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DEVELOPMENT AND CLIMATE CHANGE

The Costs of **Agricultural Adaptation** to Climate Change

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The Costs of **Agricultural Adaptation** to Climate Change

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Please note that the estimates of costs of adaptation for the agricultural sector presented in this report differ from the cost estimates used in the synthesis report of the "Economics of Adaptation to Climate Change." The note below provides an explanation for this difference.

ADJUSTMENTS TO THE IFPRI EACC ESTIMATES FOR AGRICULTURE

BACKGROUND

The adjustments made to IFPRI's original estimates of the cost of adaptation for agriculture have to be understood within the framework of analysis that was established for the EACC Global Analysis. The key elements are as follows:

(a) The costs are restricted to those incurred by the public sector and exclude what is often referred to as "autonomous" adaptation—i.e. investment or expenditures by private individuals or companies in response to changes in market prices or other signals linked to climate change.
(b) Adaptation is measured relative to an "efficient" baseline scenario economic and social development without climate change. This scenario allows for the impact of economic growth, population increase, urbanisation, etc up to 2050 on the level and composition of public spending and investment.
(c) The cost of adaptation is defined as the additional public expenditures necessary either to ensure that sector welfare with climate change is not worse than the level of sector welfare on the baseline without climate change. Sector welfare is given different interpretations according to the context, but in general the idea is to maintain the output of sector-specific services or outcomes—i.e. the level of malnutrition for agriculture, infant mortality and life expectancy for health, infrastructure services, etc.
(d) As far as possible the analysis takes account of linkages across sectors so as to avoid duplication of estimates and the likelihood that changes in the development baseline in one sector will affect the cost of adaptation for other sectors.

Many economic scenarios have been used for discussions of climate change and the differences between them are a significant source of difficulty in making comparisons. Rather than reinvent the wheel, the development baseline for the EACC study was linked to the UN's Medium Fertility population projection and average regional rates of economic growth derived from the main economy-environment models used for economic analyses of climate change. These assumptions define a consistent framework for analysing the costs of adaptation.

They do not represent an attempt to generate a definitive set of economic projections up to 2050. Since many of the component costs of adaptation are affected directly or indirectly by economic growth, monetary estimates of the cost of adaptation depend upon these projections. Expressing the costs of adaptation as percentages of either GDP or sector expenditures under the baseline is likely to provide a more robust way of assessing the overall burden of adapting to climate change.

AN ILLUSTRATION – COASTAL PROTECTION

The implementation of this approach can be illustrated by reference to coastal protection.

Step 1 – A baseline scenario for development without climate change is defined. This includes a set of rules that govern the construction of coastal defences that take account of growth in urban population and GDP in coastal zones. The time profile of public investment and associated expenditure on O&M in the sector is estimated for the baseline scenario. Even without climate change there will be significant expenditures on coast defences because (a) the increase in the value of income & urban assets in coastal zones due to economic growth justifies higher levels of protection against flooding and storms, and (b) long run changes means that some coastal zones are sinking and would require greater protection even without climate change—this is partly due to extraction of groundwater (Bangkok, Jakarta) or shifts in continental plates.

Step 2 - The time profile of public investment and associated expenditure on O&M in the sector is estimated for a specific climate scenario, on the assumptions that (i) baseline rates of population growth, GDP growth, urbanisation, etc remain the same, and (ii) expenditures are adjusted to hold the level of services or of welfare achieved equivalent to the levels projected under the baseline scenario. For coastal protection, this is interpreted as applying the same rules for when coast defences would be built (in terms of the risks of flooding or storm damage) and then calculating any changes in the damage caused to assets and people who are not protected.

Step 3 - The cost of adaptation is then calculated as the difference between the total of investment and O&M expenditures under the climate scenario and the equivalent total under the baseline scenario without climate change. This corresponds to identifying the costs associated with climate change while holding constant the baseline assumptions for economic development, etc.

APPLICATION TO AGRICULTURE – MAINTAINING WELFARE

The IMPACT model used as the basis for estimating the costs of adaptation for agriculture is, in effect, a computable general equilibrium model of the world agricultural market which incorporates detailed agro-economic information to underpin the projections of crop and other agricultural production. The baseline projections of the EACC model are used to determine demand for agricultural products while climate variables, specified in considerable detail, influence patterns of land use and agricultural production. Agricultural markets clear through adjustments in the prices of agricultural products and volumes of trade, taking account of distribution and transport margins.[1]

The key measure of welfare is the level of child malnutrition in each country and for developing countries in total. This is estimated using an equation that includes demographic variables and food availability in kilocalories per capita per day. Higher food prices lead to lower consumption (availability) of food and thus higher malnutrition holding other variables constant. Thus, the key impact of climate change on agricultural welfare is mediated through food prices and their effect on food consumption, since the other influences—life expectancy, female education and access to safe water—are held constant across climate scenarios.

In the baseline scenario without climate change (NoCC) the IPRI results show that calorie availability in developing countries would increase from an average of about 2700 kcal per person per day in 2000 to about 2890 in 2050, whereas it would fall to about 2420 under both the NCAR and the CSIRO scenarios. Given other changes in the baseline scenario, the total number of malnourished children falls from about 147 million in 2000 to 113 million in 2050 without climate change. However, with climate change the reduction from the 2000 figure is much lower—only down to 137–138 million depending upon the climate scenario used.[2]

In the IMPACT model certain types of public spending—primarily investments in irrigation expansion and rural roads—are partly driven by changes in agricultural

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[1] The IMPACT model is described in detail in a number of technical papers produced by IFPRI. The discussion here relies upon Rosengrant et al (2002) and Rosengrant et al (2008).

[2] All of the figures are taken from the December 2009 version of the paper but they are the same in earlier and later versions. The climate scenarios do not take account of the impact of carbon fertilisation.

production. Thus, the NoCC scenario assumes that the increase in food availability is underpinned by expenditures on irrigation and rural roads. Since overall food production is lower in the NCAR and CSIRO scenarios, public expenditures in these categories is also lower. So, without any adaptation to climate change public spending would fall but the level of welfare—measured by child malnutrition—would also be lower.

The reference point for adaptation is to restore welfare to its baseline level, i.e. to reduce child malnutrition country by country to the levels that would have prevailed without climate change. In principle, this could be achieved by public spending outside agriculture and linked sectors, for example by measures to increase life expectancy, female education or access to clean water. A full optimisation model would look for the cheapest way of reducing child malnutrition and compute the cost of adaptation in that way. However, the EACC study focuses on sector-specific adaptation, so the IMPACT model is used to estimate what public spending upon agricultural research, irrigation and roads is required to restore child malnutrition to its baseline values country by country.

It should be noted that a part of the additional spending is driven directly by adaptation measures while the remainder is a consequence of the complementary spending required to support the increased level of food production. This distinction is important. Setting aside changes in the location and composition of food production, adaptation will restore food availability under each of the climate scenarios to what it would have been without climate change. To the extent that food production is the same under the NoCC and, say, NCAR with adaptation scenarios, public spending on complementary inputs (irrigation, roads, etc) will be the same in these two runs. Thus, the cost of adaptation will be the direct expenditures required to restore food production. In practice, the calculations are rather more complex because trade and changes in comparative advantage mean that food production is not exactly restored on a country-by-country basis.

This is where the first of the adjustments to the IFPRI estimates is required. What IFPRI reports as the cost of adaptation is the difference between the overall levels of public spending on research, irrigation and roads for each climate scenario with and without adaptation. This includes public spending that is built into the baseline scenario as it is required to support the level of food production that yields the reduction in child malnutrition projected under the baseline scenario. Hence, the cost on adaptation generated by the IMPACT model that is consistent with the EACC definition is the difference between public spending on agricultural research, irrigation and roads for NCAR with adaptation scenario and public spending on the same categories for the NoCC scenario. As explained, it is necessary to adjust IFPRI's reported costs of adaptation to obtain these estimates for each country.

RURAL ROADS

A second adjustment is required to ensure that the treatment of rural roads is consistent across different sectors covered by the EACC study. The issue may be explained as follows.

The development baseline for infrastructure without climate change assumes that public spending on paved and unpaved roads grows in accordance with equations which explain the total length of roads and the proportion of roads that are paved as functions of income per person, total population, urbanisation and a range of country characteristics. Estimates of the cost of adaptation for roads are based on the additional costs of ensuring that these roads are built and maintained to design standards that reflect the changes in climate conditions projected under each climate scenario. However, the baseline scenario implies that there may be some substantial increase in the length of rural roads purely as a consequence of economic development without taking any account of the requirement to get food products to market.

On the other hand, the IMPACT model treats public spending on rural roads partly as complementary to food production and partly as a source of adaptation. It does not attempt to calculate whether the spending on rural roads that it identifies as being necessary for either the baseline or the climate change with adaptation scenario would be covered by the expansion in roads built into the development baseline for the infrastructure sector.

To address this, consider a hypothetical country A. In 2000 it has 100,000 km of roads of which 40,000 km are intra-urban and inter-urban highways and 60,000 km are rural roads. By 2050 the baseline development projection for roads implies that it will have 300,000 km of roads. Allowing for increases in income and urban population suggests that the length of intra- and inter-urban roads will increase to 200,000 km, so that the length of rural roads will grow from 60,000 km to 100,000 km.

Quite separately, suppose that the IFPRI analysis based on the IMPACT model indicates that the length of rural roads required in the NoCC scenario as to support the projected increase in food production up to 2050 will be 90,000 km. In that case, the apparent requirement for additional public spending on rural roads in the NoCC identified by the IFPRI is covered by the increase in the provision of rural roads from 60,000 km to 100,000 km under the development scenario.

Next, the IFPRI analysis concludes that the total length of rural roads under the NCAR with adaptation scenario would have to be 110,000 km in order to support the restoration of food production to a level which is consistent with the NoCC estimate of child malnutrition. Comparison of the IFPRI scenarios with and without climate change means that the cost of adaptation for rural roads is equivalent to the cost of building and maintaining 20,000 km [= 110,000 km (IMPACT NCAR with adaptation) – 90,000 km (IMPACT NoCC)] of rural roads.

However, taking account of the expansion in the provision of rural roads built into the infrastructure baseline means that the adjusted cost of adaptation should only include the cost of building and maintaining 10,000 km [= 110,000 km (IMPACT NCAR with adaptation) – 100,000 km (Infrastructure NoCC baseline)] of rural roads. This is the consequence of ensuring that the same baseline scenario without climate change is applied across all sectors.

The calculations required to make this adjustment are a little more complicated than the initial adjustment to the IFPRI costs of adaptation described above, but they are relatively straightforward once the full set of possible inequalities has been enumerated. The adjustment that has been applied uses the baseline development scenario for roads together with information on intra- and inter-urban roads plus rural roads obtained from World Road Statistics and IFPRI.

1. INTRODUCTION

Climate change will have large, but still uncertain, effects on agriculture. In this report we provide estimates of the impacts on human well-being through effects on agricultural production, prices, and trade. Two indicators provide the metrics to assess the impacts on human well-being—per capita calorie consumption and child malnutrition count. We use these metrics to assess the costs of adaptation with three types of investment—agricultural research, rural roads, and irrigation infrastructure and efficiency improvement. To provide some idea of the uncertainties inherent in the climate change simulations, two general circulation models (GCMs) using the A2 SRES scenario from the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC et al., 2007) provide the climate inputs to the modeling work.

The challenge of modeling climate change impacts in agriculture arises in the wide ranging nature of processes that underlie the working of markets, ecosystems, and human behavior. Our analytical framework integrates modeling components that range from the macro to the micro and from processes that are driven by economics to those that are essentially biological in nature.

We begin this report with a discussion of the modeling methodology and data used. The second part of the report provides the results of the analysis. An Annex provides additional technical details.

2. OVERVIEW OF THE MODELING METHODOLOGY

An illustrative schematic of the links between the partial agriculture equilibrium model that emphasizes policy and trade simulations and the biophysical modeling that emphasizes hydrology and agronomic potential is shown in Figure 1. The modeling methodology reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships at a national level with detailed models of dynamic biophysical processes. The biophysical modeling combines crop modeling results from the Decision Support System for Agrotechnology Transfer (DSSAT) crop modeling suite (J. W. Jones et al., 2003), which simulates responses of five important crops (rice, wheat, maize, soybeans, and groundnuts) to climate, soil, and nutrients and the SPAM data set of crop location and management techniques (Liang You and Stanley Wood, 2006). This analysis is done at a spatial resolution of one half degree. The results are fed into IFPRI's global agricultural supply and demand projection model, IMPACT. An overview of the modeling process is presented here with more details in the Annex.

2.1 CLIMATE DATA

To simulate today's climate the Worldclim current conditions data set (www.worldclim.org) is used which is representative of 1950–2000 and reports monthly average minimum and maximum temperatures and monthly average precipitation.

Future climate data are assumed to be for the year 2050. To provide some idea of the uncertainties inherent in the climate change simulations, results from two general circulation models (GCMs)—from NCAR (NCAR-CCSM3) and CSIRO (CSIRO-Mk3.0)—using the A2 SRES scenario from the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, 2007) are used.[1] At one time the A2 scenario was considered extreme although recent findings suggest it may not be. All scenarios have higher temperature in 2050, which results in greater evaporation. When this water eventually returns to the earth as precipitation, it can fall either on land or the oceans. The NCAR scenario is "wet" in the sense that average precipitation on land increases by about 10 percent between 2000 and 2050. The CSIRO scenario is "dry", with land-based precipitation totals increasing only about 2 percent.

All climate variables are assumed to change linearly between their values in 2000 and 2050. This assumption eliminates any random extreme events such as droughts or high rainfall periods and also assumes that the forcing effects of GHG emissions proceed linearly; that is,

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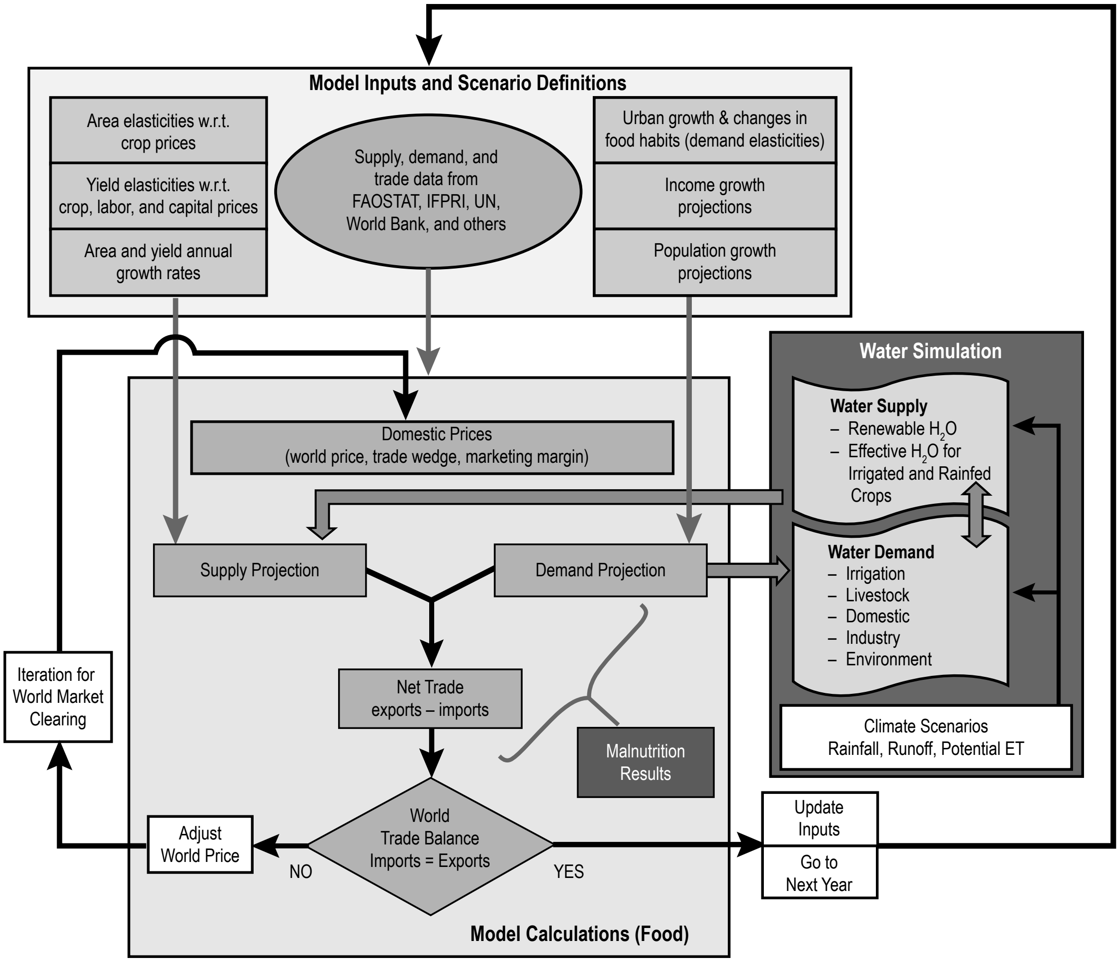
[1] NCAR and CSIRO AR4 data were downscaled by Kenneth Strzepek and colleagues at the MIT's Center for Global Change Science. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

FIGURE 1. THE IMPACT 2009 MODELING FRAMEWORK



Source: Rosegrant et al. 2001.

with no gradual speedup in climate change. The effect of this assumption is to underestimate negative effects from climate variability.

Figure 2 and Figure 3 show the change in average maximum temperature between 2000 and 2050 for the CSIRO and NCAR scenarios. Figure 4 and Figure 5 show changes in average precipitation. In each set of figures the legend colors are identical; i.e., a specific color represents the same change in temperature or precipitation across the two scenarios. A quick glance at these figures shows the substantial differences that exist across these two climate scenarios. For example the NCAR scenario has substantially higher average maximum temperatures than does CSIRO. The CSIRO scenario has substantial precipitation declines in the western Amazon while NCAR shows declines in the eastern Amazon. These figures illustrate qualitatively the range of potential climate outcomes with current climate modeling capabilities and thus an indication of the uncertainty in climate change impacts.

2.2 CROP MODELING

DSSAT provides a common data interfaces to several extremely detailed process models of the daily development of different crop varieties from planting to

FIGURE 2. CHANGE IN AVERAGE MAXIMUM TEMPERATURE, 2000–50, CSIRO

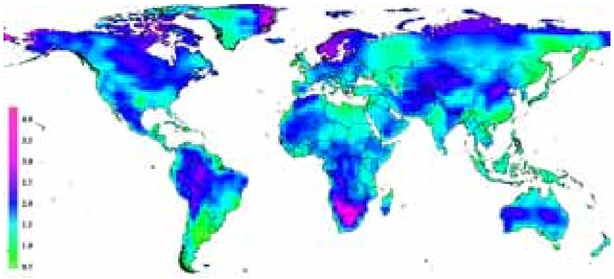


FIGURE 3. CHANGE IN AVERAGE MAXIMUM TEMPERATURE, 2000–50, NCAR

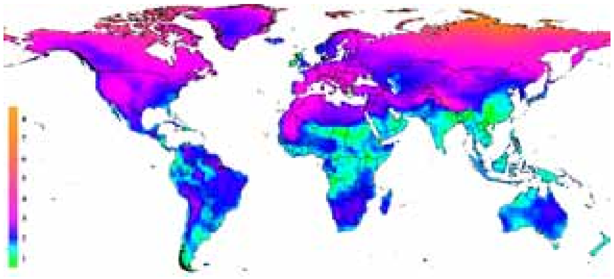


FIGURE 4. CHANGE IN PRECIPITATION, 2000–50, CSIRO

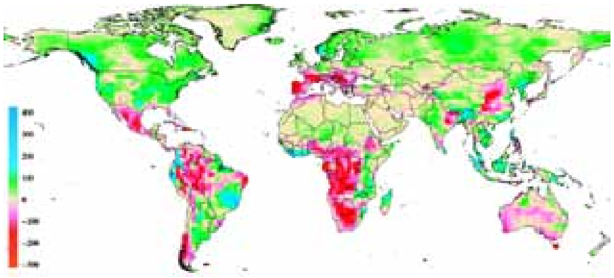
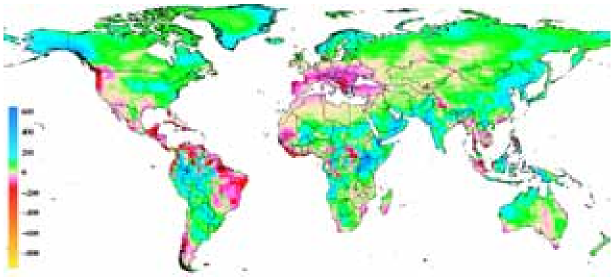


FIGURE 5. CHANGE IN PRECIPITATION, 2000–50, NCAR



Source: Authors' data.

harvest-ready. The system requires daily weather data, including maximum and minimum temperature, solar radiation, and precipitation, a description of the soil physical and chemical characteristics of the field, and crop management, including crop, variety, planting date, plant spacing, and inputs such as fertilizer and irrigation. For this report, five crops—rice, wheat, maize, soybeans, and groundnuts—are directly modeled with DSSAT. All other crops in the IMPACT model are mapped to one or more of these crops based on similarity in photosynthetic metabolic pathways.

Not all of the data needed for DSSAT are readily available, so various approximation techniques were developed, as described in the Annex. DSSAT is run at 0.5 degree intervals for the locations where the SPAM data set says the crop is currently grown. The results from this analysis are then aggregated to the IMPACT FPU level as described below.

2.3 THE IMPACT2009 MODEL[2]

The IMPACT model was initially developed at the International Food Policy Research Institute (IFPRI) to project global food supply, food demand, and food security to 2020 and beyond (M.W. Rosegrant, S. Msangi, C. Ringler, T.B. Sulser, T. Zhu and S.A. Cline, 2008). It is a partial equilibrium agricultural model with 32 crop and livestock commodities, including cereals, soybeans, roots and tubers, meats, milk, eggs, oilseeds, oilcakes and meals, sugar, and fruits and vegetables. IMPACT has 115 country (or in a few cases country aggregate) regions, within each of which supply, demand, net trade, and prices for agricultural commodities are determined. Large countries are further divided into major river basins. The result, portrayed in Figure 6, is 281 discrete locations, called food production units (FPUs). The model links the various countries and regions through

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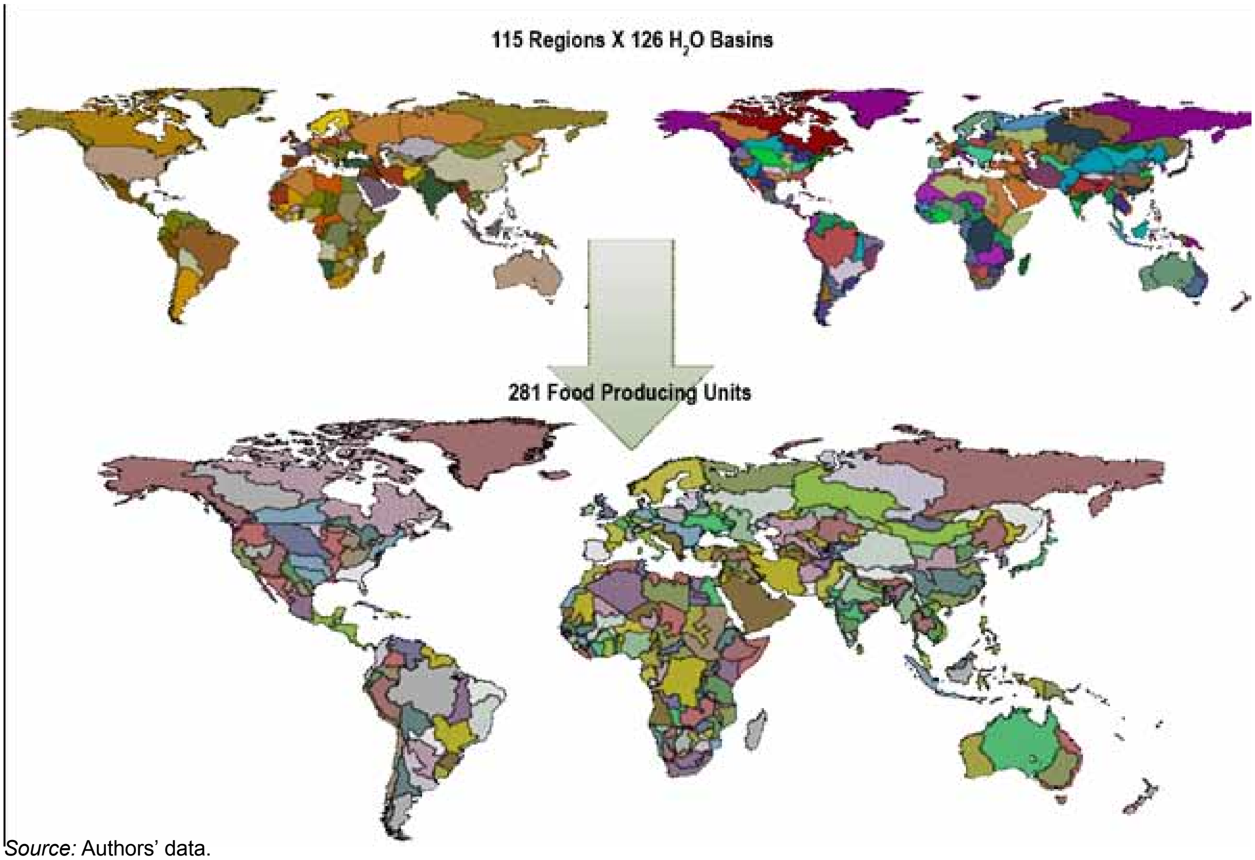
[2] Rosegrant et al. (2008) provides technical details on the IMPACT model.

FIGURE 6. IMPACT MODEL UNITS OF ANALYSIS, THE FOOD PRODUCTION UNIT (FPU)



Source: Authors' data.

international trade using a series of linear and nonlinear equations to approximate the underlying production and demand relationships. World agricultural commodity prices are determined annually at levels that clear international markets. Growth in crop production in each country is determined by crop and input prices, exogenous rates of productivity growth and area expansion, investment in irrigation, and water availability. Demand is a function of prices, income, and population growth and contains four categories of commodity demand—food, feed, biofuels feedstock, and other uses.

2.4 MODELING CLIMATE CHANGE IN IMPACT

Climate change effects on crop productivity enter into the IMPACT model by affecting both crop area and yield. For example, yields (*YC*) are altered through the intrinsic yield growth coefficient, gy_{tni}, in the yield equation (1) as well as the water availability coefficient (*WAT*) for irrigated crops. See Table 24 at the end of the Annex for intrinsic growth coefficients for selected crops. These rates depend on crop, management system, and location. For most crops, the average is about 1 percent per year from effects that are not modeled. But in some countries the growth is assumed to be negative, while in others it is as high as 5 percent per year for some years.

$$YC_{tni} = \beta_{tni} \times (PS_{tni})^{\gamma_{iin}} \times \prod_k (PF_{tnk})^{\gamma_{ikn}} \times (1 + gy_{tni}) - \Delta YC_{tni}(WAT_{tni}) \qquad (1)$$

We generate relative climate change productivity effects by calculating location-specific yields based on DSSAT results for 2000 and 2050 climate as described above and then construct a set of yield growth rate changes cause by climate change. These rate changes are then used to alter gy_{tni}. Rainfed crops react to changes in precipitation and temperature as modeled in DSSAT. For irrigated crops, the effect of temperature is derived from the DSSAT results and water stress effects are captured in the hydrology model built into IMPACT, increasing the value of *WAT* in equation (1).

One of the more significant challenges for this research is spatial aggregation. FPUs are large areas. For example, the Ganges FPU in India is the entire length of the Ganges River in India. Within an FPU, there can be large variation in climate and agronomic characteristics. A major challenge was to come up with an aggregation scheme to take outputs from the crop modeling process to the IMPACT FPUs. The process used starts with the SPAM data set, with a spatial resolution of 5 arc-minutes (approximately 10 km at the equator) that corresponds to the crop/management combination. The physical area in the SPAM data set is then used as the weight to find the area-weighted average yield across each FPU. This is done for each climate scenario including the no-climate-change baseline. The ratio of the area-weighted average yield in 2050 to the no-climate-change yield is used to adjust the yield growth rate in equation (1) to reflect the effects of climate change.

In some cases the simulated changes in yields from climate change are large and positive. This usually has one of two causes; starting from a low base (which can be common in marginal production areas) and unrealistically large effects of CO_2 fertilization. To avoid these artifacts, we place a 20 percent cap on yield increases over the no-climate-change amount at the pixel level.

Harvested areas in the IMPACT model are also affected by climate change. In any particular FPU, land may become more or less suitable for a crop and will impact the intrinsic area growth rate ga_{ini} in the area growth calculation. Water availability from the hydrology model will affect the *WAT* variable for irrigated crops as it does with yields.

$$AC_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} (PS_{tnj})^{\varepsilon_{ijn}} \times (1 + ga_{tni}) - \Delta AC_{tni}(WAT_{tni}) \qquad (2)$$

Crop calendar changes due to climate change cause two distinct issues. When the crop calendar in an area changes so that a crop that was grown in 2000 can no longer be grown in 2050, we implement an adjustment to ga_{tni} that will bring the harvested area to zero by 2050. However, when it becomes possible to grow a crop in 2050 where it could not be grown in 2000, we do not add this new area. For example, the growing season in parts of Ontario, Canada is too short for maize in 2000 but adequate in 2050. Because we do not include this added area in 2050 our estimates of future production are biased downward somewhat. The effect is likely to be small, however, as new areas have other constraints on crop productivity, in particular soil characteristics.

3. MODELING RESULTS

The results of our analysis are reported in three parts—the biological effects of climate change on crop yields, the resulting impacts on economic outcomes including prices, production, consumption, trade, calorie availability and child malnutrition, and finally the costs of adaptation to climate change.

3.1 THE EFFECTS OF CLIMATE CHANGE ON YIELDS

Climate change alters temperature and precipitation patterns as shown in Figure 2 to Figure 5. These changes have both a direct effect on crop production and indirect effects through changes in irrigation water availability and evapotranspiration potential. In this section, we report on the direct effects on rainfed yields of changing temperature and precipitation, irrigation yields through temperature effects alone, and the indirect effects of water availability through irrigation-related changes in water availability.

A particular challenge is how to include the effects of CO_2 fertilization. Plants produce more vegetative matter as atmospheric concentrations of CO_2 increase. The effect depends on the nature of the photosynthetic process used by the plant species. So-called C3 plants use CO_2 less efficiently than C4 plants so C3 plants are more sensitive to higher concentrations of CO_2. It remains an open question whether these laboratory results translate to actual field conditions. A recent report on field experiments on CO_2 fertilization (Stephen P. Long et al., 2006), finds that the effects in the field are approximately 50 percent less than in experiments in enclosed containers. And another report (Jorge A. Zavala et al., 2008) finds that higher levels of atmospheric CO_2 increase the susceptibility of soybean plants to the Japanese beetle and maize to the western corn rootworm. So the actual, field benefits of CO_2 fertilization remain uncertain.

DSSAT has an option to include CO_2 fertilization effects at different levels of atmospheric concentration. To capture the uncertainty in actual field effects, we simulate two levels of atmospheric CO_2 in 2050—369 ppm (the level in 2000) and 532 ppm, the levels in 2050 used in the A2 scenario GCM runs. The results with 369 ppm are called the no-CO_2 fertilization; with 532, the results are called with-CO_2 fertilization. For most tables, we report only no-CO_2 fertilization results under the assumption that this is the most likely outcome in farmers' fields.

3.1.1 Direct climate change effects on rainfed and irrigated yields

Table 1 reports the statistics and Figure 7 presents figures that show the direct biological effects of the two climate change scenarios on yields with and without CO_2 fertilization on the five crops we model with DSSAT. Rainfed crops are modeled with both water and temperature stress effects. For irrigated crops, only temperature stress is included here. Water scarcity effects on irrigation are dealt with in a later section.

For most crops, yield declines predominate when no CO_2 fertilization is allowed. Irrigated and rainfed wheat and irrigated rice are especially hard hit. The East Asia and the Pacific region combines both China, which is temperate for the most part, and Southeast Asia, which is tropical, so the differential effects of climate change in these two climate zones are masked. In China, some crops fare reasonably well, because higher future temperatures are favorable in locations where current temperatures are at the low end of the crop's optimal temperature. India and other parts of South Asia are particularly hard hit by climate change. With the CO_2 fertilization effect allowed, yields decline less and in many locations some yield increases occur relative to 2000 climate. However, rainfed maize and irrigated and rainfed wheat still see substantial areas of reduced yields. Sub-Saharan Africa sees mixed results with small declines or increases in maize yields and large negative effects on rainfed wheat. The Latin America and Caribbean region has mixed yield effects, with some crops up slightly and some down.

TABLE 1. YIELD CHANGES BY CROP AND MANAGEMENT SYSTEM UNDER CURRENT CLIMATE AND TWO CLIMATE CHANGE SCENARIOS WITH AND WITHOUT CO_2 FERTILIZATION EFFECTS (% CHANGE FROM YIELDS WITH 2000 CLIMATE)

Region	*CSIRO NoCF*	*NCAR NoCF*	*CSIRO CF*	*NCAR CF*
Maize, irrigated				
East Asia and the Pacific	–1.3	–2.6	–0.8	–1.9
Europe and Central Asia	0.0	–1.3	0.1	–1.2
Latin America and the Caribbean	–2.8	–3.0	–2.3	–2.5
Middle East and North Africa	0.1	–1.0	–0.4	–1.1
South Asia	–6.4	–5.5	–4.4	–3.6
Sub–Saharan Africa	0.3	0.6	0.5	0.8
Developing Countries	–2.0	–2.8	–1.4	–2.1
Developed Countries	–1.2	–8.7	–1.2	–8.6
World	–0.8	–5.6	–0.6	–5.2
Maize, rainfed				
East Asia and the Pacific	1.5	–3.9	3.7	–2.0
Europe and Central Asia	25.0	3.7	32.8	12.4
Latin America and the Caribbean	–0.4	–1.9	2.2	0.4
Middle East and North Africa	58.6	–46.7	61.8	–46.3
South Asia	–2.9	–7.8	0.2	–4.9
Sub–Saharan Africa	–2.4	–4.6	–0.8	–2.7
Developing Countries	0.2	–2.9	2.6	–0.8
Developed Countries	0.6	–5.7	9.5	2.5
World	1.0	–3.4	5.3	0.5
Rice, irrigated				
East Asia and the Pacific	–13.0	–19.8	4.4	–1.1
Europe and Central Asia	–4.1	–15.1	15.0	5.7
Latin America and the Caribbean	–6.4	–0.8	–1.2	7.0
Middle East and North Africa	–13.3	–29.5	1.7	–14.4
South Asia	–15.5	–17.5	2.5	1.4
Sub–Saharan Africa	–11.4	–14.1	5.7	2.4
Developing Countries	–14.4	–18.5	2.4	–0.5

(Continued on next page)

TABLE 1. *(continued)*

Region	*CSIRO NoCF*	*NCAR NoCF*	*CSIRO CF*	*NCAR CF*
Developed Countries	–3.5	–5.5	10.5	9.0
World	–13.8	–17.8	2.8	–0.0
Rice, rainfed				
East Asia and the Pacific	–4.5	–5.8	2.5	1.8
Europe and Central Asia	49.8	–1.0	61.3	–6.1
Latin America and the Caribbean	5.3	–1.8	12.7	6.7
Middle East and North Africa	0	0	0	0.0
South Asia	0.1	2.6	8.5	10.2
Sub–Saharan Africa	0.1	–0.5	8.1	7.3
Developing Countries	–1.3	–1.4	6.5	6.4
Developed Countries	17.3	10.3	23.4	17.8
World	–1.3	–1.4	6.5	6.4
Soybean, irrigated				
East Asia and the Pacific	–8.2	–13.4	9.1	3.6
Europe and Central Asia	31.9	30.1	32.9	30.5
Latin America and the Caribbean	–1.2	–2.5	19.5	18.2
Middle East and North Africa	–4.2	–14.0	5.6	–5.0
South Asia	–9.5	–11.5	12.0	10.3
Sub–Saharan Africa	4.6	5.0	17.8	17.8
Developing Countries	–8.0	–12.3	10.3	5.8
Developed Countries	2.5	–2.7	15.0	9.0
World	–0.4	–5.4	13.7	8.0
Soybean, rainfed				
East Asia and the Pacific	–3.6	–8.6	17.0	11.5
Europe and Central Asia	25.5	5.9	37.0	5.9
Latin America and the Caribbean	–2.6	4.2	19.1	19.1
Middle East and North Africa	17.5	–84.2	26.0	–76.4
South Asia	–13.8	–13.6	4.4	7.9
Sub–Saharan Africa	–3.5	–5.8	19.1	17.8
Developing Countries	–2.3	1.7	19.5	18.0
Developed Countries	14.1	6.6	19.5	15.1
World	1.1	2.3	18.0	16.3
Wheat, irrigated				
East Asia and the Pacific	–2.7	–7.1	3.7	–0.6
Europe and Central Asia	–9.4	–19.8	–3.3	–14.7
Latin America and the Caribbean	0.3	–5.6	6.5	0.9
Middle East and North Africa	–12.8	–19.7	–5.8	–13.4
South Asia	–47.1	–53.9	–38.3	–45.8
Sub–Saharan Africa	0.7	1.4	7.3	9.7
Developing Countries	–28.3	–34.3	–20.8	–27.2
Developed Countries	–5.7	–4.9	–1.3	–0.1
World	–25.6	–31.1	–18.5	–24.4

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TABLE 1. *(continued)*

Region	*CSIRO NoCF*	*NCAR NoCF*	*CSIRO CF*	*NCAR CF*
Wheat, rainfed				
East Asia and the Pacific	–14.8	–16.1	–5.4	–9.2
Europe and Central Asia	–0.3	–1.8	8.5	8.0
Latin America and the Caribbean	2.3	4.2	12.2	11.8
Middle East and North Africa	–2.6	–8.1	8.8	2.0
South Asia	–44.4	–43.7	–28.9	–28.0
Sub–Saharan Africa	–19.3	–21.9	–11.2	–15.9
Developing Countries	–1.4	–1.1	9.3	8.5
Developed Countries	3.1	2.4	9.7	9.5
World	1.0	0.8	9.7	9.1
Groundnut, irrigated				
East Asia and the Pacific	–11.1	–13.7	3.6	1.2
Europe and Central Asia	–34.4	–50.3	–22.6	–41.5
Latin America and the Caribbean	0.0	0.0	0.0	0.0
Middle East and North Africa	–11.6	–28.5	4.3	–15.6
South Asia	–6.7	–10.6	9.4	5.0
Sub–Saharan Africa	–11.5	–11.3	3.9	4.2
Developing Countries	–10.0	–13.1	5.2	2.0
Developed Countries	–4.6	–10.7	12.1	5.0
World	–9.2	–12.7	6.2	2.5
Groundnut, rainfed				
East Asia and the Pacific	–5.1	–6.5	11.3	9.7
Europe and Central Asia	0.0	0.0	0.0	0.0
Latin America and the Caribbean	0.9	7.1	18.1	17.9
Middle East and North Africa	–20.5	23.6	–11.8	23.6
South Asia	–8.1	–8.9	9.1	6.7
Sub–Saharan Africa	–4.1	–8.6	14.2	8.8
Developing Countries	–4.7	–7.9	12.9	8.6
Developed Countries	–18.3	–5.0	2.7	11.6
World	–4.9	–7.9	12.7	8.7

Source: Authors' estimates. The results in this table are derived by growing a crop in DSSAT at 0.5 degree intervals around the world. At each location, the yield is calculated with 2000 climate, existing soil conditions, and rates of nitrogen application assumed relevant for that country. Then 2050 climate data replace the 2000 climate data and the crop is grown again. The values reported in this table are the area-weighted averages of these two figures. The first two columns report results without CO_2 fertilization; the last two columns with CO_2 fertilization.

3.1.2 *Indirect effects from climate change: Water stress for irrigated crops*

Climate change will have a direct impact on regional hydrology and therefore affect agricultural production though water availability for irrigated crops. In addition, higher temperatures under climate change will for the most part increase evapotranspiration requirements of crops. The impacts of climate change on effective rainfall, potential and actual evapotranspiration and runoff

FIGURE 7. YIELD CHANGES BY CROP AND MANAGEMENT SYSTEM UNDER CURRENT CLIMATE AND TWO CLIMATE CHANGE SCENARIOS WITH AND WITHOUT CO_2 FERTILIZATION EFFECTS (% CHANGE FROM YIELDS WITH 2000 CLIMATE)

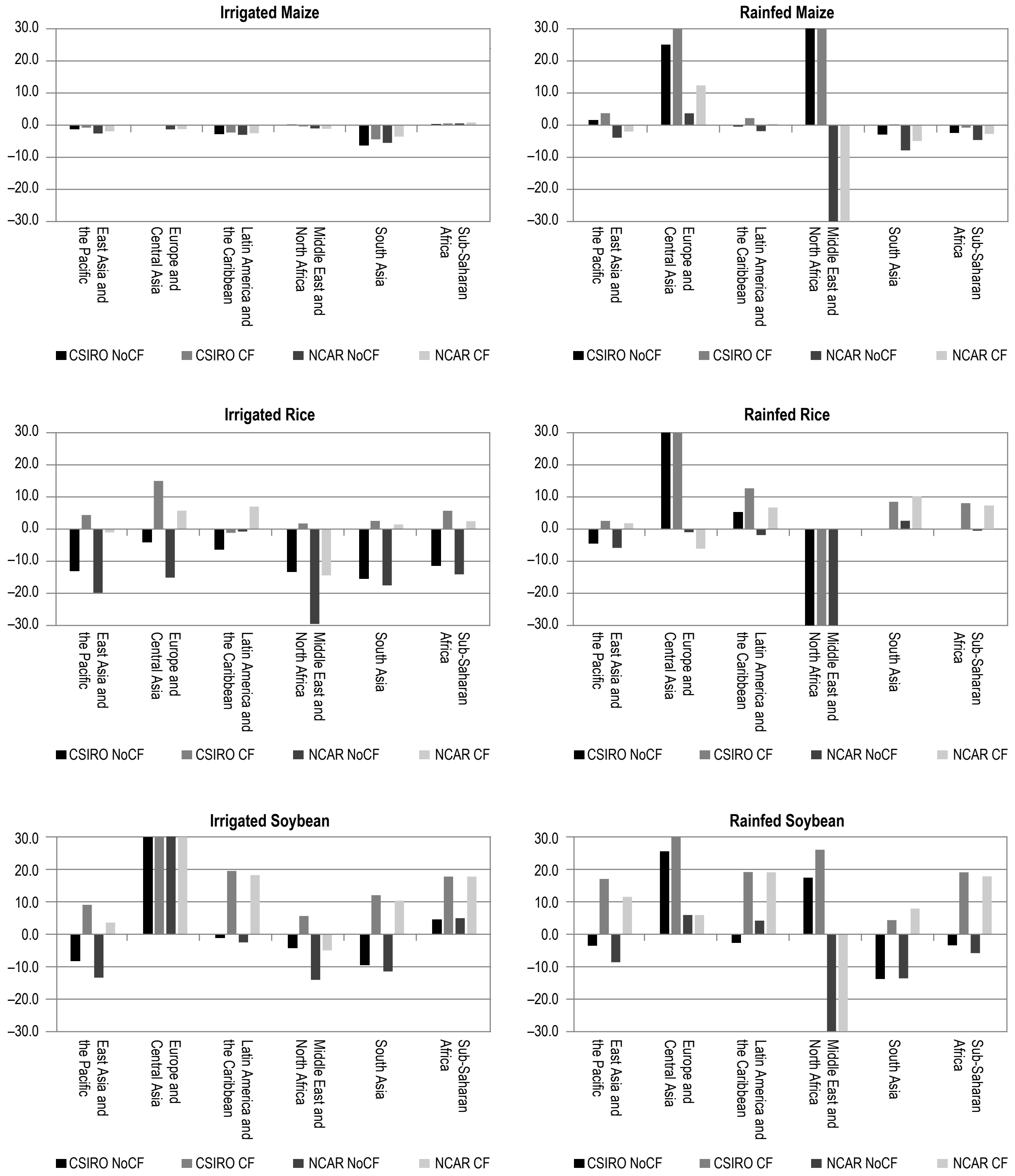

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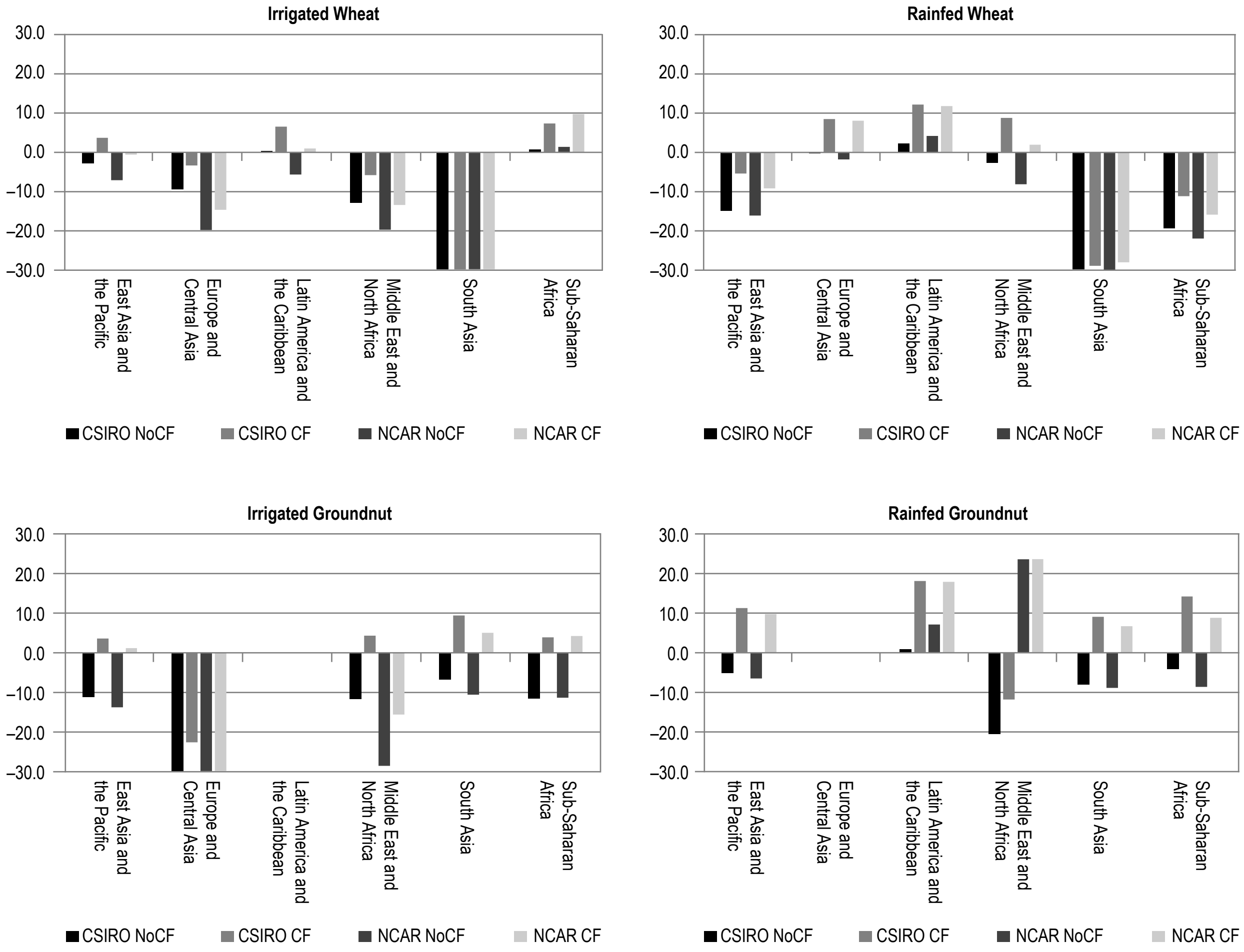
FIGURE 7. *(continued)*



Source: Authors' data.

(or internal renewable water) were analyzed for the two climate change scenarios using the global hydrological model linked with IMPACT.

Table 3 shows water availability and use results. For each region we report internal renewable water (IRW), irrigation water requirements, actual consumption and the ratio of consumption to requirements, called the irrigation water supply reliability index (IWSR).

IRW is the water (surface runoff plus net groundwater recharge) available from precipitation falling on a study area such as a river basin or a country. In the NCAR results, all regions see increased IRW in 2050. With CSIRO, IRW increase is less than with NCAR; the Middle East & North Africa and Sub-Saharan Africa regions both see reductions of about 4 percent.

Irrigation water requirement is the amount of water needed to grow irrigated crops without water stress. Table 2 reports irrigation water requirements in 2000 and 2050 under current climate, and the percent changes in 2050 under the two climate change scenarios relative to 2050 requirements under current climate. Changes in irrigation water requirements from 2000 to 2050 reflect the increased demand for food, changes in irrigated area, and changes in irrigation water use efficiency. Changes in 2050 irrigation water requirements

TABLE 2. WATER AVAILABILITY AND USE UNDER CURRENT CLIMATE, AND PERCENT CHANGES UNDER TWO CLIMATE CHANGE SCENARIOS IN 205

	Water availability and use in 2000, current climate (km3/yr)	*Water availability and use in 2050, no climate change (km3/yr)*	*Water availability and use change, 2000–2050, no climate change (%)*	*Water availability and use change, 2000–2050, NCAR relative to no climate change (%)*	*Water availability and use change, 2000–2050, CSIRO relative to no climate change (%)*
East Asia & Pacific					
Internal renewable water	9,248.0	9,248.0	0	8.2	4.3
Irrigation water requirement	345.2	277.4	–19.7	5.3	1.2
Irrigation water consumption	238.6	219.0	–8.2	5.1	1.5
IWSR (%)	69.1	78.9		15.1	–12.7
Europe & Central Asia					
Internal renewable water	4,916.0	4,916.0	0	18.0	8.8
Irrigation water requirement	77.9	70.1	–9.9	–11.0	0.6
Irrigation water consumption	72.6	65.7	–9.6	–6.7	–3.8
IWSR (%)	93.3	93.6		–4.1	–5.7
Latin America & Caribbean					
Internal renewable water	13,232.0	13,232.0	0	10.7	0.6
Irrigation water requirement	103.0	108.9	5.8	–13.3	8.9
Irrigation water consumption	96.1	103.4	7.6	–0.3	–4.9
IWSR (%)	93.3	94.9		1.8	0.3
Middle East & North Africa					
Internal renewable water	179.0	179.0	0	11.5	–3.6
Irrigation water requirement	89.3	101.3	13.4	2.8	–6.5
Irrigation water consumption	85.9	97.4	13.4	–1.4	–11.8
IWSR (%)	96.2	96.1		0.0	1.2
South Asia					
Internal renewable water	1,788.0	1,788.0	0	14.0	2.0
Irrigation water requirement	489.1	515.3	5.4	–2.6	0.9
Irrigation water consumption	367.1	386.5	5.3	–0.9	1.3
IWSR (%)	75.1	75.0		2.8	–1.2
Sub–Saharan Africa					
Internal renewable water	3,762.0	3,762.0	0	6.5	–3.9
Irrigation water requirement	38.3	51.0	33.2	–8.5	–9.7
Irrigation water consumption	37.9	50.3	32.6	–8.5	–8.5
IWSR (%)	99.0	98.5		–0.5	–0.4
Developed					
Internal renewable water	7,479.0	7,479.0	0	10.9	7.3
Irrigation water requirement	103.8	107.6	3.8	5.3	1.2
Irrigation water consumption	102.4	106.0	3.5	5.1	1.5
IWSR (%)	98.7	98.5		–0.2	0.3
Developing					
Internal renewable water	33,101.0	33,101.0	0	10.8	2.4
Irrigation water requirement	1,142.8	1,124.1	–1.6	–11.0	0.6
Irrigation water consumption	898.3	922.1	2.7	–6.7	–3.8
IWSR (%)	78.6	82.0		4.9	–4.4

Source: Authors' estimates.

Note: The values in the last two columns are the percent change in the row variable relative to an outcome with no climate change. For example, in the East Asia and Pacific region, IWSR is 78.9 percent in 2050 without climate change. With the NCAR scenario, the ISWR increases to 90.8 percent, an increase of 15.1 percent.

under climate change scenarios are due to changes in crop evapotranspiration potential from higher temperatures, changes in effective rainfall, and changes in crop irrigated harvested areas as a result of supply effects from changes in agricultural commodity prices.

Irrigation water consumption is the water actually used by irrigated crops. The consumption value is always smaller than the requirements value because it is impossible in practice to deliver precisely the correct amount of water. The ratio of consumption to requirements is called irrigation water supply reliability (IWSR). The smaller the ratio, the greater the water stress on irrigated crop yields.

Across the group of developing countries, IWSR improves under the NCAR GCM and worsens under the CSIRO GCM. However regional effects of climate change vary. Reliability improves slightly for Latin America and the Caribbean and for the Middle East and North Africa. For Sub-Saharan Africa reliability worsens slightly under both scenarios. In East Asia and the Pacific and South Asia, reliability increases under the NCAR scenario but declines under the CSIRO scenario.

Yield reductions of irrigated crops due to water stress are directly estimated in IMPACT using empirical relationships developed by FAO (Doorenbos and Kassam, 1979), taking into account the growing demand for water outside agriculture as well as agricultural demands. The results are shown in Table 3. Both NCAR and CSIRO scenarios result in more precipitation over land than with no climate change in most parts of the world, but the CSIRO scenario has relatively small increases. Combined with growing demand for water outside of agriculture the consequence is often substantial yield decline. For example, in East Asia and the Pacific, with no climate change, the combined effects of non-agricultural demand growth and increased irrigated area result in an average 4.8 percent decline in irrigated rice yields. With the NCAR scenario, that decline is only 1.2 percent. However, with the drier CSIRO scenario the irrigated yield loss is 6.7 percent. Irrigated rice, wheat, and maize yield losses are all large with CSIRO for East Asia and the Pacific. South Asia yields for all crops see large yield declines under both scenarios. In Sub-Saharan Africa, irrigated maize yields decline under *both* scenarios but the CSIRO effects are especially large. Latin America and the Caribbean yields are relatively unaffected, although this is in part due to the small amount of irrigated production in that region.

TABLE 3. YIELD CHANGES FOR IRRIGATED CROPS DUE TO WATER STRESS UNDER CURRENT CLIMATE AND TWO CLIMATE CHANGE SCENARIOS (% CHANGE FROM 2000 YIELDS)

	2050		
Region	*No climate change*	*NCAR*	*CSIRO*
Rice			
East Asia & Pacific	–4.8	–1.2	–6.7
Europe & Central Asia	–1.9	–3.2	–3.3
Latin America & Caribbean	–0.1	–0.1	–0.1
Middle East & North Africa	–8.3	–3.3	–3.2
South Asia	–8.9	–6.3	–8.1
Sub-Saharan Africa	–0.3	–0.4	–0.3
Developed	0.0	0.0	0.0
Developing	–6.3	–3.5	–7.0
Wheat			
East Asia & Pacific	–21.9	–3.1	–32.6
Europe & Central Asia	–0.9	–1.1	–0.5
Latin America & Caribbean	–0.2	–2.1	–0.2
Middle East & North Africa	–1.4	–5.6	–0.5
South Asia	–14.4	–17.4	–14.8
Sub-Saharan Africa	–0.3	–0.8	–0.6
Developed	–1.7	0.0	–1.7
Developing	–11.6	–4.1	–15.3
Maize			
East Asia & Pacific	–9.0	–8.7	–19.9
Europe & Central Asia	–0.8	–0.4	–0.8
Latin America & Caribbean	–4.1	–0.1	–3.0
Middle East & North Africa	–7.2	–1.5	–5.5
South Asia	–20.0	–13.9	–21.1
Sub-Saharan Africa	–9.0	–8.7	–19.9
Developed	–0.1	–1.4	0.0
Developing	–8.0	–9.1	–14.0

Source: Authors' estimates.

TABLE 4. POPULATION AND INCOME GROWTH ASSUMPTIONS

	2000 (million)	*2050 (million)*	*Average annual growth rate (%)*	*2000 (constant 2000 US$)*	*2050 (constant 2000 US$)*	*Average annual growth rate (%)*
		Population			*Per capita income*	
South Asia	1,361	2,306	1.05	462	3,490	4.04
East Asia and Pacific	1,825	2,218	0.39	906	10,344	4.87
Europe and Central Asia	488	456	–0.14	2,600	17,269	3.79
Latin America and the Caribbean	513	754	0.77	3,999	16,091	2.78
Middle East and North Africa	259	453	1.12	1,597	5,908	2.62
Sub-Saharan Africa	666	1,732	1.91	563	1,247	1.59
Developed	948	1,163	0.41	28,629	79,951	2.05
Developing	5,136	7,961	0.88	1,333	7,362	3.42
World	6,084	9,124	0.81	5,588	16,612	2.18

Source: EACC Study estimates.

3.2 CLIMATE CHANGE IMPACTS ON AGRICULTURE AND HUMAN WELL-BEING

The direct and indirect effects of climate change on agriculture play out through the economic system, altering prices, production, productivity investments, food demand, food consumption and ultimately human well-being.

For this study, a common set of income and population growth assumptions were used. Table 4 provides an overview of these assumptions. Population growth is assumed to be highest in Sub-Saharan Africa at 1.91 percent per annum. Per capita income growth is assumed to be highest in East Asia and the Pacific at 4.87 percent per annum. Sub-Saharan Africa has the lowest growth per capita income growth at 1.59 percent per annum.

3.2.1 Prices and production

World prices are a useful single indicator of the effects of climate change on agriculture. Table 5 shows the prices effects of various permutations of climate change, with and without the CO_2 fertilization effect. Figure 8 show world price effects for the major grains respectively, assuming no CO_2 fertilization effect.

TABLE 5. WORLD PRICES OF SELECTED CROPS AND LIVESTOCK PRODUCTS (US$/METRIC TON)

		2050				
		No climate change	*NCAR No CF*	*CSIRO No CF*	*NCAR CF effect*	*CSIRO CF effect*
Agricultural products	*2000*	*US$/metric ton (% increase over 2000)*			*% change from 2050 No CF results*	
Rice	190	307 (61.6)	421 (121.6)	406 (113.7)	–17.0	–15.1
Wheat	113	158 (39.8)	334 (195.6)	307 (171.7)	–11.4	–12.5
Maize	95	155 (63.2)	235 (147.4)	240 (152.6)	–11.2	–12.6
Soybeans	206	354 (71.8)	394 (91.3)	404 (96.1)	–60.6	–62.2

(Continued on next page)

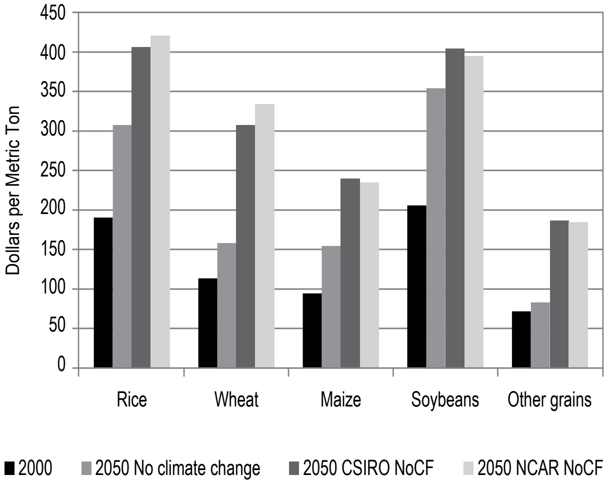
TABLE 5. *(continued)*

		2050				
		No climate change	*NCAR No CF*	*CSIRO No CF*	*NCAR CF effect*	*CSIRO CF effect*
Agricultural products	*2000*	*US$/metric ton (% increase over 2000)*			*% change from 2050 No CF results*	
Beef	1,925	2,556 (32.8)	3,078 (59.9)	3,073 (59.6)	–1.3	–1.5
Pork	911	1,240 (36.1)	1,457 (59.9)	1,458 (60.0)	–1.3	–1.5
Poultry	1,203	1,621 (34.7)	1,968 (63.6)	1,969 (63.7)	–1.9	–2.1

Source: Authors' estimates.

Notes: Prices are in 2000 US$. Numbers in parantheses are percent increases over 2000. The last two columns in this table report the percentage difference between the price in 2050 with and without the CO_2 fertilization effect. For example, with the NCAR scenario, assuming CO_2 fertilization is effective in the field results in a 17.0 percent reduction in the 2050 world rice price relative to the level reached with no CO_2 fertilization. The decline in prices of livestock products with CO_2 fertilization reflects the reduced cost of feed.

FIGURE 8. WORLD PRICES OF MAJOR GRAINS (2000 US$)



Source: Authors' estimates.

With no climate change, world prices for the most important agricultural crops—rice, wheat, maize, and soybeans will increase between 2000 and 2050, driven by population and income growth and biofuels demand. Even with no climate change, the price of rice would rise by 62 percent, maize by 63 percent, soybeans by 72 percent and wheat by 39 percent. Climate change results in additional price increases—a total of 32 to 37 percent for rice, 94 to 111 percent for wheat, 52 to 55 percent for maize and 11 to 14 percent for soybeans. If CO_2 fertilization is effective in farmers' fields, these price increases are 11 percent to 17 percent smaller for rice, wheat, and maize and over 60 percent smaller for soybeans.

Livestock are not directly affected by climate change in the IMPACT model but the effects of higher feed prices caused by climate change pass through to livestock, resulting in higher meat prices. For example, beef prices are 33 percent higher by 2050 with no climate change and 60 percent higher with climate change and no CO_2 fertilization of crops. With CO_2 fertilization, crop-price increases are less so the beef price increase is about 1.5 percent less than with no CO_2 fertilization.

Table 6 combines the biophysical effects of climate change on yields with the indirect effects from water stress in irrigated crops and autonomous adjustments to yield due to price effects directly on yields and on productivity growth.

Table 7 reports crop production effects of climate change, accounting for both the changes in yield shown in Table 6, and changes in crop area induced by climate change. For each crop the first row is 2000 production and the second is 2050 production with no climate change. The third to fifth rows are the difference between the scenario with climate change production and no-climate-change production in 2050. For

TABLE 6. COMBINED BIOPHYSICAL AND ECONOMIC YIELD EFFECTS FROM CLIMATE CHANGE, NO CO_2 FERTILIZATION

	South Asia	*East Asia and the Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developed Countries*	*Developing Countries*	*World*
Rice									
2000 (kg/ha)	2,068	3,054	2,077	2,438	4,076	1,089	4,437	2,549	2,606
2050 No CC (kg/ha)	3,175	3,859	4,272	3,568	6,246	2,269	6,226	3,486	3,556
NCAR (%)	–11.1	–5.2	2.0	0.9	–6.0	–0.5	2.7	–7.1	–6.9
CSIRO (%)	–10.9	–8.1	–0.1	2.7	–15.5	–3.1	2.8	–8.8	–8.4
Wheat									
2000 (kg/ha)	2,503	3,782	2,075	2,463	1,680	1,827	3,375	2,468	2,726
2050 No CC (kg/ha)	5,559	5,476	4,186	3,941	3,753	3,353	5,329	4,596	4,778
NCAR (%)	–44.9	10.1	–6.5	2.3	3.9	–26.5	1.3	–14.1	–9.3
CSIRO (%)	–48.5	10.9	–15.1	4.8	–2.4	–30.5	–2.8	–18.0	–13.1
Maize									
2000 (kg/ha)	1,868	4,214	3,706	2,957	5,696	1,483	8,625	3,029	4,404
2050 No CC (kg/ha)	2,464	7,292	6,676	4,927	7,268	2,206	12,799	5,124	7,170
NCAR (%)	4.4	7.9	18.8	5.0	4.1	–1.7	5.4	4.7	9.8
CSIRO (%)	1.1	10.2	13.4	2.4	–1.5	0.1	–1.9	6.7	5.1
Millet									
2000 (kg/ha)	800	1,528	844	1,512	1,017	655	1,436	753	759
2050 No CC (kg/ha)	1,689	3,009	2,368	3,585	1,812	1,772	2,142	1,811	1,814
NCAR (%)	–0.7	10.9	3.5	7.5	–0.4	8.0	–0.1	6.8	6.8
CSIRO (%)	–2.7	8.7	4.1	6.6	1.6	6.6	–1.4	5.1	5.0
Sorghum									
2000 (kg/ha)	799	3,089	1,237	2,891	4,978	843	3,596	1,124	1,395
2050 No CC (kg/ha)	1,438	5,665	4,706	5,440	5,708	1,663	5,142	2,101	2,335
NCAR (%)	1.5	9.3	10.7	2.4	0.8	8.6	2.5	8.7	8.2
CSIRO (%)	–0.9	6.9	6.6	2.9	–0.4	5.8	–0.9	6.6	5.4

Source: Authors' estimates.

Note: The rows labeled "NCAR (% change)" and "CSIRO (% change)" indicate the percent change in yield due to climate change in 2050 relative to yields in 2050 without climate change. For example, South Asia rice yields were 2,068 kg/ha in 2000. With no climate change, South Asia rice yields are predicted to increase to 3,054 kg/ha in 2050. With the CSIRO scenario, South Asia rice yields predictions are 10.9 percent lower than with no climate change in 2050.

example Sub-Saharan agriculture maize production would increase by 45 percent with no climate change (from 37.1 mmt to 53.9 mmt). Relative to no climate change, the 2050 CSIRO climate results in a 9.6 percent decline in production.

The negative effects of climate change are especially pronounced in Sub-Saharan Africa and South Asia; all of the major crops have production declines (relative to the no climate change scenario) under the two GCMs. For East Asia and the Pacific, the results are mixed, and depend on both crop and GCM. Rice production effects are uniformly negative, while wheat and maize are mixed. Comparing the all- developed-country average to the all-developing country average, developing countries fare worse for almost all crops under both scenarios. One striking result is that maize production in developed countries increases substantially with climate change. This result is due entirely to increases in the U.S. Both GCMs show substantial precipitation increases in the U.S. Midwest allowing substantially higher biological yields. For other major producing areas, lower precipitation and higher temperatures mean lower yields. With increasing incomes and population, growth in demand for meat means higher consumption of maize for feed. The resulting higher maize prices induce further yield growth and area expansion in the US. Note that this result is driven by the choice of GCM. Other GCMs report lower precipitation in the US Midwest and would result in dramatically different scenario outcomes.

TABLE 7. CLIMATE CHANGE EFFECTS ON CROP PRODUCTION, NO CO_2 FERTILIZATION

	South Asia	*East Asia and the Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developed Countries*	*Developing Countries*	*World*
Rice									
2000 (mmt)	119.8	221.7	1.1	14.9	5.5	7.5	20.4	370.3	390.7
2050 No CC (mmt)	168.9	217.0	2.6	17.8	10.3	18.3	20.3	434.9	455.2
2050 No CC (%)	41.0	–2.1	143.0	19.9	88.0	145.6	–0.2	17.4	16.5
CSIRO (% change)	–14.3	–8.1	–0.2	–21.7	–32.9	–14.5	–11.8	–11.9	–11.9
NCAR (% change)	–14.5	–11.3	–0.8	–19.2	–39.7	–15.2	–10.6	–13.6	–13.5
Wheat									
2000 (mmt)	96.7	102.1	127.5	23.5	23.6	4.5	205.2	377.9	583.1
2050 No CC (mmt)	191.3	104.3	252.6	42.1	62.0	11.4	253.7	663.6	917.4
2050 No CC (%)	97.8	2.2	98.1	79.1	162.7	153.3	23.6	75.6	57.3
CSIRO (% change)	–43.7	1.8	–43.4	11.4	–5.1	–33.5	–7.6	–29.2	–23.2
NCAR (% change)	–48.8	1.8	–51.0	17.4	–8.7	–35.8	–11.2	–33.5	–27.4
Maize									
2000 (mmt)	16.2	141.9	38.0	80.1	8.2	37.1	297.9	321.3	619.2
2050 No CC (mmt)	18.7	264.7	62.7	143.1	13.1	53.9	505.1	556.2	1,061.3
2050 No CC (%)	15.4	86.5	65.0	78.7	59.8	45.3	69.6	73.1	71.4
CSIRO (% change)	–18.5	–12.7	–19.0	–0.3	–6.8	–9.6	11.5	–10.0	0.2
NCAR (% change)	–8.9	8.9	–38.3	–4.0	–9.8	–7.1	1.8	–2.3	–0.4
Millet									
2000 (mmt)	10.6	2.3	1.2	0.0	0.0	13.1	0.5	27.3	27.8

(Continued on next page)

TABLE 7. *(continued)*

	South Asia	*East Asia and the Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developed Countries*	*Developing Countries*	*World*
2050 No CC (mmt)	12.3	3.5	2.14	0.1	0.1	48.1	0.8	66.2	67.0
2050 No CC (%)	16.0	52.2	78.3			267.2	60.0	142.5	141.0
CSIRO (% change)	–19.0	4.2	–4.3	8.8	–5.5	–6.9	–3.0	–8.5	–8.4
NCAR (% change)	–9.5	8.3	–5.2	7.2	–2.7	–7.6	–5.6	–7.0	–7.0
Sorghum									
2000 (mmt)	8.4	3.1	0.1	11.4	1.0	19.0	16.9	43.0	59.9
2050 No CC (mmt)	9.6	3.4	0.4	28.0	1.1	60.1	20.9	102.6	123.5
2050 No CC (%)	14.3	9.7	300.0	145.6	10.0	216.3	23.7	138.6	106.2
CSIRO (% change)	–19.6	1.4	–2.7	2.3	0.3	–2.3	–3.1	–2.5	–2.6
NCAR (% change)	–12.2	6.7	–10.4	4.3	0.7	–3.0	–7.3	–1.5	–2.5

Source: Authors' estimates.

Note: The rows labeled "2050 No CC (% change)" indicate the percent change between production in 2000 and 2050 with no climate change. The rows labeled "CSIRO (% change)" and "NCAR (% change)" indicate the additional percent change in production in 2050 due to climate change relative to 2050 with no climate change. For example, South Asia sorghum production was 8.4 mmt in 2000. With no climate change, South Asia sorghum production is predicted to increase to 9.6 mmt in 2050, an increase of 13.9 percent. With the CSIRO scenario, South Asia sorghum production in 2050 is 19.6 percent lower than with no climate change in 2050 (7.72 mmt instead of 9.6 mmt); mmt = million metric tons.

3.2.2 Trade in agricultural commodities

As with the earlier studies, our simulations result in trade flow adjustments with climate change. Table 8 and Figure 9 report net cereal flows. With no climate change, developed-country net exports increase from 83.4 mmt to 105.8 mmt between 2000 and 2050, an increase of 27 percent. Developing-country net imports mirror this change. With the NCAR results and no CO_2 fertilization, developed-country net exports increase slightly (0.9 mmt) over no climate change. With the drier CSIRO scenario, on the other hand, developed-country net exports increase by 39.9 mmt.[3]

Regional results show important differences in the effects of climate change on trade and the differential effects of the three scenarios. For example, South Asia is a small net exporter in 2000 and becomes a net importer of cereals in 2050 with no climate change. Both climate change scenarios result in substantial increases in South Asian net imports relative to no climate change. The East Asia and Pacific region is a net importing region in 2000 and imports grow substantially with no climate change. Depending on climate change scenario, this region either has slightly less net imports than with the no-climate-change scenario or becomes a net exporter. In Latin America and the Caribbean, the 2050 no-climate-change scenario is increased imports relative to 2000 but the CSIRO and NCAR climate scenarios result in smaller net imports in 2050 than in 2000.

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[3] The results with CO_2 fertilization increase developed-country exports by an additional 12 to 18 percent relative to no climate change.

The effects of climate change on trade flow values are even more dramatic than on production because of climate change effects on prices. Without climate change, the value of developing country net imports of cereals in 2050 is 214 percent greater than in 2000. With the wetter NCAR scenario, 2050 net imports value is 262 percent greater than in 2000; with the drier CSIRO scenario it is 361 percent greater.

The climate scenario differences in trade flows are driven by geographical differences in production effects. For example, without climate change, 2050 developed country production of maize increases by 207.2 mmt (an increase of 70 percent); in developing countries, maize production increases by 234.9 mmt (73 percent). With both CSIRO and NCAR scenarios, developed country production increases more than developing country production, but the magnitudes of these changes are much greater with CSIRO than with NCAR. The result is much greater net exports of maize (and other major rainfed crops) from developed countries with CSIRO than with NCAR. Similar differences

TABLE 8. NET CEREAL (RICE, WHEAT, MAIZE, MILLET, SORGHUM, AND OTHER GRAINS) EXPORTS BY REGION IN 2000 AND 2050 UNDER SCENARIOS WITH AND WITHOUT CLIMATE CHANGE (000 MT

		2050				
Region	*2000*	*No Climate Change*	*CSIRO No CF*	*NCAR No CF*	*CSIRO CF effects (%)*	*NCAR CF effects (%)*
South Asia	15,013	–19,791	–53,823	–51,663	–15.0	–8.1
East Asia and the Pacific	–19,734	–72,530	–55,086	8,158	9.1	–58.5
Europe and Central Asia	8,691	178,097	64,916	34,760	4.4	6.5
Latin America and the Caribbean	–11,358	–38,063	–3,114	–2,848	251.7	239.5
Middle East and North Africa	–51,753	–84,592	–66,708	–64,459	–0.0	0.6
Sub-Saharan Africa	–22,573	–65,122	–29,236	–28,011	53.1	49.5
Developed Countries	83,352	105,809	145,740	106,672	12.1	18.4
Developing Countries	–83,352	–105,809	–145,740	–106,672	12.1	18.4

Source: Authors' estimates.

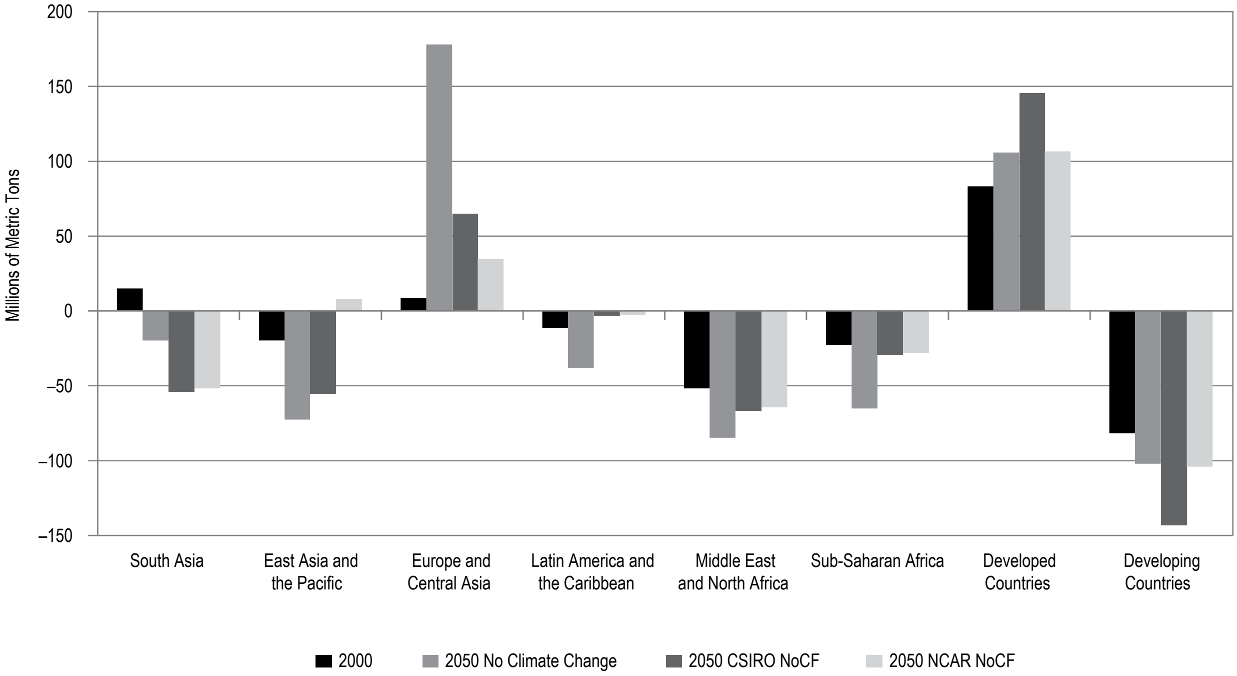
Note: The last two columns in this table report the percentage difference between the net imports in 2050 with climate change and with the CO_2 fertilization effect. For example, Sub-Saharan countries import 28.0 mmt under the NCAR climate scenario and no CO_2 fertilization effects. CO_2 fertilization adds 49.5 percent.

TABLE 9. VALUE OF NET CEREAL TRADE BY REGION (MILLION US$)

	2000	*2050 No Climate Change*	*2050 CSIRO No CF*	*2050 NCAR No CF*
South Asia	2,589	–2,238	–14,927	–14,727
East Asia and the Pacific	–1,795	–7,980	–8,879	6,530
Europe and Central Asia	750	24,276	14,377	6,662
Latin America and the Caribbean	–1,246	–6,027	–342	480
Middle East and North Africa	–5,600	–12,654	–17,723	–17,703
Sub-Saharan Africa	–2,995	–12,870	–10,914	–11,153
Developed Countries	8,500	18,184	39,219	30,733
Developing Countries	–8,500	–18,184	–39,219	–30,733

Source: Authors' estimates.

FIGURE 9. NET CEREAL (RICE, WHEAT, MAIZE, MILLET, SORGHUM, AND OTHER GRAINS) TRADE BY REGION IN YEAR 2000 AND 2050 UNDER SCENARIOS WITH AND WITHOUT CLIMATE CHANGE (MMT)



Source: Authors' estimates.

exist for wheat, where the climate change effects on yield are much more dramatic in developing countries than in developed countries.

3.2.3 Food demand

The level of food available for consumption is determined by the interaction of supply, demand, and the resulting prices with individual preferences and income. Table 10 shows average per capita consumption of cereals and meat products in 2000 and in 2050 under various climate change scenarios. In the developing country group per capita cereal consumption declines and per capita meat consumption increases between 2000 and 2050 with no climate change. Climate change reduces meat consumption growth slightly and causes a more substantial fall in cereals consumption. These results are the first evidence of the negative welfare effects of climate change. Both climate change scenarios have similar consequences. Meat consumption with climate change declines about 10 percent in developing countries and 9 percent in developed countries. Cereal consumption decrease from climate change is 25 percent in developed countries and 21 percent in developing countries.

3.2.4 Welfare effects

Our measures of the welfare effects of climate change are the change in calorie availability and in the number of malnourished children brought about by climate change.

The declining consumption for cereals in particular translates into similarly large declines in calorie availability as the result of climate change. Results are presented in Table 11 and Figure 10. Without climate change, calorie availability increases throughout the world between 2000 and 2050. The largest increase, of 13.8 percent, is in East Asia and the Pacific, but the

TABLE 10. PER CAPITA FOOD CONSUMPTION (KG PER YEAR) OF CEREALS AND MEATS WITH AND WITHOUT CLIMATE CHANGE

		2050				
	2000	*No Climate Change*	*CSIRO No CF*	*NCAR No CF*	*CSIRO CF effect (%)*	*NCAR CF effect (%)*
Meat						
South Asia	6	16	14	14	0.9	0.8
East Asia and the Pacific	40	71	66	66	0.7	0.6
Europe and Central Asia	42	56	51	51	0.8	0.7
Latin America and the Caribbean	57	71	64	64	1.0	0.9
Middle East and North Africa	23	39	36	36	0.7	0.6
Sub-Saharan Africa	11	18	16	16	1.0	0.8
Developed Countries	88	100	92	92	0.8	0.7
Developing Countries	28	41	37	37	0.8	0.7
Cereals						
South Asia	164	157	124	121	7.0	7.1
East Asia and the Pacific	184	158	124	120	8.1	8.3
Europe and Central Asia	162	169	132	128	5.3	4.9
Latin America and the Caribbean	123	109	89	87	6.1	5.9
Middle East and North Africa	216	217	172	167	5.5	5.1
Sub-Saharan Africa	117	115	89	89	7.4	7.1
Developed Countries	118	130	97	94	6.8	6.3
Developing Countries	164	148	116	114	7.1	7.1

Source: Authors' estimates.

TABLE 11. DAILY PER CAPITA CALORIE AVAILABILITY WITH AND WITHOUT CLIMATE CHANGE

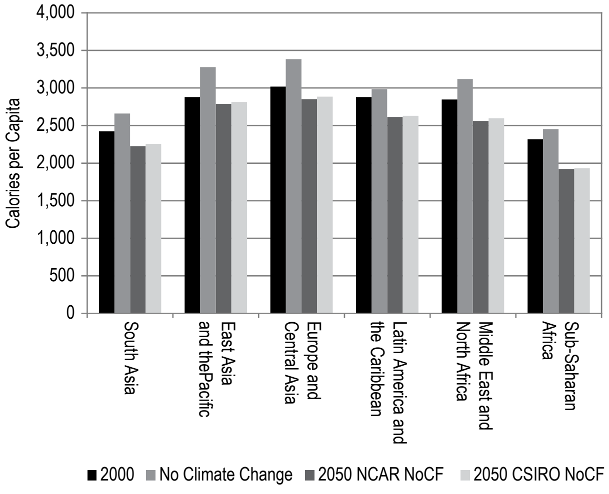
		2050				
	2000	*No Climate Change kcal/day*	*NCAR No CF kcal/day*	*CSIRO No CF kcal/day*	*NCAR CF effects (%)*	*CSIRO CF effects (%)*
South Asia	2,424	2,660	2,226	2,255	4.3	4.3
East Asia and the Pacific	2,879	3,277	2,789	2,814	4.3	4.3
Europe and Central Asia	3,017	3,382	2,852	2,885	2.7	2.9
Latin America and the Caribbean	2,879	2,985	2,615	2,628	2.7	2.8
Middle East and North Africa	2,846	3,119	2,561	2,596	3.6	3.7
Sub-Saharan Africa	2,316	2,452	1,924	1,931	6.5	6.9
Developed Countries	3,450	3,645	3,190	3,215	2.3	2.5
Developing Countries	2,696	2,886	2,410	2,432	4.4	4.4

Source: Authors' estimates.

average consumer in all countries gains—by 3.7 percent in Latin America, 5.9 percent in Sub-Saharan Africa, and 9.7 percent in South Asia.

With climate change, however, calorie availability in 2050 is not only lower than the no-climate-change scenario in 2050; calorie availability actually declines

FIGURE 10. DAILY PER CAPITA CALORIE AVAILABILITY WITH AND WITHOUT CLIMATE CHANGE



Source: Authors' estimates.

relative to 2000 levels throughout the world. For the average consumer in a developing country the decline is 10 percent relative to 2000. With CO_2 fertilization, the declines are 3 percent to 7 percent less severe but still large relative to the no climate change scenario. There is almost no difference in calorie outcome between the two climate scenarios.

Table 12 reports summary statistics for the child malnourishment indicator. With no climate change only Sub-Saharan Africa sees an increase in the number of malnourished children between 2000 and 2050. All other parts of the developing world see declines in the number of malnourished children, driven by rapid income and agricultural productivity growth. Climate change eliminates much of that improvement. In East Asia and the Pacific, instead of 10 million malnourished children in 2050, we find 14.2 to 14.5 million. In South Asia, instead of 52.3 million malnourished children in 2050, we find 58.5 to 59.1 million. In Sub-Saharan Africa, the effect of climate change is to increase the no-climate-change result by some 11 million children. If CO_2 fertilization is in fact effective in the field, the negative effect of climate change on child malnutrition is reduced somewhat but not enough to offset the negative effects of climate change on child malnutrition.

3.3 THE COSTS OF ADAPTATION

The challenge of estimating the costs of adaptation includes both choosing a baseline and then determining

TABLE 12. TOTAL NUMBER OF MALNOURISHED CHILDREN IN 2000 AND 2050 (MILLION CHILDREN UNDER 5 YRS)

		2050				
	2000	*No Climate Change*	*NCAR No CF*	*CSIRO No CF*	*NCAR CF effect (%)*	*CSIRO CF effect (%)*
South Asia	75.62	52.29	59.06	58.56	–2.7	–2.7
East Asia and Pacific	23.81	10.09	14.52	14.25	–9.0	–9.0
Europe and Central Asia	4.11	2.70	3.73	3.66	–4.4	–4.9
Latin America and Caribbean	7.69	4.98	6.43	6.37	–4.7	–4.8
Middle East and North Africa	3.46	1.10	2.09	2.01	–10.3	–11.3
Sub-Saharan Africa	32.67	41.72	52.21	52.06	–5.4	–5.6
All Developing Countries	147.36	112.88	138.04	136.91	–4.6	–4.8

Source: Authors' estimates.

Note: The last three columns in this table report the percentage difference between the number of malnourished children in 2050 with and without the CO_2 fertilization effect. For example, with the NCAR GCM, assuming CO_2 fertilization is effective in the field results in a 2.7 percent decline in the number of malnourished children in South Asia relative to the climate change outcome in 2050 without CO_2 fertilization.

what to include in the adaptation costs. The metric used to determine costs is the number of malnourished children. The assumed public sector goal is to invest in agricultural productivity enhancements that return the number of malnourished children with climate change to the number that occur in the baseline. For the EACC study of which this report is a part, the baseline is a world without climate change.

The choice of baseline affects some of the investments considered in the costs of adaptation. For example, climate change reduces the productivity of agricultural investments so investments made in a no-climate change scenario become less productive when climate change occurs. So investments must compensate both for the reduced productivity of existing investments and the need for additional productivity to deal with climate change effects.

A second issue is how to account for costs undertaken by the private sector as it adjusts to climate change. An important example of this is the change in trade flows indicated in Table 9. As farmers cope with changes in productivity brought about because of climate change, production levels are altered and trade flows are changed. There are clearly costs associated with these adjustments. Farmers must alter production practices, buy new seeds, and perhaps change capital equipment. However, we have no mechanism to estimate these private sector expenditures so these costs are not included.

Three categories of productivity-enhancing investments are considered—agricultural research, irrigation expansion and efficiency improvements, and rural roads. We do two experiments. The first experiment, reported in the first part of Table 13, is investments in the developing world only needed to reduce childhood malnutrition near the levels of the without-climate-change scenario. The second experiment is to include additional productivity enhancements in developed countries to assess the potential for spillovers.

TABLE 13. INVESTMENT AND PRODUCTIVITY SCENARIOS FOR CLIMATE CHANGE ADAPTATION

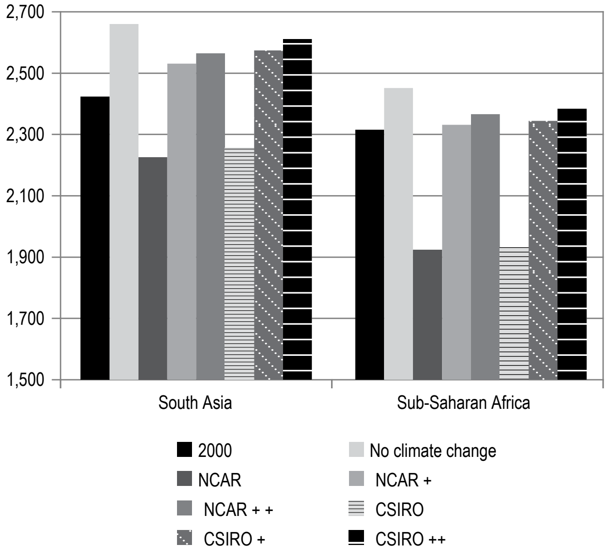
Developing country agricultural productivity investments, increase in intrinsic productivity growth rates over baseline growth rates
Yield growth rate for all crops – 60%
Animal numbers growth rate – 30%
Production growth rate for oils and meals – 40%
Irrigated area growth rate – 25%
Rainfed area growth rate – 15% decrease
Increase in basin water efficiency – 0.15 by 2050
Developed country agricultural productivity investments
Yield growth rate for all crops – 30%
Animal numbers growth rate – 15%
Production growth rate for oils and meals – 30%

Source: Authors' data.

Table 14 reports the effects on daily per capita calorie availability for these two experiments. Table 15 reports the results for child malnutrition for the two climate scenarios relative to the no-climate-change scenario. Figure 11 and Figure 14 are graphs of the calorie and malnutrition counts for the various developing country regions. Finally, Table 16 reports the annualized additional investment costs needed to meet the malnutrition numbers in Table 15.

The additional investments needed to reduce child malnutrition numbers to the no-climate-change results

FIGURE 11. DAILY CALORIE AVAILABILITY, SOUTH ASIA AND SUB-SAHARAN AFRICA



Source: Authors' data.

TABLE 14. DAILY CALORIE PER CAPITA CONSUMPTION WITH ADAPTIVE INVESTMENTS (KCALS/PERSON/DAY

	South Asia	*Europe and Central Asia*	*East Asia and the Pacific*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developing Countries*
2000	2,424	2,879	3,017	2,879	2,846	2,316	2,696
2050							
No climate change	**2,660**	**3,277**	**3,382**	**2,985**	**3,119**	**2,452**	**2,886**
NCAR	2,226	2,789	2,852	2,615	2,561	1,924	2,410
NCAR +	2,531	3,161	3,197	2,994	2,905	2,331	2,768
NCAR + +	2,564	3,198	3,235	3,027	2,941	2,367	2,803
CSIRO	2,255	2,814	2,885	2,628	2,596	1,931	2,432
CSIRO +	2,574	3,200	3,243	3,011	2,954	2,344	2,801
CSIRO ++	2,612	3,241	3,285	3,048	2,996	2,384	2,840

Source: Authors' estimates

Note: NCAR + and CSIRO + include only agricultural productivity investments in the developing world. NCAR ++ and CSIRO ++ include all productivity improvements in developed countries. The climate change results presented in this table assume no CO_2 fertilization effects.

TABLE 15. NUMBER OF MALNOURISHED CHILDREN WITH ADAPTIVE INVESTMENTS (MILLION CHILDREN, UNDER 5 YEARS)

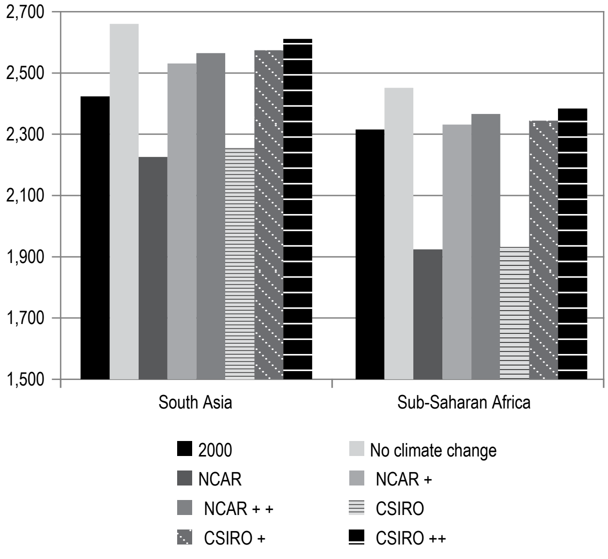
	South Asia	*Sub-Saharan Africa*	*East Asia and the Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Developing World*
2000	75.62	32.67	23.81	4.11	7.69	3.46	147.36
2050							
No climate change	52.37	38.78	12.02	2.96	5.43	1.15	112.71
NCAR	58.16	48.72	16.55	3.91	6.73	2.02	136.10
NCAR +	53.19	40.03	12.40	3.15	5.29	1.23	115.28
NCAR + +	52.73	39.26	12.05	3.08	5.16	1.18	113.47
CSIRO	58.17	49.02	16.52	3.91	6.72	2.02	136.37
CSIRO +	53.04	40.32	12.25	3.12	5.26	1.21	115.20
CSIRO ++	52.53	39.44	11.86	3.04	5.12	1.16	113.16

Source: Authors' estimates.

Note: NCAR + and CSIRO + include only agricultural productivity investments in developing countries. NCAR ++ and CSIRO ++ include all productivity improvements in developed countries. The climate change results presented in this table assume no CO_2 fertilization effects.

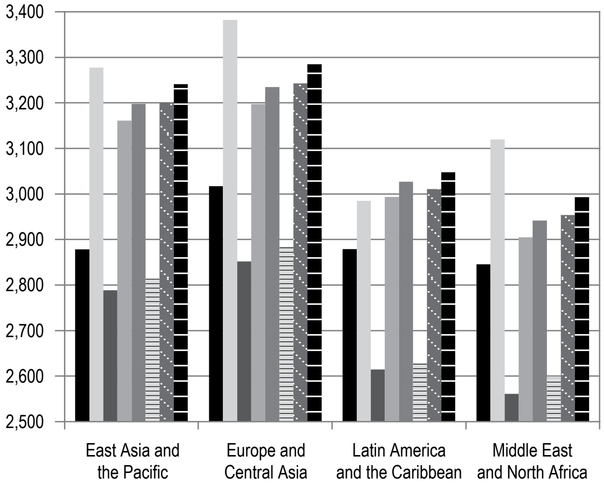
are shown in Table 16. The additional annual investments vary somewhat by climate scenario. With the wetter NCAR scenario the additional annual costs are $7.1 billion. With the drier CSIRO scenario the costs increase to $7.3 billion. Sub-Saharan African investment needs dominate, making up about 40 percent of the total. Of that amount, the vast majority is for rural roads. South Asia investments are about $1.5 billion per year with Latin America and Caribbean close behind with $1.2 billion per year. East Asia and

FIGURE 12. CHILD MALNUTRITION EFFECTS, SOUTH ASIA AND SUB-SAHARAN AFRICA (MILLIONS OF CHILDREN)



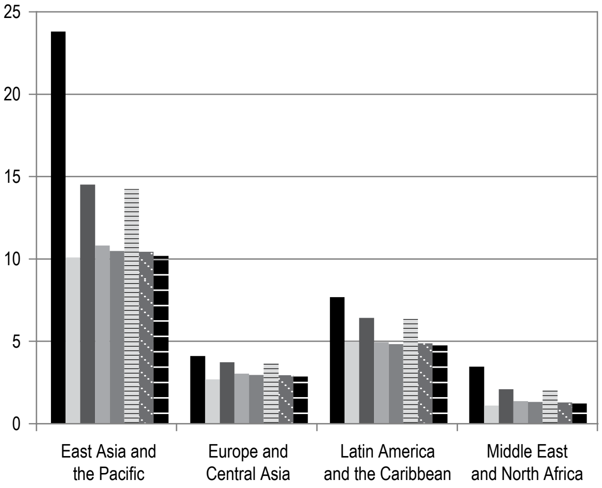
Source: Authors' data.

FIGURE 13. DAILY CALORIE AVAILABILITY, EAST ASIA AND THE PACIFIC, EUROPE AND CENTRAL ASIA, LATIN AMERICA AND THE CARIBBEAN, AND MIDDLE EAST AND NORTH AFRICA



Source: Authors' data.

FIGURE 14. CHILD MALNUTRITION EFFECTS, EAST ASIA AND THE PACIFIC, EUROPE AND CENTRAL ASIA, LATIN AMERICA AND THE CARIBBEAN, AND MIDDLE EAST AND NORTH AFRICA (MILLIONS OF CHILDREN)



Source: Authors' data.

the Pacific needs are just under $1 billion per year. Agricultural research is important in all three of these regions with irrigation efficiency investments substantial as well. Unlike Sub-Saharan Africa, road investments in these regions are relatively small.

With additional investments in the developed countries, spillover effects to the developing world reduce the need for adaptation investments slightly. For example, with the NCAR scenario, the annual investment need is $7.1 billion if productivity expenditures are only in the developing world. With developed country productivity investments, that amount drops to $6.8 billion.

The key message embodied in these results is the importance of improving agricultural productivity as a means of meeting the challenges that climate change represents. The path to the needed agricultural productivity gains varies by region and to some extent by climate scenario.

3.4 SENSITIVITY ANALYSIS

To assess the sensitivity of our results, we did three types of sensitivity analysis—a 10 percent increase in

TABLE 16. ADDITIONAL ANNUAL INVESTMENT EXPENDITURE NEEDED TO COUNTERACT THE EFFECTS OF CLIMATE CHANGE ON NUTRITION (MILLION 2000 US$)

	South Asia	*East Asia and Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developing World*
NCAR with developing country investments							
Ag. Research	172	151	84	426	169	314	1,316
Irrig. Expansion	344	15	6	31	–26	537	907
Irrig. Efficiency	999	686	99	129	59	187	2,158
Rural Roads (Area Exp.)	8	73	0	573	37	1,980	2,671
Rural Roads (Yield Incr.)	9	9	10	3	1	35	66
Total	1,531	934	198	1,162	241	3,053	7,118
NCAR with developing country and developed country investments							
Ag. Research	158	141	46	385	146	297	1,174
Irrig. Expansion	331	12	5	29	–31	528	874
Irrig. Efficiency	995	684	98	128	59	186	2,151
Rural Roads (Area Exp.)	6	61	0	528	31	1,911	2,536
Rural Roads (Yield Incr.)	8	8	9	3	1	33	62
Total	1,499	905	159	1,072	206	2,956	6,797
CSIRO with developing country investments							
Ag. Research	185	172	110	392	190	326	1,373
Irrig. Expansion	344	1	1	30	–22	529	882
Irrig. Efficiency	1,006	648	101	128	58	186	2,128
Rural Roads (Area Exp.)	16	147	0	763	44	1,911	2,881
Rural Roads (Yield Incr.)	13	9	11	3	1	36	74
Total	1,565	977	222	1,315	271	2,987	7,338
CSIRO with developing country and developed country investments							
Ag. Research	168	157	66	335	162	302	1,191
Irrig. Expansion	330	1	–1	28	–27	519	850
Irrig. Efficiency	1,002	645	100	127	58	185	2,119
Rural Roads (Area Exp.)	14	129	0	686	36	1,822	2,687
Rural Roads (Yield Incr.)	13	8	9	3	1	34	68
Total	1,528	941	174	1,179	230	2,863	6,915

Source: Authors' estimates.

Note: These results are based on yield changes that do not include the CO_2 fertilization effect.

per capita income everywhere, a 10 percent increase in intrinsic productivity growth everywhere, and a 10 percent increase in population. The results can be interpreted as elasticities. For example, the elasticity of malnourished children with respect to GDP is –0.14 and with intrinsic productivity growth from –0.28 to –0.32.

Population growth has the largest effect in absolute terms with elasticities ranging from 0.5 to 1.3 and the effect is negative. With all other exogenous variables held constant, more population growth means more malnourished children. Productivity growth is more effective than income growth in reducing the number of malnourished children. For example, a 10 percent increase in intrinsic productivity reduces the number of malnourished children in the developing world by 2.9 to 3.2 percent. A 10 percent increase in income reduces the number of malnourished children by only 1.4 percent.

3.5 LIMITATIONS

There are seven categories of climate change impacts that cannot currently be modeled due to data limitations. Incorporation of most of these effects would almost certainly make the effects of climate change significantly worse than the already negative picture shown here. First, direct effects on livestock are not included. These effects range from less productive pastures for ruminants because of heat and precipitation changes to increased stress in livestock confinement systems. Second, pests and diseases, from traditional weeds that are more robust to larger insect populations to more infectious diseases, might be a more serious problem with higher temperatures and locations with more precipitation. Third, the analysis does not take into account the effect of sea level rise on coastal agricultural resources. Coastal rice paddies might see saline intrusion, coastal seafood pens might be lost, and marine fisheries made less productive as mangrove swamps are affected. Rice production in river deltas will be particularly hard hit. For example, over 30 percent of the rice growing area in Vietnam would be lost to a 1 meter sea level rise. Fourth, some parts of the world, in particular the rivers that derive from glaciers in the mountains of Asia, might see more varied flows with effects on irrigated agriculture and fisheries based on water sourced from rivers. Fifth, we do not include autonomous adjustment costs such as those incurred by farmers and traders as they adjust to changes in trade flows. Sixth, we do not include the potential production in FPUs where production is not possible under current climate conditions but might be with 2050 cliamte. Finally, we do not include the effect of climate variability and extreme events as current GCM scenarios do not account for them.

3.6 CONCLUSIONS

This analysis brings together, for the first time, detailed modeling of crop growth under climate change with insights from a detailed global partial agriculture equilibrium trade model. Several important conclusions can be drawn.

TABLE 17. PERCENTAGE CHANGE IN MALNOURISHED CHILDREN WITH 10 PERCENT INCREASES IN GDP, PRODUCTIVITY GROWTH, AND POPULATION

	South Asia	*East Asia and the Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developing Countries*
10 percent increase in GDP everywhere							
No CC (% change)	–0.9	–1.0	–0.3	–0.2	–2.6	–2.3	–1.4
NCAR (% change)	–0.8	–3.5	–0.3	–0.2	–3.5	–1.7	–1.4
CSIRO (% change)	–0.8	–3.5	–0.3	–0.2	–3.6	–1.7	–1.4
10 percent increase in intrinsic productivity growth everywhere							
No CC (% change)	–2.1	–2.8	–5.6	–5.6	–6.4	–4.2	–3.2
NCAR (% change)	–1.7	–4.8	–3.9	–4.5	–7.7	–3.0	–2.8
CSIRO (% change)	–1.8	–5.1	–4.2	–4.6	–8.5	–3.2	–2.9
10 percent increase in population everywhere							
No CC (% change)	5.4	5.0	5.8	6.4	8.1	13.1	8.3
NCAR (% change)	5.2	5.9	5.0	5.7	10.0	11.9	7.9
CSIRO (% change)	5.2	6.0	5.1	5.7	10.2	11.9	7.9

Source: Authors' estimates.

Regardless of climate change scenario, agriculture will be negatively affected by climate change. When biophysical impacts of climate change are integrated into the IMPACT economic modeling framework, food prices increase sharply for key crops with adverse consequences for the poor. Even without climate change, world prices are forecast to increase, from 39 to 72 percent for the most important crops, driven by population and income growth in the developing world outstripping expected productivity enhancements. Climate change from unmitigated emissions of greenhouse gases will cause even greater price increases. Rice prices are projected to be 13 percent higher in 2050 compared to a no-climate change case, wheat prices 70 to 87 percent higher, and maize prices rise 34 percent. Price increases due to climate change are lower if CO_2 fertilization is considered, but the recent insights from field experiments suggest that benefits from carbon fertilization are less than previously estimated. Higher food prices as a result of lower crop yields mean reduced food availability and more malnourished children.

There remains great uncertainty about where the particular impacts will occur and the resulting production, consumption and trade flow effects exhibit considerable differences depending on the climate scenario.

Increases in investments to increase agricultural productivity, including agricultural research, improvements in irrigation efficiency and expansion of irrigated area, and rural road construction can compensate for much of the effects of climate change on calorie availability and child malnutrition. We estimate these costs to be in the range of US$7.1–7.3 billion annually (constant 2000 dollars) for direct agriculture and related investments (public agricultural research and development, irrigation efficiency and expansion, and rural roads.

Changes in the volume and direction of international trade in agricultural commodities are another important avenue to compensate for the differential impacts of climate change, which is also taken into account in our modeling framework. Thus, more open international trade should continue to be promoted to partially offset adverse effects and uncertainty from climate change.

4. ANNEX. IFPRI'S CLIMATE CHANGE MODELING METHODOLOGY

The challenge of modeling climate change impacts arises in the wide ranging nature of processes that underlie the working of markets, ecosystems, and human behavior. Our analytical framework integrates modeling components that range from the macro to the micro and from processes that are driven by economics to those that are essentially biological in nature.

An illustrative schematic of the linkage in IFPRI's IMPACT model between the global agricultural policy and trade modeling of the partial agriculture equilibrium model with the hydrology and agronomic potential modeling is shown in Figure 1.

The modeling methodology used here reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships at a national or even more aggregate regional level with detailed models of dynamic biophysical processes. The climate change modeling system combines a biophysical model (the DSSAT crop modeling suite) of responses of selected crops to climate, soil and nutrients with the SPAM data set of crop location and management techniques (Liang You and Stanley Wood, 2006), illustrated in Figure 15. These results are then aggregated and fed into the IMPACT model.

4.1 CROP MODELING

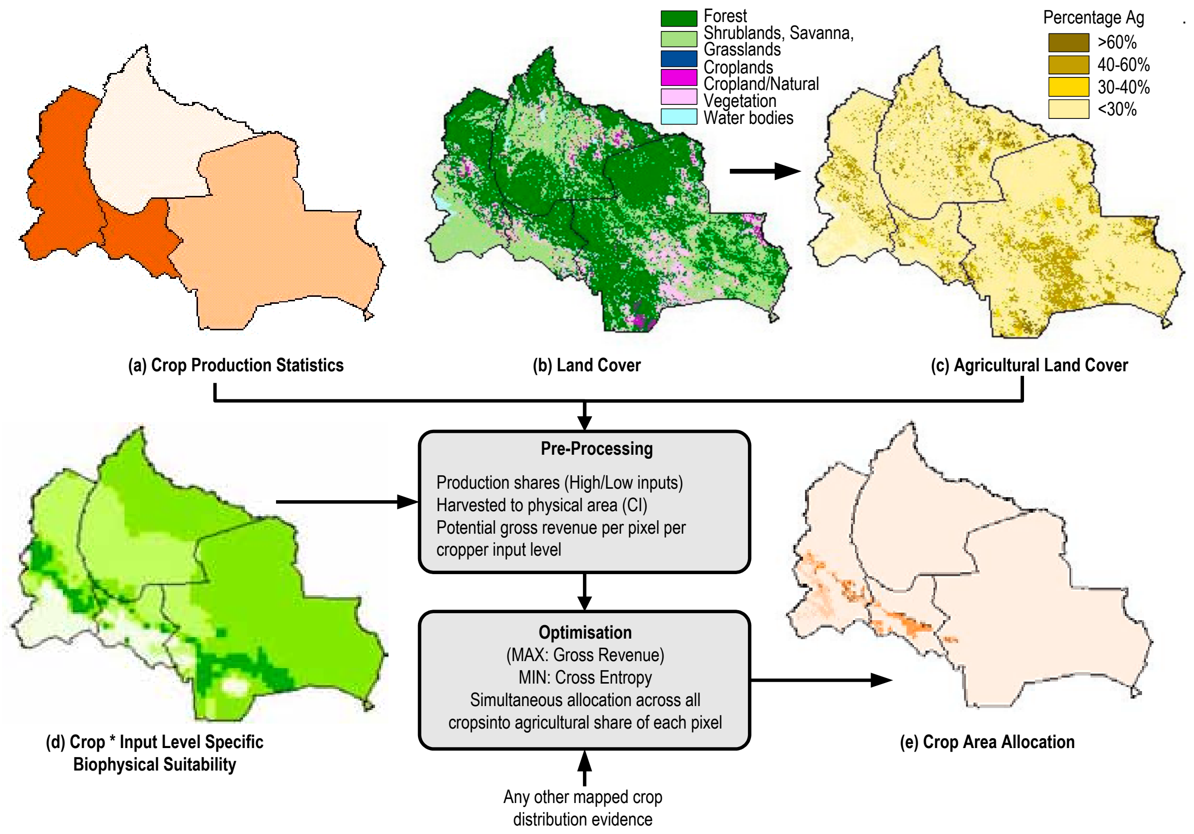
The DSSAT crop simulation model is an extremely detailed process model of the daily development of a crop from planting to harvest-ready. It requires daily weather data, including maximum and minimum temperature, solar radiation, and precipitation, a description of the soil physical and chemical characteristics of the field, and crop management, including crop, variety, planting date, plant spacing, and inputs such as fertilizer and irrigation.

For maize, wheat, rice, groundnuts, and soybeans, we use the DSSAT crop model suite, version 4.0 (J. W. Jones, G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. Gijsman and J. T. Ritchie, 2003). For mapping these results to other crops in IMPACT, the primary assumption is that plants with similar photosynthetic metabolic pathways will react similarly to any given climate change effect in a particular geographic region. Millet, sorghum, sugarcane, and maize all use the C4 pathway and are assumed to follow the DSSAT results for maize in the same geographic regions. The remainder of the crops use the C3 pathway. The climate effects for the C3 crops not directly modeled in DSSAT follow the average from wheat, rice, soy, and groundnut from the same geographic region, with two exceptions. The IMPACT commodities of "other grains" and dryland legumes are directly mapped to the DSSAT results for wheat and groundnuts, respectively.

4.2 CLIMATE DATA

DSSAT requires detailed daily climate data, not all of which are readily available, so various approximation techniques were developed. To simulate today's climate we use the Worldclim current conditions data set (www.worldclim.org) which is representative of

FIGURE 15. THE SPAM DATA SET DEVELOPMENT PROCESS



Source: Authors' data.

1950–2000 and reports monthly average minimum and maximum temperatures and monthly average precipitation. Site-specific daily weather data are generated stochastically using the SIMMETEO software. At each location, 30 iterations were run and the mean of the yield values used to represent the effect of the climate variables.

Precipitation rates and solar radiation data were obtained from NASA's LDAS website (http://ldas.gsfc.nasa.gov/). We used the results from the Variable Infiltration Capacity (VIC) land surface model. For shortwave radiation (the sunlight plants make use of), monthly averages at 10 arc-minute resolution were obtained for the years 1979–2000. Overall averages for each month were computed between all the years (for example, the January average was computed as [January 1979 + January 1980 + … + January 2000] / 22). Rainfall rates were obtained at three-hourly intervals for the years 1981, 1985, 1991, and 1995. A day was determined to have experienced a precipitation event if the average rainfall rate for the day exceeded a small threshold. The number of days experiencing a rainfall event within each month was then counted up and averaged over the four years.

The monthly values were regressed nonlinearly using the Worldclim monthly temperature and climate data, elevation from the GLOBE dataset (http://www.ngdc.noaa.gov/mgg/topo/globe.html) and latitude. These regressions were used to estimate monthly solar radiation data and the number of rainy days for both today and the future. These projections were then used by SIMETEO to generate the daily values used in DSSAT.

For future climate, we use the fourth assessment report A2 runs using the CSIRO and NCAR models.[4] At one time the A2 scenario was considered an extreme scenario although recent findings suggest it may not be. We assume that all climate variables change linearly between their values in 2000 and 2050. This assumption eliminates any random extreme events such as droughts or high rainfall periods and also assumes that the forcing effects of GHG emissions proceed linearly; that is, we do not see a gradual speedup in climate change. The effect of this assumption is to underestimate negative effects from climate variability.

4.3 OTHER AGRONOMIC INPUTS

Six other agronomic inputs are needed—soil characteristics, crop variety, cropping calendar, CO_2 fertilization effects, irrigation, and nutrient levels.

4.3.1 Soil characteristics

DSSAT uses many different soil characteristics in determining crop progress through the growing season. John Dimes of ICRISAT and Jawoo Koo of IFPRI collaborated to classify the FAO soil types into 27 meta-soil types. Each soil type is defined by a triple of soil organic carbon content (high/medium/low), soil rooting depth as a proxy for available water content (deep/medium/shallow), and major constituent (sand/loam/clay). The dominant soil type in a pixel is used to represent the soil type for the entire pixel.

4.3.2 Crop variety

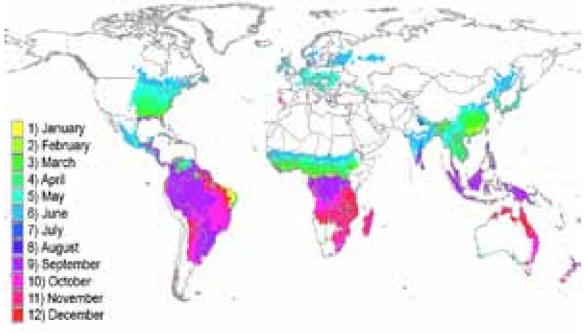
DSSAT includes many different varieties of each crop. For the results reported here, we use the maize variety Garst 8808, a winter wheat variety, a large-seeded Virginia runner type groundnut variety, a maturity group 5 soybean variety, and for rice, a recent IRRI indica rice variety and a Japonica variety. The rice varieties are assigned by geographic area according to whichever is more commonly cultivated within the region.

4.3.3 Cropping calendar

Climate change will alter the cropping calendar in some locations, shifting the month in which a crop can be safely planted forward or back. Furthermore, in some locations crops can be grown in 2000 but not in 2050, or vice versa. For rainfed crops, we assume that a crop is planted in the first month of a four month contiguous block of months where monthly average maximum temperature does not exceed 37 degrees Celsius (about 99 degrees F), monthly average minimum temperature does not drop below 5 degrees Celsius (about 41 degrees F) and monthly total precipitation is not less than 60 mm. See Figure 16 to Figure 18.

For irrigated crops we assume that precipitation is not a constraint and only temperature matters, avoiding freezing periods. The starting month of the irrigated growing season is identified by 4 contiguous months where the monthly average maximum temperature does not exceed 45 degrees Celsius (about 113 degrees F) and the monthly average minimum temperature does not drop below 8.5 degrees Celsius (about 47 degrees F). See Figure 19 to Figure 21.

FIGURE 16. RAINFED CROP PLANTING MONTH, 2050 CLIMATE



Source: Compiled by Authors.

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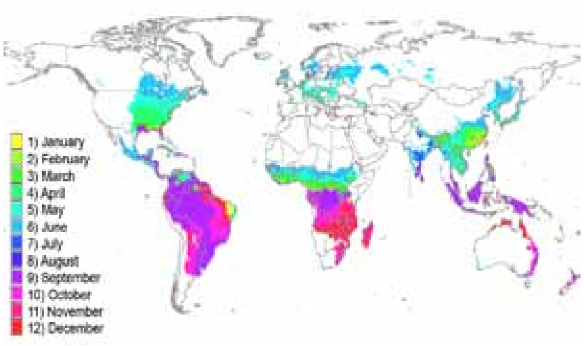
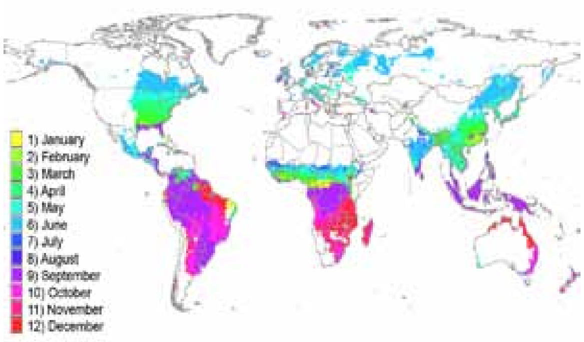
[4] NCAR and CSIRO AR4 data downscaled by Kenneth Strzepek and colleagues at the MIT's Center for Global Change Science. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

FIGURE 17. RAINFED PLANTING MONTH, 2050 CLIMATE, CSIRO GCM A2 SCENARIO (AR4)



Source: Compiled by Authors.

FIGURE 18. RAINFED PLANTING MONTH, 2050 CLIMATE, NCAR GCM A2 SCENARIO (AR4)



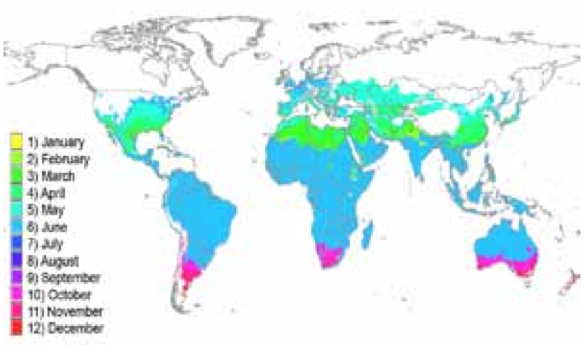
Source: Compiled by Authors.

Developing a climate based growing season algorithm for winter wheat was challenging. Our solution was to treat winter wheat differently than other crops. Rather than using a cropping calendar, we let DSSAT use planting dates throughout the year and choose the date that provides the best yield for each pixel.

4.3.4 CO_2 fertilization effects

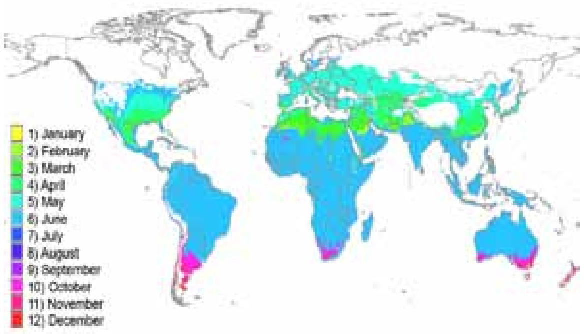
Plants produce more vegetative matter as atmospheric concentrations of CO_2 increase. The effect depends on the nature of the photosynthetic process used by the plant species. So-called C3 plants use CO_2 less efficiently than C4 plants so C3 plants are more sensitive to higher concentrations of CO_2. It remains an open

FIGURE 19. IRRIGATED PLANTING MONTH, 2050 CLIMATE



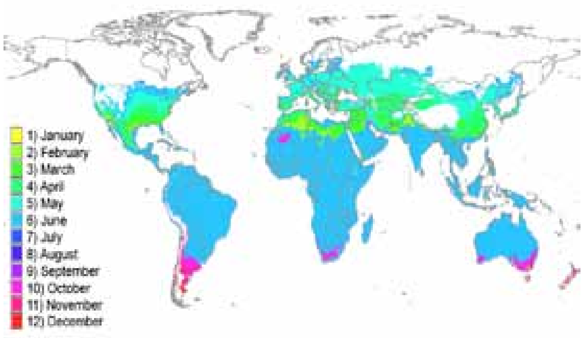
Source: Compiled by Authors.

FIGURE 20. IRRIGATED PLANTING MONTH, 2050 CLIMATE, CSIRO GCM A2 SCENARIO (AR4)



Source: Compiled by Authors.

FIGURE 21. IRRIGATED PLANTING MONTH, 2050 CLIMATE, NCAR GCM A2 SCENARIO (AR4)



Source: Compiled by Authors.

question whether these laboratory results translate to actual field conditions. A recent report on field experiments on CO_2 fertilization (Stephen P. Long, Elizabeth A. Ainsworth, Andrew D. B. Leakey, Josef Nosberger and Donald R. Ort, 2006), finds that the effects in the field are approximately 50 percent less than in experiments in enclosed containers. And another report (Jorge A. Zavala, Clare L. Casteel, Evan H. DeLucia and May R. Berenbaum, 2008) finds that higher levels of atmospheric CO_2 increase the susceptibility of soybean plants to the Japanese beetle and maize to the western corn rootworm. So the actual, field benefits of CO_2 fertilization remain uncertain.

DSSAT has an option to include CO_2 fertilization effects at different levels of CO_2 atmospheric concentration. To capture the uncertainty in actual field effects, we simulate two levels of atmospheric CO_2 in 2050—369 ppm (the level in 2000) and 532 ppm, the CO_2 levels in 2050 actually used in the A2 scenario.

Our aggregation process from SPAM pixels and the crop model results to IMPACT FPUs results in some improbable yield effects in a few locations. To deal with these, we introduce the following caps. In the crop modeling analysis we cap yield increases at 20 percent at the pixel level. In addition, we cap the FPU-level yield increase at 30 percent. Finally, we limit the negative effect of climate on yield growth in IMPACT to –2 percent per year.

4.3.5 Water availability

Rainfed crops receive water either from precipitation at the time it falls or from soil moisture. Soil characteristics influence the extent to which previous precipitation events provide water for growth in future periods. Irrigated crops receive water automatically in DSSAT as needed. Soil moisture is completely replenished at the beginning of each day in a model run. To assess the effects of water stress on irrigated crops, a separate hydrology model is used, as described below.

4.3.6 Nutrient level

DSSAT allows a choice of nitrogen application amounts and timing. We vary the amount of elemental N from 15 to 200 kg per hectare depending on crop, management system (irrigated or rainfed) and country.

4.4 FROM DSSAT TO THE IMPACT MODEL

DSSAT is run for five crops—rice, wheat, maize, soybeans, and groundnuts—at 0.5 degree intervals for the locations that the SPAM data set says the crop is currently grown. Other crops are assumed to have productivity effects similar to these five crops as described above. The results from this analysis are then aggregated to the IMPACT FPU level as described below.

4.5 THE IMPACT2009 MODEL[5]

The IMPACT model was initially developed at the International Food Policy Research Institute (IFPRI) to project global food supply, food demand and food security to year 2020 and beyond (Rosegrant et al. (2008)). It is a partial equilibrium agricultural model with 32 crop and livestock commodities, including cereals, soybeans, roots and tubers, meats, milk, eggs, oilseeds, oilcakes and meals, sugar, and fruits and vegetables. IMPACT has 115 country (or in a few cases country aggregate) regions, within each of which supply, demand, and prices for agricultural commodities are determined. Large countries are further divided into major river basins. The result, portrayed in Figure 22, is 281 spatial units, called food production units (FPUs). The model links the various countries and regions through international trade using a series of linear and nonlinear equations to approximate the underlying production and demand relationships. World agricultural commodity prices are determined annually at levels that clear international markets. Growth in crop production in each country is determined by crop and input prices, exogenous rates of productivity growth and area expansion, investment in irrigation, and water availability. Demand is a function of prices, income, and population growth and contains four categories of commodity demand—food, feed, biofuels feedstock, and other uses.

4.6 MODELING CLIMATE CHANGE IN IMPACT

Climate change effects on crop production enter into the IMPACT model by altering both crop area and yield. Yields are altered through the intrinsic yield

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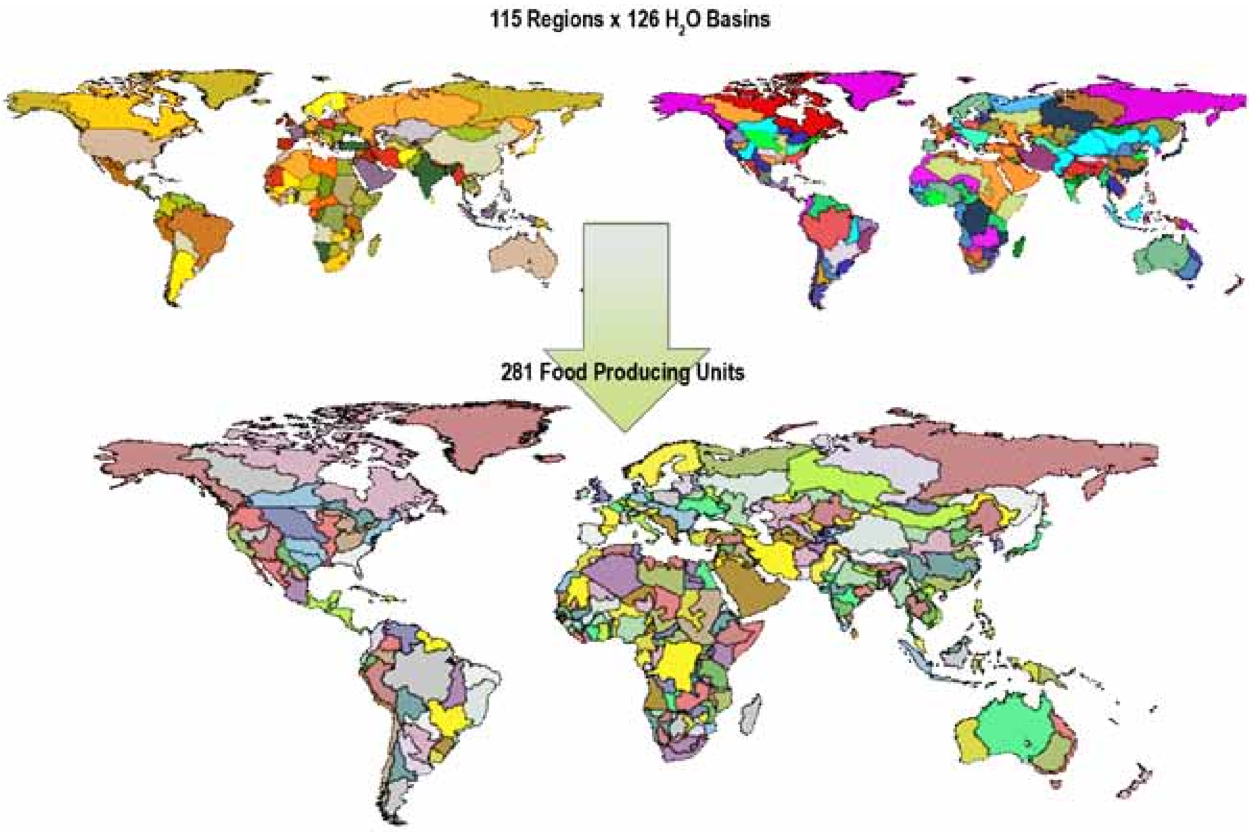
[5] See Rosegrant et al. 2008 for technical details.

FIGURE 22. IMPACT MODEL UNITS OF ANALYSIS, THE FOOD PRODUCTION UNIT (FPU)



Source: Authors' data.

growth coefficient, gy_{tni} , in the yield equation (1) as well as the water availability coefficient (*WAT)* for irrigated crops. See Table 24 for figures showing these rates for the most important crops. These growth rates range depend on crop, management system, and location. For most crops, the average of this rate is about 1 percent per year from effects that are not modeled. But in some countries the growth is assumed to be negative while in others it is as high as 5 percent per year for some years.

$$YC_{tni} = \beta_{tni} \times (PS_{tni})^{\gamma_{iin}} \times \prod_k (PF_{tnk})^{\gamma_{ikn}} \times (1 + gy_{tni}) - \Delta YC_{tni}(WAT_{tni})^{6} \qquad (1)$$

Climate change productivity effects are produced by calculating location-specific yields for each of the five crops modeled with DSSAT for 2000 and 2050 climate as described above and converted to a growth rate which is then used to alter gy_{tni}. Rainfed crops react to changes in precipitation as modeled in DSSAT.

For irrigated crops, water stress from climate change is captured as part of the hydrology model built into IMPACT, a semi-distributed macro-scale hydrology module that covers the global land mass (except Antarctica and Greenland). It conducts continuous hydrological simulations at monthly or daily time steps at a spatial resolution of 30 arc-minutes. The hydrological module simulates the rainfall-runoff process, partitioning incoming precipitation into evapotranspiration and runoff

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[6] β_{tni} - yield intercept for year t, determined by yield in previous year; PS_{tni} - output price in year t; PF_{tni} - input prices in year t. ε - input and output price elasticities.

that are modulated by soil moisture content. A unique feature of the module is that it uses a probability distribution function of soil water holding capacity within a grid cell to represent spatial heterogeneity of soil properties, enabling the module to deal with sub-grid variability of soil. A temperature-reference method is used to judge whether precipitation comes as rain or snow and determines the accumulation or melting of snow accumulated in conceptual snow storage. Model parameterization was done to minimize the differences between simulated and observed runoff processes, using a genetic algorithm. The model is spun up for five years at the beginning for each simulation run to minimize any arbitrary assumption of initial conditions. Finally, simulated runoff and evapotranspiration at 30 arc-minute grid cells are aggregated to the 281 FPUs of the IMPACT model.

One of the more challenging aspects of this research has been to deal with spatial aggregation issues. FPUs are large areas. For example, the India Ganges FPU is the entire length of the Ganges River in India. Within an FPU, there can be large variations in climate and agronomic characteristics. A major challenge was to come up with an aggregation scheme to take outputs from the crop modeling process to the IMPACT FPUs. The process we used proceeds as follows. First, within an FPU, choose the appropriate SPAM data set, with a spatial resolution of 5 arc-minutes (approximately 10 km at the equator) that corresponds to the crop/management combination. The physical area in the SPAM data set is then used as the weight to find the weighted-average-yield across the FPU. This is done for each climate scenario (including the no-climate-change scenario). The ratio of the weighted-average-yield in 2050 to the no-climate-change yield is used to adjust the yield growth rate in equation (1) to reflect the effects of climate change.

In some cases the simulated changes in yields from climate change are large and positive. This usually arises from two major causes; (1) starting from a low base (which can occur in marginal production areas) and (2) unrealistically large effects of carbon dioxide fertilization. To avoid these artifacts, we place a cap on the changes in yields at 20 percent gains over the no-climate-change outcome at the pixel level.

Harvested areas in the IMPACT model are also affected by climate change. In any particular FPU, land may become more or less suitable for any crop and will impact the intrinsic area growth rate, in the area growth calculation. Water availability will affect the *WAT* factor for irrigated crop area.

$$AC_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} (PS_{tnj})^{\varepsilon_{ijn}} \times (1 + ga_{tni}) - \Delta AC_{tni}(WAT_{tni}) \qquad (2)$$

Crop calendar changes due to climate change cause two distinct issues. When the crop calendar in an FPU changes so that a crop that was grown in 2000 can no longer be grown in 2050, we implement an adjustment to ga_{tni} that will bring the harvested area to zero—or nearly so—by 2050. However, when it becomes possible to grow a crop in 2050 where it could not be grown in 2000, we do not add this new area. An example is that parts of Ontario, Canada that have too short a growing season in 2000 will be able to grow maize in 2050, according to the climate scenarios used. As a result our estimates of future production are biased downward somewhat. The effect is likely to be small, however, as new areas have other constraints on crop productivity, in particular soil characteristics.

4.7 MODELING THE COSTS OF ADAPTATION TO CLIMATE CHANGE

This section describes the methodology used to provide estimates of the costs of adapting to climate.

A key issue is the metric for adaptation. We use average per capita calorie consumption and an associated measure of human well-being, the number of malnourished children under 5. We use the underweight definition of malnutrition, the proportion of children under five falling below minus 2 standard deviations from the median weight-for-age standard set by the U.S. National Center for Health Statistics and the World Health Organization[7].

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[7] We use the underweight definition of malnutrition, which is low weight for age or weight for age; more than a standard deviation of 2 below the median value of the reference (healthy) population. Two alternate definitions are

- Stunting. Low height for age or height for age more than a standard deviation of 2 below the median value of the reference (healthy) population
- Wasting. Low weight for height or weight for height more than a standard deviation of 2 below the median value of the reference (healthy) population.

4.8 ESTIMATING CHILD MALNUTRITION

The IMPACT model provides data on the per capita calorie availability by country. Child malnutrition has many determinants of which calorie intake is one. The percentage of malnourished children under the age of five is estimated from the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation (Rosegrant et al. (2008)). The precise relationship used to project the percentage of malnourished children is based on a cross-country regression relationship of Smith and Haddad (2000), and can be written as follows:

$$\Delta_{t,2000}MAL = -25.24 \times \ln\left[\frac{KCAL_t}{KCAL_{2000}}\right] - 71.76 \times \Delta_{t,2000}LFEXPRAT - 0.22 \times \Delta_{t,2000}SCH - 0.08 \times \Delta_{t,2000}WATER$$

where

MAL = percentage of malnourished children

$KCAL$ = per capita kilocalorie availability

$LFEXPRAT$ = ratio of female to male life expectancy at birth

SCH = total female enrollment in secondary education (any age group) as a percentage of the female age-group corresponding to national regulations for secondary education, and

$WATER$ = percentage of population with access to safe water

$\Delta_{t,t2000}$ = the difference between the variable values at time t and the base year t2000

Data on the percentage of malnourished children (*MAL* are taken from the World Development Indicators. Other data sources include the FAO FAOSTAT database, and the UNESCO UNESCOSTAT database.

$$NMAL_t = MAL_t \times POP5_t$$

where $NMAL$ = number of malnourished children, and

$POP5$ = number of children 0–5 years old in the population

For this report, we assume that life expectancy, maternal education and clean water access are held constant in all future scenarios and limit investments to three areas: agricultural research and development spending, rural roads, and irrigation area expansion and efficiency improvements that alter calorie availability and child malnutrition estimates. The approach is to estimate the productivity growth needed to meet a malnutrition or calorie availability target and then estimate the investment expenditures needed in research, irrigation, and road to generate that productivity growth. The basic process is as follows.

- Run the NoCC scenario and estimate the number of malnourished children in 2050
- Run a CC scenario and estimate the number of malnourished children in 2050
- Find a blend of agricultural productivity growth rate increases (crop, animal numbers and oils and meals) that produces a scenario with climate change where number of the malnourished children in 2050 is roughly equal to the number of malnourished children in 2050 for the NoCC scenario and estimate the implied investment costs.

4.9 AGRICULTURAL RESEARCH INVESTMENTS

The process of estimating agricultural research investments uses published research and expert opinion to estimate yield responsiveness to research expenditures and estimation of future expenditures on the basis of historical expenditure growth rates. Most of the data on public agricultural research are from the Agricultural Science and Technology Indicators (ASTI) data set available at http://www.asti.cgiar.org/ and converted into 2000 US$ values by the GDP deflator obtained from the IMF's International Financial Statistics. For a few countries, OECD Science and Technology Indicators data and Eurostat data on gross domestic expenditure on R&D for agricultural sciences are used after being converted to 2000 US $ values.[8] For China, the Ministry of Science and Technology (MOST) data for public agricultural research spending is used. For some countries where public agricultural research data are not available, ASTI estimates of public agricultural research are used.[9] For these countries, ASTI uses agricultural GDP of the country and the average intensity ratio of the region that the country is located to generate an estimate.

Baseline research expenditures in 2050 are estimated by applying the multipliers, g_a , in Table 18 to the historical growth rates, g_h , obtained from data on agricultural and research spending discussed above. The historical growth rate for most countries is computed as an average of the annual historical growth rates for a recent ten year period (or less when data are not available). For the remaining countries, regional average historical growth rates are computed from the data set and used for individual countries.

TABLE 18. ASSUMED MULTIPLIERS OF HISTORIC GROWTH RATES OF AGRICULTURAL RESEARCH EXPENDITUR

Period	*Multiplier of historic growth rate (%)*
2000–2010	9
2011–2020	8
2021–2030	7
2031–2040	6
2040–2050	5

Source: Compiled by authors.

For the main results, it is assumed that the yield elasticity with respect to research expenditures is $\left(\varepsilon_{\text{Research}}^{\text{Yield}}\right)$ 0.296 for all countries and regions.

Agricultural research investment (*ARn*) for every year after 2010 is calculated as follows:

$$AR_n = \left[\left(\frac{g_h g_a}{100} + 1\right) AR_{n-1}\right] \tag{3}$$

Total investments over the period are:

$$AR_{baseline} = \sum_{n=2010}^{2050} AR_n \tag{4}$$

For a given scenario, we determine the change in investment implied in changes in agricultural performance relative to the baseline. The scenario agricultural research costs ($AR_{scenario}$) are computed as follows:

$$AR_{Scenario} = \left[1 + \frac{\dfrac{Yld_{2050}^{Scenario} - Yld_{2050}^{Baseline}}{Yld_{2050}^{Baseline}}}{\varepsilon_{\text{Research}}^{\text{Yield}}}\right] AR_{Baseline} \tag{5}$$

with Yld_{2050}^{y} being the average of cereal yields.

$AR_{Scenario}$ represents the change needed to achieve the new level of productivity to achieve the target.

4.9.1 Agricultural Research Investments Sensitivity Analysis

Since the initial analysis was done, an improved methodology to estimate agricultural research investments has been developed. This new methodology uses more detailed estimates of yield responsiveness to research expenditures. It also introduces lags between research expenditure and the resulting increase in productivity. The estimation of baseline agricultural research spending remains the same.

The first change is to differentiate yield elasticity with respect to research expenditures ($\varepsilon_{\text{Research}}^{\text{Yield}}$) by the following regions—Asia, Sub-Saharan Africa (SSA), Latin America and the Caribbean (LAC), Western Asia and North Africa (WANA), and North America and Europe (NAE), based on the following references—A.D. Alene and O. Coulibaly (2009), A. K. Kiani et al.

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[8] There are no data or estimates for North Korea, Singapore, Afghanistan, Equatorial Guinea, Somalia, Djibouti, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Armenia, Azerbaijan, Belarus, and Georgia.

[9] These countries are Angola, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Guinea Bissau, Lesotho, Liberia, Mozambique, Namibia, Rwanda, Sao Tome and Principe, Sierra Leone, Swaziland, Zimbabwe, Bolivia, Ecuador, Peru, Venezuela, Antigua and Barbuda, Guyana, Jamaica, Surinam, Trinidad and Tobago, Algeria, Bahrain, Iraq, Israel, Lebanon, Kuwait, Libya, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Bhutan, Cambodia, Mongolia, and Luxembourg.

(2008), C. Thirtle et al.(2003), and (D. Schimmelpfenig and C. Thirtle (1999). The regional elasticities are 0.344 for Asia, 0.363 for SSA, 0.197 for LAC, and 0.171 for WANA, and 0.063 for NAE.

We also take into consideration the time lag between investments and impacts on productivity. The initial effects are small, grow over time until the maximum effect on yield is reached and then taper off. We assume that the elasticities described above are the cumulative effect of the initial expenditure. The scenario agricultural research costs for each region $\left(AR_{Scenario}\right)$ are computed as follows:

$$AR_{Scenario} = \left[1 + \frac{\left(yld_{Scenario} - yld_{Baseline}\right)}{yld_{Baseline}}\right] \cdot \left(\Sigma_{t=2010}^{2050} \frac{AR_{Scenario,t}}{e^{Yield}_{Research,t}}\right)$$

The resulting level of spending $\left(AR_{Scenario}\right)$ computed for each region represents the change needed to achieve the new level of productivity to achieve the target. The effect of this new methodology is to raise the estimate of developing country research investment costs by about $900 million annually.

4.10 RURAL ROADS

Higher yields and more cropped area require maintaining and increasing the density of rural road networks to increase market access and reduce transaction costs. We consider two relationships between roads and agricultural production—the effects of area expansion and yield growth.

4.10.1 Area effect

Expanded crop area requires roads to deliver inputs and move goods from fields to market. We assume that any growth in cropped area requires a similar growth in rural roads and that it is a one to one relationship. Rural road length data were taken from World Road Statistics 2002. We use information from the latest available year, typically 2000, to calculate rural road length (*r2000*) as total roads minus highways minus motorways.

Rural road investment costs are calculated by multiplying the extra road length between 2000 and 2050 by the road construction cost per km (C_r) values in Table 20, derived from various World Bank road construction project documents. The values in the table are in 2005 US dollars; they are deflated to 2000 US dollars for the analysis.

We calculate the extra road length required due to area increase (ra) as follows:

$$r_a = r_{2000} \times \left(\frac{a_{2050} - a_{2000}}{a_{2000}}\right) \qquad (6)$$

TABLE 19. RESEARCH INVESTMENT SENSITIVITY ANALYSIS

	South Asia	*East Asia and Pacific*	*Europe and Central Asia*	*Latin America and the Caribbean*	*Middle East and North Africa*	*Sub-Saharan Africa*	*Developing World*
NCAR with developing country investments							
Original	172	151	84	426	169	314	1,316
Revised	195	145	688	653	312	259	2,252
NCAR with developing country and developed country investments							
Original	158	141	46	385	146	297	1,174
Revised	181	137	587	596	278	245	2,024
CSIRO with developing country investments							
Original	185	172	110	392	190	326	1,373
Revised	223	154	744	594	338	268	2,322
CSIRO with developing country and developed country investments							
Original	168	157	66	335	162	302	1,191
Revised	206	143	615	517	297	249	2,027

Source: Authors' estimates.

TABLE 20. ROAD CONSTRUCTION COSTS (2005 US$ PER KM)

South Asia	575,000
Sub-Saharan Africa	600,000
Middle East and North Africa	585,000
Latin America and Caribbean	580,000
East Asia and Pacific	555,000
ECA	590,000
Developed	621,000

Source: Various World Bank road construction project documents.

$$\text{if } a_{2050} - a_{2000} < 0 \text{ then } r_a = 0$$

Finally we multiply r_a by road unit cost to get the cost of new roads needed to support crop area expansion (RR_a).

$$RR_a = r_a C_r \qquad (7)$$

4.10.2 Yield effect

Rural road density has been shown to be among the most important contributors to productivity growth in agriculture. This is due to the impact that better roads have in reducing the transport component of input costs and transaction costs of marketing products. In addition, roads improve the flow of information on market conditions, new technologies, and reduce the potential risks to their enterprises.

The investments in rural roads needed to achieve a given yield effect includes two components. The first, called says how much of a given yield increase is driven by road expansion. Table 21 reports regional averages for this variable. For example, in Latin America 4.3 percent of any yield increase is driven by road expansion.

The second component is the elasticity of yields with respect to road expansion. Table 6 in Fan, P. Hazell and S. Thorat (1998) reports the elasticity of total factor productivity to road investments as 0.072 in India using data from the 1970s through the early 1990s. We use this value for all countries.

TABLE 21. PERCENT YIELD INCREASE WITH RESPECT TO ROAD LENGTH ($yldinc_{Roads}$), REGIONAL AVERAGES

Latin America	0.043
Sub-Saharan Africa	0.240
Western Asia and North Africa	0.085
South Asia	0.170
East Asia and the Pacific	0.158
Eastern Europe and Central Asia	0.141

Source: Compiled by authors.

The yield values used in this calculation (yld_{xxxx}) are an average for all cereals modeled—rice, wheat maize, sorghum, millet and an 'other grains' category. We calculate the increase in road investment due to a yield increase (RR_y) as follows:

$$RR_y = \left(\frac{\left(\frac{yld_{2050}}{yld_{2000}} - 1 \right) \times yldinc_{Roads}}{e^{Yield}_{Roads}} \right) \times r_{2000} \times C_r \qquad (8)$$

The total investment in rural roads ($RR_{baseline}$) for the baseline run is calculated as follows:

$$RR_{baseline} = RR_a + RR_y \qquad (9)$$

4.10.3 Scenario Results and Additional Road Costs

To calculate the effect of a particular scenario on road costs, we use the cereal yield in 2050 from the baseline and the respective scenario model run, e^{Yield}_{Roads} and $yldinc_{Roads}$ to calculate the target costs of rural roads ($RR_{Scenario}$) as follows:

$$RR_{Scenario} = \left[1 + \frac{\left(\frac{yld^{Scenario}_{2050}}{yld^{Baseline}_{2050}} - 1 \right) \times yldinc_{Roads}}{e^{Yield}_{Roads}} \right] RR_{Baseline} \qquad (10)$$

4.11 IRRIGATION

Irrigation investments to meet a productivity target include two components. Costs for expanding irrigated area and costs related to the increase of irrigation water use efficiency.

4.11.1 Area expansion

The total investments in irrigation area are calculated by multiplying the estimated net irrigated area increase between 2000 and 2050 by the cost of irrigation per hectare. Total irrigated area data generated by IMPACT have to be adjusted for cropping intensity $\left(r_n\right)$ because the IMPACT results include multiple cropping seasons and therefore overstates the physical area.

Net irrigated area $\left(a_n^{Net}\right)$ for each year *n* is calculated as follows:

$$a_n^{Net} = \frac{\frac{a_n}{1000}}{r_n} \times 100 \qquad (11)$$

The annual changes in net irrigated area for each year are given by

$$\Delta a_n^{Net} = a_{n+1}^{Net} - a_n^{Net} \qquad (12)$$

$$if\ \Delta a_n^{Net} < 0\ then\ \Delta a_n^{Net} = 0 \qquad (13)$$

The year-to-year changes are summed for the entire period between 2000 and 2050 to get aggregate net irrigated area change $\Delta a_{2050-2000}^{Net}$. The aggregate year-to-year change between 2000 and 2050 is multiplied by irrigation unit cost $\left(c_{Irrig}\right)$ to get the total costs of increased irrigation between 2000 and 2050 (IR).

$$IR = \Delta a_{2050-2000}^{Net} \times c_{irrig} \qquad (14)$$

Irrigation unit costs vary by region, as indicated in Table 23. In a few countries where better information is available, it is used instead.

TABLE 22. IRRIGATION INVESTMENT COST (US 2000$ PER HECTARE)

Region	*Irrigation cost*
South Asia	6,023
East Asia and Pacific	9,916
Eastern Europe and Central Asia	4,997
Latin America and Caribbean	15,929
Middle East and North Africa	9,581
Sub-Saharan Africa	18,252

Source: Literature review of World Bank, Food and Agriculture Organization (FAO) and International Water Management Institute (IWMI) documents, project reports, and meta-evaluations directly related to completed and on-going irrigation projects.

4.11.2 Irrigation efficiency improvements

Improvements in irrigation efficiency are another source of agricultural productivity improvements, especially as water scarcity becomes a world-wide problem. In IMPACT, the concept of basin efficiency (*BE*) is used to account for changes in irrigation efficiency at all levels within a river basin (N. Haie and A.A. Keller, 2008, A. Keller and J. Keller, 1995). It fully accounts for the portion of diverted irrigation water that returns to rivers or aquifer systems and can be reused repeatedly by downstream users. This approach avoids the limitation of the classical irrigation efficiency concept that treats return flow as "losses."

BE is defined as the ratio of beneficial irrigation water consumption (*BC*) to total irrigation water consumption (*TC*); that is, changes in precipitation are excluded from this calculation:

$$BE = \frac{BC}{TC} \qquad (15)$$

BE in the base year is calculated as the ratio of the net irrigation water demand (*NIRWD*) to the total irrigation water consumption based on Shiklomanov (1999). *NIRWD* is defined as.

$$NIRWD = \sum_{cp}\sum_{st}\left(kc^{cp,st} \cdot ET_0^{st} - PE^{cp,st}\right) \cdot AI^{cp} \qquad (16)$$

- *cp*—index for the IMPACT crop. Includes all IMPACT crops that receive irrigation
- *st*—index for the crop growth stages. FAO has divided the crop growing period into four stages,

each with separate crop coefficient (kc) values. See R.G. Allen et al. (1998) for details.

- *kc* —crop coefficient. Each crop growth stage is associated with a corresponding crop coefficient (R.G. Allen, et al., 1998) that adjusts reference ET for the characteristics of a particular crop.
- ET_0 —reference evapotranspiration. Evapotranspiration describes the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and water bodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. Reference evapotranspiration is defined as the *ET* that occurs from a standardized "reference" crop such as clipped grass or alfalfa.
- *PE*—effective rainfall (rainfall that is actually available for plant growth)
- AI^{cp} —irrigated area for crop *cp* in the basin

This calculation generates globally consistent estimates for BE for the base year.

For the future, we project small enhancements in *BE,* with levels increasing to 0.5–0.8 by 2050 under the baseline. An upper level of *BE* is set at 0.85 as a practical maximum.

To account for the investment costs associated with increasing irrigation efficiency, we used one-third of the cost of recent irrigation modernization projects using sprinklers as a proxy. Based on a literature review of World Bank, FAO, and International Water Management Institute (IWMI) documents, project reports, and meta-evaluations directly related to completed and on-going irrigation projects focusing on irrigation modernization only, we identified per-hectare investment cost of US$2,144 for East, South, Southeast, and Central Asia; US$4,311 for Sub-Saharan Africa and Latin America; and US$953 for the Middle East and North Africa. We used one third of these values to proxy investment costs for irrigation efficiency enhancement under alternative climate change scenarios.

For an increased agricultural investment cost scenario, we increase *BE* values by a given amount (0.15 for this report) and calculated associated investment costs. Let subscript "0" denote the base scenario and "1" denote an alternate irrigation investment scenario, and assume that area with more efficient irrigation (for example, through adoption of enhanced management or advanced technologies such as sprinklers) accounts for a share of *X* of total irrigated area in 2050, we have:

$$\begin{aligned} TC_1 &= BC_0 \times \frac{(1-X)}{E_0} + BC_0 \times X \\ &= TC_0 + BC_0 \times X \end{aligned} \tag{17}$$

We assume all consumption in high efficiency irrigation is beneficial consumption. Assuming that beneficial consumption is the same in the base scenario as in the alternate scenario,

$$E_1 = \frac{BC_0}{TC_1} \tag{18}$$

Bringing (17) into (18) and simplifying results in:

$$X = \left(1 - \frac{E_0}{E_1}\right) \Big/ \left(1 - E_0\right) \tag{19}$$

4.11.3 *Irrigation investments sensitivity analysis*

An alternate methodology uses beneficial consumption in the base and alternative investment scenarios from IMPACT model simulations, rather than assuming that beneficial consumption is the same in both scenarios. This leads to:

$$TC_1 = \frac{BC_0 \times (1-X)}{BE_0} + BC_1 \times X \tag{20}$$

In the above equation we still assume that all water consumption in the high irrigation efficiency areas is beneficial consumption.

Bring $BE_0 = BC_0/TC_0$ and $BE_1 = BC_1/TC_1$ into the above equation and simplify to get:

$$X = \left(1 - \alpha \frac{BE_0}{BE_1}\right) \Big/ \left(1 - BE_0\right) \tag{21}$$

in which α is the ratio of beneficial consumption of 2050 in the alternate investment scenario to that in the baseline scenario, namely $\alpha = BC_1/BC_0$. The values of

α can be calculated from beneficial consumption results of IMPACT simulations for the baseline and alternate irrigation investment scenarios. TC_1 is bounded by the available renewable water supply for irrigation.

We then multiply X by the investment costs and irrigated area in 2050.

$$IE_{inv} = X \times IE_{cost} \times AI \qquad (22)$$

Table 23 provides a comparison between old and new results for irrigation efficiency investments (method 1 and alternate estimate 1, respectively). Our base year basin efficiency values range from 0.41 (Brazil) to 0.82 (Colorado Basin, United States). A reviewer comment suggested setting the minimum basin efficiency value to 0.55. We implemented this sensitivity analysis using the alternate estimate methodology and results are also presented in Table 23 (alternate estimate 2). As can be seen, total costs under estimate 2 are slightly higher than under estimate 1. The reason for this is that beneficial consumption is now already higher in the base year while the denominator is smaller (see Eq. 21), and this increase continues out into the future. In none of the cases is the maximum achievable BE value of 0.85 reached.

TABLE 23. RESULTS FROM ALTERNATE ESTIMATION OF IRRIGATION EFFICIENCY IMPROVEMENT COSTS (US 2000 MILLION PER YEAR)

NCAR w. Developing Country Investments	*Method 1*	*Alternate estimate 1*	*Alternate estimate 2*
South Asia	999	343	351
East Asia and Pacific	686	522	533
Europe and Central Asia	99	107	110
Latin America and Caribbean	129	190	208
Middle East and North Africa	59	71	71
Sub-Saharan Africa	187	203	249
Developing	2,158	1,436	1,522
NCAR w. Developing Country Investments + Developed Country Productivity Increases			
South Asia	995	342	351
East Asia and Pacific	684	521	531
Europe and Central Asia	98	107	110
Latin America and Caribbean	128	190	207
Middle East and North Africa	59	70	71
Sub-Saharan Africa	186	202	249
Developing	2,151	1,433	1,519
CSIRO w. Developing Country Investments			
South Asia	1,006	347	356
East Asia and Pacific	648	499	510
Europe and Central Asia	101	110	113
Latin America and Caribbean	128	189	206
Middle East and North Africa	58	70	70
Sub-Saharan Africa	186	202	248
Developing	2,128	1,417	1,503
CSIRO w. Developing Country Investments + Developed Country Productivity Increases			
South Asia	1,002	347	356
East Asia and Pacific	645	498	509

(Continued on next page)

TABLE 23. *(continued)*

NCAR w. Developing Country Investments	*Method 1*	*Alternate estimate 1*	*Alternate estimate 2*
Europe and Central Asia	100	110	112
Latin America and Caribbean	127	189	206
Middle East and North Africa	58	70	70
Sub-Saharan Africa	185	201	247
Developing	2,119	1,413	1,500

Source: Author calculations.

4.12 POPULATION, INCOME AND CLIMATE FUTURE SCENARIO ASSUMPTIONS

All simulations use standard IMPACT model assumptions for elasticities and intrinsic productivity and area growth changes. Income elasticities decline with income growth. For population growth, we use the 2006 UN medium variant projections. For income growth, we rely on the estimates provided by the World Bank for this study. All income and price values are in constant 2000 US dollars.

We report results for two climate scenarios—the NCAR and CSIRO GCMs with the A2 scenario from AR4. For each of the two 2050 scenarios we use crop model results with 369 ppm CO_2 to be the no-CO_2 fertilization results and with 532 ppm CO_2 to represent CO_2 fertilization results.

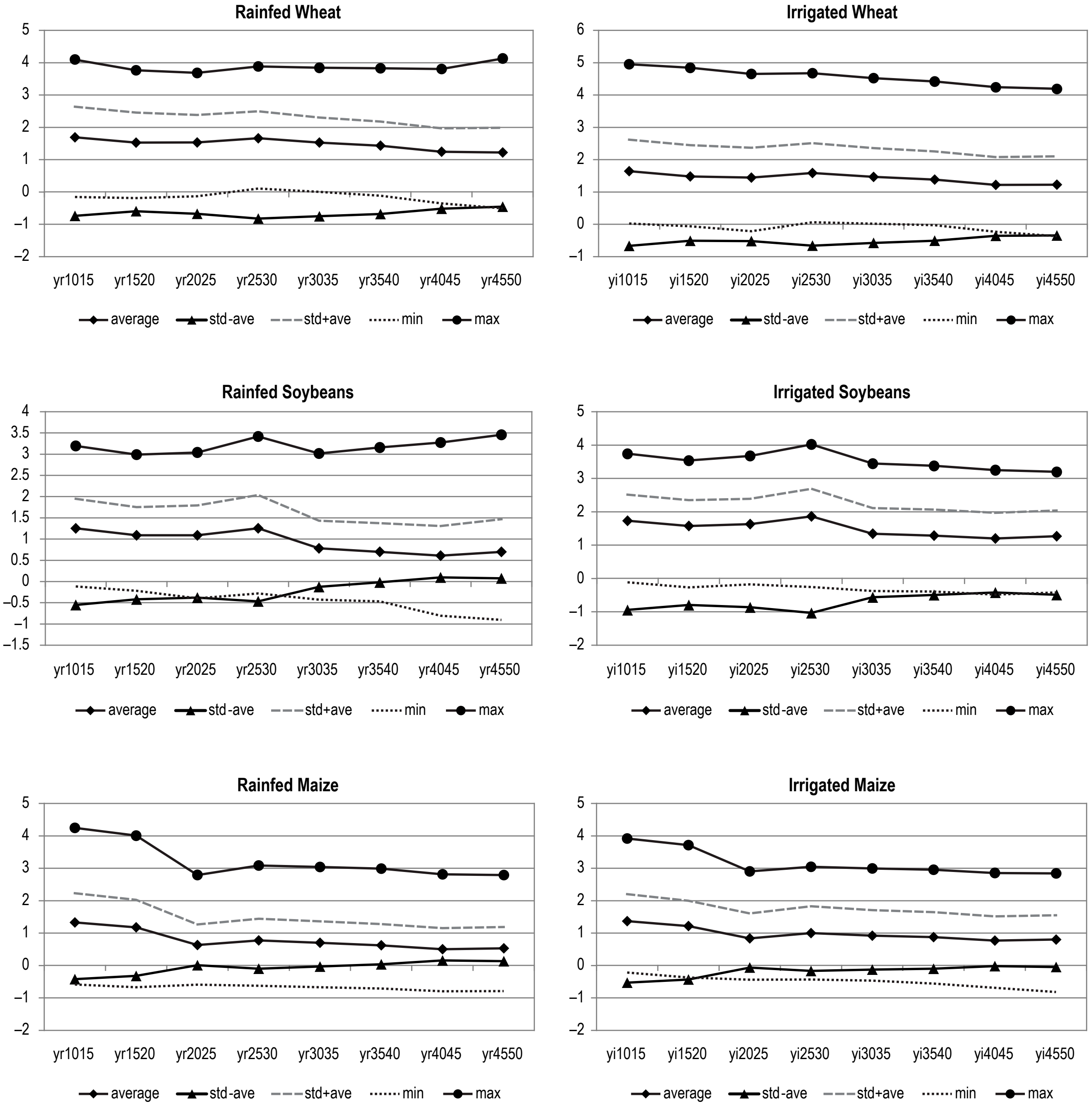
Then we simulate agricultural productivity increases in the developing world needed to address the malnourished children goals.

TABLE 24. PRECIPITATION AND TEMPERATURE REGIONAL AVERAGE CHANGES, 2000 TO 2050

	GCM	*prec (mm)*	*prec (%)*	*tmin (C)*	*tmax (C)*
East Asia and Pacific	CSIRO	21.9	2.1	1.66	1.56
East Asia and Pacific	NCAR	76.21	7.6	2.61	2.08
Europe and Central Asia	CSIRO	26.21	6.1	1.82	1.67
Europe and Central Asia	NCAR	56.14	13.2	4.35	3.65
Latin America and the Caribbean	CSIRO	–8.36	–0.6	1.57	1.62
Latin America and the Caribbean	NCAR	28.39	1.9	2.03	1.91
Middle East and North Africa	CSIRO	–2.36	–2.0	1.65	1.56
Middle East and North Africa	NCAR	26.96	22.1	2.8	2.54
South Asia	CSIRO	14.51	1.6	1.79	1.64
South Asia	NCAR	100.95	11.2	2.37	1.76
Sub-Saharan Africa	CSIRO	–27.75	–3.5	1.69	1.79
Sub-Saharan Africa	NCAR	69.58	8.6	2.29	1.77
All Developing	CSIRO	6.44	0.8	1.71	1.66
All Developing	NCAR	56.85	7.5	3.08	2.58
World	CSIRO	9.09	1.8	1.3	1.22
World	NCAR	45.55	9.1	2.28	1.91

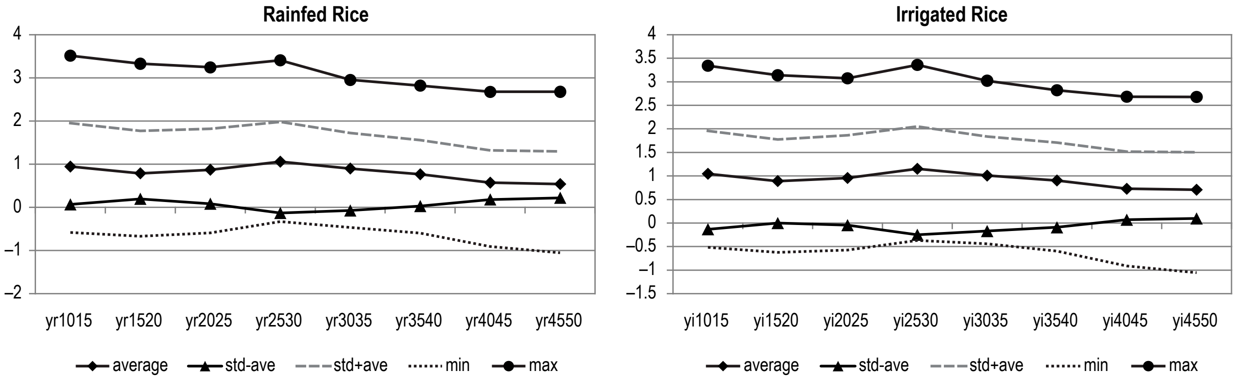
Source: Compiled by authors.

FIGURE 23. EXOGENOUS PRODUCTIVITY GROWTH RATES (% PER YEAR) FOR SELECTED CROPS AND MANAGEMENT TYPE



(Continued on next page)

FIGURE 23. (*continued*)



Source: Food and Agriculture Organization (FAO).

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