent for the SRES A1B and A2 scenario, respectively. For the same simulation scenario and time period, reductions in regional water use are more pronounced in water-scare regions such as North Africa and the Middle East. Water use in these regions decreases by between 24 to 50 percent, depending on the SRES scenario. Increases in agricultural water use are higher in China and Australia and New Zealand, between 9 to 13 percent depending on the SRES scenario.

Table V-5 shows changes in welfare by region, time period and scenario. At the global level, changes in welfare are larger in the 2050s. Although $CO_2$ fertilization improves agricultural production and generates welfare gains (*precipitation-$CO_2$* scenario), they are not strong enough to offset the negative effects of changes in precipitation and higher temperature (*precipitation-temperature-$CO_2$* scenario). At the regional level, changes in welfare vary across regions and SRES scenarios. Under the *precipitation-temperature-$CO_2$* scenario, welfare gains are expected in most of the developed regions and welfares losses affect most of the developing regions.

Above, we mimic previous studies. Below we take advantage of the distinction between rainfed and irrigated agriculture in GTAP-W. As the risk of climate change is lower for irrigated agriculture, the initial decrease in global irrigated crop production under the *precipitation-only* scenario turns into an increase under the *water-only* scenario (Table V-6). That is, changes in precipitation do not have a direct effect on irrigated crop production but changes in river flow do (*water-only* scenario). Therefore, irrigated crop production is less vulnerable to changes in water resources due to climate change.

While global irrigated production decreases and rainfed production increases under the *precipitation-only* scenario, an opposite trend is observed under the *water-only* scenario (except for the SRES A2 scenario in the 2020s). However, changes in total world crop production under both scenarios are similar (Table V-6). This implies that whenever irrigation is possible (*water-only* scenario) food production relies on irrigated crops. As a result, global water use increases or decreases less and global welfare losses are smaller or even positive (Table V-6). For the 2050s, global welfare losses are about half those under the *precipitation-only* scenario. At the regional level, differences in the results are larger for water-scarce regions such as North Africa and the Middle East, where irrigation plays an important role in crop production.

**Table V–5. Changes in regional welfare for two time periods and SRES scenarios by simulation scenario (million USD), changes with respect to the baseline (no climate change) simulations**

| Regions | Precipitation-only | | Precipitation-$CO_2$ | | Precip.-Temp.-$CO_2$ | | Water-only | | Water-land | | All-factors | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 |
| ***Results for the 2020s*** | | | | | | | | | | | | |
| United States | 718 | 352 | 1,098 | 796 | -931 | -1,859 | 571 | 105 | 1,014 | 254 | -606 | -2,055 |
| Canada | 61 | 74 | -42 | -32 | -39 | -4 | 65 | 69 | 43 | 65 | -60 | -20 |
| Western Europe | 113 | 32 | 2,542 | 2,379 | 1,138 | 1,420 | 101 | 7 | 200 | -104 | 1,248 | 1,325 |
| Japan and South Korea | 298 | 198 | 1,702 | 1,562 | -168 | -276 | 271 | 182 | 514 | 279 | 55 | -189 |
| Australia and New Zealand | -73 | 134 | -485 | -318 | 781 | 1,023 | -64 | 117 | -92 | 135 | 756 | 1,022 |
| Eastern Europe | 66 | 63 | 1,563 | 1,503 | 678 | 593 | 47 | 50 | 0 | -2 | 618 | 538 |
| Former Soviet Union | 444 | 499 | 1,469 | 1,471 | -5,515 | -6,680 | 371 | 426 | 406 | 460 | -5,654 | -6,865 |
| Middle East | -422 | -976 | 834 | 352 | -2,584 | -3,496 | -305 | -767 | -245 | -878 | -2,353 | -3,344 |
| Central America | 46 | -25 | 87 | 28 | -86 | -165 | 67 | -37 | 154 | -84 | 46 | -240 |
| South America | -244 | -151 | -721 | -633 | 436 | 828 | -230 | -147 | -334 | -169 | 332 | 805 |
| South Asia | 198 | 885 | 4,968 | 5,338 | -5,541 | -3,292 | 58 | 630 | -141 | 601 | -5,948 | -3,632 |
| Southeast Asia | 470 | 70 | 2,209 | 1,806 | -3,157 | -3,759 | 403 | 44 | 493 | 30 | -3,137 | -3,813 |
| China | -124 | -336 | 1,843 | 1,596 | 795 | 529 | -116 | -250 | -503 | -819 | 441 | 71 |
| North Africa | -398 | -830 | 22 | -328 | -1,299 | -2,078 | -93 | -205 | -89 | -177 | -859 | -1,107 |
| Sub-Saharan Africa | -89 | -49 | -238 | -204 | 157 | 266 | -92 | -47 | -113 | -32 | 129 | 283 |
| Rest of the World | 2 | 1 | 178 | 171 | -334 | -293 | -2 | -3 | -4 | -11 | -340 | -308 |
| **Total** | **1,064** | **-58** | **17,027** | **15,488** | **-15,669** | **-17,245** | **1,053** | **174** | **1,303** | **-452** | **-15,333** | **-17,530** |
| ***Results for the 2050s*** | | | | | | | | | | | | |
| United States | 8,549 | 5,232 | 13,803 | 12,241 | -22,875 | -30,028 | 3,137 | 1,646 | 4,663 | 2,295 | -29,695 | -34,251 |
| Canada | 2,937 | 3,209 | -125 | -22 | 1,244 | 1,865 | 2,308 | 2,325 | 2,057 | 2,274 | 22 | 462 |
| Western Europe | -8,293 | -8,657 | 50,244 | 50,387 | 7,952 | 7,795 | -6,081 | -5,726 | -4,622 | -6,398 | 13,627 | 11,767 |
| Japan and South Korea | 1,864 | 1,025 | 15,961 | 15,469 | 6,141 | 6,201 | 1,717 | 1,002 | 4,317 | 2,471 | 9,265 | 8,012 |
| Australia and New Zealand | -3,131 | -1,129 | -8,504 | -7,685 | 18,303 | 19,333 | -3,535 | -1,873 | -4,003 | -1,947 | 15,560 | 16,912 |
| Eastern Europe | -3,649 | -4,653 | 26,928 | 26,485 | -9,300 | -9,518 | -2,435 | -3,129 | -2,129 | -3,568 | -7,011 | -7,797 |
| Former Soviet Union | 6,180 | 5,521 | 25,337 | 24,976 | -183,783 | -173,842 | 6,103 | 5,757 | 7,161 | 6,601 | -179,459 | -169,498 |
| Middle East | -30,700 | -19,816 | -3,892 | 1,407 | -73,756 | -54,302 | -26,475 | -16,681 | -26,354 | -16,958 | -66,360 | -49,479 |
| Central America | 1,687 | 1,228 | -4,220 | -4,446 | 10,908 | 9,566 | 1,029 | 428 | 458 | -638 | 8,535 | 6,188 |
| South America | 7,919 | 8,898 | -28,850 | -28,467 | 60,915 | 59,061 | 4,389 | 4,292 | 1,819 | 3,552 | 49,634 | 48,800 |
| South Asia | -1,252 | 1,922 | 79,826 | 81,526 | -94,676 | -77,829 | 1,169 | 3,978 | 3,664 | 4,991 | -86,006 | -72,555 |
| Southeast Asia | 3,646 | -362 | 23,908 | 21,652 | -42,111 | -43,539 | 3,577 | 97 | 4,955 | 609 | -38,809 | -41,028 |
| China | 2,727 | 389 | 24,389 | 23,365 | 17,399 | 17,160 | 2,644 | -559 | 6,398 | -905 | 20,873 | 14,920 |
| North Africa | -25,704 | -33,257 | -11,473 | -14,585 | -53,774 | -71,418 | -7,444 | -10,289 | -7,309 | -9,876 | -17,871 | -26,039 |
| Sub-Saharan Africa | 4,775 | 5,196 | -13,511 | -13,376 | 33,606 | 32,786 | 2,872 | 2,966 | 1,918 | 2,947 | 27,964 | 28,202 |
| Rest of the World | 256 | 35 | 1,811 | 1,706 | -3,481 | -3,463 | 255 | 13 | 367 | 8 | -3,197 | -3,405 |
| **Total** | **-32,189** | **-35,220** | **191,633** | **190,634** | **-327,288** | **-310,173** | **-16,771** | **-15,752** | **-6,641** | **-14,542** | **-282,929** | **-268,788** |

**Table V–6. Summary of the climate change impacts on agricultural production by simulation scenario, percentage change with respect to the baseline simulations**

| Description | Baseline | Precipitation-only | | Precipitation-$CO_2$ | | Precip.-Temp.-$CO_2$ | | Water-only | | Water-land | | All-factors | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 |
| ***Results for the 2020s*** | | | | | | | | | | | | | |
| Total production (thousand mt) | 9,466,600 | 0.03 | -0.04 | 0.54 | 0.46 | -0.36 | -0.42 | 0.00 | -0.06 | -0.04 | -0.13 | -0.45 | -0.53 |
| Rainfed production (thousand mt) | 5,413,975 | 0.09 | 0.41 | -2.30 | -1.85 | 1.68 | 2.08 | -0.07 | 0.06 | -0.11 | 0.48 | 1.54 | 2.16 |
| Irrigated production (thousand mt) | 4,052,625 | -0.04 | -0.65 | 4.33 | 3.54 | -3.08 | -3.76 | 0.09 | -0.22 | 0.04 | -0.96 | -3.10 | -4.12 |
| Total area (thousand ha) | 1,293,880 | -- | -- | -- | -- | -- | -- | -- | -- | 0.04 | -0.30 | 0.04 | -0.30 |
| Rainfed area (thousand ha) | 851,843 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Irrigated area (thousand ha) | 442,036 | -- | -- | -- | -- | -- | -- | -- | -- | 0.11 | -0.88 | 0.11 | -0.88 |
| Total water used ($km^3$) | 6,156 | -0.01 | -0.10 | 1.27 | 1.13 | -1.17 | -1.16 | 0.00 | -0.08 | -0.09 | -0.25 | -1.27 | -1.33 |
| Green water used ($km^3$) | 4,511 | 0.03 | 0.09 | 0.21 | 0.26 | -0.07 | 0.09 | -0.04 | -0.03 | -0.18 | -0.10 | -0.30 | -0.12 |
| Blue water used ($km^3$) | 1,645 | -0.14 | -0.64 | 4.19 | 3.51 | -4.17 | -4.59 | 0.11 | -0.21 | 0.17 | -0.65 | -3.95 | -4.64 |
| Change in welfare (million USD) | -- | 1,064 | -58 | 17,027 | 15,488 | -15,669 | -17,245 | 1,053 | 174 | 1,303 | -452 | -15,333 | -17,530 |
| Change in GDP (million USD) | -- | 1,064 | -57 | 17,041 | 15,503 | -15,651 | -17,229 | 1,053 | 174 | 1,304 | -451 | -15,314 | -17,513 |
| Change in GDP (percentage) | -- | 0.00 | 0.00 | 0.03 | 0.03 | -0.03 | -0.03 | 0.00 | 0.00 | 0.00 | 0.00 | -0.03 | -0.04 |
| ***Results for the 2050s*** | | | | | | | | | | | | | |
| Total production (thousand mt) | 13,664,884 | 0.03 | -0.09 | 2.85 | 2.74 | -2.64 | -2.46 | 0.02 | -0.13 | 0.24 | -0.09 | -2.28 | -2.38 |
| Rainfed production (thousand mt) | 7,749,674 | 1.15 | 1.14 | -1.94 | -1.93 | 1.31 | 1.39 | -0.47 | -0.38 | -0.81 | -0.35 | -0.28 | 0.09 |
| Irrigated production (thousand mt) | 5,915,210 | -1.43 | -1.70 | 9.12 | 8.86 | -7.83 | -7.50 | 0.66 | 0.20 | 1.62 | 0.23 | -4.89 | -5.63 |
| Total area (thousand ha) | 1,315,381 | -- | -- | -- | -- | -- | -- | -- | -- | 0.79 | 0.28 | 0.79 | 0.28 |
| Rainfed area (thousand ha) | 851,036 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Irrigated area (thousand ha) | 464,345 | -- | -- | -- | -- | -- | -- | -- | -- | 2.25 | 0.79 | 2.25 | 0.79 |
| Total water used ($km^3$) | 8,068 | 0.21 | 0.10 | 4.30 | 4.19 | -2.81 | -2.44 | 0.50 | 0.22 | 0.77 | 0.26 | -2.19 | -2.31 |
| Green water used ($km^3$) | 5,910 | 1.00 | 0.85 | 3.05 | 2.91 | -0.72 | -0.44 | 0.55 | 0.28 | 0.52 | 0.17 | -1.04 | -1.10 |
| Blue water used ($km^3$) | 2,158 | -1.97 | -1.95 | 7.70 | 7.69 | -8.53 | -7.91 | 0.35 | 0.06 | 1.43 | 0.51 | -5.33 | -5.64 |
| Change in welfare (million USD) | -- | -32,189 | -35,220 | 191,633 | 190,634 | -327,288 | -310,173 | -16,771 | -15,752 | -6,641 | -14,542 | -282,929 | -268,788 |
| Change in GDP (million USD) | -- | -31,956 | -34,958 | 193,057 | 192,083 | -322,895 | -306,087 | -16,684 | -15,688 | -6,555 | -14,476 | -279,560 | -265,699 |
| Change in GDP (percentage) | -- | -0.03 | -0.04 | 0.20 | 0.20 | -0.33 | -0.32 | -0.02 | -0.02 | -0.01 | -0.01 | -0.29 | -0.28 |

The distinction between rainfed and irrigated agriculture in GTAP-W allows us to separate green (rainfall) and blue (irrigation) water used in crop production. While changes in irrigated production modify the use of blue water resources, changes in rainfed and irrigated production modify the use of green water resources. Comparing the *precipitation-only* and the *water-only* scenario, blue water use follows the same pattern as irrigated crop production (Table V-6). It decreases under the *precipitation-only* scenario and increases under the *water-only* scenario.

When irrigated crop areas are affected by changes in irrigation water supply (*water-land* scenario), global irrigated crop production decreases slightly for the 2020s and increases for the 2050s (compared to the *water-only* scenario). The same trend is observed for global crop production and welfare. Following changes in regional water supply, the world's irrigated crop areas expand under both time periods and emission scenarios, except for the SRES A2 scenario in the 2020s (*water-land* scenario) (Table V-6). For the 2020s, world irrigated areas are expected to increases by around 0.5 million hectares under the SRES A1B scenario and decrease by around 4 million hectares under the SRES A2 scenario. For the 2050s, world irrigated areas increase by about 10 and 4 million hectares under the SRES A1B and A2 scenarios, respectively. At regional level (results not shown), irrigated areas expand mainly in the United States (SRES A1B - 2020s), China (SRES A1B - 2050s) and South Asia (SRES A1B and A2 - 2050s). Irrigated crop areas decline mainly in China and the Middle East under the SRES A2 scenario in the 2020s.

Impacts of changes in precipitation, temperature, $CO_2$ fertilization, river flow and irrigation area on world agriculture are analyzed in the *all-factors* scenario. At the global level, total production decreases by around 0.5 percent in the 2020s and by around 2.3 in the 2050s. The decline is slightly more pronounced under the SRES A2 scenario (Table V-3). At the regional level, total crop production increases in developed regions, with the exception of the former Soviet Union, the United States and Canada. Total crop production decreases in most of the developing regions, particularly in the Middle East, Southeast Asia and North Africa.

Changes in water supply for rainfed and irrigated agriculture lead to shifts in rainfed and irrigated production. Despite the increase in irrigated crop areas, global irrigated production declines between 3 to 6 percent, depending on the SRES scenario and time period. Expected declines are marked for the SRES A2 scenario and for the 2050s (Table V-6, *all-factors* scenario). Irrigated crop production declines mainly in the United States, the Middle East, North Africa and South Asia (results not shown). These are regions with high negative yield responses to changes in temperature and where irrigated production contributes substantially to total crop production.

Changes in irrigated production drive changes in water use under the *all-factors* scenario. Blue, green and total water use decline with irrigated production. Under the SRES A2 scenario, climate change leads to a reduction in total water use world-wide by around 1.3 percent in the 2020s (82 cubic kilometres) and around 2.3 percent in the 2050s (187 cubic kilometres). Declines are less pronounced under the SRES A1 scenario (Table V-4). At regional level, total water use declines largely in the Middle East, the former Soviet Union, Southeast Asia and the United States. Total water use reductions in these regions most than double in the 2050s.

Climate change modifies agricultural productivity affecting crop production and hence food prices. Figure V-4 shows the percentage changes in sectoral crop production and world market prices for the *all-factors* scenario compared to the baseline simulations. Sectoral crop production decreases and market prices increase under both emission scenarios and time periods. With the exception of vegetables, fruits and nuts, larger declines in sectoral production and hence higher food prices are expected under the SRES A2 scenario in the 2020s. Changes in sectoral production and food prices are more pronounced in the 2050s and vary according to the crop type and SRES scenario. Higher market prices are expected for cereal grains, sugar cane, sugar beet and wheat (between 39 to 43 percent depending on the SRES scenario).

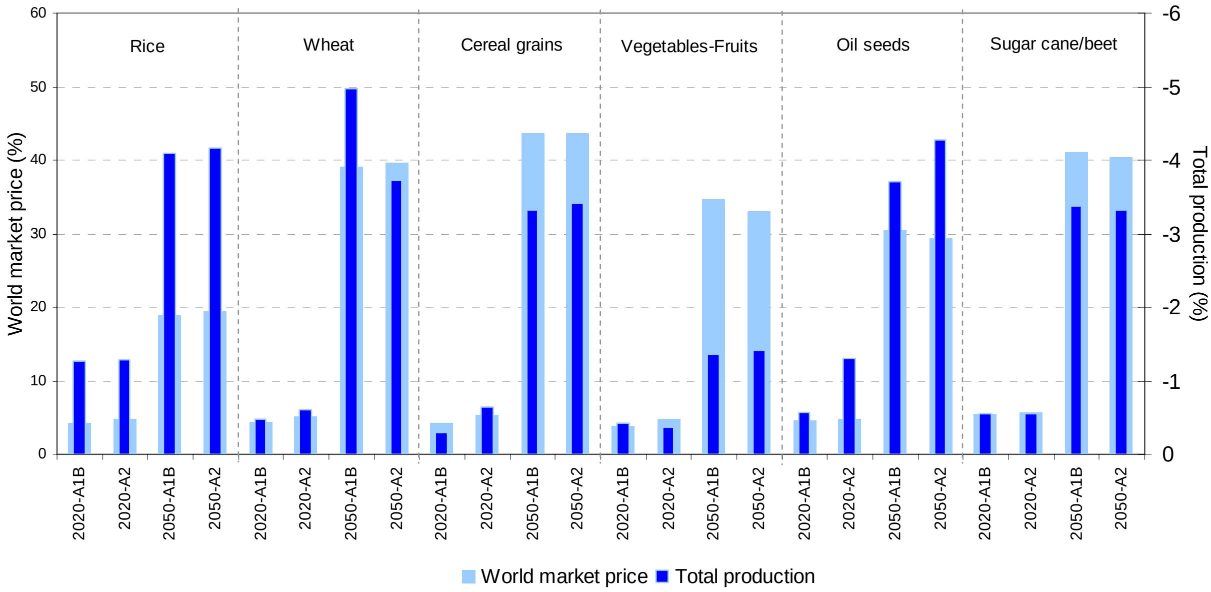


**Figure V–4. Changes in total agricultural production and world market price by crop, *all-factors* scenario**

Own calculations.

Changes in agricultural production and prices induce changes in welfare. For the *all-factors* scenario, global welfare losses in the 2050s (around 283 and 269 billion USD under the SRES A1B and A2 scenario, respectively) are more than 15 times larger than those expected in the 2020s. Global welfare losses are slightly larger under the SRES A2 scenario in the 2020s and under the SRES A1B scenario in the 2050s (Table V-5). The largest loss in global GDP due to climate change is estimated under the SRES A1B scenario at 280 billion USD, equivalent to 0.29 percent of global GDP (Table V-6).

Figure V-5 shows changes in global welfare by scenario and individual input variable. Comparing the differences between *water-land* and *all-factors* on the one hand and *precipitation-only* and *precipitation-temperature-*$CO_2$ on the other hand, we see that adding carbon dioxide fertilization and warming to the mix has a clear negative effect on welfare. Comparing the individual effects of the input variables on welfare, we find that there is a small positive effect of carbon dioxide fertilization and a large negative effect of warming. However, the negative effect of warming is much smaller if we distinguish between rainfed and irrigated agriculture (by considering changes in river flow) and let irrigated areas adjust to the new situation.

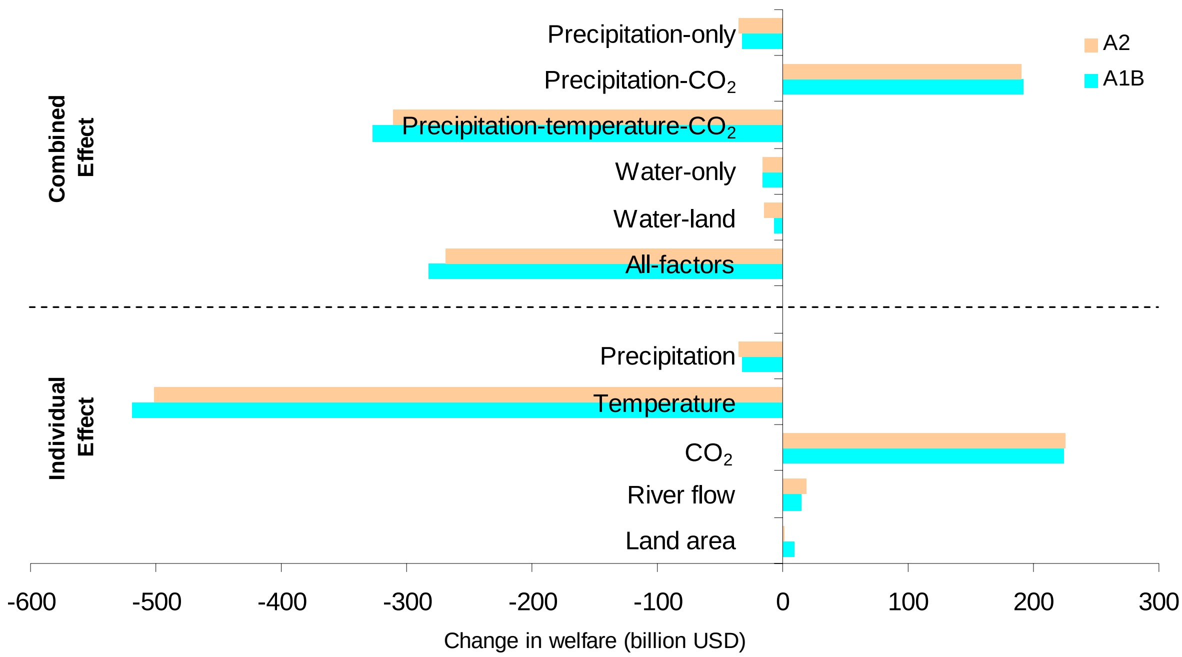


**Figure V–5. Changes in global welfare by scenario (combined effect) and input variable (individual effect), results for the 2050's**

Individual effects on welfare are computed as follows: Precipitation is the *precipitation-only* scenario. Temperature is the difference between the *precipitation-temperature-*$CO_2$ and *precipitation-*$CO_2$ scenarios. Carbon dioxide fertilization ($CO_2$) is the difference between the *precipitation-*$CO_2$ and *precipitation-only* scenarios. River flow is the difference between the *water-only* and *precipitation-only* scenarios. Irrigated land area is the difference between the *water-land* and *water-only* scenarios.

At the regional level, welfare varies widely showing that regions are not only influenced by regional climate change, but also by climate-induced changes in competitiveness. Figure V-6 shows, for the *all-factors* scenario, changes in welfare as a function of the regional changes in precipitation and the terms of trade. Each (x,y) pair contains information for a specific region, time period and emission scenario. Temperature is the main climate variable explaining welfare changes. Figure V-6(a) shows a negative relationship between welfare and temperature. Temperature alone is able to explain around 20 percent of the variation in regional welfare ($R^2$ = 0.21). However, this negative trend is mainly driven by large welfare losses and temperature increase in the former Soviet Union for the 2050's (right bottom of the figure). The adjusted trend line without those observations shows no relationship between welfare and temperature, suggesting that positive and negative welfare impacts are likely to be distributed unevenly. Climate change impacts agricultural productivity and hence modifies the comparative advantages of regional agricultural production. Figure V-6(b) shows a clear positive relationship between changes in regional welfare and the terms of trade. Around 70 percent of the regional variations in welfare are explained by changes in the terms of trade ($R^2$ = 0.71).

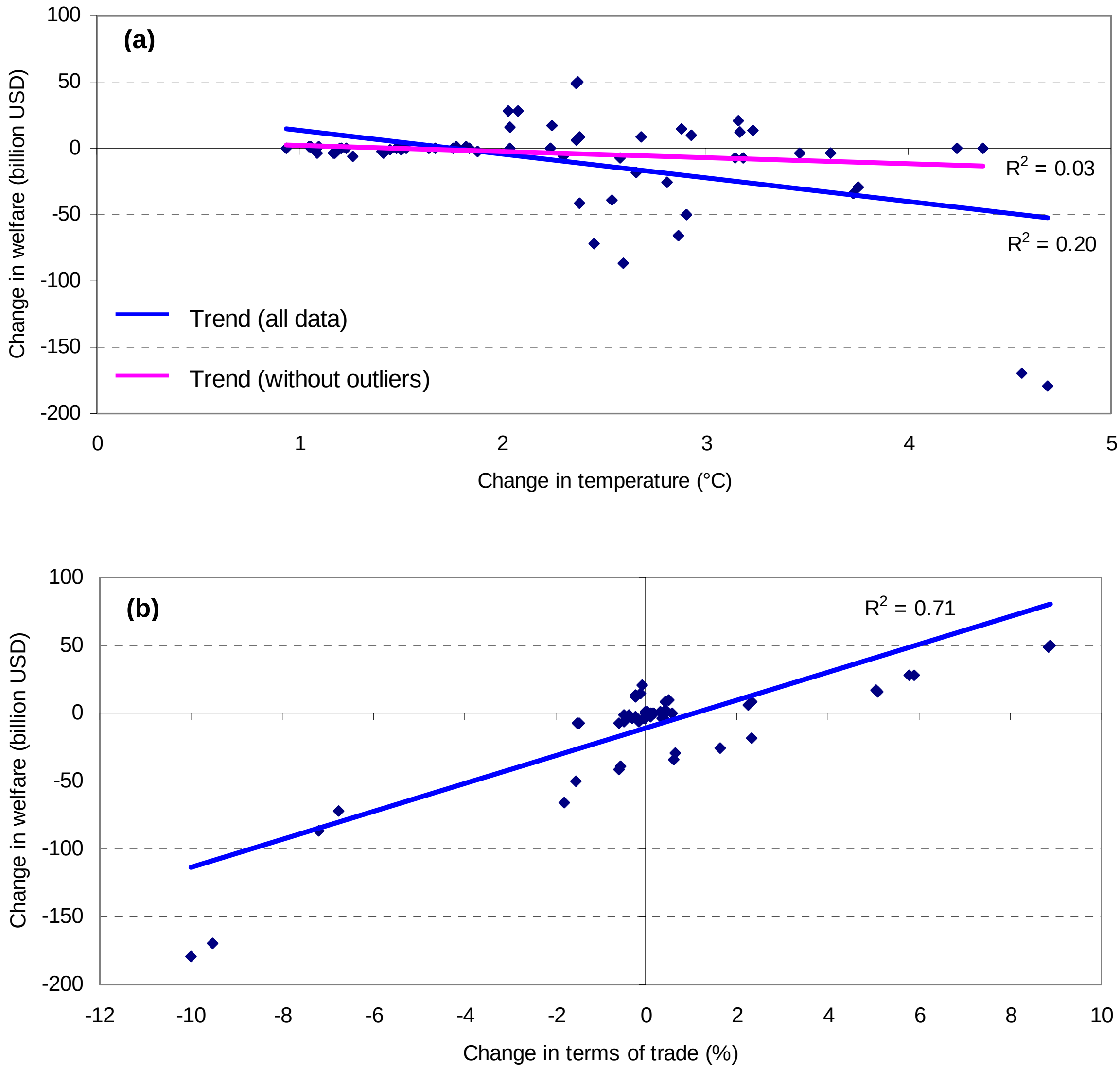


**Figure V–6. Changes in regional welfare as a function of temperature and the terms of trade, *all-factors* scenario**

Under the *all-factors* scenario, welfare declines mainly in regions with high yield responses to changes in temperature (the former Soviet Union, South Asia, the Middle East and Southeast Asia). Regional welfare gains are relatively low in magnitude compared to welfare losses. Regions like South America, Sub-Saharan Africa and China benefit through shifts in competitiveness and international trade. Although both developed and developing regions are expected to face welfare losses, climate change is expected to reduce welfare in a higher number of developing regions.

## 7. Discussion and conclusions

In this paper, we use a global computable general equilibrium model including water resources (GTAP-W) to assess climate change impacts on global agriculture. 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. While previous studies do not differentiate rainfed and irrigated agriculture, this distinction is crucial, because rainfed and irrigated agriculture face different climate risk levels. Thus, in GTAP-W, changes in future water availability have different effects on rainfed and irrigated crops. While changes in precipitation are directly related to runoff and soil moisture and hence to rainfed production, changes in river flow are directly related to irrigation water availability and hence to irrigated production.

We use predicted changes in precipitation, temperature and river flow under the IPCC SRES A1B and A2 scenarios to simulate climate change impacts on global agriculture at two time periods: the 2020s and 2050s. We include in the analysis $CO_2$ fertilization as well. Six scenarios are used, the first three scenarios analyzes agricultural impacts of changes in precipitation, temperature and $CO_2$ fertilization without differentiating between rainfed and irrigated crops. The last three scenarios fully exploit the GTAP-W model and discriminate impacts in rainfed and irrigated systems.

The results show that when only projected changes in water availability are considered (*precipitation-only* and *water-only* scenario), total agricultural production in both time periods is expected to slightly increase under the SRES A1B scenario and decrease under the SRES A2 scenario. As expected, the inclusion of $CO_2$ fertilization in the analysis causes an increase in world food production and generates welfare gains (*precipitation-*$CO_2$ scenario). However, it is not strong enough to offset the negative effects of changes in precipitation and temperature (*precipitation-temperature-*$CO_2$ scenario). For the 2050s and under the SRES A1B scenario, global agricultural production is expected to decrease by around 2.6 percent and welfare losses reach more than 327 billion USD. Results for the SRES A2 scenario are less pronounced.

Distinguishing between rainfed and irrigated agriculture, we find that irrigated production is less vulnerable to changes in water resources. When irrigation is possible, food production relies on irrigated crops, thus welfare losses are smaller. For the 2050s, global welfare losses account for less than half of the initially drop (compare *precipitation-only* and *water-only* scenario).

A joint analysis of the main climate variables affecting agricultural production (precipitation, temperature, river flow and $CO_2$ fertilization) shows that global food production declines by around 0.5 percent in the 2020s and by around 2.3 in the 2050s. Declines under the SRES A2 scenario are slightly more pronounced (*all-factors* scenario).

While crop production increases in many developed regions (exceptions are of the former Soviet Union, the United States and Canada), it decreases in most of the developing regions (mainly in the Middle East, Southeast Asia and North Africa).

Despite the increase in irrigated crop areas promoted by a higher irrigation water supply, global irrigated production declines between 3 to 6 percent, depending on the SRES scenario and time period. Irrigated crop production declines in regions with high negative yield responses to changes in temperature as well as regions where irrigated production contributes substantially to total crop production (the United States, the Middle East, North Africa and South Africa).

Global blue, green and total water use decline in the *all-factors* scenario. Climate change leads to a reduction in total water use world-wide by around 1.3 percent in the 2020s (82 cubic kilometres) and around 2.3 percent in the 2050s (187 cubic kilometres) (SRES A2 scenario). At regional level, total water use declines largely in the Middle East, the former Soviet Union, Southeast Asia and the United States.

Declines in food production rise food prices. Higher market prices are expected for all crops, mainly for cereal grains, sugar cane, sugar beet and wheat (between 39 to 43 percent depending on the SRES scenario).

Changes in agricultural production and prices induce changes in welfare and GDP. Global welfare losses in the 2050s are expected to account for more than 265 billion USD, around 0.28 percent of global GDP (*all-factors* scenario). Independently of the SRES emission scenario and time period, the results show that regional welfare decreases with higher temperature levels and increases with improvements in the terms of trade. Thus, regions are not only affected by regional climate change, but also by climate-induced competitiveness changes.

Several limitations apply to the above results. First, in our analysis changes in precipitation, temperature and river flow are defined based on regional averages. We do not take into account differences between river basins within the same region. These local effects are averaged out. Second, we use annual average precipitation, temperature and river flow data, therefore we do not consider changes in the seasonality nor extreme events. Third, we have made no attempt to address uncertainty in our scenarios, other than by the use of two emission scenarios from only one climate model, which could generate biased estimates. Forth, in our analysis we do not consider any cost or investment associated to the expansion of irrigated areas. Therefore, our results might overestimate the benefits of some scenarios. These issues should be addressed in future research.

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## Annex A

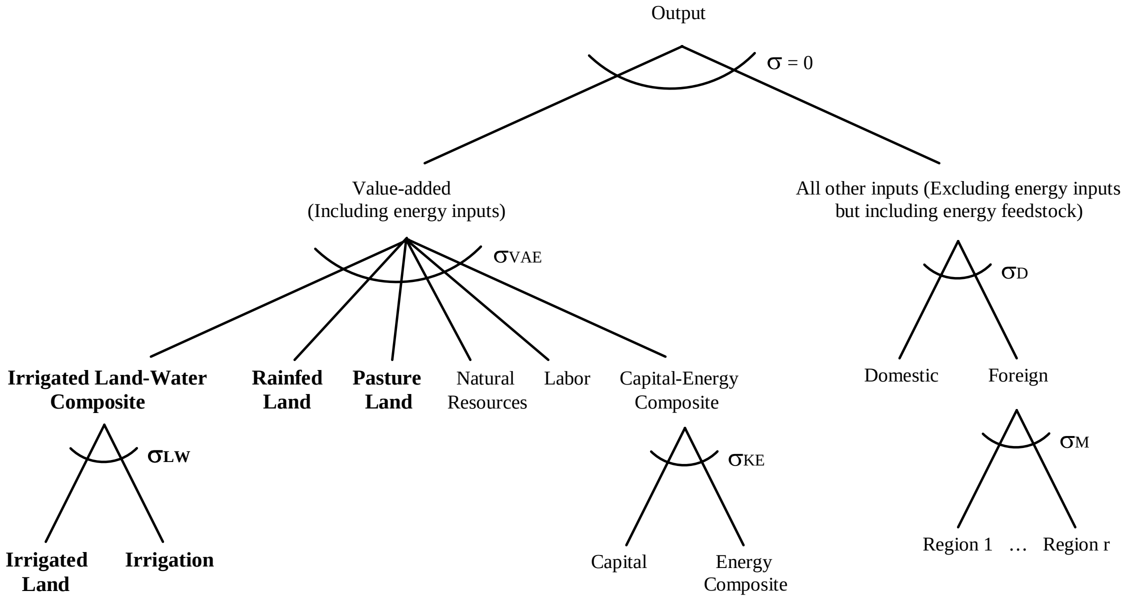


**Figure V–A1. Nested tree structure for industrial production process in GTAP-W (truncated)**

Note: The original land endowment has been split into pasture land, rainfed land, irrigated land and irrigation (bold letters). σ is the elasticity of substitution between value added and intermediate inputs, σVAE is the elasticity of substitution between primary factors, σLW is the elasticity of substitution between irrigated land and irrigation, σKE is the elasticity of substitution between capital and the energy composite, σD is the elasticity of substitution between domestic and imported inputs and σM is the elasticity of substitution between imported inputs.

**Table V–A1. Aggregations in GTAP-W**

| *A. Regional Aggregation* | *B. Sectoral Aggregation* |
|---|---|
| **1. USA -** United States | **1. Rice** - Rice |
| **2. CAN -** Canada | **2. Wheat** - Wheat |
| **3. WEU -** Western Europe | **3. CerCrops** - Cereal grains (maize, millet, sorghum and other grains) |
| **4. JPK -** Japan and South Korea | **4. VegFruits -** Vegetable, fruits, nuts |
| **5. ANZ -** Australia and New Zealand | **5. OilSeeds -** Oil seeds |
| **6. EEU -** Eastern Europe | **6. Sug_Can -** Sugar cane, sugar beet |
| **7. FSU -** Former Soviet Union | **7. Oth_Agr -** Other agricultural products |
| **8. MDE -** Middle East | **8. Animals -** Animals |
| **9. CAM -** Central America | **9. Meat -** Meat |
| **10. SAM -** South America | **10. Food_Prod -** Food products |
| **11. SAS -** South Asia | **11. Forestry -** Forestry |
| **12. SEA -** Southeast Asia | **12. Fishing -** Fishing |
| **13. CHI -** China | **13. Coal -** Coal |
| **14. NAF -** North Africa | **14. Oil -** Oil |
| **15. SSA -** Sub-Saharan Africa | **15. Gas -** Gas |
| **16. ROW -** Rest of the World | **16. Oil_Pcts -** Oil products |
| *C. Endowments* | **17. Electricity -** Electricity |
| **Wtr -** Irrigation | **18. Water -** Water |
| **Lnd -** Irrigated land | **19. En_Int_Ind -** Energy intensive industries |
| **RfLand -** Rainfed land | **20. Oth_Ind -** Other industry and services |
| **PsLand -** Pasture land | **21. Mserv -** Market services |
| **Lab -** Labour | **22. NMServ -** Non-market services |
| **Capital -** Capital | |
| **NatlRes -** Natural resources | |

# Annex B

**Table V–B1. 2000 baseline data: Crop harvested area and production by region and crop**

| Description | Rainfed Agricultural Area (thousand ha) | Rainfed Agricultural Production (thousand mt) | Irrigated Agricultural Area (thousand ha) | Irrigated Agricultural Production (thousand mt) | Total Area (thousand ha) | Total Production (thousand mt) | Share of irrigated agriculture in total Area (%) | Share of irrigated agriculture in total Production (%) |
|---|---|---|---|---|---|---|---|---|
| **Regions (total, all crops)** | | | | | | | | |
| United States | 35,391 | 209,833 | 67,112 | 440,470 | 102,503 | 650,303 | 65.5 | 67.7 |
| Canada | 27,267 | 65,253 | 717 | 6,065 | 27,984 | 71,318 | 2.6 | 8.5 |
| Western Europe | 59,494 | 462,341 | 10,130 | 146,768 | 69,624 | 609,108 | 14.5 | 24.1 |
| Japan and South Korea | 1,553 | 23,080 | 4,909 | 71,056 | 6,462 | 94,136 | 76.0 | 75.5 |
| Australia and New Zealand | 21,196 | 67,204 | 2,237 | 27,353 | 23,433 | 94,557 | 9.5 | 28.9 |
| Eastern Europe | 37,977 | 187,468 | 5,958 | 40,470 | 43,935 | 227,939 | 13.6 | 17.8 |
| Former Soviet Union | 85,794 | 235,095 | 16,793 | 74,762 | 102,587 | 309,857 | 16.4 | 24.1 |
| Middle East | 29,839 | 135,151 | 21,450 | 118,989 | 51,289 | 254,140 | 41.8 | 46.8 |
| Central America | 12,970 | 111,615 | 8,745 | 89,637 | 21,715 | 201,252 | 40.3 | 44.5 |
| South America | 79,244 | 649,419 | 9,897 | 184,304 | 89,141 | 833,723 | 11.1 | 22.1 |
| South Asia | 137,533 | 491,527 | 114,425 | 560,349 | 251,958 | 1,051,877 | 45.4 | 53.3 |
| Southeast Asia | 69,135 | 331,698 | 27,336 | 191,846 | 96,471 | 523,543 | 28.3 | 36.6 |
| China | 64,236 | 615,196 | 123,018 | 907,302 | 187,254 | 1,522,498 | 65.7 | 59.6 |
| North Africa | 15,587 | 51,056 | 7,352 | 78,787 | 22,938 | 129,843 | 32.0 | 60.7 |
| Sub-Saharan Africa | 171,356 | 439,492 | 5,994 | 43,283 | 177,349 | 482,775 | 3.4 | 9.0 |
| Rest of the World | 3,810 | 47,466 | 1,093 | 23,931 | 4,903 | 71,397 | 22.3 | 33.5 |
| **World** | **852,381** | **4,122,894** | **427,164** | **3,005,371** | **1,279,545** | **7,128,265** | **33.4** | **42.2** |
| **Crops (total, all regions)** | | | | | | | | |
| Rice | 59,678 | 108,179 | 93,053 | 294,934 | 152,730 | 403,113 | 60.9 | 73.2 |
| Wheat | 124,147 | 303,638 | 90,492 | 285,080 | 214,639 | 588,718 | 42.2 | 48.4 |
| Cereal grains | 225,603 | 504,028 | 69,402 | 369,526 | 295,005 | 873,554 | 23.5 | 42.3 |
| Vegetables, fruits, nuts | 133,756 | 1,374,128 | 36,275 | 537,730 | 170,031 | 1,911,858 | 21.3 | 28.1 |
| Oil seeds | 68,847 | 125,480 | 29,578 | 73,898 | 98,425 | 199,379 | 30.1 | 37.1 |
| Sugar cane, sugar beet | 16,457 | 846,137 | 9,241 | 664,023 | 25,699 | 1,510,161 | 36.0 | 44.0 |
| Other agricultural products | 223,894 | 861,303 | 99,122 | 780,180 | 323,017 | 1,641,483 | 30.7 | 47.5 |
| **Total** | **852,381** | **4,122,894** | **427,164** | **3,005,371** | **1,279,545** | **7,128,265** | **33.4** | **42.2** |

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

**Table V–B2. 2020 no climate change simulation: Crop harvested area and production by region and crop**

| Description | Rainfed Agricultural | | Irrigated Agricultural | | Total | | Share of irrigated agriculture in total | |
|---|---|---|---|---|---|---|---|---|
| | Area (thousand ha) | Production (thousand mt) | Area (thousand ha) | Production (thousand mt) | Area (thousand ha) | Production (thousand mt) | Area (%) | Production (%) |
| **Regions** **(total, all crops)** | | | | | | | | |
| United States | 33,927 | 267,740 | 68,072 | 606,204 | 101,999 | 873,944 | 66.7 | 69.4 |
| Canada | 25,091 | 81,239 | 678 | 7,460 | 25,769 | 88,699 | 2.6 | 8.4 |
| Western Europe | 51,622 | 472,176 | 9,391 | 166,310 | 61,013 | 638,485 | 15.4 | 26.0 |
| Japan and South Korea | 1,375 | 25,068 | 4,453 | 72,230 | 5,828 | 97,299 | 76.4 | 74.2 |
| Australia and New Zealand | 20,698 | 83,292 | 2,216 | 35,441 | 22,915 | 118,733 | 9.7 | 29.8 |
| Eastern Europe | 34,492 | 210,311 | 5,520 | 53,325 | 40,012 | 263,636 | 13.8 | 20.2 |
| Former Soviet Union | 83,591 | 309,682 | 16,838 | 100,534 | 100,430 | 410,215 | 16.8 | 24.5 |
| Middle East | 30,232 | 163,563 | 22,561 | 176,977 | 52,793 | 340,539 | 42.7 | 52.0 |
| Central America | 13,152 | 163,265 | 9,383 | 136,479 | 22,535 | 299,744 | 41.6 | 45.5 |
| South America | 87,571 | 1,152,723 | 11,360 | 344,208 | 98,931 | 1,496,931 | 11.5 | 23.0 |
| South Asia | 121,508 | 551,783 | 126,468 | 822,052 | 247,977 | 1,373,835 | 51.0 | 59.8 |
| Southeast Asia | 72,405 | 431,084 | 27,457 | 282,402 | 99,863 | 713,486 | 27.5 | 39.6 |
| China | 61,761 | 691,581 | 120,838 | 1,014,241 | 182,600 | 1,705,822 | 66.2 | 59.5 |
| North Africa | 16,011 | 73,390 | 7,726 | 106,969 | 23,737 | 180,359 | 32.5 | 59.3 |
| Sub-Saharan Africa | 194,346 | 665,335 | 7,847 | 85,687 | 202,193 | 751,022 | 3.9 | 11.4 |
| Rest of the World | 4,060 | 71,744 | 1,227 | 42,107 | 5,287 | 113,851 | 23.2 | 37.0 |
| **Total** | **851,843** | **5,413,975** | **442,036** | **4,052,625** | **1,293,880** | **9,466,600** | **34.2** | **42.8** |
| | | | | | | | | |
| **Crops** **(total, all regions)** | | | | | | | | |
| Rice | 53,799 | 107,477 | 91,696 | 327,822 | 145,495 | 435,299 | 63.0 | 75.3 |
| Wheat | 117,231 | 358,153 | 89,017 | 375,312 | 206,248 | 733,466 | 43.2 | 51.2 |
| Cereal grains | 222,513 | 646,828 | 73,584 | 524,949 | 296,097 | 1,171,777 | 24.9 | 44.8 |
| Vegetables, fruits, nuts | 140,559 | 1,742,380 | 40,067 | 748,817 | 180,625 | 2,491,196 | 22.2 | 30.1 |
| Oil seeds | 70,829 | 135,312 | 30,504 | 94,146 | 101,333 | 229,458 | 30.1 | 41.0 |
| Sugar cane, sugar beet | 20,753 | 1,473,872 | 11,446 | 1,080,858 | 32,198 | 2,554,730 | 35.5 | 42.3 |
| Other agricultural products | 226,160 | 949,953 | 105,723 | 900,721 | 331,883 | 1,850,674 | 31.9 | 48.7 |
| **Total** | **851,843** | **5,413,975** | **442,036** | **4,052,625** | **1,293,880** | **9,466,600** | **34.2** | **42.8** |

Note: Linear interpolation between 2000 baseline data and 2050 simulation without climate change.
Source: IMPACT.

**Table V–B3. 2050 no climate change simulation: Crop harvested area and production by region and crop**

| Description | Rainfed Agricultural Area (thousand ha) | Rainfed Agricultural Production (thousand mt) | Irrigated Agricultural Area (thousand ha) | Irrigated Agricultural Production (thousand mt) | Total Area (thousand ha) | Total Production (thousand mt) | Share of irrigated agriculture in total Area (%) | Share of irrigated agriculture in total Production (%) |
|---|---|---|---|---|---|---|---|---|
| **Regions (total all crops)** | | | | | | | | |
| United States | 31,731 | 359,608 | 69,511 | 872,566 | 101,243 | 1,232,174 | 68.7 | 70.8 |
| Canada | 21,827 | 97,335 | 620 | 9,640 | 22,447 | 106,975 | 2.8 | 9.0 |
| Western Europe | 39,815 | 452,254 | 8,282 | 188,597 | 48,097 | 640,851 | 17.2 | 29.4 |
| Japan and South Korea | 1,107 | 27,348 | 3,770 | 72,337 | 4,876 | 99,685 | 77.3 | 72.6 |
| Australia and New Zealand | 19,952 | 109,152 | 2,186 | 49,047 | 22,137 | 158,200 | 9.9 | 31.0 |
| Eastern Europe | 29,264 | 232,260 | 4,864 | 69,807 | 34,127 | 302,068 | 14.3 | 23.1 |
| Former Soviet Union | 80,287 | 412,791 | 16,906 | 142,725 | 97,194 | 555,515 | 17.4 | 25.7 |
| Middle East | 30,822 | 210,882 | 24,227 | 279,714 | 55,049 | 490,596 | 44.0 | 57.0 |
| Central America | 13,425 | 259,733 | 10,341 | 221,277 | 23,766 | 481,010 | 43.5 | 46.0 |
| South America | 100,062 | 2,230,050 | 13,553 | 675,050 | 113,615 | 2,905,101 | 11.9 | 23.2 |
| South Asia | 97,471 | 645,050 | 144,534 | 1,287,136 | 242,005 | 1,932,186 | 59.7 | 66.6 |
| Southeast Asia | 77,311 | 602,597 | 27,640 | 451,659 | 104,951 | 1,054,256 | 26.3 | 42.8 |
| China | 58,049 | 808,747 | 117,569 | 1,183,716 | 175,619 | 1,992,463 | 66.9 | 59.4 |
| North Africa | 16,647 | 113,839 | 8,288 | 159,094 | 24,935 | 272,933 | 33.2 | 58.3 |
| Sub-Saharan Africa | 228,831 | 1,070,839 | 10,628 | 174,781 | 239,459 | 1,245,619 | 4.4 | 14.0 |
| Rest of the World | 4,435 | 117,189 | 1,427 | 78,062 | 5,862 | 195,251 | 24.3 | 40.0 |
| **Total** | **851,036** | **7,749,674** | **464,345** | **5,915,210** | **1,315,381** | **13,664,884** | **35.3** | **43.3** |
| | | | | | | | | |
| **Crops (total, all regions)** | | | | | | | | |
| Rice | 44,981 | 105,044 | 89,661 | 373,142 | 134,642 | 478,186 | 66.6 | 78.0 |
| Wheat | 106,856 | 427,710 | 86,806 | 500,301 | 193,662 | 928,011 | 44.8 | 53.9 |
| Cereal grains | 217,878 | 860,509 | 79,858 | 788,785 | 297,735 | 1,649,294 | 26.8 | 47.8 |
| Vegetables, fruits, nuts | 150,763 | 2,346,842 | 45,754 | 1,124,570 | 196,517 | 3,471,412 | 23.3 | 32.4 |
| Oil seeds | 73,803 | 148,761 | 31,892 | 127,020 | 105,696 | 275,782 | 30.2 | 46.1 |
| Sugar cane, sugar beet | 27,197 | 2,799,190 | 14,752 | 1,914,327 | 41,948 | 4,713,517 | 35.2 | 40.6 |
| Other agricultural products | 229,558 | 1,061,618 | 115,623 | 1,087,064 | 345,182 | 2,148,682 | 33.5 | 50.6 |
| **Total** | **851,036** | **7,749,674** | **464,345** | **5,915,210** | **1,315,381** | **13,664,884** | **35.3** | **43.3** |

Source: IMPACT, 2050 simulation without climate change (April 2008).

**Table V–B4. Crop yield responses to changes in precipitation and temperature by crop type**

| Regions | Precipitation | | | | Temperature | | | |
|---|---|---|---|---|---|---|---|---|
| | -20 % | | +20 % | | +2 °C | | +4 °C | |
| | C3 crops | C4 crops | C3 crops | C4 crops | C3 crops | C4 crops | C3 crops | C4 crops |
| United States | -17.83 | -13.00 | 12.50 | 7.33 | -18.67 | -10.67 | -34.00 | -20.33 |
| Canada | -31.00 | -31.00 | 26.14 | 26.14 | -21.14 | -21.14 | -37.14 | -37.14 |
| Western Europe | -7.27 | 5.49 | 4.58 | 0.60 | -4.06 | -1.06 | -12.71 | -9.82 |
| Japan and South Korea | -7.50 | -7.50 | 3.67 | 3.67 | -10.33 | -4.50 | -18.00 | -17.83 |
| Australia and New Zealand | -37.65 | -37.65 | 29.02 | 29.02 | 10.59 | 10.59 | -1.57 | -1.57 |
| Eastern Europe | -7.27 | 5.49 | 4.58 | 0.60 | -4.06 | -1.06 | -12.71 | -9.82 |
| Former Soviet Union | -12.50 | -12.50 | 7.00 | 7.00 | -21.50 | -21.50 | -39.00 | -39.00 |
| Middle East | -37.65 | -37.65 | 29.02 | 29.02 | -17.29 | -13.03 | -29.32 | -24.95 |
| Central America | -3.46 | -3.77 | 2.10 | 2.52 | -13.93 | -8.81 | -29.08 | -18.87 |
| South America | -3.62 | -0.26 | 2.44 | -1.01 | -14.57 | -10.37 | -30.20 | -19.83 |
| South Asia | 1.67 | 1.67 | 11.11 | 11.11 | -16.38 | -16.38 | -30.49 | -30.49 |
| Southeast Asia | 1.67 | 1.67 | 11.11 | 11.11 | -23.71 | -23.71 | -43.60 | -43.60 |
| China | -7.50 | -2.00 | 5.00 | 1.00 | -0.67 | -7.00 | -7.33 | -17.00 |
| North Africa | -37.65 | -37.65 | 29.02 | 29.02 | -17.29 | -13.03 | -29.32 | -24.95 |
| Sub-Saharan Africa | -3.62 | -0.26 | 2.44 | -1.01 | -10.91 | -10.91 | -25.40 | -25.40 |
| Rest of the World | -3.46 | -3.77 | 2.10 | 2.52 | -13.93 | -8.81 | -29.08 | -18.87 |

Source: Based on Rosenzweig and Iglesias (1994) and Jin and Zhu (2008).
Note: In GTAP-W, rice, wheat, vegetables, fruits, nuts, oil seeds and other agricultural products are considered C3 crops. Cereal grains, sugar cane and sugar beet are considered C4 crops.

# VI

## ECONOMYWIDE IMPACTS OF CLIMATE CHANGE ON AGRICULTURE IN SUB-SAHARAN AFRICA

**Abstract**

Two possible adaptation options to climate change for Sub-Saharan Africa are analyzed under the SRES B2 scenario. The first scenario doubles the irrigated area in Sub-Saharan Africa by 2050, compared to the baseline, but keeps total crop area constant. The second scenario increases both rainfed and irrigated crop yields by 25 percent for all Sub-Saharan African countries. The two adaptation scenarios are analyzed with IMPACT, a partial equilibrium agricultural sector model combined with a water simulation module, and with GTAP-W, a general equilibrium model including water resources. The methodology combines the advantages of a partial equilibrium approach, which considers detailed water-agriculture linkages, with a general equilibrium approach, which takes into account linkages between agriculture and nonagricultural sectors and includes a full treatment of factor markets. The efficacy of the two scenarios as adaptation measures to cope with climate change is discussed. Due to the limited initial irrigated area in the region, an increase in agricultural productivity achieves better outcomes than an expansion of irrigated area. Even though Sub-Saharan Africa is not a key contributor to global food production or irrigated food production, both scenarios help lower world food prices, stimulating national and international food markets.

**Keywords:** Computable General Equilibrium, Climate Change, Agriculture, Sub-Saharan Africa

**JEL Classification:** D58, Q54, Q17, N57

## 1. Introduction

Agriculture is of great importance to most Sub-Saharan African economies, supporting between 70 and 80 percent of employment and contributing an average of 30 percent of gross domestic product (GDP) and at least 40 percent of exports (Commission for Africa 2005). However, specific agro-ecological features, small farm sizes, poor access to services and knowledge, and low investment in infrastructure and irrigation schemes have limited agricultural development in Sub-Saharan Africa (Faurès and Santini 2008).

Rainfed farming dominates agricultural production in Sub-Saharan Africa, covering around 97 percent of total cropland, and exposes agricultural production to high seasonal rainfall variability. Although irrigation systems have been promoted in the region, the impact has not been as expected. Reasons include a lack of demand for irrigated products, poor market access, low incentives for agricultural intensification, unfavorable topography, low-quality soils, and inadequate policy environments (Burke, Riddell, and Westlake 2006; Faurès and Santini 2008). Although the cost of irrigation projects implemented in developing countries has generally decreased over the last four decades, and performance of irrigation projects has improved (Inocencio et al. 2007), the situation in Sub-Saharan Africa is different. This region has higher costs than other regions in terms of simple averages. However, some projects have been implemented successfully with lower costs compared to other regions.

Agriculture in Sub-Saharan Africa is characterized by comparably low yields. While Asia experienced a rapid increase in food production and yields during the Green Revolution in the late 1970s and early 1980s, in Sub-Saharan Africa per capita food production and yields have stagnated. The failure of agriculture to take off in Sub-Saharan Africa has been attributed to the dependence on rainfed agriculture; low population densities; the lack of infrastructure, markets, and supporting institutions; the agro-ecological complexities and heterogeneity of the region; low use of fertilizers; and degraded soils (Johnson, Hazell, and Gulati 2003; World Bank 2007).

In Sub-Saharan Africa, rural poverty accounts for 90 percent of total poverty in the region, and approximately 80 percent of the poor still depend on agriculture or farm labor for their livelihoods (Dixon, Gulliver, and Gibbon 2001). High population growth rates, especially in rural areas, increase the challenge of poverty reduction and raise pressure on agricultural production and natural resources. According to the Food and Agriculture Organization of the United Nations (FAO 2006), the population in Sub-Saharan Africa could double by 2050, increasing agricultural consumption by 2.8 percent annually until 2030, and by 2.0 percent annually from 2030 to 2050. During these same periods, agricultural production is projected to increase by 2.7 and 1.9 percent per year, respectively. As a consequence, net food imports are expected to rise.

The *World Development Report 2008* (World Bank 2007) suggests that the key policy challenge in agriculture-based economies such as those in Sub-Saharan Africa is to help agriculture play its role as an engine of growth and poverty reduction. Development of irrigation and improvements in agricultural productivity have proven to be effective in this regard. Hussain and Hanjra (2004) identify three main pathways through which irrigation can impact poverty. Irrigation, in the micro-pathway, increases returns to the physical, human, and social capital of poor households and enables smallholders to achieve higher yields and revenues from crop production. The meso-pathway includes new employment opportunities on irrigated farms or higher wages on rainfed farms. Lower food prices are also expected, as irrigation enables farmers to obtain more output per unit of input. In the macro-pathway, or growth path, gains in agricultural productivity through irrigation can stimulate national and international markets, improving economic growth and creating second-generation positive externalities. In a similar way, Lipton, Litchfield, and Faurès (2003) analyze the conditions under which irrigation has positive effects on poverty reduction and classify them into direct and indirect effects.

Faurès and Santini (2008) suggests that improvements in agricultural productivity can provide a pathway out of poverty for rural households in several ways. Poor households that own land benefit from improvements in crop and livestock yields through greater output and higher incomes. Households that do not own land but provide farm labor benefit from higher demand for farm labor and wages. Households that do not own land or provide farm labor benefit from a greater supply of agricultural products and lower food prices. Improvements in agricultural productivity can also benefit nonagricultural rural households and urban households through greater demand for food and other products (stimulated by higher agricultural incomes and higher net incomes in nonagricultural households). Food processing and marketing activities can also be promoted in urban areas. When agricultural productivity improves by means of water management, the incremental productivity of complementary inputs raises and expands the demand for these inputs, which in turn stimulates nonagricultural economic activities.

However, the effectiveness of irrigation and agricultural productivity in reducing poverty and promoting economic growth is affected by the availability of affordable complementary inputs, the development of human capital, access to markets and expansion of markets to achieve economies of scale, and institutional arrangements that promote farm-level investments in land and water resources (CA 2007; Faurès and Santini 2008).

Sub-Saharan Africa has the potential for expanding irrigation and increasing agricultural productivity. The *World Development Report 2008* (World Bank 2007) points out that the new generation of better-designed irrigation projects and the large untapped water resources generate opportunities to invest in irrigation in Sub-Saharan Africa. New investments in irrigation need complementary investments in roads, extension services, and access to markets. The Comprehensive Assessment of Water Management in Agriculture (CA 2007) suggests that where yields are already high and the exploitable gap is small, projected growth rates are low, whereas low yields present a large potential for improvement. In Sub-Saharan Africa, observed yields are less than one-third of the maximum attainable yields. The potential for productivity enhancement is therefore large, particularly for maize, sorghum, and millet. Although water is often the principal constraint for agricultural productivity, optimal access to complementary inputs and investment in research and development are also necessary.

Future climate change may present an additional challenge for agriculture in Sub-Saharan Africa. According to the Intergovernmental Panel on Climate Change (IPCC) (Watson, Zinyowera, and Moss 1997), Africa is the most vulnerable region to climate change because widespread poverty limits adaptive capacity. The impacts of climate change on agriculture could seriously worsen livelihood conditions for the rural poor and increase food insecurity in the region. The *World Development Report 2008* (World Bank 2007) identifies five main factors through which climate change will affect agricultural productivity: changes in temperature, changes in precipitation, changes in carbon dioxide ($CO_2$) fertilization, increased climate variability, and changes in surface water runoff. Increased climate variability and droughts will affect livestock production as well. Smallholders and pastoralists in Sub-Saharan Africa will need to gradually adapt and adopt technologies that increase the productivity, stability, and resilience of production systems (Faurès and Santini 2008).

As discussed above, the development of irrigation and improvements in agricultural productivity are key variables, not only for future economic development, poverty reduction, and food security in Sub-Saharan Africa but also for climate change adaptation. In this sense, the aim of our paper is to analyze the economywide impacts of expanding irrigation and increasing agricultural productivity in Sub-Saharan Africa under the SRES B2 scenario[1] of the IPCC. We use a combination of a partial equilibrium model (IMPACT) and a general equilibrium model (GTAP-W). The link between the two models allows us to improve calibration and exploit their different capabilities.

The IMPACT model (Rosegrant, Cai, and Cline 2002) is a partial agricultural equilibrium model that allows for the combined analysis of water and food supply and demand. Based on a loose coupling with global hydrological modeling, climate change impacts on water and food can be analyzed as well (Zhu, Ringler, and Rosegrant 2008). The GTAP-W model (Calzadilla, Rehdanz, and Tol 2008) is a global computable general equilibrium (CGE) model that allows for a rich set of economic feedbacks and for a complete assessment of the welfare implications of alternative development pathways. Unlike the predecessor GTAP-W (Berrittella et al. 2007), the revised GTAP-W model distinguishes between rainfed and irrigated agriculture.

While partial equilibrium analysis focuses on the sector affected by a policy measure and assumes that the rest of the economy is not affected, general equilibrium models consider other sectors or regions as well to determine economywide effects; partial equilibrium models tend to have more detail.

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[1] As described in the (SRES) (IPCC 2000), the B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with a slowly but continuously increasing global population and intermediate levels of economic and technological development. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The remainder of the paper is organized as follows: the next section briefly describes the IMPACT and GTAP-W models and the link of the two models, as well as projections out to 2050 undertaken for this study. Section 3 focuses on the baseline results and climate change impacts. Section 4 presents two alternative adaptation scenarios and discusses and compares the results from both models, including outcomes for malnutrition. Section 5 contains discussion and conclusions.

## 2. Models and baseline simulations

### 2.1. The IMPACT model

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was developed at the International Food Policy Research Institute (IFPRI) in the early 1990s, upon the realization that there was a lack of long-term vision and consensus among policymakers and researchers about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base (Rosegrant et al. 2005). The IMPACT model encompasses most countries and regions and the main agricultural commodities produced in the world. 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. World agricultural commodity prices are determined annually at levels that clear international markets. Country and regional agricultural submodels are linked through trade. Within each country or regional submodel, supply, demand, and prices for agricultural commodities are determined.

The original IMPACT model assumed "normal" climate conditions, and therefore the impacts of annual climate variability on food production, demand, and trade were not reflected. The inclusion of a water simulation module (WSM) enables IMPACT to reflect the effects of water demand and availability on food production and consumption, the inter-annual variability of water demand and availability, and the competition for water among various economic sectors (Rosegrant, Cai, and Cline 2002). Within the model, WSM projects water demand for major water-use sectors and balances water availability and inter- and intra-sector water use by simulating seasonal storage regulation and water allocation at river-basin scale. In addition to variability, long-term trends in water availability and use for different sectors are projected, with exogenous drivers including population and income growth, changes in irrigated areas, and improvements in water-use technology such as irrigation efficiency and new water sources (Rosegrant, Cai, and Cline 2002).

The spatial representation of global economic regions and natural river basins has recently been enhanced. The model now 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.

Recent progress in climate research has strengthened confidence in human-induced global warming (IPCC 2007), with important implications for socioeconomic and agricultural systems. To analyze the impacts of global change, especially climate change, on regional and global food systems and to formulate appropriate adaptation measures, the IMPACT model was extended to include climate change components such as the yield effects of $CO_2$ fertilization and temperature changes, as well as altered hydrological cycles and changes in (irrigation) water demand and water availability through the development of a separate global hydrological model. This semidistributed global hydrology model parameterizes the dominant hydrometeorological processes taking place at the land surface–atmosphere interface with a global scope. The model runs on a half-degree latitude-longitude grid, and global half-degree climate, soil, and land surface cover data are used to determine a number of spatially distributed model parameters. The remaining parameters are determined through model calibrations using global river discharge databases and data sets available elsewhere, using genetic algorithms. For river basins for which data are not available for detailed calibration, regionalized model parameters are applied. The global hydrology model is able to convert the projections for future climate from global circulation models into hydrologic components such as evapotranspiration, runoff, and soil moisture, which are used in this study (Zhu, Ringler, and Rosegrant 2008).

In this analysis, we use the intermediate growth B2 scenario from the *Special Report on Emission Scenario* (SRES) scenario family (IPCC 2000) for the baseline projections out to 2050. The effects of temperature and $CO_2$ fertilization on crop yields are based on simulations of the IMAGE model (Bouwman, Kram, and Klein Goldewijk 2006). Recent research findings show that the stimulation of crop yield observed in the global Free Air Carbon Enrichment (FACE) experiments fell well below (about half) the value predicted from chambers (Long et al. 2006). These FACE experiments clearly show that much lower $CO_2$ fertilization factors (compared with chamber results) should be used in model projections of future yields. Therefore, we apply 50 percent of the $CO_2$ fertilization factors from the IMAGE model simulation in IMPACT (Rosegrant, Fernandez, and Sinha 2009).

In addition to the effects of higher $CO_2$ concentration levels and changes in temperature, climate change is likely to affect the volume and the spatial and temporal distribution of rainfall and runoff, which in turn affect the number and distribution of people under water stress and the productivity of world agricultural systems. We use climate input from the Hadley Centre Coupled Model (HadCM3) run of the B2 scenario that was statistically downscaled to the 0.5 degree latitude/longitude global grid using the pattern scaling method of the Climate Research Unit at the University of East Anglia (Mitchell et al. 2004). The semidistributed macro-scale hydrology module of IMPACT derives effective precipitation, potential and actual evapotranspiration, and runoff at these 0.5 degree pixels and scales them up to each of the 281 FPUs, the spatial operational units of IMPACT. Projections for water requirements, infrastructure capacity expansion, and improvement in water-use efficiency are conducted by IMPACT. These projections are combined with the simulated hydrology model to estimate water use and consumption through water system simulation by IMPACT.

To explore food security effects, the model projects the percentage and number of malnourished preschool children (0–5 years old) in developing countries. A malnourished child is a child whose weight for age is more than two standard deviations below the median reference standard set by the U.S. National Center for Health Statistics / World Health Organization. The number of malnourished preschool children in developing countries is projected as a function of per capita calorie availability, the ratio of female to male life expectancy at birth, total female enrollment in secondary education as a percentage of the female age-group corresponding to national regulations for secondary education, and the percentage of population with access to safe water. These variables were found to be key determinants of childhood malnutrition in a meta-analysis performed by Smith and Haddad (2000).

### 2.2. The GTAP-W model

In order to assess the systemic general equilibrium effects of alternative strategies of adaptation to climate change in Sub-Saharan Africa, we use a multiregional world CGE model, called GTAP-W. The model is a further refinement of the GTAP model[2] (Hertel 1997) and is based on the version modified by Burniaux and Truong[3] (2002) as well as on the previous GTAP-W model introduced by Berrittella et al. (2007).

The revised 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.[4] 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 pastureland (grazing land used by livestock) and land for rainfed and for irrigated agriculture. 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

[2] The GTAP model is a standard CGE static model distributed with the Global Trade Analysis Project (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.

[3] 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.

[4] See Table VI-A1 in Annex A for the regional, sectoral, and factoral aggregation used in GTAP-W.

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, irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability. The tree diagram in Figure VI-A1 in Annex A 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, paragraph AN.211). To accomplish this, we split for each region and each crop the value of land included in the GTAP social accounting matrix into the value of rainfed land and the value of irrigated land using its proportionate contribution to total production. The value of pastureland is derived from the value of land in the livestock breeding sector.

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. The numbers indicate how relatively more valuable irrigated agriculture is compared to rainfed agriculture. The magnitude of additional yield differs not only with respect to the region but also to the crop. On average, producing rice using irrigation is relatively more productive than using irrigation for growing oilseeds, for example.

The procedure we described above to introduce the four new endowments (pastureland, 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’ 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. For detailed information about the social accounting matrix representation of the GTAP database, see McDonald, Robinson, and Thierfelder (2005).

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 production functions are specified via a series of nested constant elasticity of substitution (CES) functions (Figure VI-A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called Armington assumption, which accounts for product heterogeneity.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, pastureland, rainfed land, irrigated land, irrigation, labor, and capital). Capital and labor are perfectly mobile domestically, but immobile internationally. Pastureland, rainfed land, irrigated land, irrigation, and natural resources are imperfectly mobile. National income is allocated between aggregate household consumption, public consumption, and savings. Expenditure shares are generally fixed, which amounts to saying that the top-level utility function has a Cobb-Douglas specification. 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 original GTAP-E 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 (Figure VI-A1). The procedure for obtaining the elasticity of factor substitution between land and irrigation ($\sigma_{LW}$) is explained in greater detail in Calzadilla, Rehdanz, and Tol (2008). Next, the irrigated land-water composite is combined with pastureland, 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 ($\sigma_{VAE}$) 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. The distinction between rainfed and irrigated agriculture within the production structure of the GTAP-W model allows us to study expected physical constraints on water supply due to, for example, climate change. In fact, changes in rainfall patterns can be exogenously modeled in GTAP-W by changes in the productivity of rainfed and irrigated land. In the same way, water excesses or shortages in irrigated agriculture can be modeled by exogenous changes to the initial irrigation water endowment.

We have not implemented in-depth interactions between IMPACT and GTAP-W for this particular paper (see Rosegrant, Fernandez, and Sinha 2009). The innovation presented in this paper is not yet again interactions between a partial equilibrium model and a general equilibrium model. Instead, the innovation is the development of the first general equilibrium model capable of realistically analyzing the impacts of climate change on water and food supply and demand and welfare.

### 2.3. Baseline simulations

The IMPACT *baseline simulation* out to 2050 incorporates moderate climate change impacts based on the SRES B2 scenario. The results are compared to an alternative *no climate change simulation* assuming normal climate conditions. The GTAP-W model uses these outputs from IMPACT to calibrate a hypothetical general equilibrium in 2050 for each of these two simulations.

To obtain a 2050 benchmark equilibrium data set for the GTAP-W model, we use the methodology described by Dixon and Rimmer (2002). This methodology allows us to find a hypothetical general equilibrium state in the future by imposing forecasted values for some key economic variables in the initial calibration data set. That is, we impose a forecast closure exogenizing macroeconomic variables for which forecasts are available. In this way, we impose forecasted changes in regional endowments (labor, capital, natural resources, rainfed land, irrigated land, and irrigation), in regional factor-specific and multifactor productivity, and in regional population. We use estimates of regional labor productivity, labor stock, and capital stock from the G-Cubed model (McKibbin and Wilcoxen 1998). Changes in the allocation of rainfed and irrigated land within a region, as well as irrigation and agricultural land productivity, are implemented according to the values obtained from IMPACT. Finally, we use the medium-variant population estimates for 2050 from the Population Division of the United Nations (United Nations 2004).

The link of the two models allows for improved calibration and enhanced insights into policy impacts. In fact, 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 the GTAP-W model with detailed information for a robust calibration of a new data set and allows us to run climate change scenarios. The links between IMPACT and GTAP-W are shown in Figure VI-A2 in Annex A.

### 3. Baseline simulation results

As can be seen in Tables VI-1 and VI-2, expansion of area harvested will contribute little to future food production growth under historic climate conditions. In China, area is expected to contract at 0.18 percent per year. An exception is Sub-Saharan Africa, where crop area is still expected to increase at 0.6 percent annually. The projected slowdown in crop area expansion places the burden to meet future food demand on crop yield growth. However, although yield growth will vary considerably by commodity and country, in the aggregate and in most countries it also will continue to slow down. The global yield growth rate for all cereals is expected to decline from 1.96 percent per year in 1980-2000 to 1.01 percent per year in 2000-2050. By 2050, approximately one third of crop harvested area is projected to be under irrigation. In Sub-Saharan Africa, irrigated harvested area is projected to grow more than twice as fast as rainfed area (79 percent compared to 34 percent). However, the proportion of irrigated area to total area in 2050 is only 1 percent higher compared to 2000 (4.5 and 3.4 percent, respectively).

Impacts of future climate change on food production, demand, and trade are reflected in the 2050 (SRES B2) baseline simulation. Table VI-3 reports the percentage change in crop harvested area and production by region and by crop for Sub-Saharan Africa as well as changes in regional GDP and welfare between the 2050 no climate change simulation and the 2050 (SRES B2) baseline simulation. According to the analysis, the world’s crop harvested area and food production decrease by 0.30 and 2.66 percent, respectively. The picture is similar for irrigated production: both area and production are projected to be lower, by 1.55 and 3.99 percent, respectively. Global rainfed production decreases by 1.65 percent, despite an increase in rainfed area of about 0.38 percent. The regional impacts of climate change on rainfed, irrigated, and total crop production vary widely. In Sub-Saharan Africa, both rainfed and irrigated harvested areas decrease when climate change is considered (by 0.59 and 3.51 percent, respectively). Rainfed production, in contrast, increases by 0.70 percent, while irrigated production drops sharply, by 15.30 percent, as some of the irrigated crops, such as wheat, are more susceptible to heat stress, and runoff available to irrigation declines significantly in some African basins. As a result, total crop harvested area and production in Sub-Saharan Africa decrease by 0.72 percent and 1.55 percent, respectively. Most of the decline in production can be attributed to wheat (24.11 percent) and sugarcane (10.58 percent). As a result, irrigated wheat might not be significant in the food production systems of Sub-Saharan Africa. Other crops in Sub-Saharan Africa actually do better because of climate change and particularly $CO_2$ fertilization.

**Table VI–1. 2000 Baseline data: Crop harvested area and production by region and for Sub-Saharan Africa**

| Description | Rainfed Agriculture | | Irrigated Agriculture | | Total Agriculture | | Share of Irrigated Agriculture in Total | |
|---|---|---|---|---|---|---|---|---|
| | Area (1000 ha) | Production (1000 t) | Area (1000 ha) | Production (1000 mt) | Area (1000 ha) | Production (1000 mt) | Area (%) | Production (%) |
| **Regions** | | | | | | | | |
| United States | 38,471 | 211,724 | 69,470 | 442,531 | 107,942 | 654,255 | 64.4 | 67.6 |
| Canada | 27,267 | 65,253 | 717 | 6,065 | 27,984 | 71,318 | 2.6 | 8.5 |
| Western Europe | 59,557 | 462,403 | 10,164 | 146,814 | 69,721 | 609,217 | 14.6 | 24.1 |
| Japan and South Korea | 1,553 | 23,080 | 4,909 | 71,056 | 6,462 | 94,136 | 76.0 | 75.5 |
| Australia and New Zealand | 21,500 | 67,641 | 2,387 | 27,656 | 23,886 | 95,297 | 10.0 | 29.0 |
| Eastern Europe | 38,269 | 187,731 | 6,091 | 40,638 | 44,360 | 228,369 | 13.7 | 17.8 |
| Former Soviet Union | 86,697 | 235,550 | 18,443 | 75,798 | 105,139 | 311,347 | 17.5 | 24.3 |
| Middle East | 30,553 | 135,872 | 21,940 | 119,626 | 52,493 | 255,498 | 41.8 | 46.8 |
| Central America | 13,030 | 111,665 | 8,794 | 89,698 | 21,824 | 201,364 | 40.3 | 44.5 |
| South America | 80,676 | 650,313 | 10,138 | 184,445 | 90,814 | 834,758 | 11.2 | 22.1 |
| South Asia | 143,427 | 492,718 | 120,707 | 563,161 | 264,134 | 1,055,879 | 45.7 | 53.3 |
| Southeast Asia | 69,413 | 331,755 | 27,464 | 191,890 | 96,876 | 523,645 | 28.3 | 36.6 |
| China | 66,715 | 617,460 | 124,731 | 909,561 | 191,446 | 1,527,021 | 65.2 | 59.6 |
| North Africa | 15,714 | 51,163 | 7,492 | 78,944 | 23,206 | 130,107 | 32.3 | 60.7 |
| Sub-Saharan Africa | 175,375 | 440,800 | 6,243 | 43,398 | 181,618 | 484,199 | 3.4 | 9.0 |
| Rest of the World | 3,813 | 47,467 | 1,094 | 23,931 | 4,906 | 71,398 | 22.3 | 33.5 |
| **Total** | **872,029** | **4,132,597** | **440,782** | **3,015,211** | **1,312,811** | **7,147,808** | **33.6** | **42.2** |
| | | | | | | | | |
| **Sub-Saharan African crops** | | | | | | | | |
| 1 Rice | 6,015 | 6,117 | 965 | 1,606 | 6,979 | 7,723 | 13.8 | 20.8 |
| 2 Wheat | 2,043 | 3,288 | 422 | 1,340 | 2,465 | 4,628 | 17.1 | 28.9 |
| 3 Cereal grains | 65,723 | 65,912 | 2,394 | 3,286 | 68,117 | 69,197 | 3.5 | 4.7 |
| 4 Vegetables, fruits, nuts | 31,570 | 224,570 | 1,111 | 9,846 | 32,681 | 234,415 | 3.4 | 4.2 |
| 5 Oilseeds | 9,969 | 8,804 | 551 | 554 | 10,520 | 9,358 | 5.2 | 5.9 |
| 6 Sugarcane, sugar beet | 822 | 35,280 | 309 | 25,614 | 1,131 | 60,894 | 27.3 | 42.1 |
| 7 Other agricultural products | 59,235 | 96,830 | 490 | 1,153 | 59,725 | 97,983 | 0.8 | 1.2 |
| **Total** | **175,375** | **440,800** | **6,243** | **43,398** | **181,618** | **484,199** | **3.4** | **9.0** |

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

The last three columns in Table VI-3 show the impact of climate change on regional GDP and welfare. At the global level, GDP is expected to decrease with climate change by US$87 billion, equivalent to 0.09 percent of global GDP. At the regional level, only Australia and New Zealand experience a positive GDP impact under climate change: GDP is expected to increase by US$1.07 billion. Projected declines in GDP are particularly high for the United

States, South Asia, and South America (US$19.77 billion, US$17.27 billion, and US$10.70 billion, respectively). In relative terms, declines are largest for South Asia, the former Soviet Union, and Eastern Europe (0.64, 0.58, and 0.38 percent, respectively). For Sub-Saharan Africa, losses in GDP due to climate change are estimated at US$3.33 billion, equivalent to 0.20 percent of regional GDP. These losses in GDP are used to evaluate the efficacy of the two adaptation scenarios to cope with climate change. Alternatively, when yield effects of $CO_2$ fertilization are not considered, GDP losses in Sub-Saharan Africa are estimated to be slightly higher (US$4.46 billion).

**Table VI–2. 2050 no climate change simulation: Crop harvested area and production by region and for Sub-Saharan Africa**

| Description | Rainfed Agriculture | | Irrigated Agriculture | | Total Agriculture | | Share of Irrigated Agriculture in Total | |
|---|---|---|---|---|---|---|---|---|
| | Area (1000 ha) | Production (1000 mt) | Area (1000 ha) | Production (1000 mt) | Area (1000 ha) | Production (1000 mt) | Area (%) | Production (%) |
| **Regions** | | | | | | | | |
| United States | 34,549 | 363,602 | 71,736 | 877,262 | 106,285 | 1,240,864 | 67.5 | 70.7 |
| Canada | 21,827 | 97,335 | 620 | 9,640 | 22,447 | 106,975 | 2.8 | 9.0 |
| Western Europe | 39,852 | 452,311 | 8,310 | 188,656 | 48,162 | 640,967 | 17.3 | 29.4 |
| Japan and South Korea | 1,107 | 27,348 | 3,770 | 72,337 | 4,876 | 99,685 | 77.3 | 72.6 |
| Australia and New Zealand | 20,143 | 109,878 | 2,281 | 49,614 | 22,424 | 159,492 | 10.2 | 31.1 |
| Eastern Europe | 29,491 | 232,568 | 4,983 | 70,048 | 34,474 | 302,616 | 14.5 | 23.1 |
| Former Soviet Union | 81,142 | 413,531 | 18,703 | 144,623 | 99,845 | 558,154 | 18.7 | 25.9 |
| Middle East | 31,498 | 212,401 | 24,624 | 280,975 | 56,122 | 493,376 | 43.9 | 56.9 |
| Central America | 13,501 | 259,872 | 10,425 | 221,510 | 23,926 | 481,382 | 43.6 | 46.0 |
| South America | 101,888 | 2,232,862 | 13,842 | 675,526 | 115,729 | 2,908,388 | 12.0 | 23.2 |
| South Asia | 101,386 | 646,745 | 152,776 | 1,293,716 | 254,161 | 1,940,461 | 60.1 | 66.7 |
| Southeast Asia | 77,618 | 602,683 | 27,764 | 451,772 | 105,382 | 1,054,454 | 26.3 | 42.8 |
| China | 61,100 | 813,928 | 120,562 | 1,191,019 | 181,662 | 2,004,948 | 66.4 | 59.4 |
| North Africa | 16,849 | 114,127 | 8,426 | 159,367 | 25,274 | 273,494 | 33.3 | 58.3 |
| Sub-Saharan Africa | 235,169 | 1,074,930 | 11,194 | 175,561 | 246,363 | 1,250,491 | 4.5 | 14.0 |
| Rest of the World | 4,439 | 117,191 | 1,428 | 78,063 | 5,867 | 195,254 | 24.3 | 40.0 |
| **Total** | **871,559** | **7,771,313** | **481,443** | **5,939,688** | **1,353,002** | **13,711,001** | **35.6** | **43.3** |
| | | | | | | | | |
| **Sub-Saharan African crops** | | | | | | | | |
| 1 Rice | 6,068 | 11,829 | 2,362 | 9,893 | 8,430 | 21,722 | 28.0 | 45.5 |
| 2 Wheat | 2,885 | 12,576 | 574 | 3,589 | 3,458 | 16,165 | 16.6 | 22.2 |
| 3 Cereal grains | 83,488 | 180,022 | 3,505 | 12,972 | 86,994 | 192,994 | 4.0 | 6.7 |
| 4 Vegetables, fruits, nuts | 40,634 | 535,837 | 2,213 | 40,862 | 42,846 | 576,700 | 5.2 | 7.1 |
| 5 Oilseeds | 13,456 | 15,782 | 655 | 1,115 | 14,110 | 16,897 | 4.6 | 6.6 |
| 6 Sugarcane, sugar beet | 1,661 | 117,818 | 727 | 101,199 | 2,388 | 219,016 | 30.4 | 46.2 |
| 7 Other agricultural products | 86,978 | 201,066 | 1,159 | 5,930 | 88,136 | 206,997 | 1.3 | 2.9 |
| **Total** | **235,169** | **1,074,930** | **11,194** | **175,561** | **246,363** | **1,250,491** | **4.5** | **14.0** |

Source: IMPACT, 2050 simulation without climate change (April 2008).

Like global GDP, global welfare is expected to decline with climate change (US$87 billion). However, welfare losses due to declines in agricultural productivity and crop harvested area are not general; in some regions, welfare increases as their relative competitive position improves with respect to other regions. This is the case for South America, Australia and New Zealand, Sub-Saharan Africa, and Canada. Projected welfare losses are larger for

South Asia, the United States, and Western Europe. The US$2 billion welfare increase in Sub-Saharan Africa is explained as follows. First, only some crops in Sub-Saharan Africa are badly hit by climate change. Second, crops in other parts of the world are hit too—and relatively harder than those in Sub-Saharan Africa. The result is an increase in food prices and exports. This improves welfare (as measured by the Hicksian Equivalent Variation), but it also increases malnutrition.

**Table VI–3. Impact of climate change in 2050: Percentage change in crop harvested area and production by region and for Sub-Saharan Africa as well as change in regional GDP**

| | Rainfed Agriculture | | Irrigated Agriculture | | Total Agriculture | | Change in GDP* | | Change in Welfare* |
|---|---|---|---|---|---|---|---|---|---|
| Description | Area | Production | Area | Production | Area | Production | (%) | (Million USD) | (Million USD) |
| **Regions** | | | | | | | | | |
| United States | 1.56 | -1.68 | -3.26 | -7.18 | -1.70 | -5.57 | -0.07 | -19,768 | -17,076 |
| Canada | 2.02 | -2.99 | 3.32 | 7.67 | 2.05 | -2.03 | -0.05 | -992 | 1,737 |
| Western Europe | 1.21 | -0.18 | 1.64 | 0.10 | 1.28 | -0.10 | -0.01 | -1,942 | -12,612 |
| Japan and South Korea | -0.74 | 0.26 | 0.02 | 1.20 | -0.15 | 0.94 | 0.00 | -582 | -2,190 |
| Australia and New Zealand | 2.24 | 3.16 | 2.64 | 1.05 | 2.28 | 2.51 | 0.09 | 1,074 | 5,784 |
| Eastern Europe | 1.20 | -1.73 | 2.18 | -1.21 | 1.34 | -1.61 | -0.38 | -5,201 | -9,537 |
| Former Soviet Union | 1.55 | -4.16 | 0.51 | 2.97 | 1.36 | -2.31 | -0.58 | -8,734 | -12,039 |
| Middle East | 0.44 | -3.85 | -9.02 | -9.76 | -3.71 | -7.22 | -0.23 | -6,724 | -8,853 |
| Central America | 0.98 | -8.59 | -0.01 | -3.13 | 0.55 | -6.08 | -0.21 | -5,133 | -914 |
| South America | 0.22 | -3.43 | -2.42 | -8.42 | -0.10 | -4.59 | -0.21 | -10,697 | 6,055 |
| South Asia | 0.20 | 1.71 | 1.47 | -2.06 | 0.96 | -0.80 | -0.64 | -17,271 | -24,573 |
| Southeast Asia | 0.19 | -0.28 | -0.70 | -1.94 | -0.04 | -0.99 | -0.12 | -4,073 | -9,644 |
| China | 0.37 | -0.38 | -3.61 | -1.65 | -2.27 | -1.14 | -0.01 | -677 | -2,710 |
| North Africa | 0.66 | -3.42 | -2.87 | -1.78 | -0.52 | -2.47 | -0.14 | -1,146 | -108 |
| Sub-Saharan Africa | -0.59 | 0.70 | -3.51 | -15.30 | -0.72 | -1.55 | -0.20 | -3,333 | 1,786 |
| Rest of the World | 0.60 | -2.85 | -2.87 | -4.86 | -0.25 | -3.65 | -0.22 | -1,716 | -2,111 |
| **Total** | **0.38** | **-1.65** | **-1.55** | **-3.99** | **-0.30** | **-2.66** | **-0.09** | **-86,914** | **-87,004** |
| **Sub-Saharan African crops** | | | | | | | | | |
| 1 Rice | -1.95 | 0.88 | -2.50 | 5.44 | -2.10 | 2.96 | | | |
| 2 Wheat | 2.14 | -24.86 | -7.86 | -21.47 | 0.48 | -24.11 | | | |
| 3 Cereal grains | 0.63 | 1.26 | -1.24 | -1.63 | 0.55 | 1.07 | | | |
| 4 Vegetables, fruits, nuts | -0.34 | 1.14 | -1.53 | -1.93 | -0.41 | 0.92 | | | |
| 5 Oilseeds | -1.16 | 0.33 | -0.67 | 1.68 | -1.14 | 0.42 | | | |
| 6 Sugarcane, sugar beet | 1.27 | 2.11 | -23.85 | -25.35 | -6.37 | -10.58 | | | |
| 7 Other agricultural products | -1.81 | -0.19 | -2.95 | 0.16 | -1.83 | -0.18 | | | |
| **Total** | **-0.59** | **0.70** | **-3.51** | **-15.30** | **-0.72** | **-1.55** | | | |

Source: IMPACT, 2050 (SRES B2) baseline simulation and simulation without climate change.
Note: * Data from GTAP-W.

Figure VI-1 shows for the 2050 (SRES B2) baseline simulation a global map of irrigated harvested area as a share of total crop area by country. Approximately 63 percent of the world's irrigated harvested area in 2050 is in Asia, which accounts for about 22 percent of the world's total crop harvested area. By contrast, irrigated agriculture in Sub-Saharan Africa is small; only 4.4 percent of the total crop harvested area is expected to be irrigated by 2050. Most of the countries in Sub-Saharan Africa are expected to continue to use irrigation on less than 5 percent of cropland. Madagascar and Swaziland are exceptions; they are expected to be irrigating 67 percent and 60 percent of their total crop area, respectively. The numbers for Somalia and South Africa are much lower (34 and 24 percent, respectively). The most populous country in the region, Nigeria, accounts for about 23 percent of the region's crop harvested area. However, around 97 percent of Nigeria's production is rainfed.

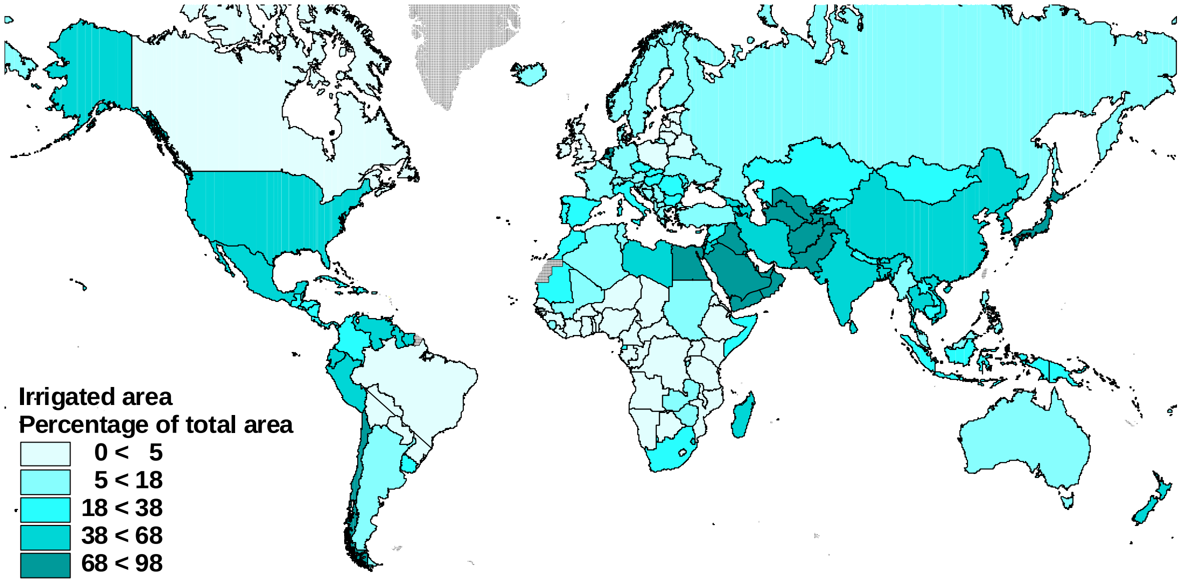


**Figure VI–1. 2050 SRES B2 baseline simulation: Irrigated harvested area as a share of total crop harvested area**

Source: IMPACT, 2050 baseline simulation.

Agricultural crop productivity is commonly measured by the amount of output per unit of area, such as yield in kilograms per hectare.[5] Table VI-4 presents average yields by crop type for the 2050 (SRES B2) baseline simulation. Displayed are global average levels as well as minimum and maximum levels for rainfed and irrigated harvested area according to the 16 GTAP-W regions defined in Table VI-A1. In addition, average yield levels for Sub-Saharan Africa as well as information on the minimum and maximum yields in individual countries are provided. Clearly, the performance of Sub-Saharan Africa is poor when compared to the regional and global averages. Compared with other regions, the average agricultural productivity in Sub-Saharan Africa is the lowest or is close to the minimum for all crops, except for irrigated rice, wheat, and sugarcane, which have levels close to the global average. Agricultural productivity within the Sub-Saharan African region varies widely. Some countries are highly productive on very small areas—for example, Tanzania with sugarcane and South Africa with most agricultural crops. Most countries, however, fare poorly on large rainfed areas with low yields.

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[5] Zepeda (2001) subdivides agricultural productivity measures into partial and total measures. Partial measures are the amount of output per unit of a particular input (e.g., yield and labor productivity). Total measures consider the total factor productivity, which is the ratio of an index of agricultural output to an index of agricultural inputs.

**Table VI–4. 2050 baseline simulation: Crop yields (kilograms per hectare)**

| Agricultural Products | Global Average | Regional Crop Yield* Minimum | Regional Crop Yield* Maximum | Crop Yield in Sub-Saharan Africa Average | Crop Yield in Sub-Saharan Africa Minimum | Crop Yield in Sub-Saharan Africa Maximum |
|---|---|---|---|---|---|---|
| **Rice** | | | | | | |
| Rainfed | 2,446 | 1,965 | 6,787 | 2,006 | 685 | 6,184 |
| Irrigated | 4,251 | 3,444 | 8,977 | 4,530 | 1,074 | 11,461 |
| **Wheat** | | | | | | |
| Rainfed | 3,781 | 1,745 | 6,906 | 3,207 | 753 | 9,225 |
| Irrigated | 5,183 | 3,311 | 9,123 | 5,330 | 934 | 10,442 |
| **Cereal grains** | | | | | | |
| Rainfed | 3,868 | 1,435 | 9,656 | 2,170 | 550 | 4,958 |
| Irrigated | 9,087 | 3,686 | 13,906 | 3,686 | 1,567 | 8,062 |
| **Vegetables, fruits, nuts** | | | | | | |
| Rainfed | 15,356 | 10,940 | 35,855 | 13,384 | 2,920 | 27,451 |
| Irrigated | 24,650 | 18,390 | 57,046 | 18,390 | 2,506 | 37,986 |
| **Oilseeds** | | | | | | |
| Rainfed | 2,080 | 901 | 2,926 | 1,191 | 432 | 1,875 |
| Irrigated | 3,865 | 1,743 | 4,616 | 1,743 | 713 | 3,464 |
| **Sugarcane, sugar beet** | | | | | | |
| Rainfed | 99,303 | 34,494 | 129,276 | 71,501 | 9,113 | 203,921 |
| Irrigated | 129,646 | 50,363 | 187,128 | 136,497 | 36,924 | 232,523 |
| **Other agricultural products** | | | | | | |
| Rainfed | 4,669 | 2,022 | 26,371 | 2,482 | 287 | 16,602 |
| Irrigated | 9,484 | 2,640 | 81,150 | 8,912 | 1,138 | 11,579 |

Source: IMPACT, 2050 (SRES B2) baseline simulation.
Notes: * Regional average according to the 16 GTAP-W regions defined in Table VI-A1.
Crop yields are computed as a weighted average by area.

Table VI-5 presents for the 2050 (SRES B2) baseline simulation crop harvested area and production in Sub-Saharan Africa by crop. Only 4.4 percent of the total crop harvested area is expected to be under irrigation by 2050, while irrigated production is expected to account for 12.1 percent of the total agricultural production in the region. The two major irrigated crops are rice and sugarcane. Irrigated rice is expected to account for more than one-fourth of the total rice harvested area and to contribute almost half of the total rice production. For irrigated sugarcane the picture is similar. Almost one-fourth of the total crop area is projected to be under irrigation, and around 38.6 percent of the total crop production is expected to be irrigated. Most of the total crop area under irrigation is devoted to the production of cereal grains; rice; and vegetables, fruits, and nuts. However, with the exception of rice, the share of irrigated harvested area as a percentage of total crop harvested area is projected to be less than 5.1 percent. Similarly, almost 80 percent of the total rainfed harvested area in Sub-Saharan Africa is projected to be used for the production of cereals; roots and tubers; and vegetables, groundnuts, and fruits.

## 4. Strategies for adaptation to climate change

We evaluate the effects on production and income of two possible strategies for adaptation to climate change in Sub-Saharan Africa. Both adaptation scenarios are implemented based on the 2050 (SRES B2) baseline. The first adaptation scenario assumes an expansion in the capacity of irrigated agriculture and doubles the irrigated area in Sub-Saharan Africa. The second adaptation scenario considers improvements in productivity for both rainfed and irrigated agriculture—increasing rainfed and irrigated yields in Sub-Saharan Africa by 25 percent through investments in agricultural research and development and enhanced farm management practices.

**Table VI–5. 2050 baseline simulation: Crop harvested area and production in Sub-Saharan Africa**

| Agricultural Products (according to GTAP-W) | Rainfed Agriculture Area (1000 ha) | Rainfed Agriculture Production (1000 mt) | Irrigated Agriculture Area (1000 ha) | Irrigated Agriculture Production (thousand mt) | Total Agriculture Area (1000 ha) | Total Agriculture Production (1000 mt) | Share of Irrigated Agriculture in Total Area (%) | Share of Irrigated Agriculture in Total Production (%) |
|---|---|---|---|---|---|---|---|---|
| 1 Rice | 5,950 | 11,933 | 2,303 | 10,432 | 8,253 | 22,364 | 27.9 | 46.6 |
| 2 Wheat | 2,946 | 9,450 | 529 | 2,818 | 3,475 | 12,268 | 15.2 | 23.0 |
| 3 Cereal grains | 84,012 | 182,298 | 3,462 | 12,761 | 87,474 | 195,058 | 4.0 | 6.5 |
| 4 Vegetables, fruits, nuts | 40,493 | 541,953 | 2,179 | 40,072 | 42,673 | 582,025 | 5.1 | 6.9 |
| 5 Oilseeds | 13,300 | 15,834 | 650 | 1,134 | 13,950 | 16,968 | 4.7 | 6.7 |
| 6 Sugarcane, sugar beet | 1,683 | 120,306 | 553 | 75,545 | 2,236 | 195,851 | 24.8 | 38.6 |
| 7 Other agricultural products | 85,400 | 200,684 | 1,125 | 5,939 | 86,525 | 206,623 | 1.3 | 2.9 |
| **Total** | **233,784** | **1,082,457** | **10,801** | **148,701** | **244,585** | **1,231,158** | **4.4** | **12.1** |

Source: IMPACT, 2050 (SRES B2) baseline simulation.

According to the first adaptation scenario, irrigated areas in Sub-Saharan Africa are assumed to double by 2050, as compared to the 2050 (SRES B2) baseline, while total cropland does not change. Around 11 million hectares are thus transferred from rainfed agriculture to irrigated agriculture, increasing irrigated areas in the region from a very small base to nearly 9 percent of the total crop area in the region. In GTAP-W, the initial irrigated land and irrigation endowments are doubled; the rainfed land endowment is reduced accordingly. In IMPACT, for each FPU and each crop, irrigated area growth is doubled for the region. Rainfed area is reduced by an equal amount to keep total crop area constant. Other growth assumptions remain unchanged.

In the second adaptation scenario, agricultural crop productivity for both rainfed and irrigated crops in Sub-Saharan Africa is increased by 25 percent compared to the 2050 (SRES B2) baseline. In GTAP-W, the primary factor productivity of rainfed land, irrigated land, and irrigation is increased by 25 percent. In IMPACT, crop-yield growth rates are increased to reach values 25 percent above baseline values.

For both adaptation scenarios, investment or cost implications are not incorporated into the modeling frameworks, and the additional irrigation water used does not violate any sustainability constraints.

### 4.1. Adaptation scenario 1: Expansion of irrigated agriculture

In the original GTAP model, land is specific to the agricultural sector but not to individual crops, which compete for land. In the GTAP-W model this proposition also holds. Rainfed land, irrigated land, and irrigation are sector-specific, but individual crops compete for them. Pastureland is used by only a single sector, livestock. Therefore, when the capacity of irrigated agriculture is increased by transferring land from rainfed agriculture to irrigated agriculture, the additional land in irrigated agriculture is not allocated uniformly. Irrigated wheat production uses a higher proportion of the new land and irrigation than other crops (Table VI-6), an outcome that is mostly driven by a strong regional consumption of locally produced wheat. Similarly, the reduction in rainfed land is not proportional among crops. While the use of rainfed land decreases between 0.04 and 0.53 percent for most crops, the use of rainfed land for wheat production increases by 1.35 percent. The combined effect is an increase in total wheat production of 2.12 percent, which is consistent with an increase in irrigated and rainfed production of 102.24 and 0.49 percent, respectively. The change in production of oilseeds shows a similar picture: irrigated and rainfed production increase by 100.12 and 0.03 percent, respectively. For the rest of the crops, irrigated production increases and rainfed production decreases, resulting in an increase in total crop production. The only exception is the "other agricultural products" sector, for which total production decreases by 0.05 percent.

The expansion of irrigated areas in the region from a very small base helps farmers achieve higher yields per hectare. This is followed by an increase in total crop production and a drop in agricultural commodity prices. The last two columns in Table VI-6 show a reduction in domestic and global market prices for all crops (an exception is the increase in the domestic price of other agricultural products).

As a general equilibrium model, GTAP-W accounts for impacts in nonagricultural sectors as well. Changes in total crop production have a mixed effect on nonagricultural sectors; the domestic and world prices of nonagricultural products increase under this alternative scenario. An exception is the food products sector, in which prices decline because production is promoted by a higher supply and lower price of crops.

Factor market prices change according to the new factor composition. The increase in the supply of irrigated land and irrigation pushes down their market prices, while prices for rainfed land, as it becomes scarcer, experience a relative increase. Market prices for the rest of the primary factors increase as the economy expands (Table VI-6). Regional welfare increases by only about US$119 million. This adaptation scenario leads to a small increase in GDP in Sub-Saharan Africa (0.007 percent, equivalent to US$113 million), which is insufficient to compensate for the regional GDP losses expected under climate change (US$3.33 billion).

Results from the IMPACT model are shown in Table VI-7. The expansion of irrigated areas in Sub-Saharan Africa increases cereal production in the region by 5 percent, and meat production by 1 percent. No change can be seen for root and tuber production. The results are not readily comparable to those obtained by the GTAP-W due to the differences in aggregation. Contrary to the IMPACT results, meat production in the GTAP-W decreases slightly, by 0.06 percent.

**Table VI–6. Adaptation scenario 1: Percentage change in the demand for endowments, total production, and market price in Sub-Saharan Africa (outputs from GTAP-W, percentage change with respect to the 2050 baseline simulation)**

| GTAP-W Sectors | Change in Demand for Endowments (%) | | | | | | | | Change in Production (%) | | | Change in Market Price (%) | Change in World Market Price (%)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Irrigation | Irrigated land | Rainfed land | Pasture-land | Unskilled labor | Skilled labor | Capital | Natural resources | Irrigated | Rainfed | Total | | |
| 1 Rice | 99.57 | 99.60 | -0.18 | | -0.17 | -0.17 | -0.17 | | 99.59 | -2.57 | 0.16 | -1.12 | -0.06 |
| 2 Wheat | 102.63 | 102.66 | 1.35 | | 1.73 | 1.73 | 1.73 | | 102.24 | 0.49 | 2.12 | -1.17 | -0.05 |
| 3 Cereal grains | 99.85 | 99.87 | -0.04 | | 0.00 | 0.00 | 0.00 | | 99.87 | -0.47 | 0.05 | -0.14 | -0.02 |
| 4 Vegetable, fruits, nuts | 99.94 | 99.96 | 0.00 | | 0.06 | 0.05 | 0.05 | | 98.06 | 0.00 | 0.09 | -0.10 | -0.01 |
| 5 Oilseeds | 100.14 | 100.17 | 0.11 | | 0.18 | 0.18 | 0.18 | | 100.12 | 0.03 | 0.24 | -0.18 | -0.02 |
| 6 Sugarcane, sugar beet | 98.87 | 98.89 | -0.53 | | -0.61 | -0.61 | -0.61 | | 98.88 | -7.32 | 0.17 | -1.87 | -0.17 |
| 7 Other agricultural products | 99.76 | 99.78 | -0.09 | | -0.05 | -0.05 | -0.06 | | 99.78 | -0.17 | -0.05 | 0.01 | -0.01 |
| 8 Animals | | | | 0 | 0.02 | 0.02 | 0.02 | | | | 0.00 | 0.07 | 0.01 |
| 9 Meat | | | | | -0.06 | -0.06 | -0.06 | | | | -0.06 | 0.05 | 0.00 |
| 10 Food products | | | | | 0.11 | 0.11 | 0.11 | | | | 0.11 | -0.17 | -0.01 |
| 11 Forestry | | | | | 0.00 | 0.00 | 0.00 | 0.00 | | | 0.00 | 0.02 | 0.00 |
| 12 Fishing | | | | | 0.04 | 0.04 | 0.04 | 0.00 | | | 0.02 | 0.12 | 0.01 |
| 13 Coal | | | | | -0.01 | -0.01 | -0.01 | 0.00 | | | -0.01 | 0.01 | 0.00 |
| 14 Oil | | | | | -0.02 | -0.02 | -0.02 | 0.00 | | | -0.02 | 0.01 | 0.00 |
| 15 Gas | | | | | -0.04 | -0.04 | -0.04 | 0.00 | | | -0.03 | 0.01 | 0.00 |
| 16 Oil products | | | | | -0.01 | -0.01 | 0.01 | | | | 0.01 | 0.01 | 0.00 |
| 17 Electricity | | | | | -0.01 | -0.01 | -0.01 | | | | -0.01 | 0.02 | 0.00 |
| 18 Water | | | | | 0.01 | 0.01 | 0.01 | | | | 0.01 | 0.02 | 0.00 |
| 19 Energy-intensive industries | | | | | -0.03 | -0.03 | -0.03 | 0.00 | | | -0.03 | 0.01 | 0.00 |
| 20 Other industries and services | | | | | -0.02 | -0.02 | -0.02 | | | | -0.02 | 0.01 | 0.00 |
| 21 Market services | | | | | 0.00 | 0.00 | 0.00 | | | | 0.00 | 0.01 | 0.00 |
| 22 Nonmarket services | | | | | 0.00 | 0.00 | 0.00 | | | | 0.00 | 0.01 | 0.00 |
| **Change in market price (%)** | -90.57 | -90.63 | 0.19 | 0.09 | 0.02 | 0.02 | 0.02 | 0.08 | | | | | |

Note: * World price index for total supply.

**Table VI–7. Adaptation scenario 1: Regional production and world market prices for cereals and meats, 2000 baseline data and 2050 baseline simulations (outputs from IMPACT)**

| Description | 2000 | 2050 | | Percentage |
|---|---|---|---|---|
| | Baseline Data | Baseline | Scenario 1 | Change* |
| **Cereal production (mmt):** | | | | |
| North America and Europe | 779 | 1,188 | 1,196 | 0.67 |
| Central West Asia and North Africa | 116 | 240 | 233 | -2.80 |
| East and South Asia and Pacific | 745 | 1,010 | 1,009 | -0.06 |
| Latin America and Caribbean | 133 | 262 | 263 | 0.57 |
| Sub-Saharan Africa | 78 | 211 | 222 | 5.34 |
| **Root and tuber production (mmt):** | | | | |
| North America and Europe | 171 | 198 | 198 | 0.36 |
| Central West Asia and North Africa | 21 | 48 | 46 | -2.56 |
| East and South Asia and Pacific | 281 | 371 | 371 | -0.05 |
| Latin America and Caribbean | 51 | 107 | 108 | 1.17 |
| Sub-Saharan Africa | 164 | 379 | 379 | 0.00 |
| **Meat production (mmt):** | | | | |
| North America and Europe | 93 | 122 | 122 | 0.04 |
| Central West Asia and North Africa | 11 | 33 | 33 | 0.90 |
| East and South Asia and Pacific | 88 | 202 | 203 | 0.56 |
| Latin America and Caribbean | 30 | 82 | 83 | 1.13 |
| Sub-Saharan Africa | 6 | 15 | 16 | 1.05 |
| **World market prices (USD/mmt):** | | | | |
| Rice | 186 | 299 | 296 | -0.80 |
| Wheat | 109 | 205 | 209 | 1.76 |
| Maize | 91 | 180 | 181 | 0.46 |
| Other grains | 68 | 108 | 108 | 0.08 |
| Millet | 255 | 310 | 312 | 0.62 |
| Sorghum | 93 | 169 | 172 | 1.72 |
| Potato | 213 | 210 | 206 | -1.62 |
| Sweet potato and yam | 470 | 405 | 398 | -1.53 |
| Cassava | 65 | 58 | 59 | 0.99 |
| Beef | 1,917 | 2,521 | 2,548 | 1.06 |
| Pork | 906 | 1,226 | 1,236 | 0.86 |
| Sheep and goat | 2,705 | 2,782 | 2,780 | -0.09 |
| Poultry | 1,196 | 1,661 | 1,684 | 1.39 |

Note: * Percentage change with respect to the 2050 (SRES B2) baseline simulation.

For all cereals, real commodity prices by 2050 under the baseline are expected to be higher than prices in 2000. This is a result of increased resource scarcity, for both land and water, as well as the impact of climate change, biofuel development, increased population, and income-growth-driven food demand diversification, with demand shifting toward meat, egg, and milk products that require grain as feedstock. Climate change leads to higher mean temperatures and generally raises crop water requirements, but at the same time the availability of water for crop growth may decrease in certain regions. Higher temperatures during the growing season in low-latitude regions, where such temperature-induced yield loss cannot be compensated fully by the fertilization effects of higher $CO_2$ levels, will adversely affect food production.

Similar to grain prices, in the 2050 (SRES B2) baseline, meat prices are expected to increase (Table VI-7). Livestock prices are expected to increase as a result of higher animal feed prices and rapidly growing meat demand. Even though Sub-Saharan Africa is not a key contributor to global food production or irrigated food production, both climate change adaptation scenarios focusing on the region are projected to reduce world food prices. Under this scenario, world food prices decline between 0.8 and 1.6 percent for rice, potatoes, sweet potatoes, and yams. Reductions in world market prices for both cereals and meat are more pronounced in IMPACT than in GTAP-W.

### 4.2. Adaptation scenario 2: Improvements in agricultural productivity

Improvements in agricultural productivity in both rainfed and irrigated agriculture enable farmers to obtain higher levels of output per unit of input. Table VI-8 shows an increase in total crop production, but the magnitude differs by crop type. The “other agricultural products” sector is the sector with the highest increase in production (25 percent), followed by oilseeds; wheat; and vegetables, fruits, and nuts (17, 16, and 11 percent, respectively). Rainfed and irrigated production increase for all crops, with the exception of rainfed sugarcane.

Higher levels of agricultural productivity result in a decline in production costs and consequently in a decline in market prices. Table VI-8 shows, for all crop types, a decrease in domestic and world market prices. A 25 percent increase in agricultural productivity leads to a reduction of around 10 to 13 percent in domestic market prices; only sugarcane experiences a smaller decline, at 8 percent. World market prices, in turn, decline by 3 to 4 percent.

Total production in nonagricultural sectors is also affected under this scenario. Reductions in total production are more pronounced for energy-intensive industries, other industries and services, and gas (4.8, 4.1, and 3.7 percent, respectively). The food products sector is affected positively, and its production increases by 1.4 percent. Domestic and world market prices increase for all nonagricultural sectors except for food products.

An increase in agricultural productivity reduces the demand (at constant effective prices) for rainfed land, irrigated land, and irrigation. Therefore, market prices for these three factors decrease (12.4, 41.7, and 39.9 percent, respectively). Changes in market prices for the rest of the factors are positive. Returns to unskilled labor increase more than returns to skilled labor (3.0 and 2.4 percent, respectively) (Table VI-8). Thus, an increase in agricultural productivity benefits both agricultural and non-agricultural households as suggested by FAO (2006). Regional welfare in Sub-Saharan Africa increases by US$15.44 billion. This adaptation scenario promotes GDP growth by 1.5 percent (US$25.72 billion), which more than offsets the initial reduction of 0.2 percent in GDP due to climate change as projected under the SRES B2 scenario (US$3.33 billion).

Higher rainfed and irrigated crop yields in IMPACT result in higher food production, which lowers international food prices, making food more affordable for the poor. Table VI-9 shows an increase in cereal production by around 20 percent; meat production increases by 4 percent. As expected, world market prices for all cereals and meat products decrease much more under this second adaptation scenario. Prices decline, between 15 and 31 percent, particularly for those crops that are of primary importance for Sub-Saharan Africa: roots and tubers, maize, sorghum, millet, and other coarse grains. As in the former adaptation scenario, the reductions in world market prices are more pronounced in IMPACT than in GTAP-W.

**Table VI–8. Adaptation scenario 2: Percentage change in the demand for endowments, total production, and market price in Sub-Saharan Africa (outputs from GTAP-W, percentage change with respect to the 2050 baseline simulation)**

| | Change in Demand for Endowments (%) | | | | | | | | Change in Production (%) | | | Change in Market Price (%) | Change in World Market Price (%)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GTAP-W Sectors** | **Irrigation** | **Irrigated land** | **Rainfed land** | **Pasture-land** | **Unskilled labor** | **Skilled labor** | **Capital** | **Natural resources** | **Irrigated** | **Rainfed** | **Total** | | |
| 1 Rice | -5.10 | -5.24 | -12.21 | | -3.00 | -2.85 | -2.88 | | 18.50 | 1.58 | 2.03 | -13.51 | -2.82 |
| 2 Wheat | 6.06 | 5.89 | -1.90 | | 11.31 | 11.48 | 11.38 | | 32.42 | 15.40 | 16.13 | -10.14 | -2.56 |
| 3 Cereal grains | -4.98 | -5.13 | -12.12 | | -2.87 | -2.73 | -2.77 | | 18.63 | 2.21 | 2.29 | -13.60 | -3.32 |
| 4 Vegetables, fruits, nuts | 1.99 | 1.83 | -5.66 | | 6.04 | 6.21 | 6.15 | | 27.34 | 10.88 | 10.95 | -12.77 | -2.60 |
| 5 Oilseeds | 6.44 | 6.27 | -1.55 | | 11.80 | 11.97 | 11.92 | | 32.90 | 16.82 | 16.93 | -12.90 | -2.91 |
| 6 Sugarcane, sugar beet | -5.13 | -5.28 | -12.25 | | -3.06 | -2.91 | -2.96 | | 18.45 | -0.10 | 1.21 | -7.52 | -2.81 |
| 7 Other agricultural products | 12.55 | 12.37 | 4.09 | | 19.79 | 19.97 | 19.92 | | 40.52 | 25.22 | 25.24 | -11.58 | -4.15 |
| 8 Animals | | | | 0 | 0.36 | 0.51 | 0.45 | | | | 0.06 | 3.65 | 0.78 |
| 9 Meat | | | | | -3.29 | -2.59 | -2.70 | | | | -2.96 | 2.86 | 0.17 |
| 10 Food products | | | | | 1.00 | 1.73 | 1.61 | | | | 1.38 | -1.72 | -0.99 |
| 11 Forestry | | | | | -0.06 | 0.06 | 0.03 | 0.00 | | | 0.02 | 2.49 | 0.67 |
| 12 Fishing | | | | | 1.28 | 1.41 | 1.36 | 0.01 | | | 0.51 | 5.51 | 0.76 |
| 13 Coal | | | | | -1.74 | -1.62 | -1.61 | -0.01 | | | -1.25 | 0.99 | 0.43 |
| 14 Oil | | | | | -2.86 | -2.73 | -2.75 | -0.01 | | | -2.35 | 0.67 | 0.36 |
| 15 Gas | | | | | -5.02 | -4.64 | -4.47 | -0.01 | | | -3.70 | 0.84 | 0.33 |
| 16 Oil products | | | | | -2.00 | -1.21 | 0.47 | | | | 0.41 | 1.13 | 0.32 |
| 17 Electricity | | | | | -2.50 | -1.71 | -1.51 | | | | -1.47 | 2.09 | 0.22 |
| 18 Water | | | | | -0.52 | 0.29 | 0.28 | | | | 0.14 | 2.12 | 0.15 |
| 19 Energy-intensive industries | | | | | -5.57 | -4.85 | -4.81 | 0.00 | | | -4.81 | 1.93 | 0.14 |
| 20 Other industries and services | | | | | -4.50 | -3.73 | -3.81 | | | | -4.14 | 1.43 | 0.09 |
| 21 Market services | | | | | -0.83 | 0.07 | 0.07 | | | | -0.30 | 2.09 | 0.12 |
| 22 Nonmarket services | | | | | 0.04 | 0.85 | 0.79 | | | | 0.57 | 1.68 | 0.12 |
| **Change in market price (%)** | -39.86 | -41.70 | -12.44 | 4.58 | 3.03 | 2.38 | 2.49 | 1.83 | | | | | |

Note: * World price index for total supply.

**Table VI–9. Adaptation scenario 2: Regional production and world market prices for cereals and meat in 2050 baseline simulations (outputs from IMPACT)**

| Description | 2050 Baseline | 2050 Scenario 2 | Percentage Change* |
|---|---|---|---|
| **Cereal production (mmt):** | | | |
| North America and Europe | 1,188 | 1,156 | -2.73 |
| Central West Asia and North Africa | 240 | 227 | -5.41 |
| East and South Asia and Pacific | 1,010 | 987 | -2.29 |
| Latin America and Caribbean | 262 | 254 | -3.05 |
| Sub-Saharan Africa | 211 | 254 | 20.29 |
| **Root and tuber production (mmt):** | | | |
| North America and Europe | 198 | 196 | -0.88 |
| Central West Asia and North Africa | 48 | 47 | -1.21 |
| East and South Asia and Pacific | 371 | 361 | -2.91 |
| Latin America and Caribbean | 107 | 101 | -4.99 |
| Sub-Saharan Africa | 379 | 441 | 16.27 |
| **Meat production (mmt):** | | | |
| North America and Europe | 122 | 123 | 0.90 |
| Central West Asia and North Africa | 33 | 33 | 0.91 |
| East and South Asia and Pacific | 202 | 205 | 1.31 |
| Latin America and Caribbean | 82 | 84 | 2.38 |
| Sub-Saharan Africa | 15 | 16 | 4.30 |
| **World market prices (USD/mmt):** | | | |
| Rice | 299 | 279 | -6.58 |
| Wheat | 205 | 190 | -7.50 |
| Maize | 180 | 153 | -15.05 |
| Other grains | 108 | 85 | -21.46 |
| Millet | 310 | 228 | -26.41 |
| Sorghum | 169 | 130 | -23.07 |
| Potato | 210 | 190 | -9.37 |
| Sweet potato and yam | 405 | 286 | -29.39 |
| Cassava | 58 | 40 | -30.75 |
| Beef | 2,521 | 2,507 | -0.54 |
| Pork | 1,226 | 1,213 | -1.04 |
| Sheep and goat | 2,782 | 2,752 | -1.09 |
| Poultry | 1,661 | 1,642 | -1.18 |

Note: * Percentage change with respect to the 2050 (SRES B2) baseline simulation.

**Table VI–10. Summary of the impact of climate change and adaptation on Sub-Saharan Africa**

| Description | 2050 No climate change | 2050* SRES B2 baseline | 2050** Double irrigated area | 2050** Increase crop yield |
|---|---|---|---|---|
| Total production (thousand mt) | 1,250,491 | -1.5% | 0.1% | 18.0% |
| Rainfed production (thousand mt) | 1,074,930 | 0.7% | -0.6% | 17.9% |
| Irrigated production (thousand mt) | 175,561 | -15.3% | 99.5% | 23.4% |
| Total area (thousand ha) | 246,363 | -0.7% | 0.0% | 0.0% |
| Rainfed area (thousand ha) | 235,169 | -0.6% | -4.8% | 0.0% |
| Irrigated area (thousand ha) | 11,194 | -3.5% | 100.0% | 0.0% |
| Change in welfare (USD million) | -- | 1,786 | 119 | 15,435 |
| Change in GDP (USD million) | -- | -3,333 | 113 | 25,720 |
| Change in GDP (percentage) | -- | -0.2% | 0.0% | 1.5% |
| Malnutrition (million children) | 30.2 | 32.0 | 31.7 | 30.4 |

Notes: * Percentage change with respect to the 2050 no climate change simulation.
** Percentage change with respect to the 2050 (SRES B2) baseline simulation.

### 4.3. Outcomes for malnutrition

Figure VI-2 shows the number of malnourished children in the Sub-Saharan African region for 2000 and projected to 2050. Under the SRES B2 baseline, the number of malnourished children is projected at 32 million in 2050, compared to about 30 million in 2000. This large number of malnourished children is unacceptably high. However, the share of malnourished children is projected to decline from 28 to 20 percent over the 50-year period.

Under the scenario with the doubling of irrigated area, the number of malnourished children declines by only 0.3 million children. The scenario with increased rainfed and irrigated crop productivity, in contrast, results in a decline in the number of malnourished children of 1.6 million children, which is close to the no climate change baseline. Thus, improving crop yields in both rainfed and irrigated areas is a strategy that would almost completely offset the impact of climate change on child malnutrition.

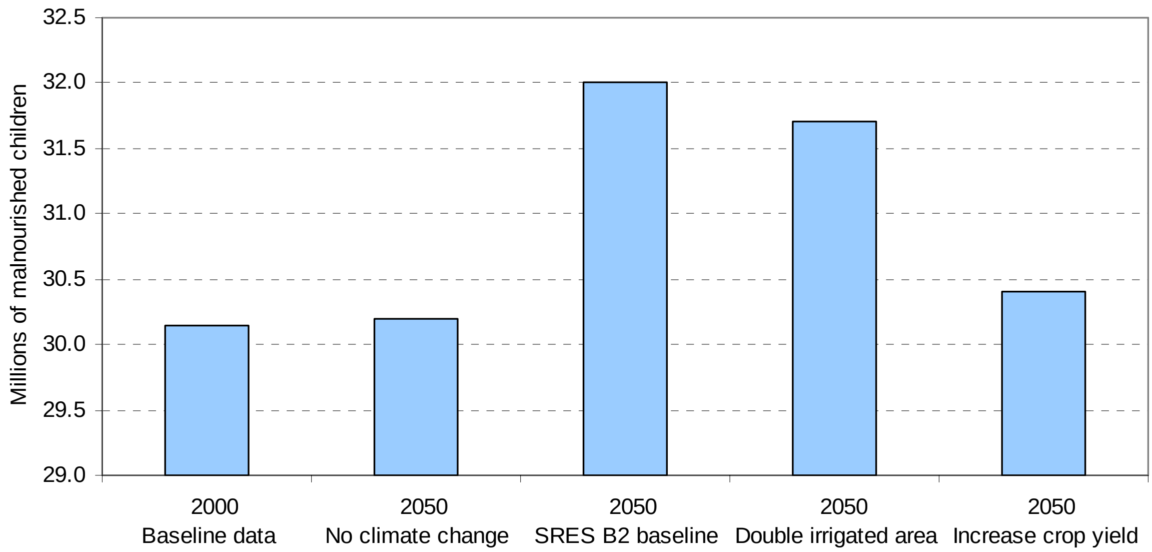


**Figure VI–2. Number of malnourished children (<5 yrs) in Sub-Saharan Africa, 2000 baseline data and projected 2050 baseline simulations and alternative adaptation scenarios (million children)**

Source: IFPRI IMPACT simulations.

## 5. Discussion and conclusions

This paper presents a combined analysis using both a global partial equilibrium agricultural sector model (IMPACT) and a global CGE model (GTAP-W) for alternative strategies for adaptation to climate change in Sub-Saharan Africa. Special emphasis is placed on the link of the two models, which allows for improved calibration and enhanced policy insights.

The methodology combines the advantages of the two types of models. IMPACT considers detailed water-agriculture linkages and provides the data underlying GTAP-W. While IMPACT can provide results for water and food supply in 281 FPUs, the model cannot examine impacts on nonagricultural sectors. GTAP-W distinguishes between rainfed and irrigated agriculture and implements water as a factor of production in the production process for irrigated agriculture. The GTAP-W model considers water quantity and prices but ignores the nonmarket benefits and costs of water use. For instance, the model is unable to predict the direct ecological impact of excessive pumping that reduces groundwater and affects the flow of streams but increases the market-based benefits from water use. As in all CGE models, GTAP-W takes into account the linkages between agricultural and nonagricultural sectors as well as a full treatment of factor markets.

Two scenarios for adaptation to climate change in Sub-Saharan Africa are analyzed. These scenarios are contrasted with the IMPACT 2050 baseline simulation, which incorporates the SRES B2 scenario and a further scenario assuming no climate change. Model outputs—including demand and supply of water, demand and supply of food, rainfed and irrigated production, and rainfed and irrigated area—are then used in GTAP-W to calibrate a hypothetical general equilibrium in 2050 for both simulations. The main results of the four scenarios are summarized in Table VI-10.

Without specific adaptation, climate change would have a negative impact on agriculture in Sub-Saharan Africa. Total food production would fall by 1.6%, with heavy losses in sugarcane (-10.6%) and wheat (-24.1%). The number of malnourished children would increase by almost 2 million.

The first adaptation scenario doubles the irrigated area in Sub-Saharan Africa, compared to the 2050 (SRES B2) baseline, but keeps total crop area constant in both models. The second adaptation scenario increases both rainfed and irrigated crop yields by 25 percent for all countries in Sub-Saharan Africa.

Because of the relatively low share of irrigated area in total agricultural area in Sub-Saharan Africa, an increase in agricultural productivity achieves much larger benefits for the region than a doubling of irrigated area. Because agriculture in Sub-Saharan Africa is far below its potential, substantial productivity gains are technically feasible. The differences between the adaptation scenarios are more pronounced in GTAP-W than in IMPACT. Both adaptation scenarios increase total crop production, but the magnitude differs according to crop type.

An increase in irrigated area and agricultural productivity leads to a decrease in the production cost of agricultural products, and consequently to a reduction in market prices. Even though Sub-Saharan Africa is not a key contributor to global food production or irrigated food production, both adaptation scenarios help lower world food prices. Both GTAP-W and IMPACT show more pronounced reductions in domestic and world market prices under the scenario simulating enhanced crop productivity.

Lower food prices make food more affordable for the poor. As a result, the number of malnourished children in Sub-Saharan Africa is projected to decline by 0.3 million children by 2050 under the doubling of irrigated area scenario and by 1.6 million children under the increased agricultural productivity scenario. The reduction in the number of malnourished children under enhanced crop productivity almost equals the increase in the projected number of malnourished children under the climate change baseline compared to a simulation without climate change.

Changes in total production in nonagricultural sectors have a mixed pattern; however, all of them show an increase in domestic and world prices. An exception is the food products sector, in which prices decline because production is promoted by a higher supply and lower price of agricultural products.

Because the first adaptation scenario transfers land from rainfed to irrigated agriculture, market prices for rainfed land increase, while market prices for irrigation and irrigated land decrease. In the second adaptation scenario, market prices for rainfed land, irrigated land, and irrigation decline. In both adaptation scenarios, market prices for the rest of the primary factors increase. The increase in the market price for unskilled labor is higher than for skilled labor under the second scenario.

Both adaptation scenarios enable farmers to achieve higher yields and revenues from crop production. The increase in regional welfare in the first scenario is modest (US$119 million) but in the second scenario reaches US$15.43 billion.

The efficacy of the two scenarios as adaptation measures to cope with climate change is measured by changes in regional GDP. An increase in agricultural productivity widely exceeds the GDP losses due to climate change; GDP increases by US$25.72 billion compared to the initial reduction in GDP of US$3.33 billion. The opposite happens for an increase in irrigated area; the GDP increase does not offset GDP losses due to climate change (GDP increases by only US$113 million). While these results are promising in terms of the potential to develop investment programs to counteract the adverse impacts of climate change, the scenario implemented here, SRES B2, is on the conservative side of the range of climate change scenarios.

Several caveats apply to the above results. First, in our analysis, increases in irrigated areas and improvements in agricultural productivity are not accompanied by changes in prices. We do not consider any cost or investment associated with irrigation expansion or improvements in agricultural productivity. Therefore, our results might overestimate the benefits of both adaptation scenarios. Second, we implicitly assume, for the expansion of irrigated agriculture, the availability and accessibility of water resources. We assume a sustainable use of water resources. Third, we do not achieve a complete integration of both models. Future work will be focused on further integration and accounting for possible feedbacks from GTAP-W to IMPACT.

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## Annex A

**Table VI–A1. Regional and sectoral mapping between IMPACT and GTAP-W**

| 16 GTAP-W Regions | 115 IMPACT Regions |
|---|---|
| United States | United States |
| Canada | Canada |
| Western Europe | Alpine Europe, Belgium and Luxembourg, British Isles, Cyprus, France, Germany, Iberia, Italy, Netherlands, Scandinavia |
| Japan and South Korea | Japan, South Korea |
| Australia and New Zealand | Australia, New Zealand |
| Eastern Europe | Adriatic, Central Europe, Poland |
| Former Soviet Union | Baltic, Caucasus, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan |
| Middle East | Gulf, Iran, Iraq, Israel, Jordan, Lebanon, Syria, Turkey |
| Central America | Caribbean Central America, Mexico |
| South America | Argentina, Brazil, central South America, Chile, Colombia, Ecuador, northern South America, Peru, Uruguay |
| South Asia | Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka |
| Southeast Asia | Indonesia, Malaysia, Mongolia, Myanmar, North Korea, Philippines, Singapore, Southeast Asia, Thailand, Vietnam |
| China | China |
| North Africa | Algeria, Egypt, Libya, Morocco, Tunisia |
| Sub-Saharan Africa | 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 | Papua New Guinea, rest of the world |
| **7 GTAP-W Crops** | **23 IMPACT Crops** |
| Rice | Rice |
| Wheat | Wheat |
| Cereal grains | Maize, millet, sorghum, other grains |
| Vegetables, fruits, nuts | Potato, sweet potatoes and yams, cassava and other roots and tubers, vegetables, (sub)tropical fruits, temperate fruits, chickpeas, pigeon peas |
| Oilseeds | Soybeans, oils, groundnuts |
| Sugarcane, sugar beet | Sugarcane, sugar beets |
| Other agricultural products | Other |
| -- | Meals, cotton, sweeteners |

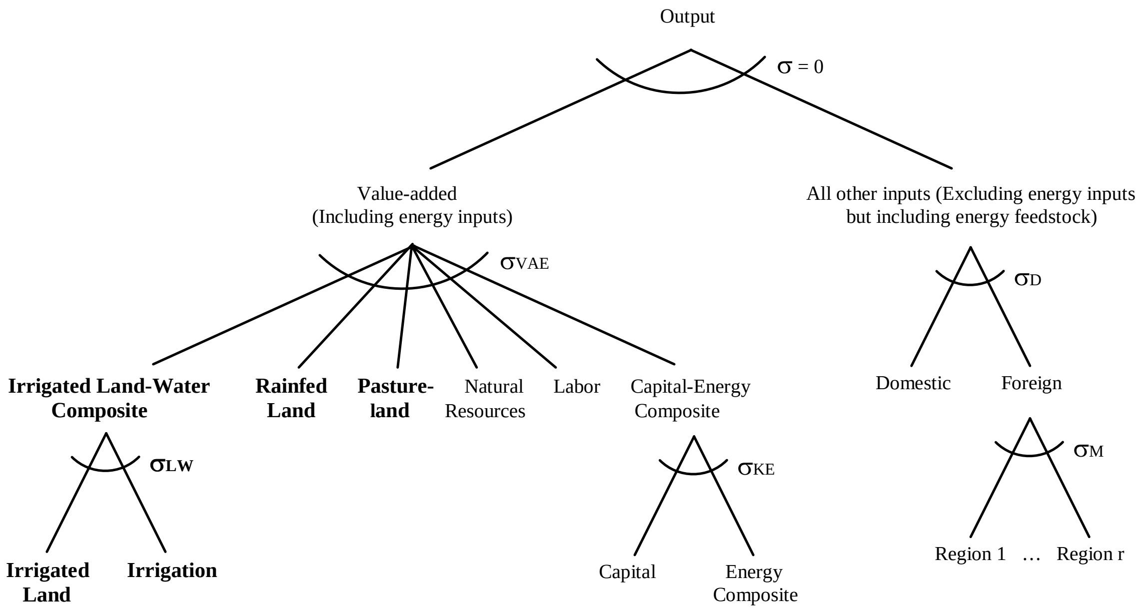


**Figure VI–A1. Nested tree structure for industrial production process in GTAP-W (truncated)**

Note: The original land endowment has been split into pastureland, rainfed land, irrigated land, and irrigation (bold letters). σ is the elasticity of substitution between value added and intermediate inputs, σVAE is the elasticity of substitution between primary factors, σLW is the elasticity of substitution between irrigated land and irrigation, σKE is the elasticity of substitution between capital and the energy composite, σD is the elasticity of substitution between domestic and imported inputs and σM is the elasticity of substitution between imported inputs.

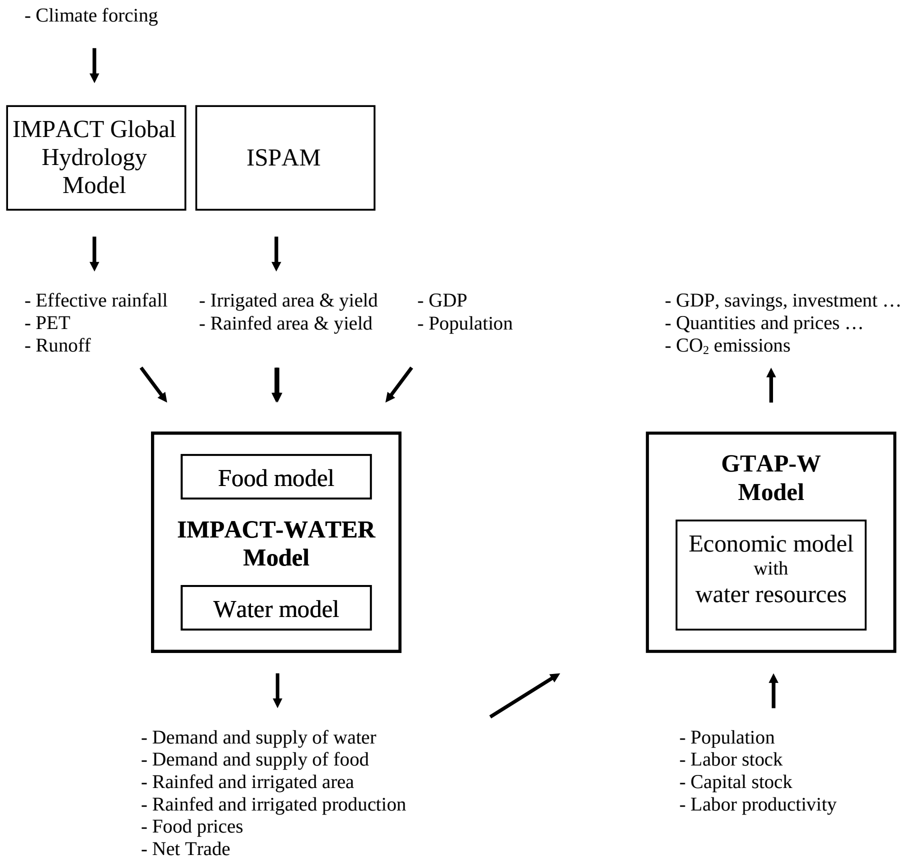


**Figure VI–A2. Model linkages between IMPACT and GTAP-W**

Note: ISPAM (spatial distribution of crops based on crop calendars, soil characteristics and climate of 20 most important crops).

# VII

## OVERALL CONCLUSIONS

The main motivation of this thesis is to investigate the role of water resources in agriculture and within the context of international trade. Therefore, we developed a new version of the GTAP-W model (introduced in the first paper *The GTAP-W Model: Accounting for Water Use in Agriculture*), which is a computable general equilibrium model of the world economy with irrigation water as an explicit factor of production. Moreover, the production structure of GTAP-W allows for substitution possibilities between irrigation water and other primary factors. 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 non-market good, not reported in national economic accounts.

These new characteristics of GTAP-W are crucially important for the assessment of water resources in agriculture. 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 essential, 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 rainfed agriculture relies on soil moisture generated from rainfall, irrigated agriculture focuses on withdrawals of water from surface and groundwater sources.

Using the GTAP-W model, different water policies in the agricultural sector have been analyzed within this thesis. In the second paper *Water Scarcity and the Impact of Improved Irrigation Management*, we explore the potential global water savings and its economic implications by improving irrigation efficiency worldwide to the maximum attainable level. We find that global water savings are achieved and the magnitude increases when more regions achieve higher levels of irrigation efficiency. 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). We find that initial water savings represent between 12-21 percent of the total irrigation currently used. Final water savings are much lower, between 5-10 percent. Therefore, ignoring adjustments in production patterns and food markets would overstate the expected amount of global water savings.

Improving irrigation efficiency promotes irrigated production, which partially offset rainfed production. This implies regional welfare losses, mostly in non-water scarce regions. However, these welfare losses are most than offset by the gains from increased irrigated production and lower food prices. We find that exports of virtual water are not exclusive of water abundant regions.

The third paper *The Economic Impact of more Sustainable Water Use in Agriculture* quantifies the welfare implications of increasing or restricting the human take of total water from nature. While a water crisis scenario explores a deterioration in current conditions and policies in the water sector, a sustainable water use scenario assumes an improvement and eliminates groundwater overdraft worldwide. We find that higher irrigation withdrawals contribute to economic welfare in the short-term. However, harm the long-term sustainability goals in countries with groundwater overdraft. The results reveal a clear trade-off between economic welfare measured by consumption of market goods versus nature conservation. In fact, since more water is available for agriculture in the water crisis scenario, the crisis is therefore not a crisis for agriculture, but rather a crisis for the natural environment which would have to make do with less water.

The fourth paper *Climate Change Impacts on Global Agriculture* analyzes potential impacts of future climate change on food production, consumption and trade. The results highlight the importance of differentiating rainfed and irrigated agriculture. When we mimic previous studies, assuming no distinction between rainfed and irrigated agriculture, welfare looses are two times higher than those obtained when rainfed and irrigated agriculture are discriminated. That is, irrigated crop production is less vulnerable to changes in water resources induced by climate change. Whenever irrigation is possible food production relies on irrigated crops.

Global food production declines in both time periods (2020s and 2050s) and emission scenarios (A1B and A2). Declines are larger in the long-term and slightly more pronounced under the SRES A2 scenario. Temperature is the main climate variable explaining welfare changes. Independently of the SRES emission scenario and time period, the results show that regional welfare decreases with higher temperature levels and increases with improvements in the terms of trade. Thus, regions are not only affected by regional climate change, but also by climate-induced competitiveness changes.

Two adaptation options to cope with climate change in Sub-Saharan Africa are analyzed in the fifth paper *Economywide Impacts of Climate Change on Agriculture in Sub-Saharan Africa*. Due to the relatively low share of irrigated area in total agricultural area in Sub-Saharan Africa, an increase in agricultural productivity achieves much larger benefits for the region than a doubling of irrigated area. In fact, an increase in agricultural productivity widely exceeds the GDP losses due to climate change. The opposite happens for an increase in irrigated area; the GDP increase does not offset GDP losses due to climate change. Similarly, the reduction in the number of malnourished children under the scenario with enhanced crop productivity almost offset the initial increase expected under climate change. Even though Sub-Saharan Africa is not a key contributor to global food production or irrigated food production, both adaptation scenarios help lower world food prices.

This thesis has contributed to a better understanding of the role of water resources in agriculture. The new version of the GTAP-W model provides insights into water modelling in CGE models. However, the thesis has also shown several limitations of the approaches used during this research. The first limitation is inherent of global models, which face a clear trade-off between regional aggregation and the costs in terms of the modelling details. Although GTAP-W considers water quantity and prices, it ignores non-market costs/benefits of water use. Our analysis has been limited to analyze water use in the agricultural sector ignoring domestic and industrial uses. Extending the GTAP-W model to incorporate agro-ecological zones and account for water use outside the agricultural sector seem to be a logical next step.