Water **2011**, *3*, 526-548; doi:10.3390/w3020526

OPEN ACCESS

water

ISSN 2073-4441
www.mdpi.com/journal/water

Article

Trade Liberalization and Climate Change: A Computable General Equilibrium Analysis of the Impacts on Global Agriculture

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Received: 30 March 2011; in revised form: 18 April 2011 / Accepted: 20 April 2011 / Published: 6 May 2011

Abstract: Based on predicted changes in the magnitude and distribution of global precipitation, temperature and river flow under the A1B and A2 scenarios of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES), this study assesses the potential impacts of climate change and CO_2 fertilization on global agriculture, and its interactions with trade liberalization, as proposed for the Doha Development Round. 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. Significant reductions in agricultural tariffs lead to modest changes in regional water use. Patterns are non-linear. On the regional level, water use may go up for partial liberalization, and down for more complete liberalization. This is because different crops respond differently to tariff reductions, and because trade

and competition matter too. Moreover, trade liberalization tends to reduce water use in water scarce regions, and increase water use in water abundant regions, even though water markets do not exist in most countries. Considering impacts of climate change, the results show that global food production, welfare and GDP fall over time while food prices increase. Larger changes are observed under the SRES A2 scenario for the medium term (2020) and under the SRES A1B scenario for the long term (2050). Combining scenarios of future climate change with trade liberalization, countries are affected differently. However, the overall effect on welfare does not change much.

Keywords: climate change; computable general equilibrium; trade liberalization; water policy; water scarcity

1. Introduction

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 flow and regional water resources [1-3]. Climate model simulations suggest that global average precipitation will increase as global temperature rises. As a result, global water availability is expected to increase but at the regional level large differences will occur. 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 [2,4]. 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 [2]. Since water is essential, the impact of climate change on water resources is potentially one of the most important reasons for concern about unabated greenhouse gas emissions.

Many studies focus on natural science aspects of water availability, but analyses on the economic responses are important as well. Economies and in particular agricultural sectors of some developing countries might be hit particularly hard by a changing climate and a change in water availability putting at risk regional food security and the livelihood conditions for the rural poor. The agricultural sector is by far the largest consumer of water and farmers operate, directly or indirectly, at the world market for agricultural products. As future climate change is expected to modify the regional distribution of freshwater water resources, it 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.

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.

One of the few analyses of the impacts of climate-change-induced changes in water resources on agriculture in the context of international trade is Calzadilla *et al.* [5]. In addition to information on predicted changes in river flows under the IPCC SRES A1B and A2 scenarios from Falloon and Betts [4], they analyze the effects of temperature, precipitation and CO_2 fertilization on crop yields. The SRES A1B scenario has relatively little warming while the SRES A2 scenario shows higher levels of greenhouse gas concentration in the atmosphere. The results show that global food production, welfare and GDP fall due to climate change while food prices increase. Larger changes are observed under the SRES A2 scenario for the medium term (2020) and under the SRES A1B scenario for the long term (2050). The results are more pronounced, if irrigation areas respond to water availability as well.

To alleviate the negative effect of climate change, trade could be liberalized to stimulate economic growth, reduce poverty, and expand market access. Agricultural trade liberalization is supposed to be beneficial, if developing countries' comparative advantages are located in agriculture. Depending on the scenario chosen, most studies find a positive economic effect of agricultural trade liberalization for developing countries [6,7].

Changes in tariffs or subsidies for agricultural goods involve regional as well as global adjustments in the production of the goods in question but have effects on other markets, such as factor input markets, as well. Water is one production factor in agriculture. Therefore, trade liberalization in agriculture might enhance or alleviate problems related to water use and water availability. To our knowledge, this is the first analysis of the interaction of trade liberalization and climate change using a multi-region, multi-sector general equilibrium model.

Most of the current analyses on agricultural trade liberalization pay no attention to the impact on water use and problems related to water availability. Some authors have looked at the potential impact on sustainable development in developing countries including water as an environmental service. George and Kirkpatrick [8] argue that further trade liberalization would lead to an improved overall availability of water through increased efficiency in all developing countries [9]. Their study does not distinguish between different developing countries nor is a quantitative assessment provided. Other studies related to water issues investigate the implications of the General Agreement on Trade in Services (GATS) negotiations on service trade liberalization on water management and the ability of governments to regulate water services (see e.g., [10,11]). All these analyses are qualitative assessments not based on economic models. Berrittella *et al.* [12] is an exception. They use a global computable general equilibrium (CGE) model including water resources (GTAP-W, Version 1) to analyze the economic impact of hypothetical Doha-like liberalization of agricultural trade on water use. The Doha Development Agenda [13], launched in 2001, is meant to improve the situation for developing countries, but is subject to seemingly interminable delays.

This paper differs from previous work in three ways. First, we use the Version 2 of the GTAP-W model. See Calzadilla *et al.* [14,15] for a detailed description of the model. Second, we base our analysis on future scenarios of climate change for two time periods (2020 and 2050) as described in Calzadilla *et al.* [5]. They investigate the effect of climate change on water use and water availability but ignore the impact that trade liberalization could have on the economy. Based on their results we,

thirdly, investigate how trade patterns would change if trade of agricultural products were liberalized. Similar to Berrittella *et al.* [12], we assume a hypothetical Doha-like liberalization but we introduce water as an explicit factor of production.

The remainder of the paper is organized as follows: Section 2 briefly presents the model used. Section 3 lays down the simulation scenarios. Section 4 discusses the results and Section 5 concludes.

2. The GTAP-W Model (Version 2)

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 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 [16]). Rosegrant *et al.* [17] use the IMPACT model to estimate demand and supply of food and water to 2025. Fraiture *et al.* [18] extend this to include virtual water trade, using cereals as an indicator. Their results suggest that the role of virtual water trade is 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 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 [14,19]). All of these CGE studies have a limited geographical scope. Berrittella *et al.* [20] and Calzadilla *et al.* [14,15] are exceptions, using GTAP-W, a static multi-region world CGE model.

With GTAP-W, it is possible to assess the systemic general equilibrium effects of climate change impacts and trade liberalization on global agriculture. The model is a further refinement of the GTAP model [21,22], and is based on the version modified by Burniaux and Truong [23,24] as well as on the previous GTAP-W model introduced by Berrittella *et al.* [20]. For a more detailed description of the model see [14].

Unlike Version 1 [20], Version 2 of the GTAP-W model [14,15], used here, distinguishes between rainfed and irrigated agriculture. In Version 1 of the GTAP-W model, substitution between intermediate inputs and value-added for the production function of tradable goods and services was not possible. As a consequence, a price-induced drop in water demand did not imply an increase in any other input. Water was a technology of land, that is, water was assumed to modify soil moisture and hence the productivity of land. In Version 2, water is an explicit factor of production in irrigated agriculture and accounts for substitution possibilities between water and other primary factors.

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, seven of which are in agriculture [25]. 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 (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 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 A1 in Annex A represents the 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" [26]. In order to include water as a factor of production in the GTAP data and model, 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 in proportion to its 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 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. On average, regions like South America seems to grow relatively more using irrigation instead of rainfed agriculture compared to countries in 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 [27].

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 functions (CES) (Figure A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called ''Armington assumption'', which accounts for product heterogeneity and non-tariff trade barriers.

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 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 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 constant elasticity of substitution function (Figure A1). The procedure how the elasticity of factor substitution between land and irrigation (σLW) was obtained is explained in detail in [14,15]. Next, the irrigated land-water composite is combined with pasture land, rainfed land, natural resources, labor and the capital-energy composite in a value-added nest through a CES structure.

The IMPACT model [17] 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) [28]. 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 of production with the volume of water used in irrigation estimated by the IMPACT model. In the model only irrigation water has a price. In contrast, any rain that falls directly on a crop, whether rainfed or irrigated, is not priced. Instead, the amount of rain that falls on a crop is modeled 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 exogenously modeled 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 modeled by exogenous changes to the initial irrigation water endowment.

3. Design of Model Experiments

Our model experiments are based on future impacts of climate change on agriculture at two time periods: 2020 and 2050 [29]. In a first step, information on the future benchmark equilibria under normal climate conditions (omitting climate change) is needed. How to find a hypothetical general equilibrium state in the future imposing forecasted values for some key economic variables in the initial calibration dataset is described in [5]. Since the GTAP-W model is a static multi-region world CGE model we are not able to look at dynamic effects over time but rather compare different points in time.

The current baseline data and future baseline simulations under normal climate conditions are shown in Annex B. These baselines are based on the IMPACT model [17]. Compared to the 2000 baseline data (Table B1) a growth in both crop harvested area as well as crop productivity under normal climate conditions (assuming no climate change) is projected for 2020 and 2050 (Table B2). For 2020 and 2050 respectively, global agricultural area increases by 1.1% and 2.8% while production rises by 32.8% and 91.7%.

To investigate the impact of climate change on global agriculture Calzadilla *et al.* [5] use information on key climate variables, which includes temperature, precipitation as well as river flow. Their analysis also includes the CO_2 fertilization effect. Predicted changes in the magnitude and distribution of global temperature, precipitation and river flow are based on [4]. They used the Hadley Centre Global Environmental Model, including a dynamic river routing model (HadGEM1-TRIP), to simulate changes in temperature, precipitation and river flow over the next century and under the IPCC SRES A1B and A2 scenarios [30]. Crop yield response to temperature and precipitation are taken from [31]. They used the CERES and SOYGRO crop models to analyze crop yield responses to arbitrary incremental changes in temperature (+2 ℃ and +4 ℃) and precipitation (+/−20%). The study was carried out in 18 countries worldwide and uses common crop growth models and methodology.

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. Regional changes in river flow are related to regional changes in water supply by the runoff elasticities of water supply estimated by [32].

The CO_2 fertilization effect on crops yields is based on information presented by [33]. They report yield response ratios for C3 and C4 crops to elevated CO_2 concentrations in the three major crop models (CERES, EPIC and AEZ). In this analysis, we use the average crop yield response of the three crop models to the CO_2 concentrations in 2020 and 2050 for the IPCC SRES A1B and A2 scenarios.

Future climate change would modify regional water endowments and soil moisture, and in response the distribution of harvested land would change. Therefore, we include a land use scenario, which explores possible shifts in the geographical distribution of irrigated agriculture. It assumes that irrigated areas could expand in regions with higher water supply. *Vice versa*, irrigated farming can become unsustainable in regions subject to water shortages.

Based on the impact of climate change on agricultural production, we analyze in a next step if trade liberalization policies would help to alleviate the negative effect of climate change. To better be able to single out the effect of trade liberalization on agricultural production, we also analyze the impact of reductions in trade barriers ignoring the effect of climate change. As indicated above, the scenarios are based on a hypothetical Doha-like liberalization of agricultural trade.

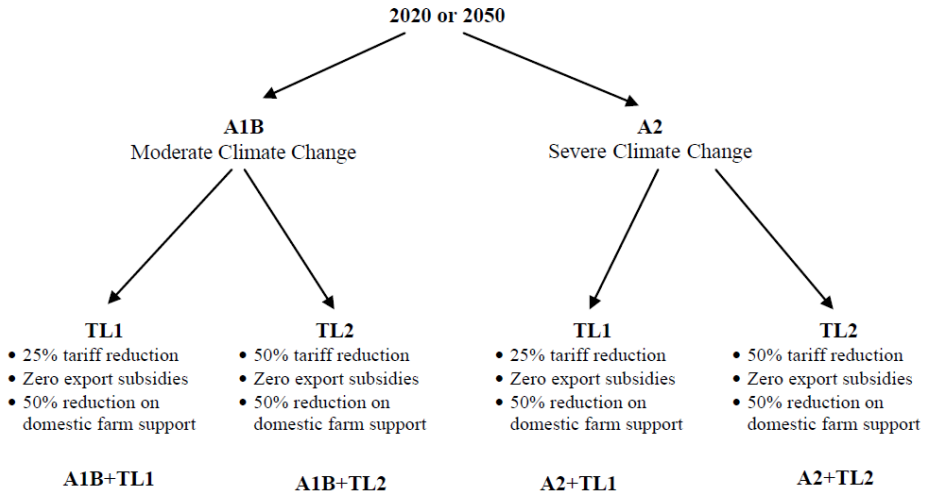
As the Doha negotiations are still ongoing (at a very slow pace), the modalities of the possible agreement are uncertain. It is clear that the parties involved have very different interests. Agricultural exporters aim for open foreign markets and reductions in distorting subsidies elsewhere. Industrial exporters in emerging economies want to remain protected. Countries with comparative advantages in services wish the GATS negotiations would be successful in reducing national regulatory in services. Therefore, any analysis investigating scenarios of trade liberalization have to take all three aspects into account. However, as our study focuses on trade liberalization in agriculture, we account for liberalization in non-agricultural sectors, but vary the levels of liberalization for the agricultural sectors only. The cut in tariffs for products in the non-agricultural sectors is 25%.

In Scenario 1, a 25% tariff reduction is chosen for all agricultural sectors (TL1). In addition, we assume zero export subsidies and a 50% reduction in domestic farm support. Scenario 2 is a variant of

Scenario 1: tariffs are reduced by 50% (TL2). According to the negotiations so far, export subsidies will be phased out over a few years. Tariff reductions will also not be implemented at once but phased in. To account for this procedure, we designed our above described scenarios for the year 2020 and 2050.

In total we have sixteen different scenarios including two climate scenarios (A1B and A2), for two future time periods (2020 and 2050) and two trade liberalization scenarios (TL1 and TL2). See Figure 1. Note that the no climate change scenarios are not displayed.

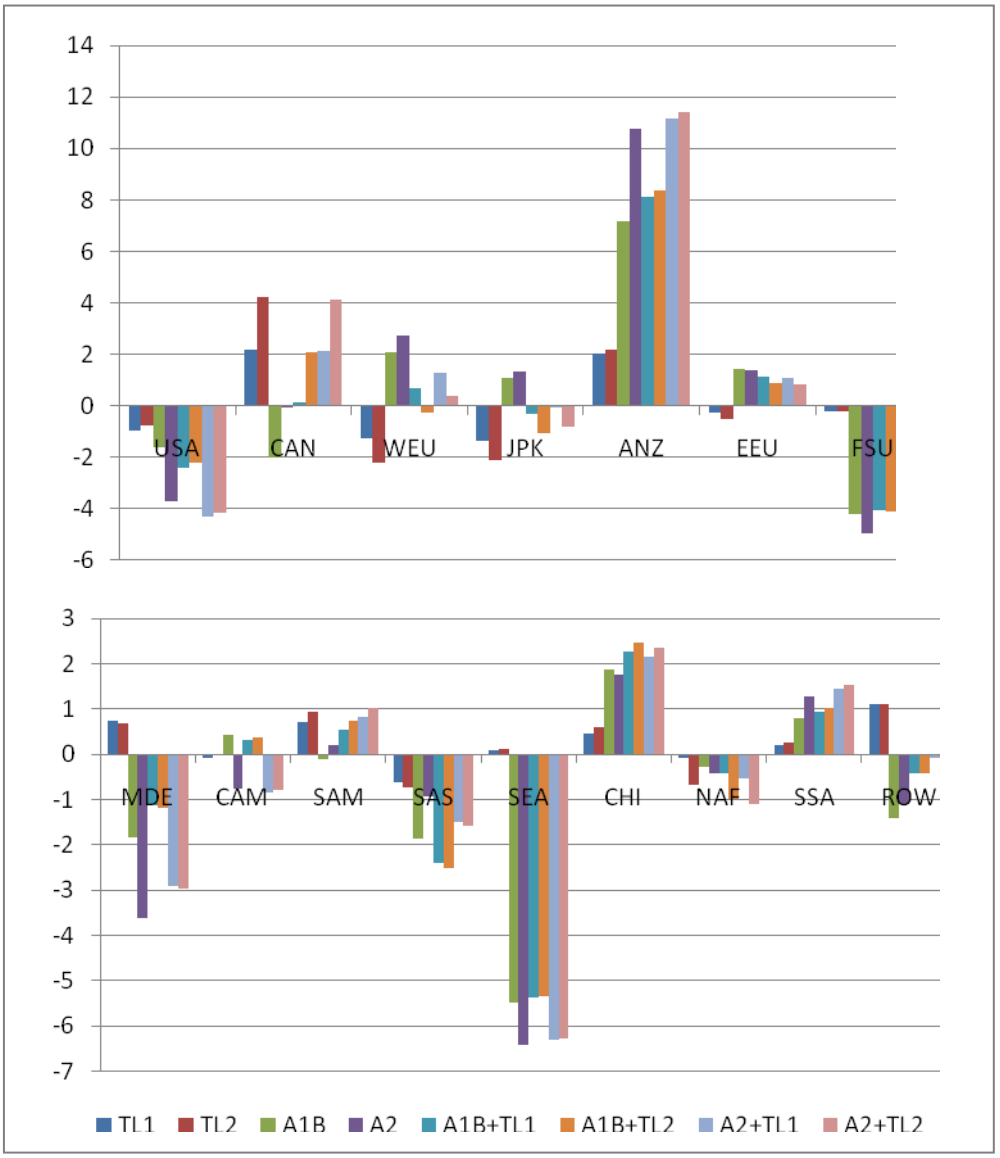
Figure 1. Structure of climate change scenarios.



4. Simulation Results

Trade liberalization only (TL1 and TL2) would have a limited effect on global production of agricultural goods (Figure 2 and Figure 3) [34]. On the regional level, the effect is different but the numbers are small. Some regions expand production (particularly Canada (CAN), Australia and New Zealand (ANZ)), while others reduce production (in 2020 particularly Western Europe (WEU), Japan and South Korea (JPK) and in 2050 particularly South Asia (SAS) and the USA). In most of the developing regions the effect of trade liberalization on agricultural production would be positive except for Central America (CAM), South Asia (SAS). For North Africa (NAF) the sign of the effect depends on the liberalization scenario chosen and the time period. For WEU and JPK the effect in 2050 is mixed as well. The relationship between trade liberalization and agricultural production is complex. Current tariffs vary widely between crops and between regions, also relative to the costs of production. Uniform cuts in nominal tariffs, as investigated here, would therefore have a non-uniform impact.

Figure 2. Change in agricultural production in 2020 (in %) relative to the baseline.



Note: Developed regions (top panel) and developing regions (bottom panel).

The effect of climate change is a reduction in global agricultural production (A1B and A2). The decrease is more pronounced in 2050 and for the A2 scenario. While in 2020 only irrigated production decreases, rainfed production falls as well in 2050 (not shown) [35]. On a regional level, the drop in production is particularly pronounced in regions such as Southeast Asia (SEA), the Middle East (MDE) and the Former Soviet Union (FSU) as well as the USA while in other regions including Australia and New Zealand (ANZ), Western Europe (WEU) and China (CHI) more is produced. Over time more regions are negatively affected but in some regions the effect of more severe climate change (A2) is less negative compared to more moderate changes (A1B).

Figure 3. Change in agricultural production in 2050 (in %) relative to the baseline.

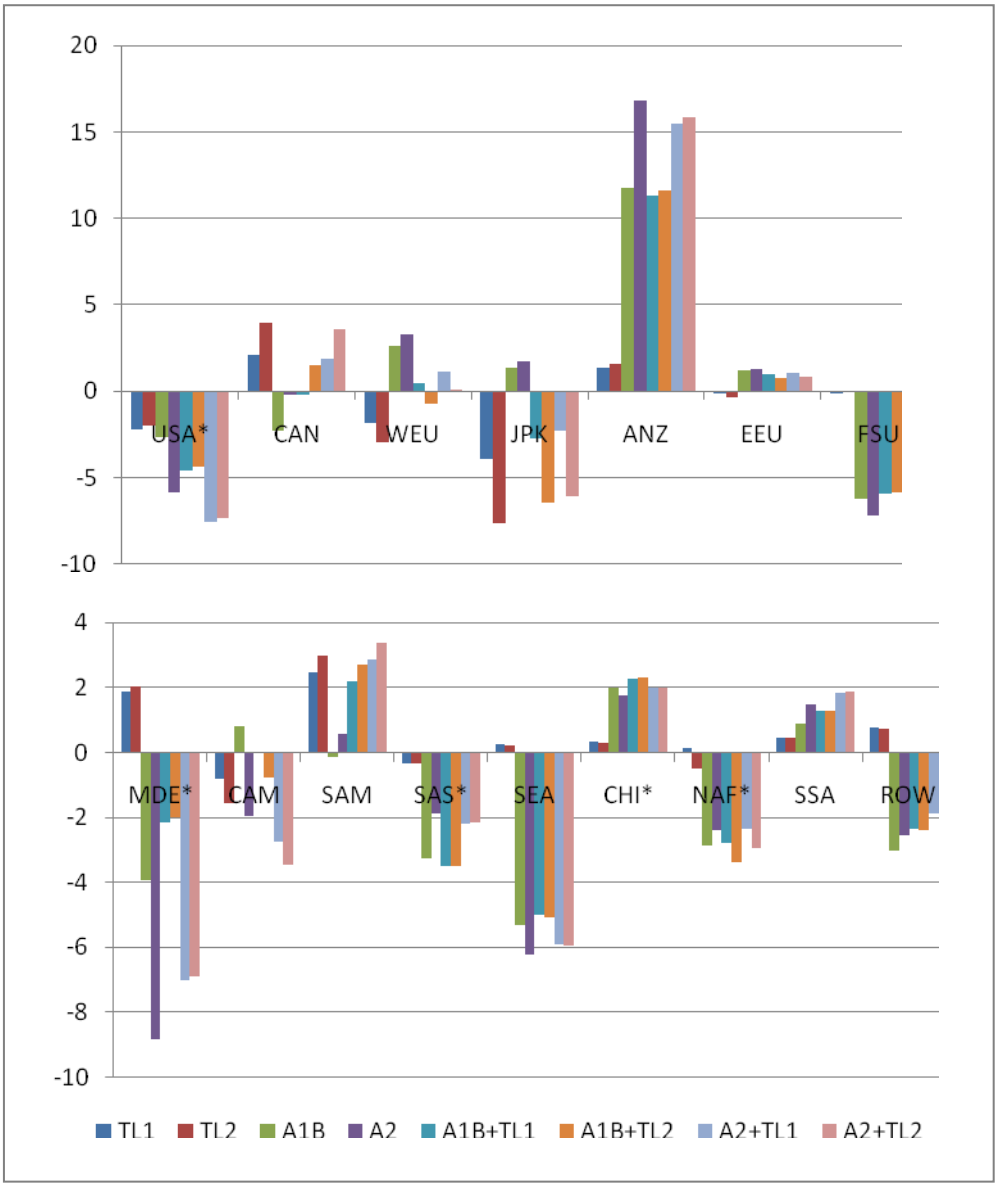
Note: Developed regions (top panel) and developing regions (bottom panel).

Climate change plus trade liberalization changes this pattern for some countries and world regions. In 2020 the impact on production is negative for Western Europe (WEU), the USA, South Asia (SAS), Japan and South Korea (JPK), it is positive (or less negative) for Canada (CAN), South America (SAM), China (CHI) and Sub-Saharan Africa (SSA). In 2050 the situation is different also with respect to the two climate scenarios. Here the effect of trade liberalization on production is negligible. The results are dominated by impacts of climate change.

Figure 4 and Figure 5 show the effect of the different scenarios on water use. Qualitatively, the pattern is the same as for agricultural production (Figure 2 and Figure 3) [36]. Trade liberalization only (TL1 and TL2) would imply an increase in water use in Canada (CAN), Australia and New Zealand (ANZ); and a reduction in the USA, Western and Eastern Europe (WEU), Japan and South Korea (JPK), and the former Soviet Union (FSU). In developing regions trade liberalization would mainly lead to higher levels of water use. However, in later years some of these regions would see an increase

in water use for a partial liberalization, but a decrease for a more complete liberalization. In all cases, changes in water use due to trade liberalization are less than 10%.

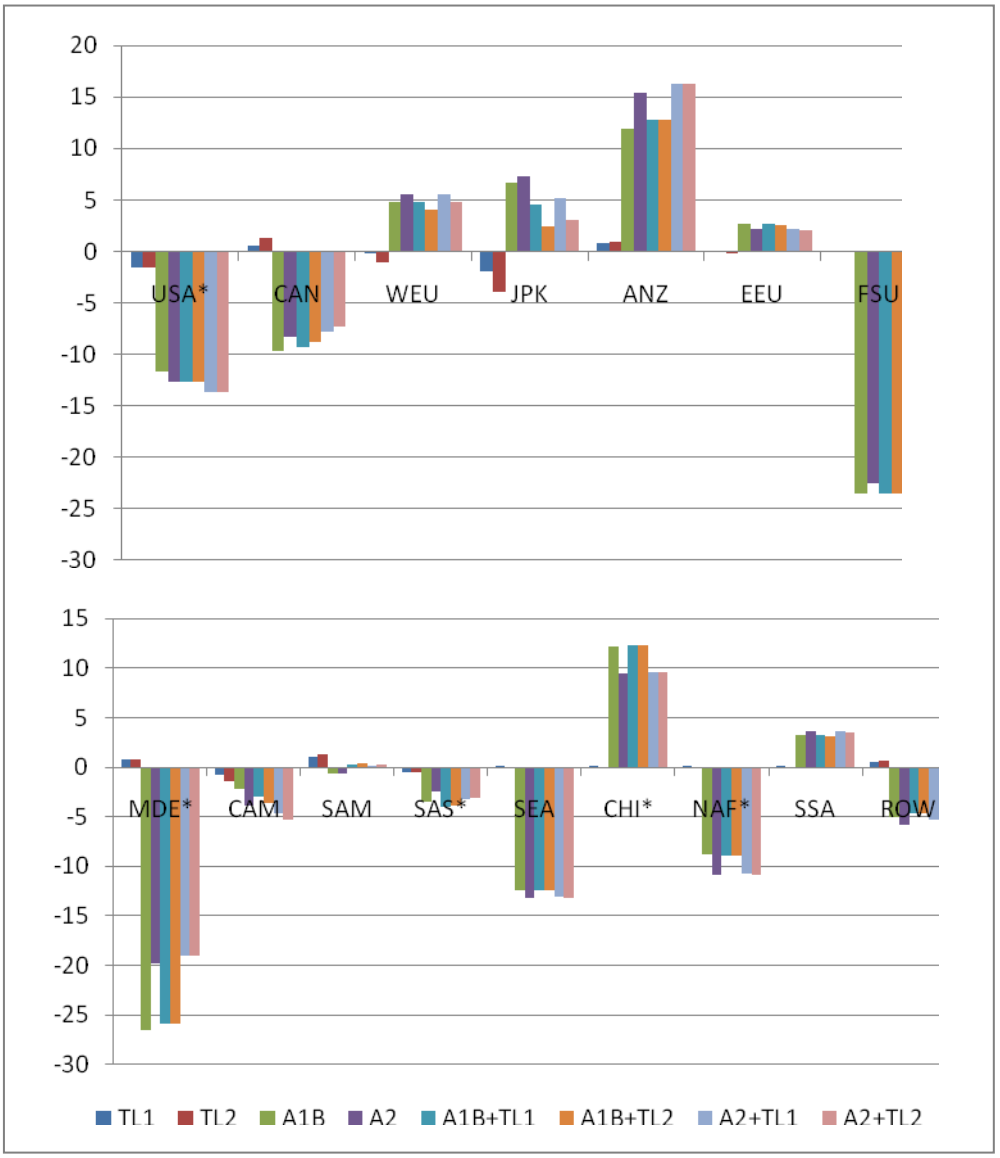
Figure 4. Change in agricultural water use in 2020 relative to baseline (in %).



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

Figure 6 and Figure 7 show the impact of climate change and trade liberalization on welfare. Trade liberalization has a positive effect on welfare of US$31 billion (bln) in 2020 and US$67 bln in 2050 for the 25% cut in tariffs (TL1). An extra 25% tariff cut further increases welfare by US$4 bln in 2020 and US$10 bln in 2050 (TL2). As expected, the first cuts have the greatest benefit. On the regional level, the effect is almost always positive, except for the USA and Canada. The impact of climate change on welfare is negative; up to US$18 bln in 2020 and US$ 283 bln in 2050.

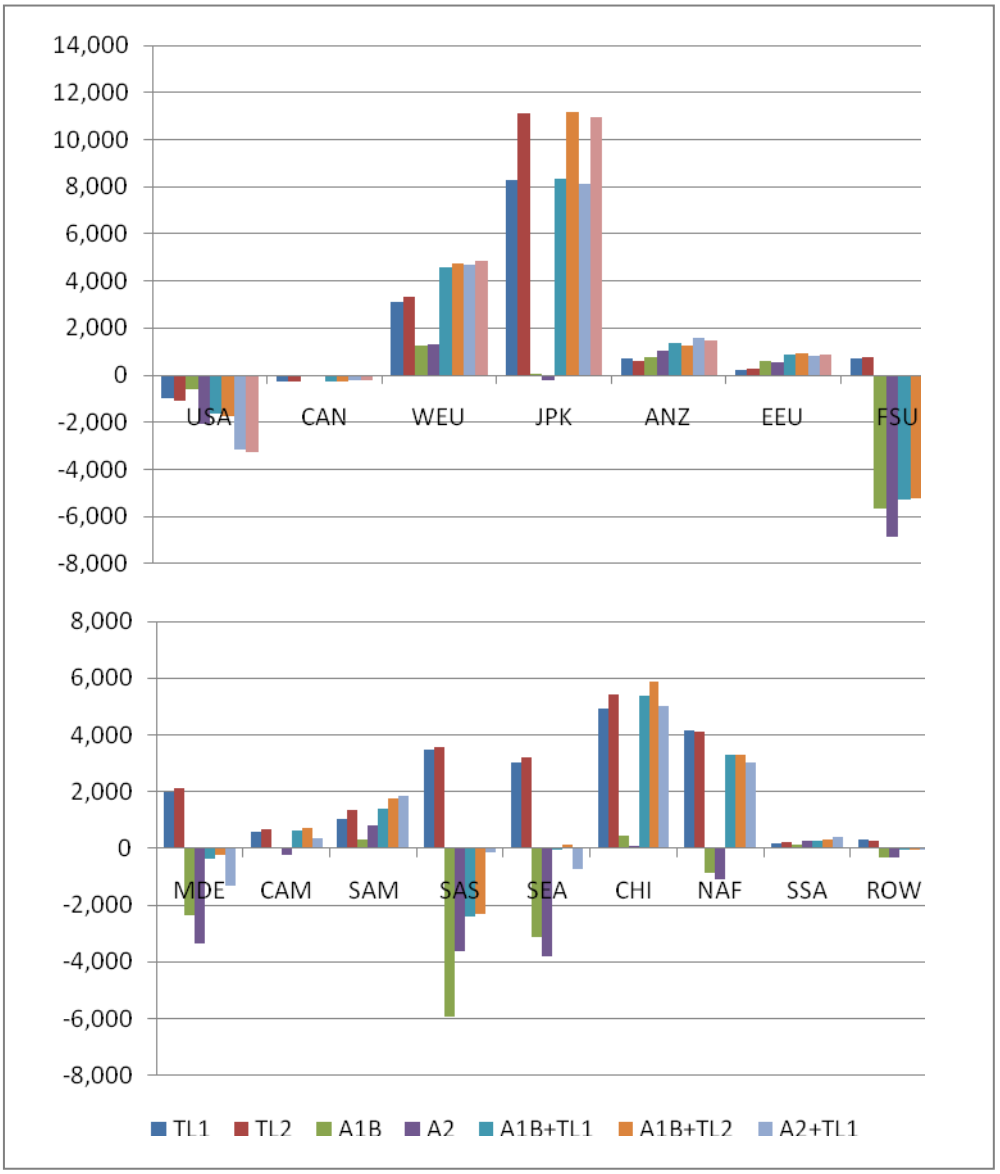
Figure 5. Change in agricultural water use in 2050 relative to baseline (in %).



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

The impact of trade liberalization varies with climate change, as regions are affected differently. In 2020, the impact of climate change is small and the effect of trade liberalization outweighs the negative impact of climate change; the combined effect is an increase of up to US$20 bln. However, in 2050 the negative impact of climate change dominates the positive effect of trade liberalization; welfare decreases by up to US $214 bln. Comparing the individual effects of trade liberalization (TL1, TL2) and climate change (A1B, A2) to the combined effect, welfare decreases less (up to US$2 bln (AB1 + TL1) or up to US$4 bln (A1B + TL2)). The assumption is as follows. Trade liberalization would make it easier to substitute domestic food production for import—and hence make it easier to adapt to climate change.

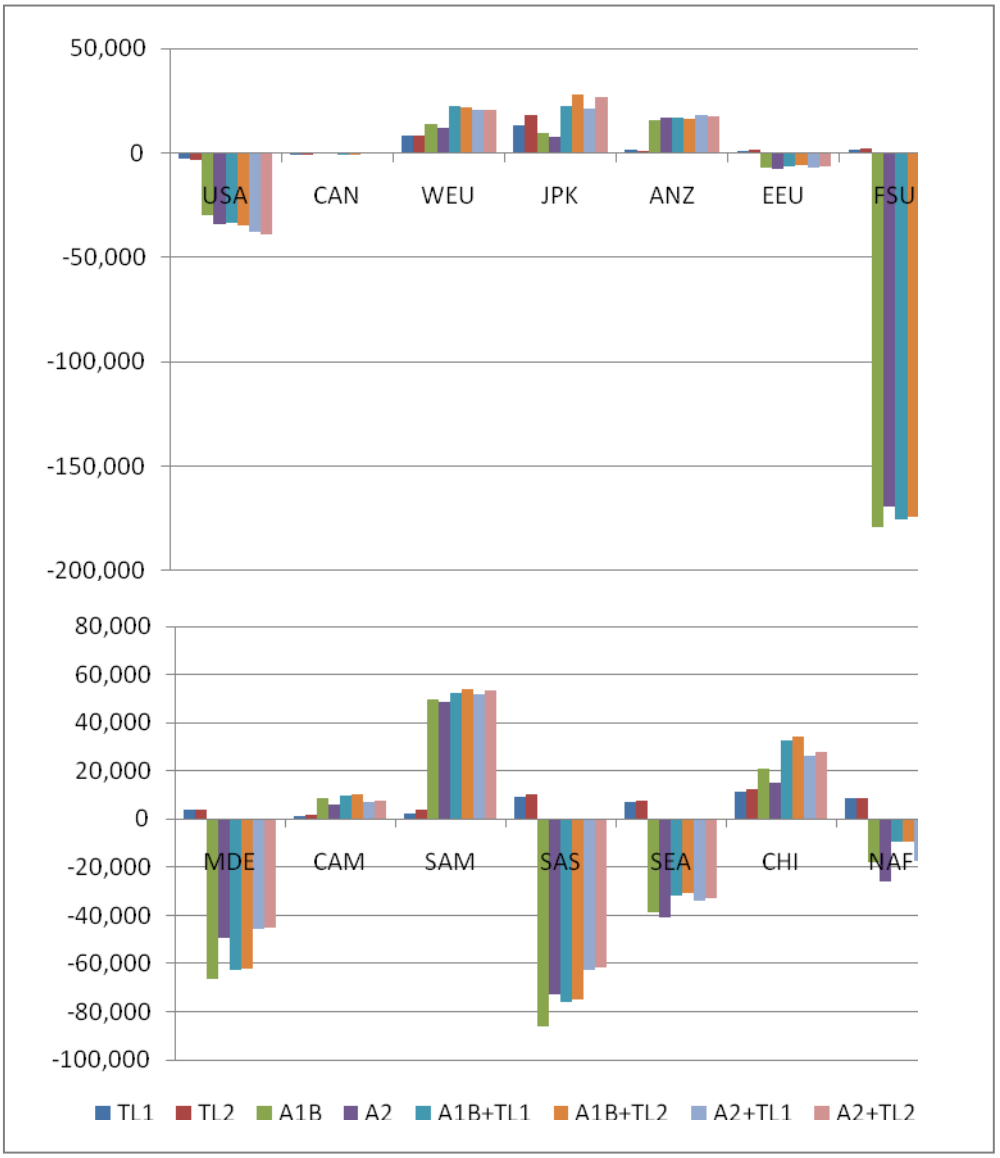
Figure 6. Change in welfare for 2020 (in Mio USD) relative to the baseline.



Note: Developed regions (top panel) and developing regions (bottom panel).

The results presented in Figure 6 and Figure 7 indicate that regions are affected very differently. In the USA, climate change has a negative impact on welfare in the first time period but the effect of trade liberalization is worse, irrespective of the climate scenario. For the Former Soviet Union the situation is more severe. The opposite is true for Western Europe and in particular for China, Japan and South Korea as well as for Northern Africa. However differences exist with respect to time. In 2050 the impact of climate change dominates and the effect of trade liberalization on welfare is minor for all regions.

Figure 7. Change in welfare for 2050 (in Mio USD) relative to the baseline.



Note: Developed regions (top panel) and developing regions (bottom panel).

5. Discussion and Conclusions

We use a global computable general equilibrium model including water resources (GTAP-W, Version 2) to assess impacts of climate change and trade liberalization on global agriculture. We find that trade liberalization has a small effect on agricultural production and on water use. Water use for some crops and some regions goes up, and it goes down for other crops and regions. Signs may switch between a modest liberalization and more substantial trade liberalization (e.g., for China and Southeast Asia). Trade liberalization reduces water use in places where it is scarce (including e.g. the Middle East, Northern Africa), and increases water use in places where it is more abundant. Overall and for most regions of the world, the effect of trade liberalization on welfare is positive.

The impact of climate change on global agriculture is much more pronounced. Agricultural production and water use decrease, as does global welfare. On a regional level, the drop in production is particularly pronounced in the Middle East, North Africa, South-East Asia as well as the USA and

Canada. Production increases in China, Japan and South Korea, Western Europe, and Australia and New Zealand. The net effect of these positive and negative changes is negative: global welfare decreases by up to US$ 283 bln (0.29% of GDP).

Trade liberalization increases the depth of the market and thus the capacity to adapt to climate change. As a result, in 2050, trade liberalization reduces the negative impact of climate change on welfare, albeit by less than 2%. In 2020, however, trade liberalization shifts production to areas that are more susceptible to climate change.

In summary, significant reductions in agricultural tariffs lead to modest changes in regional water use. Patterns are non-linear. On the regional level water use may go up for partial liberalization, and down for more complete liberalization. This is because different crops respond differently to tariff reductions, and because trade and competition matter too. Moreover, trade liberalization tends to reduce water use in water scarce regions, and increase water use in water abundant regions, even though water markets do not exist in most countries. The welfare impact of climate change is substantially larger than the welfare impact of tariff cuts. Trade liberalization reduces the negative impacts of climate change, but only slightly.

A direct comparison of the results of our study on the impact of climate change and trade liberalization to those of others is difficult since no other study exists using a global CGE approach. Earlier studies, based on other approaches and using different data, tend to find stronger impacts of climate change on agriculture [37,38]. In general, such studies have (1) a more regional focus and do not aim for a global analysis and (2) omit implications of international trade. In addition, the type of crop model chosen and the coverage of changes in the climate and hydrological system are likely to influence the results. Earlier studies are based on changes in temperature and precipitation while our analysis uses additional information on changes in river flow and CO_2 fertilization rates.

Several limitations apply to the above results. The model is static. A dynamic model may find larger effects of trade liberalization and climate change with further specialization through capital stock adjustments. The deterministic nature of our model is another limitation. In the spirit of Tyers and Anderson [39], more liberal agricultural trade should allow for smoother adjustment to shocks, at least on a global basis. This is a principal argument for a more liberal agricultural trade regime in the context of climate change but is not considered. The limited disaggregation of crops and regions may hide larger shifts in agricultural production and water use due to trade liberalization. The importance of these factors will need to be tested with a future version of the current model and with other models. Our scenarios on climate change use information on temperature, precipitation river flow based on regional averages. We do not take into account that precipitation and river flow might increase in some water basins and decrease in others within the same region. These local effects are averaged out. Also, we use annual average temperature, precipitation and river flow data; we consider neither changes in the seasonality of river flow nor extreme events. We do not take into account the effects of groundwater depletion. In addition, uncertainty exists especially regarding the future distribution of precipitation which has implications for agricultural production. Our analysis is limited to the use of results of one such study [4]. These issues are deferred to future research.

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34. Table B3 in the Annex reports the changes in agricultural production in 2020 and 2050 relative to the baseline for the different scenarios, world regions as well as crop types.
35. The data are available from the authors on request.
36. Table B4 in the Annex reports the changes in water use for agricultural production in 2020 and 2050 relative to the baseline for the different scenarios and world regions.
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Annex A

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

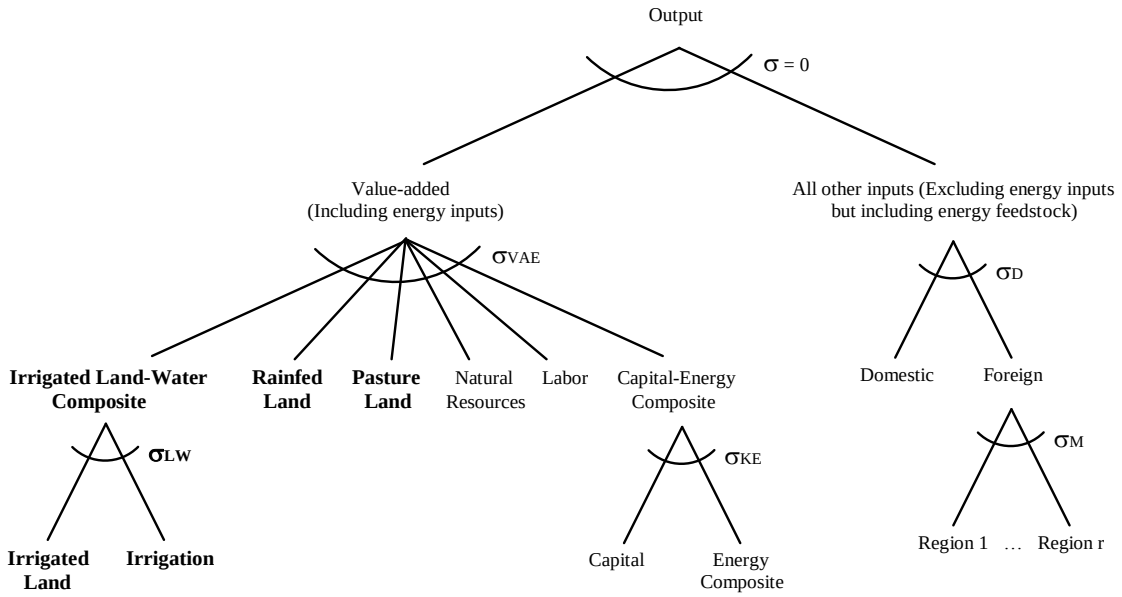

Figure A1. *Cont.*

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. Note that elasticities are commodity specific.

Table 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,
4. JPK — Japan and South Korea	sorghum and other grains)
5. ANZ — Australia and New Zealand	**4. VegFruits —** Vegetable, fruits, nuts
6. EEU — Eastern Europe	**5. OilSeeds —-** Oil seeds
7. FSU — Former Soviet Union	**6. Sug_Can —** Sugar cane, sugar beet
8. MDE — Middle East	**7. Oth_Agr —** Other agricultural products
9. CAM — Central America	**8. Animals —** Animals
10. SAM — South America	**9. Meat —** Meat
11. SAS — South Asia	**10. Food_Prod —** Food products
12. SEA — Southeast Asia	**11. Forestry —** Forestry
13. CHI — China	**12. Fishing —** Fishing
14. NAF — North Africa	**13. Coal —** Coal
15. SSA — Sub-Saharan Africa	**14. Oil —-** Oil
16. ROW — Rest of the World	**15. Gas —** Gas
	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 B1. 2000 baseline data: Crop harvested area and production by region and crop.

Description	Rainfed Agriculture		Irrigated Agriculture		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								
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**

Table B1. *Cont.*

Description	Rainfed Agriculture Area (thousand ha)	Rainfed Agriculture Production (thousand mt)	Irrigated Agriculture Area (thousand ha)	Irrigated Agriculture 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 (%)
Crops								
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 average for 1999-2001.

Source: IMPACT, 2000 baseline data (April 2008).

Table B2. No climate change simulation: Percentage change in crop harvested area and production by region and crop (2020 and 2050 relative to 2000).

Description	Rainfed Agriculture				Irrigated Agriculture				Total				Share of irrigated agriculture in total			
	Area (%)		Production (%)		Area (%)		Production (%)		Area (%)		Production (%)		Area (%)		Production (%)	
	2020	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
Regions																
United States	−4.14	−10.34	27.60	71.38	1.43	3.58	37.63	98.10	−0.49	−1.23	34.39	89.48	1.93	4.87	2.41	4.55
Canada	−7.98	−19.95	24.50	49.17	−5.40	−13.49	23.01	58.95	−7.91	−19.78	24.37	50.00	2.73	7.84	−1.10	5.97
Western Europe	−13.23	−33.08	2.13	−2.18	−7.30	−18.24	13.31	28.50	−12.37	−30.92	4.82	5.21	5.79	18.35	8.10	22.14
Japan and South Korea	−11.51	−28.76	8.61	18.49	−9.28	−23.21	1.65	1.80	−9.82	−24.54	3.36	5.89	0.59	1.77	−1.65	−3.86
Australia and New Zealand	−2.35	−5.87	23.94	62.42	−0.92	−2.30	29.57	79.31	−2.21	−5.53	25.57	67.31	1.32	3.42	3.19	7.18
Eastern Europe	−9.18	−22.94	12.18	23.89	−7.34	−18.36	31.76	72.49	−8.93	−22.32	15.66	32.52	1.74	5.11	13.92	30.16

Table B2. *Cont*.

Description	Rainfed Agriculture				Irrigated Agriculture				Total				Share of irrigated agriculture in total			
	Area (%)		Production (%)		Area (%)		Production (%)		Area (%)		Production (%)		Area (%)		Production (%)	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Regions																
Former Soviet Union	−2.57	−6.42	31.73	75.58	0.27	0.68	34.47	90.91	−2.10	−5.26	32.39	79.28	2.42	6.26	1.57	6.48
Middle East	1.32	3.29	21.02	56.03	5.18	12.95	48.73	135.08	2.93	7.33	34.00	93.04	2.18	5.23	11.00	21.77
Central America	1.40	3.51	46.28	132.71	7.30	18.25	52.26	146.86	3.78	9.45	48.94	139.01	3.39	8.04	2.23	3.28
South America	10.51	26.27	77.50	243.39	14.77	36.93	86.76	266.27	10.98	27.45	79.55	248.45	3.42	7.44	4.02	5.11
South Asia	−11.65	−29.13	12.26	31.23	10.53	26.31	46.70	129.70	−1.58	−3.95	30.61	83.69	12.30	31.51	12.32	25.05
Southeast Asia	4.73	11.83	29.96	81.67	0.45	1.11	47.20	135.43	3.52	8.79	36.28	101.37	−2.97	−7.06	8.01	16.91
China	−3.85	−9.63	12.42	31.46	−1.77	−4.43	11.79	30.47	−2.49	−6.21	12.04	30.87	0.73	1.90	−0.23	−0.31
North Africa	2.72	6.80	43.74	122.97	5.09	12.73	35.77	101.93	3.48	8.70	38.91	110.20	1.56	3.71	−2.26	−3.94
Sub−Saharan Africa	13.42	33.54	51.39	143.65	30.93	77.32	97.97	303.81	14.01	35.02	55.56	158.01	14.84	31.33	27.26	56.51
Rest of the World	6.56	16.41	51.15	146.89	12.22	30.55	75.96	226.20	7.83	19.56	59.46	173.47	4.07	9.19	10.34	19.28
Total	**−0.06**	**−0.16**	**31.31**	**87.97**	**3.48**	**8.70**	**34.85**	**96.82**	**1.12**	**2.80**	**32.80**	**91.70**	**2.34**	**5.74**	**1.54**	**2.67**
Crops																
Rice	−9.85	−24.63	−0.65	−2.90	−1.46	−3.64	11.15	26.52	−4.74	−11.84	7.98	18.62	3.44	9.30	2.93	6.65
Wheat	−5.57	−13.93	17.95	40.86	−1.63	−4.07	31.65	75.50	−3.91	−9.77	24.59	57.63	2.37	6.32	5.67	11.33
Cereal grains	−1.37	−3.42	28.33	70.73	6.03	15.07	42.06	113.46	0.37	0.93	34.14	88.80	5.63	14.01	5.91	13.06
Vegetables, fruits, nuts	5.09	12.72	26.80	70.79	10.45	26.13	39.26	109.13	6.23	15.58	30.30	81.57	3.97	9.13	6.87	15.18
Oil seeds	2.88	7.20	7.84	18.55	3.13	7.82	27.40	71.89	2.95	7.39	15.09	38.32	0.17	0.41	10.70	24.27
Sugar cane, sugar beet	26.10	65.26	74.19	230.82	23.85	59.63	62.77	188.29	25.29	63.23	69.17	212.12	−1.15	−2.21	−3.78	−7.63
Other agricultural products	1.01	2.53	10.29	23.26	6.66	16.65	15.45	39.34	2.74	6.86	12.74	30.90	3.81	9.16	2.40	6.44
Total	**−0.06**	**−0.16**	**31.31**	**87.97**	**3.48**	**8.70**	**34.85**	**96.82**	**1.12**	**2.80**	**32.80**	**91.70**	**2.34**	**5.74**	**1.54**	**2.67**

Note: 2020 values are obtained by linear interpolation between 2000 baseline data and 2050 simulation without climate change.

Table B3. Change in agricultural production in 2020 and 2050 (in %) relative to baseline.

Description	TL1		TL2		A1B		A2		A1B + TL1		A1B + TL2		A2 + TL1		A2 + TL2	
	2020	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
Regions																
United States	−0.97	−0.41	−0.75	−0.35	−1.61	−9.20	−3.73	−10.12	−2.39	−9.40	−2.20	−9.36	−4.31	−10.31	−4.15	−10.28
Canada	2.19	0.66	4.25	1.76	−2.02	−10.04	−0.05	−8.53	0.14	−9.53	2.08	−8.78	2.13	−7.99	4.11	−7.21
Western Europe	−1.26	0.21	−2.21	−0.41	2.09	4.30	2.72	4.83	0.68	4.73	−0.25	4.19	1.30	5.27	0.40	4.72
Japan and South Korea	−1.34	−0.26	−2.11	0.22	1.08	6.47	1.31	6.86	−0.29	6.61	−1.06	7.52	−0.06	7.01	−0.80	7.85
Australia and New Zealand	2.03	1.48	2.20	1.49	7.16	6.95	10.76	9.49	8.13	8.40	8.35	8.41	11.18	10.90	11.43	10.93
Eastern Europe	−0.24	−0.14	−0.49	−0.24	1.41	2.59	1.38	2.29	1.11	2.49	0.86	2.43	1.08	2.18	0.83	2.12
Former Soviet Union	−0.20	−0.15	−0.23	−0.18	−4.19	−21.28	−4.95	−20.42	−4.05	−21.30	−4.10	−21.28	−4.77	−20.41	−4.82	−20.39
Middle East	0.75	0.11	0.68	0.08	−1.83	−23.24	−3.62	−16.81	−1.12	−23.23	−1.18	−23.22	−2.91	−16.76	−2.97	−16.75
Central America	−0.08	−0.12	−0.02	−0.19	0.42	−1.70	−0.75	−2.70	0.33	−1.81	0.38	−1.89	−0.83	−2.80	−0.80	−2.88
South America	0.72	0.21	0.95	0.16	−0.12	−1.77	0.19	−1.81	0.54	−1.65	0.73	−1.76	0.83	−1.70	1.03	−1.80
South Asia	−0.61	−0.73	−0.72	−0.76	−1.87	−3.16	−0.92	−2.17	−2.39	−3.89	−2.50	−3.84	−1.49	−2.97	−1.59	−2.93
Southeast Asia	0.10	0.01	0.12	0.04	−5.48	−11.63	−6.41	−12.28	−5.38	−11.74	−5.35	−11.68	−6.31	−12.40	−6.28	−12.34
China	0.46	0.20	0.59	0.37	1.86	11.18	1.77	9.04	2.27	11.54	2.47	11.88	2.16	9.36	2.36	9.68
North Africa	−0.07	0.12	−0.68	−0.17	−0.29	−8.90	−0.42	−13.73	−0.41	−8.91	−0.98	−9.00	−0.54	−13.73	−1.10	−13.81
Sub−Saharan Africa	0.20	−0.29	0.25	−0.39	0.79	3.54	1.29	3.69	0.95	3.24	1.02	3.13	1.44	3.39	1.52	3.28
Rest of the World	1.11	0.91	1.10	0.93	−1.41	−3.58	−1.09	−3.64	−0.41	−2.82	−0.42	−2.79	−0.07	−2.89	−0.08	−2.86
Total	**0.01**	**−0.06**	**0.01**	**−0.08**	**−0.45**	**−2.28**	**−0.53**	**−2.38**	**−0.44**	**−2.31**	**−0.44**	**−2.29**	**−0.53**	**−2.43**	**−0.52**	**−2.42**

Table B3. *Cont*.

Description	TL1		TL2		A1B		A2		A1B + TL1		A1B + TL2		A2 + TL1		A2 + TL2	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Crops																
Rice	−0.19	−0.50	−0.12	−0.49	−1.27	−4.09	−1.28	−4.17	−1.44	−4.53	−1.37	−4.50	−1.45	−4.60	−1.38	−4.57
Wheat	0.15	−0.16	0.26	−0.23	−0.47	−4.97	−0.60	−3.72	−0.39	−5.39	−0.29	−5.38	−0.57	−4.24	−0.45	−4.21
Cereal grains	0.01	0.09	−0.01	0.07	−0.29	−3.32	−0.64	−3.41	−0.28	−3.23	−0.31	−3.24	−0.63	−3.34	−0.65	−3.34
Vegetables, fruits, nuts	0.08	0.02	0.10	0.03	−0.42	−1.36	−0.36	−1.41	−0.34	−1.28	−0.31	−1.23	−0.27	−1.35	−0.25	−1.29
Oil seeds	−0.98	−1.79	−1.15	−2.19	−0.57	−3.71	−1.29	−4.28	−1.40	−4.89	−1.60	−5.36	−2.01	−5.41	−2.23	−5.87
Sugar cane, sugar beet	−0.04	−0.04	−0.09	−0.10	−0.54	−3.37	−0.55	−3.31	−0.60	−3.43	−0.64	−3.48	−0.60	−3.37	−0.65	−3.42
Other agricultural products	0.11	0.04	0.11	0.12	−0.24	1.19	−0.36	0.10	−0.15	1.35	−0.10	1.52	−0.28	0.23	−0.23	0.38
Total	**0.01**	**−0.06**	**0.01**	**−0.08**	**−0.45**	**−2.28**	**−0.53**	**−2.38**	**−0.44**	**−2.31**	**−0.44**	**−2.29**	**−0.53**	**−2.43**	**−0.52**	**−2.42**

Table B4. Change in agricultural water use in 2020 and 2050 (in %) relative to baseline.

Description	TL1		TL2		A1B		A2		A1B + TL1		A1B + TL2		A2 + TL1		A2 + TL2	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Regions																
United States	−2.24	−1.57	−1.98	−1.53	−2.65	−11.69	−5.82	−12.62	−4.60	−12.69	−4.38	−12.69	−7.53	−13.61	−7.34	−13.61
Canada	2.13	0.52	3.95	1.33	−2.27	−9.70	−0.23	−8.25	−0.19	−9.31	1.51	−8.75	1.85	−7.84	3.60	−7.25
Western Europe	−1.80	−0.21	−2.98	−1.04	2.60	4.83	3.32	5.53	0.47	4.80	−0.69	4.08	1.17	5.49	0.05	4.76
Japan and South Korea	−3.88	−1.93	−7.60	−3.99	1.35	6.69	1.76	7.28	−2.72	4.56	−6.42	2.45	−2.31	5.11	−6.05	3.07
Australia and New Zealand	1.36	0.86	1.61	0.90	11.76	11.86	16.85	15.46	11.32	12.73	11.65	12.78	15.49	16.23	15.85	16.30
Eastern Europe	−0.13	−0.07	−0.37	−0.22	1.22	2.69	1.30	2.17	1.00	2.65	0.77	2.56	1.08	2.13	0.86	2.04
Former Soviet Union	−0.12	−0.11	−0.08	−0.12	−6.21	−23.52	−7.21	−22.55	−5.89	−23.49	−5.88	−23.47	−6.83	−22.47	−6.83	−22.45
Middle East	1.86	0.84	2.02	0.80	−3.94	−26.50	−8.81	−19.74	−2.17	−25.90	−2.01	−25.87	−7.03	−19.05	−6.89	−19.01
Central America	−0.81	−0.76	−1.55	−1.46	0.81	−2.20	−1.96	−3.93	−0.01	−2.92	−0.76	−3.60	−2.74	−4.63	−3.46	−5.29
South America	2.46	1.08	2.99	1.27	−0.13	−0.65	0.57	−0.67	2.20	0.21	2.70	0.33	2.87	0.19	3.38	0.31
South Asia	−0.35	−0.53	−0.33	−0.47	−3.26	−3.46	−1.88	−2.49	−3.51	−4.07	−3.48	−3.93	−2.20	−3.19	−2.17	−3.06

Table B4. *Cont*.

Description	TL1		TL2		A1B		A2		A1B + TL1		A1B + TL2		A2 + TL1		A2 + TL2	
	2020	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
Regions																
Southeast Asia	0.27	0.03	0.21	−0.08	−5.33	−12.42	−6.23	−13.13	−5.01	−12.36	−5.07	−12.46	−5.90	−13.07	−5.96	−13.15
China	0.33	0.02	0.29	−0.05	2.00	12.16	1.75	9.46	2.27	12.27	2.29	12.31	2.00	9.55	2.01	9.57
North Africa	0.14	0.10	−0.48	−0.09	−2.85	−8.76	−2.41	−10.89	−2.78	−8.89	−3.39	−8.93	−2.35	−10.78	−2.94	−10.81
Sub−Saharan Africa	0.46	0.01	0.45	−0.05	0.87	3.26	1.48	3.60	1.27	3.23	1.28	3.15	1.85	3.57	1.87	3.50
Rest of the World	0.75	0.56	0.72	0.59	−3.03	−5.09	−2.55	−5.78	−2.35	−4.61	−2.39	−4.59	−1.88	−5.30	−1.92	−5.29
Total	**0.11**	**−0.13**	**0.13**	**−0.16**	**−1.27**	**−2.19**	**−1.33**	**−2.31**	**−1.15**	**−2.31**	**−1.13**	**−2.31**	**−1.22**	**−2.45**	**−1.20**	**−2.45**