

Climate change impacts on global agriculture

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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 CO₂ 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 will 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 provide a false appreciation of the nature of changes likely to occur. Our results show that global food production, welfare and GDP fall in the two time periods and SRES scenarios. Higher food prices are expected. No matter which SRES scenario is preferred, we find that the expected losses in welfare are significant. These losses are slightly larger under the SRES A2 scenario for the 2020s and under the SRES A1B scenario for the 2050s.

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The results show that national welfare is influenced both by regional climate change and climate-induced changes in competitiveness.

1 Introduction

Most economic activities require water as an input of production but in many regions of the world, there are no markets for water. Water is also often underpriced, free or even subsidized. Because there is often no economic transaction, water use is not commonly reported in the national economic accounts, which hampers the analysis of water resources with economic models. We use the new version of the GTAP-W model, which accounts for water use in the agricultural sector, to analyze expected climate change impacts on global agricultural production. The GTAP-W model (Calzadilla et al. 2011) distinguishes between rainfed and irrigated crop production; therefore, is able to assess the role of green (effective rainfall) and blue (irrigation) water resources in agriculture. This distinction is crucial, because rainfed and irrigated agriculture face different climate risk levels.

Agriculture is by far the biggest global user of freshwater resources and consequently highly vulnerable to climate change. 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 (CO₂) 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 co-determines the availability of freshwater and the level of soil moisture, which are critical inputs for crop growth. Higher precipitation or irrigation will reduce the yield gap between rainfed and irrigated agriculture, but it may also have a negative impact if extreme precipitation causes flooding.

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 frost period, 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, particularly of C₄¹ plants, and increases water use efficiency (CO₂ fertilization) and so affects water availability (e.g. Betts et al. 2007).

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 might influence agricultural production world-wide. As climate variables we use predicted changes in global precipitation, temperature and river flow under the two IPCC SRES A1B and A2

¹ Called C₄ because the CO₂ is first incorporated into a 4-carbon compound. C₄ plants photosynthesize faster than C₃ plants under high light intensity and high temperatures, and are more water-use efficient. They include mostly tropical plants, such as grasses and agriculturally important crops like maize, sugar cane, millet and sorghum.

scenarios from Falloon and Betts (2006) and Johns et al. (2006) and include the effect of CO₂ fertilization as well. All these variables play an important role in determining agricultural outcomes. Temperature and CO₂ 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.²

The analysis is carried out using the new version of the global computable general equilibrium (CGE) model GTAP-W which includes water resources and 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 describes the data used and lays down the simulation scenarios. Section 5 discusses the principal results and Section 6 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 to do this. While partial equilibrium analysis focus on the sector affected by a policy measure assuming that the rest of the economy is not affected (e.g. Rosegrant et al. 2002), general equilibrium models consider other sectors or regions as well to determine the economy-wide effect. 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).

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 Dudu and Chumi 2008). All of these CGE studies have a limited geographical scope. Berrittella et al. (2007) and Calzadilla et al. (2011) are an exception.

Using a previous version of the GTAP-W model, Berrittella et al. (2007 and 2008) analyze 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. Applications of the model include an analysis of the economy-wide impacts of enhanced irrigation efficiency (Calzadilla et al. 2011) and the investigation of the role of green (rainfall) and blue (irrigation) water resources in agriculture (Calzadilla et al. 2010).

² 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 2001).

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). 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 CO₂ effects on plant growth. Results indicate that the inclusion of CO₂ fertilization is likely to offset some of the potential welfare losses generated by climate change (e.g. Tsigas et al. 1997; Darwin and Kennedy 2000).

Global CGE models have also been used to study the role of adaptation in adjusting to new climate condition. The results suggest that farm-level adaptations might mitigate any negative impacts induced by climate change (e.g. Darwin et al. 1995; Parry et al. 1999; Tubiello and Fischer 2007).

However, none of these studies have water as an explicit factor of production. Our GTAP-W model is the first global model to do this. Moreover, most of these studies are based on scenarios related to a doubling of CO₂ 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 CO₂ 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.

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 (Hertel 1997), and is based on the version modified by Burniaux and Truong³ (2002) as well as on the previous GTAP-W model introduced by Berritella 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 IMPACT model is a partial equilibrium agricultural sector model combined with a water simulation model (Rosegrant et al. 2002), it 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 GTAP-W model has 16 regions and 22 sectors, 7 of which are agricultural crops.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

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 CO₂ emissions related to energy consumption.

⁴ See Table S1 in the [supplemental material](#) for the regional, sectoral and factoral aggregation used in GTAP-W.

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 the cost of irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability [see [supplemental material](#), Figure S1, for the tree 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.⁵ 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.⁶

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 a detailed description of the adjustment process and economic behavior in GTAP-W see [supplemental material](#).

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.

4 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 analyze data from simulations using the Hadley Centre Global Environmental Model version 1 (HadGEM1: a version of the Met Office Unified Model, MetUM) 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 broad agreement with previous studies (e.g. Arnell 2003; Milly et al. 2005). HadGEM1 was the version of the Hadley Centre GCM used in the Intergovernmental Panel on Climate Change’s (IPCC) Fourth Assessment Report (Solomon et al. 2007) and HadGEM1 is described in detail by Johns et al. (2006) and Martin et al.

⁵ 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.

⁶ 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.

(2006). HadGEM1 has a horizontal latitude–longitude resolution of $1.25^{\circ} \times 1.875^{\circ}$ for the atmosphere and $1.0^{\circ} \times 1.0^{\circ}$ for the ocean. Compared to observations, HadGEM1 has too much annual precipitation over the Southern Ocean and high latitudes of the North Atlantic and North Pacific; over land, HadGEM1 is too wet over India and too dry over Southeast Asia, Indonesia, and the coast of western South America (Johns et al. 2006). Falloon et al. (2011) compare river flows simulated with HadGEM1-TRIP to observed flow gauge data, in general finding reasonable simulation of annual flows but much more variable skill in reproducing monthly flows.

Future changes in temperature and precipitation projected by HadGEM1 are generally similar to those projected by the range of models presented in Solomon et al. (2007). For example, HadGEM1 projects increases in precipitation over land for the Northern Hemisphere high latitudes, across southern to eastern Asia and central Africa, while decreases in precipitation are projected across the Mediterranean region, the southern United States and southern Africa (Nohara et al. 2006). Under the IPCC SRES A1B and A2 scenarios (Johns et al., 2006; Stott et al., 2006), the global mean atmospheric surface temperature rises projected by HadGEM1 between 1961–1990 and 2070–2100 were approximately 3.4 K and 3.8 K, respectively, slightly warmer than the IPCC multi-model ensemble mean (Solomon et al. 2007). Globally, future precipitation changes projected by HadGEM1 are similar to, or slightly smaller than the IPCC multi-model ensemble mean. For consistency, we note here that while these HadGEM1 simulations did include the impact of elevated CO₂ concentrations on runoff, they did not include explicit representations of crops, irrigation, groundwater or dams.

In our analysis we contrast a relatively optimistic scenario (A1B) 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 peaks in mid-century and declines thereafter. There is 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. To estimate the expected impacts of these emission scenarios in global agricultural production, we only incorporate predicted changes in climate-related variables affecting agricultural productivity. That is, precipitation, temperature, river flow and CO₂ concentrations.

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 regional average precipitation, temperature and river flow data. Therefore, in the current study we do not consider local scale impacts nor changes in seasonality or climatic extremes.

The 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 impose a forecast closure (see Dixon and Rimmer 2002) exogenizing macroeconomic

variables for which forecasts are available. See the [supplemental material](#) for a detailed description of the future baseline simulations.

4.1 River flow

Compared to the average for the 1961–1990 period (historic-anthropogenic simulation), Falloon and Betts (2006) find 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 % under the A1B scenario and 8 % under the A2 scenario). The A2 scenario produced more severe and widespread changes in river flow than the A1B scenario.

Large regional differences are observed [[supplemental material](#), Figure S2]. 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 ground-water 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 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 S1 [see [supplemental material](#)]. 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 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 % change in runoff results in a 1 % 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.

4.2 Precipitation and temperature

Falloon and Betts (2006) point 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 [[supplemental material](#), Figure S3]. 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

Table 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 ^a	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

Own calculation based on Falloon and Betts (2006)

^a Regional runoff elasticities of water supply are based on Darwin et al. (1995)

predicted along with decreases in evaporation, so changes in rainfall and evaporation both contributed to the river flow changes.

The regional patterns of temperature increases were similar for the two emission scenarios and time periods [supplemental material, Figure S4]. Larger temperature increases are expected at high latitudes and under the SRES A1B scenario.

4.3 Crop yield response

The exposure of irrigated agriculture to the risk of changes in climate conditions is more limited compared to rainfed agriculture which depends solely on precipitation. Temperature and soil moisture determine the length of growing season and control the crop's development and water requirements. Regional crop yield responses to changes in precipitation and temperature are based on Rosenzweig and Iglesias (1994) [see supplemental material, Table S6]. 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) use 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).

This data set has been widely used to assess potential climate change impacts on world crop production (e.g. Parry et al. 1999, 2004). In 2009, Iglesias and Rosenzweig (2009) updated this dataset by linking biophysical crop model and statistical models. However, they report the individual effect on crop yields only for the CO₂ fertilization effect, which limits its use in our analysis, because we are interested in assessing the individual impacts of changes in precipitation, temperature, river flow, CO₂ fertilization and adaptation on agricultural production. Besides neglecting the combined effect of these climate variables on crop yields, our analysis face an additional uncertainty related to the use of crop yield responses from only one study.

New studies based on statistical models of observed yield responses to current climate trends made an important contribution and provided useful insights on crop yield changes induced by climate change (e.g. Lobell and Field 2007; Lobell and Burke 2010). However, statistical models are data intensive which limits its application. For instance, Lobell and Field (2007) analyze the impact of recent warming on crop yields at the global scale; and Lobell and Burke (2010) and Schlenker and Lobell (2010) project crop yield changes only in Sub-Saharan Africa by 2050. Statistical models are also dependent on data quality.

4.4 CO₂ fertilization

Our estimates of the CO₂ fertilization effect on crop yields are based on information presented by Tubiello et al. (2007). They report yield response ratios for C₃ and C₄ crops to elevated CO₂ 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 CO₂ 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 CO₂ 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 % 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 % at 414 ppm for C₃ and C₄ crops, respectively. CO₂ concentration levels in 2050 are expected to be similar for both SRES scenarios (522 ppm), increasing C₃ crop yields by 12.6 % and C₄ crop yields by 5.2 %.

4.5 Simulation scenarios

Based on the regional changes in river flow (water supply), precipitation and temperature presented in Table 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 2 presents the main characteristics of the six simulation scenarios.

The first three scenarios are directly comparable to previous studies. They show the impacts of changes in precipitation, temperature and CO₂ 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-CO₂* scenario analyzes changes in precipitation and CO₂ fertilization, and the *precipitation-temperature-CO₂* scenario analyzes changes in precipitation, temperature and CO₂ 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, for simplicity we assume that this land has the same productivity as the currently irrigated land. 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 1. That is, the relative change in the supply of irrigated land equals the relative change in water supply.

Table 2 Summary of inputs for the simulation scenarios

Scenario	Changes in				
	Precipitation	CO ₂	Temperature	River flow	Land
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

Table 3 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	A1B	A2
Results for the 2020s														
Total production (thousand mt)	9,466,600	0.03	-0.04	0.03	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	2.08	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	-3.08	-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	-1.17	-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	-0.07	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	-4.17	-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	-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	-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	-0.03	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	-2.64	-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	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	-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	-2.81	-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	-0.72	-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	-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	-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	-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	-0.32	-0.02	-0.02	-0.01	-0.01	-0.29	-0.28

The last scenario, called *all-factors*, shows the impacts of all climate variables affecting agricultural production. Temperature and CO₂ 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.

5 Results

Climate change is expected to decrease global agricultural production. The decline is quite modest in the medium term, around 0.5 %, but reaches around 2.3 % in the long term (Table 3, *all-factors* scenario). However, large regional differences are expected [see [supplemental material](#), Table S7]. We did not find marked differences between the two SRES scenarios. The decline in global agricultural production is slightly more pronounced under the SRES A2 scenario.

Expected changes in water supply for rainfed and irrigated agriculture lead to shifts in rainfed and irrigated production. In the 2020s, a moderate precipitation increase reduces the yield gap between rainfed and irrigated crops increasing global rainfed production (Table 3, *all-factors* scenario). However, in the 2050s, rainfed crop production declines due to heat stress in a warmer climate. Global irrigated production declines in both periods. At the regional level (results not shown), irrigated production declines mainly in the United States, the Middle East, North Africa and South Asia. These are regions with high negative yield responses to changes in temperature and where irrigated production contributes substantially to total crop production.

Aggregation hides important sectoral differences. Figure 1 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/beet and wheat, between 39 % and 43 % depending on the SRES scenario. Production for these crops declines between 3 % and 5 %.

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 3). 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 % of global GDP (Table 3).

Disaggregating welfare losses according to the contribution of the individual climate variables, Fig. 2 shows changes in global welfare by scenario and individual input variable. Comparing the differences between the scenarios *water-land* and *all-factors* or alternatively between *precipitation-only* and *precipitation-temperature-CO₂*, we can see that adding carbon dioxide fertilization and warming to the mix has a clear negative effect on welfare. Analyzing 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.

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 (Table 3). As expected, the addition of CO₂ fertilization in the analysis causes an increase in world food production. However, the CO₂ fertilization effect is not strong enough to compensate world food losses caused by higher temperatures (compare *precipitation-CO₂* and *precipitation-temperature-CO₂* scenarios, Table 3). For the 2050s and under the *precipitation-temperature-CO₂* scenario, world food production is expected to decrease by around 2.5 % 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.

Comparing the scenarios *precipitation-only* and *water-only*, we highlight the advantage of the GTAP-W model that differentiates between rainfed and irrigated agriculture. 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 3). 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. 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 less pronounced or even positive (Table 3). For the 2050s, global welfare losses are about half those under the *precipitation-only* scenario.

Climate change impacts are expected to be unevenly distributed across world regions, because regional production and welfare are not only influenced by regional climate change, but also by climate-induced changes in competitiveness. The decomposition of welfare changes (Fig. 3) shows that changes in agricultural productivity detriment welfare in most regions. However, as regional impacts are mixed, only the most adversely affected regions suffer a deterioration in its terms of trade and a decline in welfare (mainly the former Soviet Union, South Asia and the Middle East).⁷ Other regions, such as South America, Sub-Saharan Africa, Australia and New Zealand, which are less affected by climate change, may experience welfare gains, because their relative competitive position improves with respect to other regions. Therefore, climate change is expected to generate new opportunity cost and modify comparative advantages in food production.

Figure 4 shows that welfare losses are associated with a negative change in trade balance (X-M) in agricultural products. The former Soviet Union has the largest decrease in welfare and a negative trade balance in all agricultural products. As soon as regions are able to increase food exports (or decrease food imports) of agricultural commodities, regional welfare becomes positive. Regions like South America, Sub-Saharan Africa and China have welfare gains and a positive trade balance in all agricultural products. These regions are able to grow more food and benefit from international trade.

⁷ A decomposition of the terms-of-trade effect by sector and region reveals that changes in agricultural production can explain most of it. An exception is the Former Soviet Union. Here, changes in other sectors including oil and gas mostly determine the size of the effect.

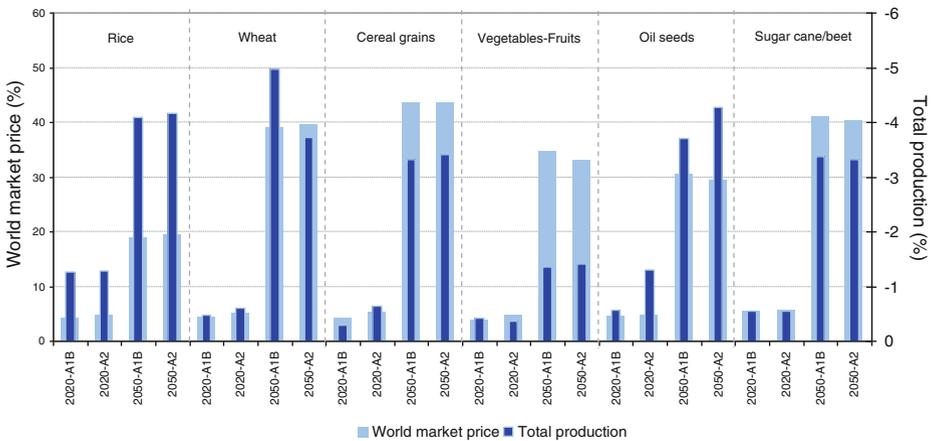


Fig. 1 Changes in total agricultural production (negative) and world market price (positive) by crop, *all-factors* scenario. Own calculations

6 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 to assess the combined and individual effects of the main climate variables affecting agricultural productivity.

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 2.64 % and welfare losses reach more than 327 billion USD. Results for the SRES A2 scenario are less pronounced.

Distinguishing between rainfed and irrigated agriculture (that is, including changes in rainfall and irrigation water in GTAP-W), we find that irrigated production is less vulnerable to changes in water availability due to climate change. When irrigation is possible, food production relies on irrigated crops, thus welfare losses are less pronounced. For the 2050s,

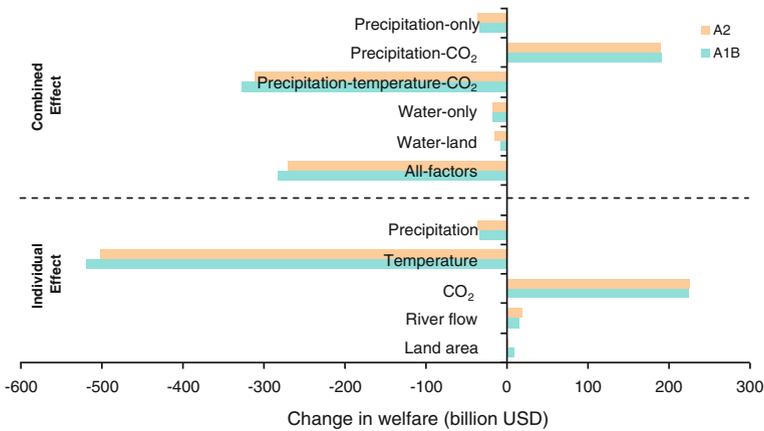


Fig. 2 Changes in global welfare by scenario (combined effect) and input variable (individual effect), results for the 2050's. Note: Individual effects on welfare are computed as follows: Precipitation is the *precipitation-only* scenario. Temperature is the difference between the *precipitation-temperature-CO₂* and *precipitation-CO₂* scenarios. Carbon dioxide fertilization (CO₂) is the difference between the *precipitation-CO₂* 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

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 CO₂ fertilization) shows that global food production declines by around 0.5 % in the 2020s and by around 2.3 % in the 2050s. We did not find marked differences between SRES scenarios. Despite the increase in irrigated crop areas promoted by a higher irrigation water supply, global irrigated production declines between 3 % and 6 %, depending on the SRES scenario and time period. Irrigated crop production declines mainly 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).

Declines in food production rise food prices. Higher market prices are expected for all crops, mainly for cereal grains, sugar cane/beet and wheat (between 39 % and 43 % 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 % of global GDP (*all-factors* scenario). Regional production and welfare are not only influenced by regional climate change, but also by climate-induced changes in competitiveness. Only the most adversely affected regions experience a deterioration in their terms of trade and a decline in welfare. Other regions, which are less affected by climate change, may experience welfare gains, because their relative competitive position improves. Regions which are able to grow more food and benefit from international trade face welfare gains. Climate change is expected to generate new opportunity cost and modify comparative advantages in food production.

Several limitations apply to the above results. First, in our analysis changes in precipitation, temperature and river flow are 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

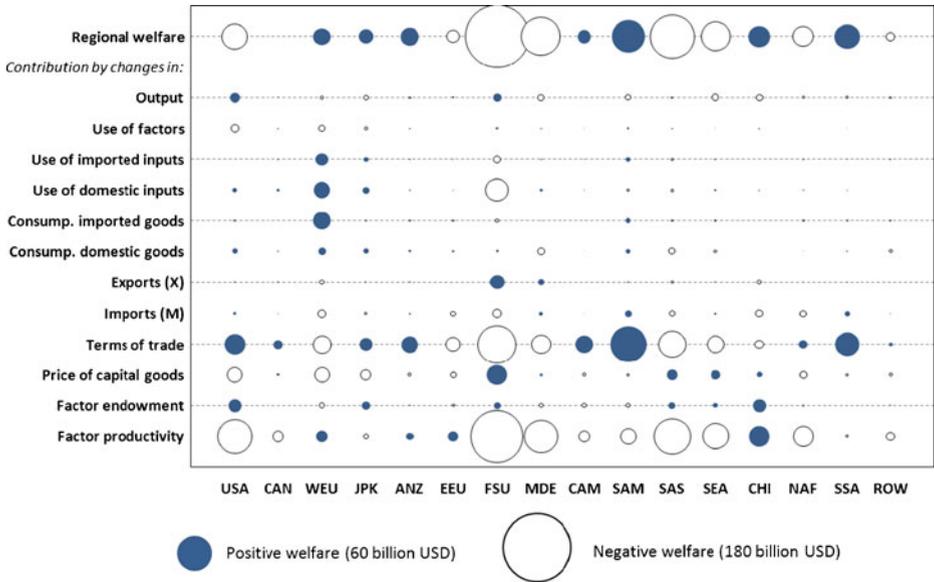


Fig. 3 2050 A1B SRES scenario: Positive welfare change and negative welfare change (decomposition), *all-factors* scenario, billion USD. Note: See supplemental material, Table S1 for regional names

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. Fifth, our model uses Armington assumptions to model substitution between domestic and imported inputs; therefore, regional trade flows are conditional to the calibrated shares and elasticities. These issues should be addressed in future research.

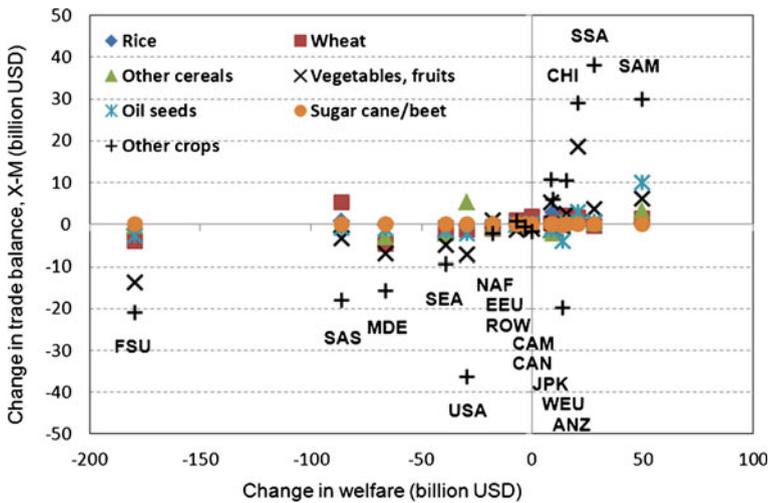


Fig. 4 2050 A1B SRES scenario: Change in trade balance and welfare, *all-factors* scenario, billion USD. Note: See supplemental material, Table S1 for regional names

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