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Economywide Impacts of Climate Change on Agriculture in Sub-Saharan Africa

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ABSTRACT

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

Keywords: computable general equilibrium, climate change, agriculture, Sub-Saharan Africa, integrated assessment

ABBREVIATIONS AND ACRONYMS

GDP	gross domestic product
FAO	Food and Agriculture Organization of the United Nations
IPCC	Intergovernmental Panel on Climate Change
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
WSM	water simulation module
SRES	Special Report on Emission Scenario
FACE	Free Air Carbon Enrichment
HadCM3	Hadley Centre Coupled Model
CES	constant elasticity of substitution
CDE	constant difference in elasticities
GTAP-W	general equilibrium model
CGE	computable general equilibrium

1. INTRODUCTION

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

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

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

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

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

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

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

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

Future climate change may present an additional challenge for agriculture in Sub-Saharan Africa. According to the Intergovernmental Panel on Climate Change (IPCC) (Watson, Zinyowera, and Moss 1997), Africa is the most vulnerable region to climate change because widespread poverty limits adaptive capacity. The impacts of climate change on agriculture could seriously worsen livelihood conditions for the rural poor and increase food insecurity in the region. The World Development Report 2008 (World Bank 2007) identifies five main factors through which climate change will affect agricultural productivity: changes in temperature, changes in precipitation, changes in carbon dioxide (CO2) fertilization, increased climate variability, and changes in surface water runoff. Increased climate variability and droughts will affect livestock production as well. Smallholders and pastoralists in Sub-Saharan Africa will need to gradually adapt and adopt technologies that increase the productivity, stability, and resilience of production systems (Faurès and Santini 2008).

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

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

While partial equilibrium analysis focuses on the sector affected by a policy measure and assumes that the rest of the economy is not affected, general equilibrium models consider other sectors or regions as well to determine economywide effects; partial equilibrium models tend to have more detail. Studies using general equilibrium approaches are generally based on data for a single country or region, assuming no interlinkages with the rest of the world regarding policy changes and shocks (e.g., Diao and Roe 2003; Gómez, Tirado, and Rey-Maquieira 2004; Letsoalo et al. 2007).

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

2. MODELS AND BASELINE SIMULATIONS

The IMPACT Model

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

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

The spatial representation of global economic regions and natural river basins has recently been enhanced. The model now uses 281 "food-producing units" (FPUs), which represent the spatial intersections of 115 economic regions and 126 river basins. Water simulation and crop production projections are conducted at the FPU level, while projections of food demand and agricultural commodity trade are conducted at the country or economic region level. The disaggregation of spatial units improves the model's ability to represent the spatial heterogeneity of agricultural economies and, in particular, water resource availability and use.

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

In this analysis, we use the intermediate growth B2 scenario[1] from the *Special Report on Emission Scenario* (SRES) scenario family (IPCC 2000) for the baseline projections out to 2050. The effects of temperature and CO_2 fertilization on crop yields are based on simulations of the IMAGE model (Bouwman, Kram, and Klein Goldewijk 2006). Recent research findings show that the stimulation of crop yield observed in the global Free Air Carbon Enrichment (FACE) experiments fell well below (about half) the value predicted from chambers (Long et al. 2006). These FACE experiments clearly show that much lower CO_2 fertilization factors (compared with chamber results) should be used in model projections of future yields. Therefore, we apply 50 percent of the CO_2 fertilization factors from the IMAGE model simulation in IMPACT (Rosegrant, Fernandez, and Sinha 2009).

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

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

The GTAP-W Model

In order to assess the systemic general equilibrium effects of alternative strategies of adaptation to climate change in Sub-Saharan Africa, we use a multiregional world CGE model, called GTAP-W. The model is a further refinement of the GTAP model (Hertel 1997) and is based on the version modified by Burniaux and Truong (2002) as well as on the previous GTAP-W model introduced by Berrittella et al. (2007). The revised GTAP-W model is based on the GTAP version 6 database, which represents the global economy in 2001. The model has 16 regions and 22 sectors, 7 of which are in agriculture. However, the most significant change and principal characteristic of version 2 of the GTAP-W model is the new production structure, in which the original land endowment in the value-added nest has been split into pastureland (grazing land used by livestock) and land for rainfed and for irrigated agriculture. The last two types of land differ, as rainfall is free but irrigation development is costly. As a result, land equipped for irrigation is generally more valuable because yields per hectare are higher. To account for this difference, we split irrigated agriculture further into the value of land and the value of irrigation. The value of irrigation includes the equipment but also the water necessary for agricultural production. In the

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

short run, irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability. The tree diagram in Figure A.1. in Appendix A represents the new production structure. Land as a factor of production in national accounts represents “the ground, including the soil covering and any associated surface waters, over which ownership rights are enforced” (United Nations 1993, paragraph AN.211). To accomplish this, we split for each region and each crop the value of land included in the GTAP social accounting matrix into the value of rainfed land and the value of irrigated land using its proportionate contribution to total production. The value of pastureland is derived from the value of land in the livestock breeding sector.

In the next step, we split the value of irrigated land into the value of land and the value of irrigation using the ratio of irrigated yield to rainfed yield. These ratios are based on IMPACT data. The numbers indicate how relatively more valuable irrigated agriculture is compared to rainfed agriculture. The magnitude of additional yield differs not only with respect to the region but also to the crop. On average, producing rice using irrigation is relatively more productive than using irrigation for growing oilseeds, for example.

The procedure we described above to introduce the four new endowments (pastureland, rainfed land, irrigated land, and irrigation) allows us to avoid problems related to model calibration. In fact, since the original database is only split and not altered, the original regions’ social accounting matrices are balanced and can be used by the GTAP-W model to assign values to the share parameters of the mathematical equations. For detailed information about the social accounting matrix representation of the GTAP database, see McDonald, Robinson, and Thierfelder (2005).

As in all CGE models, the GTAP-W model makes use of the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modeled through a representative firm, which maximizes profits in perfectly competitive markets. The production functions are specified via a series of nested constant elasticity of substitution (CES) functions (Figure A.1.). Domestic and foreign inputs are not perfect substitutes, according to the so-called Armington assumption, which accounts for product heterogeneity.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, pastureland, rainfed land, irrigated land, irrigation, labor, and capital). Capital and labor are perfectly mobile domestically, but immobile internationally. Pastureland, rainfed land, irrigated land, irrigation, and natural resources are imperfectly mobile. National income is allocated between aggregate household consumption, public consumption, and savings. Expenditure shares are generally fixed, which amounts to saying that the top-level utility function has a Cobb-Douglas specification. Private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the constant difference in elasticities (CDE) form: a nonhomothetic function, which is used to account for possible differences in income elasticities for the various consumption goods. A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.

In the original GTAP-E model, land is combined with natural resources, labor, and the capital-energy composite in a value-added nest. In our modeling framework, we incorporate the possibility of substitution between land and irrigation in irrigated agricultural production by using a nested CES function (Figure A.1.). The procedure for obtaining the elasticity of factor substitution between land and irrigation (σLW) is explained in greater detail in Calzadilla, Rehdanz, and Tol (2008). Next, the irrigated land-water composite is combined with pastureland, rainfed land, natural resources, labor, and the capital-energy composite in a value-added nest through a CES structure. The original elasticity of substitution between primary factors (σVAE) is used for the new set of endowments.

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

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

Baseline Simulations

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

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

The interaction of the two models allows for improved calibration and enhanced insights into policy impacts. In fact, the information supplied by the IMPACT model (demand and supply of water, demand and supply of food, rainfed and irrigated production, and rainfed and irrigated area) provides the GTAP-W model with detailed information for a robust calibration of a new data set and allows us to run climate change scenarios. The links between IMPACT and GTAP-W are shown in Figure A.2 in Appendix A.

3. BASELINE SIMULATION RESULTS

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

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

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

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

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

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

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

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

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

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

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

The last three columns in Table 3 show the impact of climate change on regional GDP and welfare. At the global level, GDP is expected to decrease with climate change by US$87 billion, equivalent to 0.09 percent of global GDP. At the regional level, only Australia and New Zealand experience a positive GDP impact under climate change: GDP is expected to increase by US$1.07 billion. Projected declines in GDP are particularly high for the United States, South Asia, and South America (US$19.77 billion, US$17.27 billion, and US$10.70 billion, respectively). In relative terms, declines are largest for South Asia, the former Soviet Union, and Eastern Europe (0.64, 0.58, and 0.38 percent, respectively). For Sub-Saharan Africa, losses in GDP due to climate change are estimated at US$3.33 billion, equivalent to 0.20 percent of regional GDP. These losses in GDP are used to evaluate the efficacy of the two adaptation scenarios to cope with climate change. Alternatively, when yield effects of CO_2 fertilization are not considered, GDP losses in Sub-Saharan Africa are estimated to be slightly higher (US$4.46 billion).

Like global GDP, global welfare is expected to decline with climate change (US$87 billion). However, welfare losses due to declines in agricultural productivity and crop harvested area are not general; in some regions, welfare increases as their relative competitive position improves with respect to other regions. This is the case for South America, Australia and New Zealand, Sub-Saharan Africa, and Canada. Projected welfare losses are considerable for South Asia, the United States, and Western Europe. The US$2 billion welfare increase in Sub-Saharan Africa is explained as follows. First, only some crops in Sub-Saharan Africa are badly hit by climate change. Second, crops in other parts of the world are hit too—and relatively harder than those in Sub-Saharan Africa. The result is an increase in food prices and exports. This improves welfare (as measured by the Hicksian Equivalent Variation), but it also increases malnutrition.

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

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

Agricultural crop productivity is commonly measured by the amount of output per unit of area, such as yield in kilograms per hectare. Table 4 presents average yields by crop type for the 2050 (SRES B2) baseline simulation. Displayed are global average levels as well as minimum and maximum levels for rainfed and irrigated harvested area according to the 16 GTAP-W regions defined in Table A.1. In addition, average yield levels for Sub-Saharan Africa as well as information on the minimum and maximum yields in individual countries are provided. Clearly, the performance of Sub-Saharan Africa is poor when compared to the regional and global averages. Compared with other regions, the average agricultural productivity in Sub-Saharan Africa is the lowest or is close to the minimum for all crops, except for irrigated rice, wheat, and sugarcane, which have levels close to the global average. Agricultural productivity within the Sub-Saharan African region varies widely. Some countries are highly productive on very small areas—for example, Tanzania with sugarcane and South Africa with most agricultural crops. Most countries, however, fare poorly on large rainfed areas with low yields.

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

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

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

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

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

4. STRATEGIES FOR ADAPTATION TO CLIMATE CHANGE

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

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

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

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

Adaptation Scenario 1: Expansion of Irrigated Agriculture

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

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

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

Note: * World price index for total supply.

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

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

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

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

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

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

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

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

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

Adaptation Scenario 2: Improvements in Agricultural Productivity

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

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

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

Note: * World price index for total supply

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

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

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

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

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

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

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

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

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

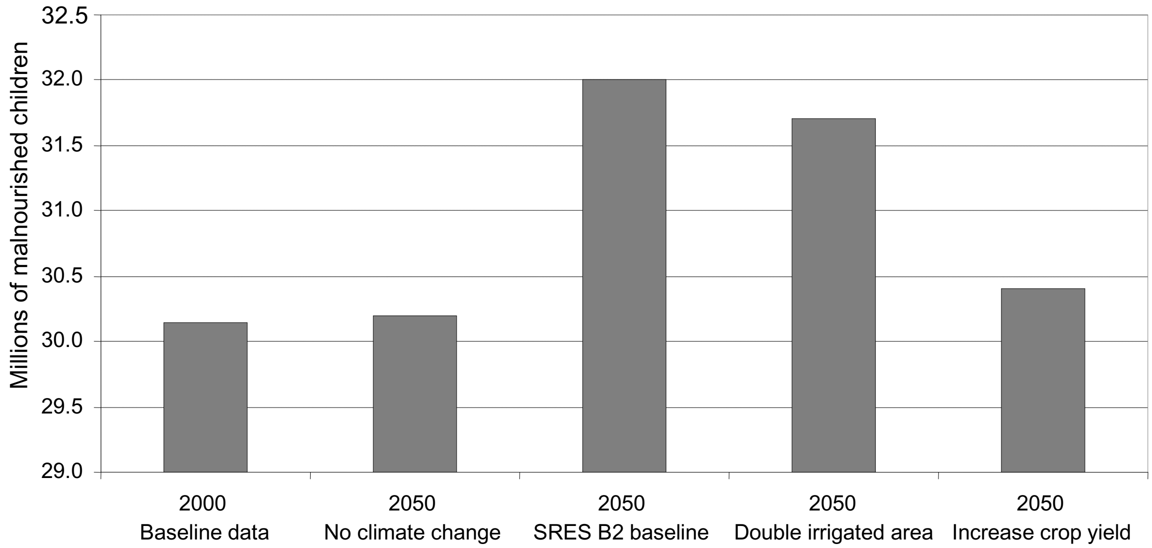
Notes: * Percentage change with respect to the 2050 no climate change simulation.
** Percentage change with respect to the 2050 (SRES B2) baseline simulation.

Outcomes for Malnutrition

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

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

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



Source: IFPRI IMPACT simulations.

5. DISCUSSION AND CONCLUSIONS

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

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

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

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

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

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

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

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

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

Because the first adaptation scenario transfers land from rainfed to irrigated agriculture, market prices for rainfed land increase, while market prices for irrigation and irrigated land decrease. In the second adaptation scenario, market prices for rainfed land, irrigated land, and irrigation decline. In both adaptation scenarios, market prices for the rest of the primary factors increase. The increase in the market price for unskilled labor is higher than for skilled labor under the second scenario.

Both adaptation scenarios enable farmers to achieve higher yields and revenues from crop production. The increase in regional welfare in the first scenario is modest (US$119 million) but in the second scenario reaches US$15.43 billion.

The efficacy of the two scenarios as adaptation measures to cope with climate change is measured by changes in regional GDP. An increase in agricultural productivity widely exceeds the GDP losses due to climate change; GDP increases by US$25.72 billion compared to the initial reduction in GDP of US$3.33 billion. The opposite happens for an increase in irrigated area; the GDP increase does not offset GDP losses due to climate change (GDP increases by only US$113 million). While these results are promising in terms of the potential to develop investment programs to counteract the adverse impacts of climate change, the scenario implemented here, SRES B2, is on the conservative side of the range of climate change scenarios.

Several caveats apply to the above results. First, in our analysis, increases in irrigated areas and improvements in agricultural productivity are not accompanied by changes in prices. We do not consider any cost or investment associated with irrigation expansion or improvements in agricultural productivity. Therefore, our results might overestimate the benefits of both adaptation scenarios. Second, we implicitly assume, for the expansion of irrigated agriculture, the availability and accessibility of water resources. We assume a sustainable use of water resources. Third, we do not achieve a complete integration of both models. Future work will be focused on further integration and accounting for possible feedbacks from GTAP-W to IMPACT.

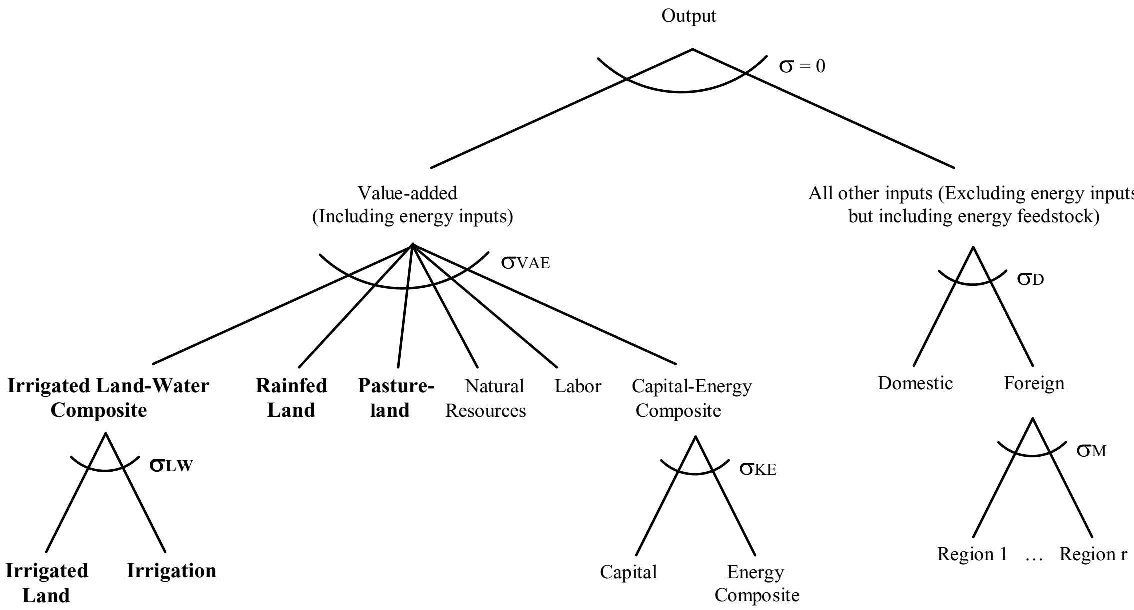
APPENDIX A: SUPPLEMENTARY TABLE AND FIGURES

Table A.1. Regional and sectoral mapping between IMPACT and GTAP-W

16 GTAP-W Regions	115 IMPACT Regions
United States	United States
Canada	Canada
Western Europe	Alpine Europe, Belgium and Luxembourg, British Isles, Cyprus, France, Germany, Iberia, Italy, Netherlands, Scandinavia
Japan and South Korea	Japan, South Korea
Australia and New Zealand	Australia, New Zealand
Eastern Europe	Adriatic, Central Europe, Poland
Former Soviet Union	Baltic, Caucasus, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Middle East	Gulf, Iran, Iraq, Israel, Jordan, Lebanon, Syria, Turkey
Central America	Caribbean Central America, Mexico
South America	Argentina, Brazil, Central South America, Chile, Colombia, Ecuador, northern South America, Peru, Uruguay
South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
Southeast Asia	Indonesia, Malaysia, Mongolia, Myanmar, North Korea, Philippines, Singapore, Southeast Asia, Thailand, Vietnam
China	China
North Africa	Algeria, Egypt, Libya, Morocco, Tunisia
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Congo, Djibouti, Democratic Republic of the Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
Rest of the World	Papua New Guinea, rest of the world

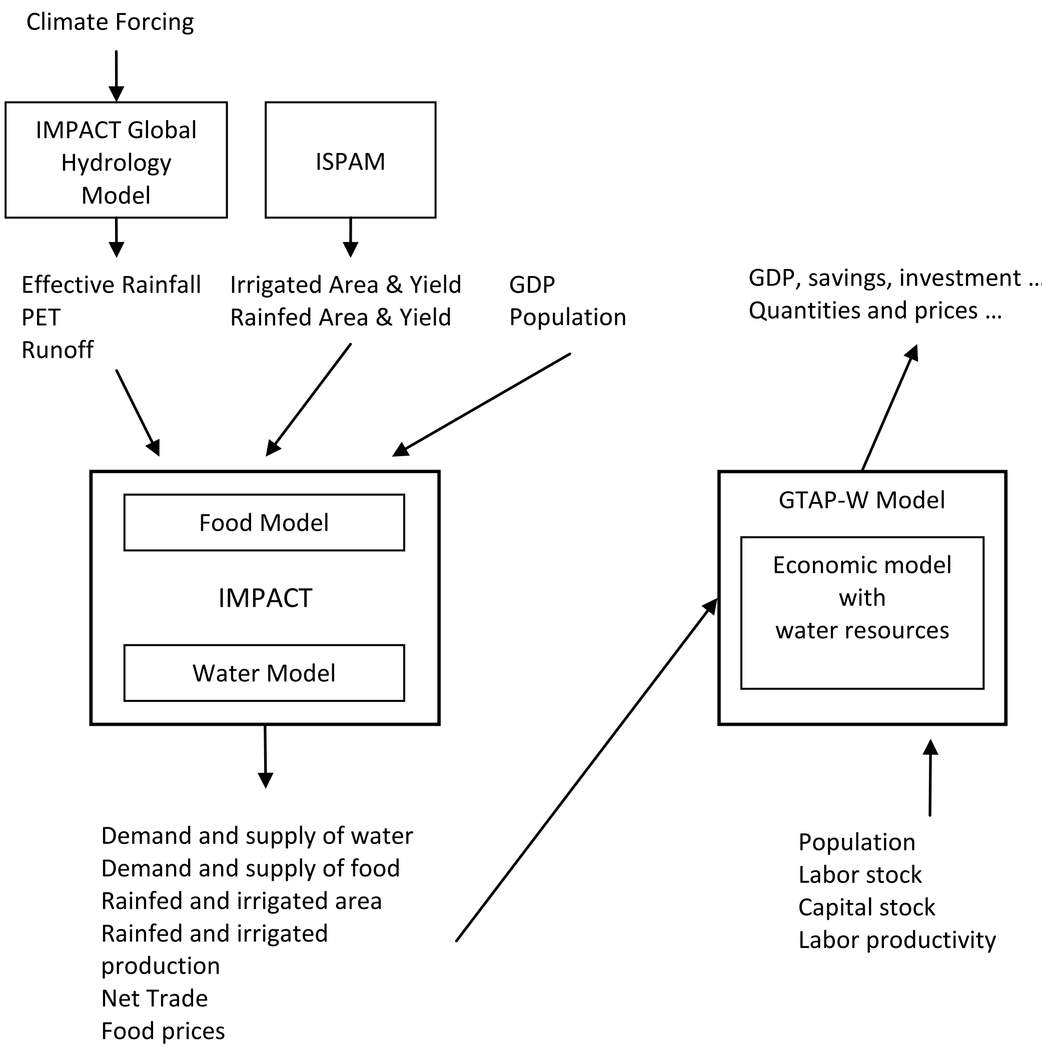
7 GTAP-W Crops	23 IMPACT Crops
Rice	Rice
Wheat	Wheat
Cereal grains	Maize, millet, sorghum, other grains
Vegetables, fruits, nuts	Potato, sweet potatoes and yams, cassava and other roots and tubers, vegetables, (sub)tropical fruits, temperate fruits, chickpeas, pigeon peas
Oilseeds	Soybeans, oils, groundnuts
Sugarcane, sugar beet	Sugarcane, sugar beets
Other agricultural products	Other
--	Meals, cotton, sweeteners

Figure A.1. Nested tree structure for industrial production process in GTAP-W (truncated)



Note: The original land endowment has been split into pastureland, rainfed land, irrigated land, and irrigation (bold letters).

Figure A.2. Model linkages between IMPACT and GTAP-W



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