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FOOD POLICY
REPORT

CLIMATE CHANGE

Impact on Agriculture and Costs of Adaptation

Gerald C. Nelson, Mark W. Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler, Siwa Msangi, Amanda Palazzo, Miroslav Batka, Marilia Magalhaes, Rowena Valmonte-Santos, Mandy Ewing, and David Lee

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Executive Summary

The Challenge

The unimpeded growth of greenhouse gas emissions is raising the earth's temperature. The consequences include melting glaciers, more precipitation, more and more extreme weather events, and shifting seasons. The accelerating pace of climate change, combined with global population and income growth, threatens food security everywhere.

Agriculture is extremely vulnerable to climate change. Higher temperatures eventually reduce yields of desirable crops while encouraging weed and pest proliferation. Changes in precipitation patterns increase the likelihood of short-run crop failures and long-run production declines. Although there will be gains in some crops in some regions of the world, the overall impacts of climate change on agriculture are expected to be negative, threatening global food security.

Populations in the developing world, which are already vulnerable and food insecure, are likely to be the most seriously affected. In 2005, nearly half of the economically active population in developing countries—2.5 billion people—relied on agriculture for its livelihood. Today, 75 percent of the world's poor live in rural areas.[1]

This Food Policy Report presents research results that quantify the climate-change impacts mentioned above, assesses the consequences for food security, and estimates the investments that would offset the negative consequences for human well-being.

This analysis brings together, for the first time, detailed modeling of crop growth under climate change with insights from an extremely detailed global agriculture model, using two climate scenarios to simulate future climate. The results of the analysis suggest that ***agriculture and human well-being will be negatively affected by climate change:***

- In developing countries, climate change will cause yield declines for the most important crops. South Asia will be particularly hard hit.
- Climate change will have varying effects on irrigated yields across regions, but irrigated yields for all crops in South Asia will experience large declines.
- Climate change will result in additional price increases for the most important agricultural crops–rice, wheat, maize, and soybeans. Higher feed prices will result in higher meat prices. As a result, climate change will reduce the growth in meat consumption slightly and cause a more substantial fall in cereals consumption.
- Calorie availability in 2050 will not only be lower than in the no–climate-change scenario—it will actually decline relative to 2000 levels throughout the developing world.
- By 2050, the decline in calorie availability will increase child malnutrition by 20 percent relative to a world with no climate change. Climate change will eliminate much of the improvement in child malnourishment levels that would occur with no climate change.
- Thus, aggressive agricultural productivity investments of US$7.1–7.3 billion[2] are needed to raise calorie consumption enough to offset the negative impacts of climate change on the health and well-being of children.

Recommendations

The results of this analysis suggest the following policy and program recommendations.

1. **Design and implement good overall development policies and programs.** Given the current uncertainty about location-specific effects of climate change, good development policies and programs are also the best climate-change adaptation investments. A pro-growth, pro-poor development agenda that supports agricultural sustainability also contributes to food security and climate-change adaptation in the developing world. Adaptation to climate change is easier when individuals have more resources and operate in an economic environment that is flexible and responsive.

2. **Increase investments in agricultural productivity.** Even without climate change, greater investments in agricultural science and technology are needed to meet the demands of a world population expected to reach 9 billion by 2050. Many of these people will live in the developing world, have higher incomes, and desire a more diverse diet. Agricultural science- and technology-based solutions are essential to meet those demands.

   Climate change places new and more challenging demands on agricultural productivity. Crop and livestock productivity-enhancing research, including biotechnology, will be essential to help overcome stresses due to climate change. Crops and livestock are needed that are doing reasonably well in a range of production environments rather than extremely well in a narrow set of climate conditions. Research on dietary changes in food animals and changes in irrigation-management practices is needed to reduce methane emissions.

   One of the key lessons of the Green Revolution is that improved agricultural productivity, even if not targeted to the poorest of the poor, can be a powerful mechanism for alleviating poverty indirectly by creating jobs and lowering food prices. Productivity enhancements that increase farmers' resilience in the face of climate-change pressures will likely have similar poverty-reducing effects.

   Rural infrastructure is essential if farmers are to take advantage of improved crop varieties and management techniques. Higher yields and more cropped area require maintaining and increasing the density of rural road networks to increase access to markets and reduce transaction costs. Investments in irrigation infrastructure are also needed, especially to improve the efficiency of water use, but care must be taken to avoid investments in places where water availability is likely to decline.

3. **Reinvigorate national research and extension programs.** Investment in laboratory scientists and the infrastructure they require is needed. Partnerships with other national systems and international centers are part of the solution. Collaboration with local farmers, input suppliers, traders, and consumer groups is also essential for effective development and dissemination of locally appropriate, cost-effective techniques and cultivars to help revitalize communications among farmers, scientists, and other stakeholders to meet the challenges of climate change.

   Within countries, extension programs can play a key role in information sharing by transferring technology, facilitating interaction, building capacity among farmers, and encouraging farmers to form their own networks. Extension services that specifically address climate-change adaptation include disseminating local cultivars of drought-resistant crop varieties, teaching improved management systems, and gathering information to facilitate national research work. Farmer organizations can be an effective information-sharing mechanism and have the potential to provide cost-effective links between government efforts and farmer activities.

4. **Improve global data collection, dissemination, and analysis**. Climate change will have dramatic consequences for agriculture. However, substantial uncertainty remains about where the effects will be greatest. These uncertainties make it challenging to move forward on policies to combat the effects of climate change. Global efforts to collect and disseminate data on the spatial nature of agriculture need to be strengthened. Regular, repeated observations of the surface of the earth via remote sensing are critical. Funding for national statistical programs should be increased so that they can fulfill the task of monitoring global change. Understanding agriculture–climate interactions well enough to support adaptation and mitigation activities based on land use requires major improvements in data collection, dissemination, and analysis.

5. **Make agricultural adaptation a key agenda point within the international climate negotiation process.** International climate negotiations provide a window of opportunity for governments and civil-society organizations to advance proposals for practical actions on adaptation in agriculture.

6. **Recognize that enhanced food security and climate-change adaptation go hand in hand.** Climate change will pose huge challenges to food-security efforts. Hence, any activity that supports agricultural adaptation also enhances food security. Conversely, anything that results in increased food security will provide the poor, especially the rural poor, with the resources that will help them adapt to climate change.

7. **Support community-based adaptation strategies.** Crop and livestock productivity, market access, and the effects of climate all are extremely location specific. International development agencies and national governments should work to ensure that technical, financial, and capacity-building support reaches local communities. They should also encourage community participation in national adaptation planning processes. Community-based adaptation strategies can help rural communities strengthen their capacity to cope with disasters, improve their land-management skills, and diversify their livelihoods. While national adaptation policies and strategies are important, the implementation of these strategies at the local level will be the ultimate test of the effectiveness of adaptation.

8. **Increase funding for adaptation programs by at least an additional $7 billion per year.** At least $7 billion per year in additional funding is required to finance the research, rural infrastructure, and irrigation investments needed to offset the negative effects of climate change on human well-being. The mix of investments differs by region: Sub-Saharan Africa requires the greatest overall investment and a greater share of investments in roads, Latin America in agricultural research, and Asia in irrigation efficiency.

Climate-Change Scenarios[3]

The research underlying this report provides detailed estimates of the impacts of climate change on agricultural production, consumption, prices, and trade, and also estimates the costs of adaptation. It uses a global agricultural supply-and-demand projection model (IMPACT 2009) linked to a biophysical crop model (DSSAT) of the impact of climate change on five important crops: rice, wheat, maize, soybeans, and groundnuts (see box). The report assesses climate-change effects on food security and human well-being using two indicators: per capita calorie consumption and child malnutrition numbers. It estimates the cost of investments—in three primary sources of increased agricultural productivity (agricultural research, rural roads, and irrigation)—needed to return the values of these two indicators from their 2050 values with climate change to their 2050 values without climate change. In other words, this report isolates the effects of climate change on future well-being and identifies only the costs of compensating for climate change.

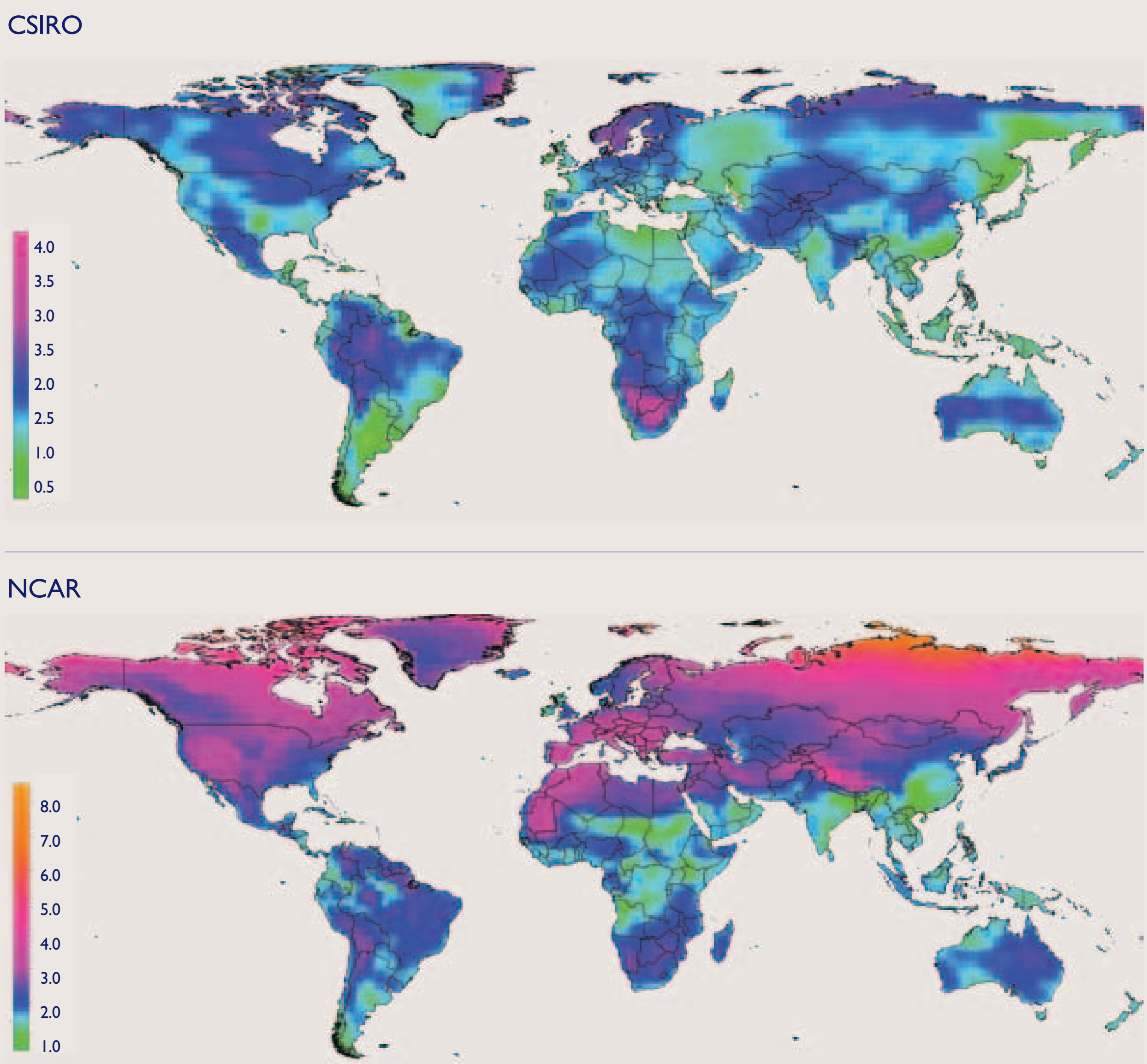
IMPACT 2009

The IMPACT model was originally developed by the International Food Policy Research Institute (IFPRI) for projecting global food supply, food demand, and food security to 2020 and beyond.[4] It analyzes 32 crop and livestock commodities in 281 regions of the world that together cover the earth's land surface (with the exception of Antarctica). These regions are called food production units (FPUs). Production and demand relationships in countries are linked through international trade flows. The model simulates growth in crop production, determined by crop and input prices, externally determined 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, and other uses. The 2009 version of the model includes a hydrology model and links to the Decision Support System for Agrotechnology Transfer (DSSAT) crop-simulation model, with yield effects of climate change at 0.5-degree intervals aggregated up to the food-production-unit level.

The DSSAT model is used to assess climate-change effects and CO_2 fertilization for five crops–rice, wheat, maize, soybeans, and groundnuts. For the remaining 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 follow the same (C4) metabolic pathway and are assumed to follow the DSSAT results for maize, in the respective geographic regions. The other crops in IMPACT follow a different pathway (C3), so the climate effects are assumed to follow the average for wheat, rice, soy, and groundnuts 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.

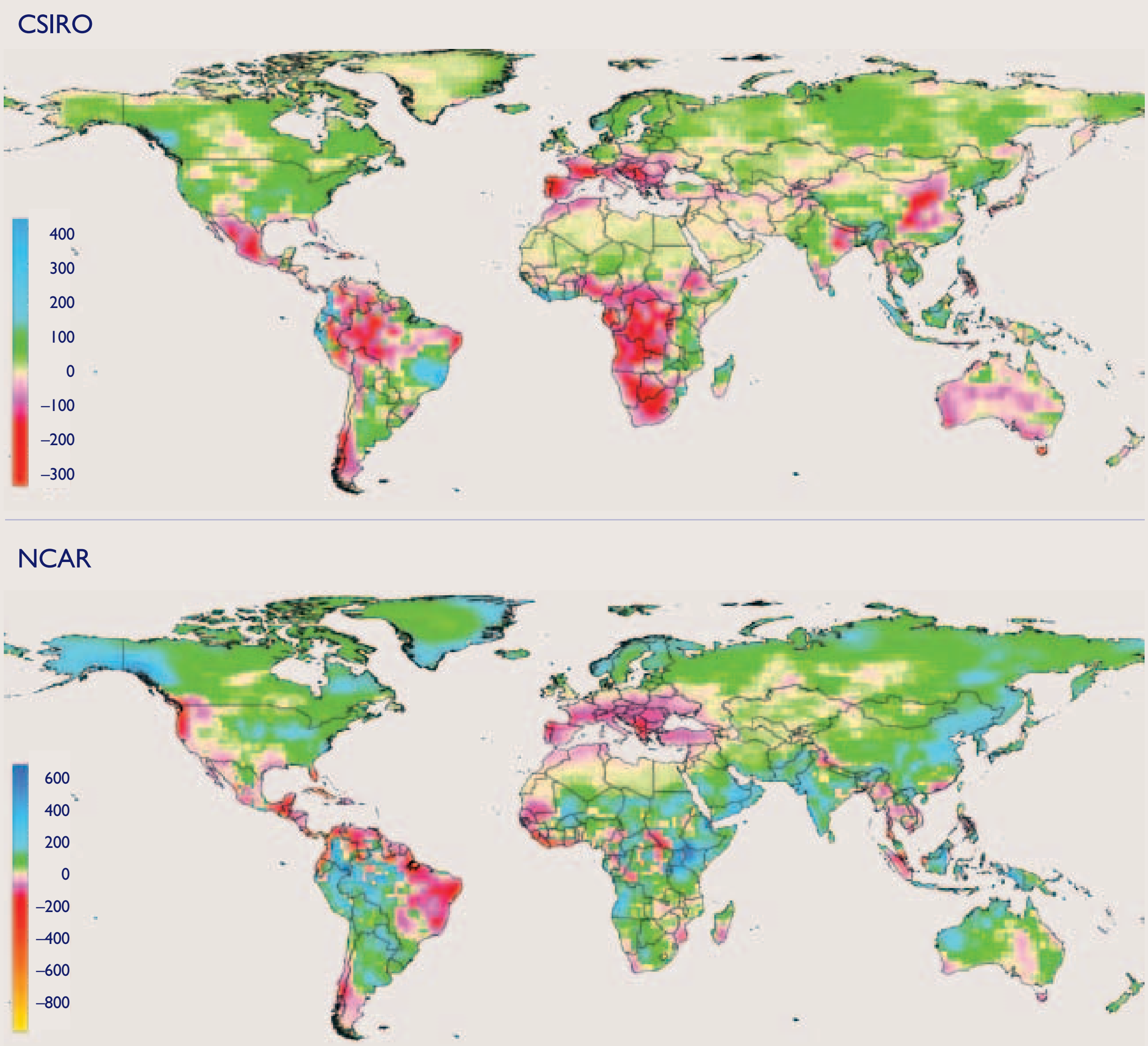
Because climate-change simulations are inherently uncertain, two climate models have been used to simulate future climate, using the A2[5] scenario of the IPCC's Fourth Assessment Report: the National Center for Atmospheric Research, US (NCAR) model and the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO) model. We refer to the combination of model runs with A2 inputs as the NCAR and CSIRO scenarios. Both scenarios project higher temperatures in 2050, resulting in higher evaporation and increased precipitation as this water vapor returns to earth. The "wetter" NCAR scenario estimates average precipitation increases on land of about 10 percent, whereas the "drier" CSIRO scenario estimates increases of about 2 percent. Figure 1 shows the change in average maximum temperature between 2000 and 2050 for the CSIRO and NCAR scenarios. Figure 2 shows changes in average precipitation. In each set of figures, the legend colors are identical; a specific color represents the same change in temperature or precipitation across the two scenarios.

Figure 1—Change in average maximum temperature (°C), 2000–2050



Source: Authors' calculations.

Figure 2—Change in precipitation (mm), 2000–2050



Source: Authors' calculations.

A quick glance at these figures shows that substantial differences exist across the two 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. The NCAR scenario has higher precipitation in Sub-Saharan Africa than does CSIRO. Northern China has both higher temperature and more precipitation under NCAR than under CSIRO. These figures qualitatively illustrate the range of potential climate outcomes using current modeling capabilities and provide an indication of the uncertainty in climate-change impacts.

Impacts of Climate Change

The impacts of climate change on agriculture and human well-being include: 1) the biological effects on crop yields; 2) the resulting impacts on outcomes including prices, production, and consumption; and 3) the impacts on per capita calorie consumption and child malnutrition. The biophysical effects of climate change on agriculture induce changes in production and prices, which play out through the economic system as farmers and other market participants adjust autonomously, altering crop mix, input use, production, food demand, food consumption, and trade.

1. The Biological Effects of Climate Change on Yields

Rising temperatures and changes in rainfall patterns have direct effects on crop yields, as well as indirect effects through changes in irrigation water availability.

Direct effects on yields: rainfed and irrigated crops

Table 1 reports the direct biological effects of the two climate-change scenarios on crop yields modeled directly with DSSAT for rainfed and irrigated crops in developing and developed countries,[6] with and without CO_2 fertilization (CF and No CF).[7] These results are created by "growing" each crop around the world at 0.5-degree intervals with 2000 climate, growing them again with a 2050 scenario value, and then calculating the ratio. In other words, no economic adjustments are included. The rainfed yield changes are driven by both precipitation and temperature changes; the irrigated yield effects are from temperature changes alone.

In developing countries, yield declines predominate for most crops without CO_2 fertilization. Irrigated wheat and irrigated rice are especially hard hit. On average, yields in developed countries are affected less than those in developing countries. For a few crops, climate change actually increases developed-country yields. In calculating these projections, the East Asia and Pacific region combines China, which is temperate for the most part, and Southeast Asia, which is tropical. The differential effects of climate change in these two climate zones are concealed. 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. Yields of important crops in Southeast Asia fall substantially in both scenarios unless CO_2 fertilization is effective in farmers' fields.

South Asia is particularly hard hit by climate change. For almost all crops, it is the region with the greatest yield decline. With CO_2 fertilization, the yield declines are lower; in many locations, some yield increases occur relative to 2000. 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 also has mixed yield effects, with some crops up slightly and some down.

Indirect effects: Irrigated crops

Climate change will have a direct impact on water availability for irrigated crops. Internal renewable water (IRW) is the water available from precipitation. Both climate scenarios result in more precipitation over land than would occur with no climate change. Under the NCAR scenario, all regions experience increased IRW. Under the CSIRO scenario, the average IRW increase is less than occurs with NCAR, and the Middle East and North Africa and Sub-Saharan Africa regions both experience reductions of about 4 percent.

In addition to precipitation changes, climate change-induced higher temperatures increase the water requirements of crops. The ratio of water consumption to requirements is called irrigation water supply reliability (IWSR). The smaller the ratio, the greater the water stress on irrigated crop yields.

Table 1—Climate-change induced yield effects by crop and management system, % change from yield with 2000 climate to yield with 2050 climate

Region	CSIRO No CF	NCAR No CF	CSIRO CF	NCAR CF
Maize, irrigated				
Developing countries	–2.0	–2.8	–1.4	–2.1
Developed countries	–1.2	–8.7	–1.2	–8.6
Maize, rainfed				
Developing countries	0.2	–2.9	2.6	–0.8
Developed countries	0.6	–5.7	9.5	2.5
Rice, irrigated				
Developing countries	–14.4	–18.5	2.4	–0.5
Developed countries	–3.5	–5.5	10.5	9.0
Rice, rainfed				
Developing countries	–1.3	–1.4	6.5	6.4
Developed countries	17.3	10.3	23.4	17.8
Wheat, irrigated				
Developing countries	–28.3	–34.3	–20.8	–27.2
Developed countries	–5.7	–4.9	–1.3	–0.1
Wheat, rainfed				
Developing countries	–1.4	–1.1	9.3	8.5
Developed countries	3.1	2.4	9.7	9.5

Source: Compiled by authors.
Note: For each crop and management system, this table reports the area weighted average change in yield for a crop grown with 2050 climate instead of 2000 climate. CF = with CO_2 fertilization; No CF = without CO_2 fertilization.

Across the group of developing countries, IWSR improves under the NCAR scenario and worsens under the CSIRO scenario. However, regional differentiation of climate-change effects is important. IWSR improves slightly for the Latin America and Caribbean region and for the Middle East and North Africa, but worsens slightly for Sub-Saharan Africa under both scenarios. For East Asia and the Pacific and for 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 the hydrology portion of IMPACT, taking into account the growing demand for water outside agriculture as well as agricultural demands. As expected, irrigated yield losses due to water stress are relatively higher under the CSIRO scenario than the NCAR scenario. For example, in East Asia and the Pacific, with no climate change, the combined effects of nonagricultural demand growth and increased irrigated area result in an average 4.8-percent decline in irrigated rice yields. Under the NCAR scenario, that decline is only 1.2 percent. However, under the drier CSIRO scenario, the irrigated yield loss from water stress is 6.7 percent. In East Asia and the Pacific, irrigated rice, wheat, and maize yield losses are all large under the CSIRO model. South Asia irrigated yields for all crops would experience large declines under both scenarios. In Sub-Saharan Africa, maize yields are less under both models, but the CSIRO effects are especially large. Latin America and the Caribbean yields are relatively unaffected, in part due to the small amount of irrigated production in that region.

2. Prices, Production, and Food Consumption

Prices

World prices are a useful single indicator of the effects of climate change on agriculture. Table 2 reports the effects of the two climate-change scenarios on world food prices, with and without CO_2 fertilization. It also reports the effects with no climate change. Figures 3 and 4 demonstrate world price effects for livestock production and major grains, respectively, assuming no CO_2 fertilization.

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, 52 to 55 percent for maize, 94 to 111 percent for wheat, and 11 to 14 percent for soybeans. If CO_2 fertilization is effective in farmers' fields, these 2050 prices are 10 percent smaller.

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.

Production

Table 3 reports the effects of climate change on crop production in 2050 compared to production without climate change, based on the NCAR and CSIRO scenarios, accounting for both the direct changes in yield and area caused by climate change and autonomous adaptation as farmers respond to changing prices with changes in crop mix and input use. The negative effects of climate change on crop production are especially pronounced in Sub-Saharan Africa and South Asia. In South Asia, the climate scenario results in a 14-percent decline in rice production relative to the no–climate-change scenario, a 44- to 49-percent decline in wheat production, and a 9- to 19-percent fall in maize production. In Sub-Saharan Africa, the rice, wheat, and maize yield declines with climate change are 15 percent, 34 percent, and 10 percent, respectively. For East Asia and the Pacific, the results are mixed and depend on both the crop and the model used. Rice production declines by around 10 percent, wheat production increases slightly, and maize production declines with the drier CSIRO scenario but increases with the NCAR scenario. Comparing average production changes, developing countries fare worse for all crops under both the CSIRO and NCAR scenarios than do developed countries.

Food Consumption

Agricultural output used for human consumption is determined by the interaction of supply, demand, and the resulting prices with individual preferences and income. Table 4 shows average per capita consumption of cereals and meat products in 2000 and in 2050 under the CSIRO and NCAR models, with and without CO_2 fertilization. It also reports consumption with no climate change.

Without climate change, rising per capita income results in reduced declines in per capita consumption of cereals in developing countries between 2000 and 2050 and increased meat consumption increases, with the meat increases more than offsetting the decline in cereals. Climate change reduces the growth in meat consumption slightly and causes a more substantial fall in the consumption of cereals. These results are the first indication of the negative welfare effects due to climate change. Both models have similar effects.

3. Per Capita Calorie Consumption and Child Malnutrition

The primary measures used for the effects of climate change on human welfare are the change in calorie availability and the change in the number of malnourished children between 2000 and 2050 without climate change, and in 2050 using the two climate-change scenarios.

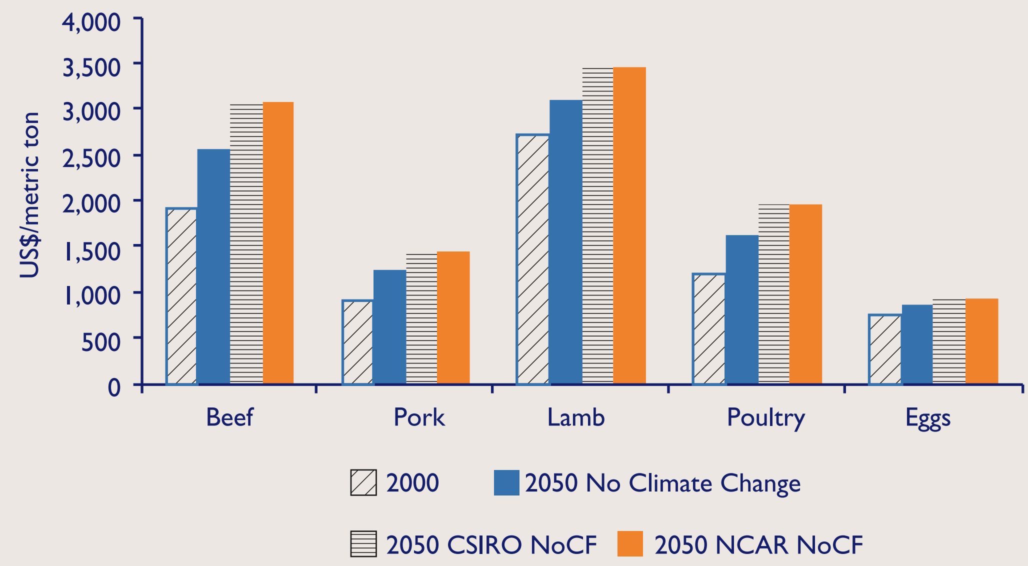
The declining consumption of cereals translates into similarly large declines in calorie availability as the result of climate change (see Figure 5 and Tables 5 and 6). Without climate change, calorie availability increases

Table 2—World food prices (US$/metric ton) in 2000 and 2050 and percent changes for selected crops and livestock products

Agricultural product	2000	2050: No climate change	2050: NCAR no CF	2050: CSIRO no CF	NCAR CF effect (% change from no CF)	CSIRO CF effect (% change from no CF)
Rice (US$/mt)	190	307	421	406	–17.0	–15.1
% change from 2000		61.6	121.2	113.4		
% change from 2050, no climate change			36.8	32.0		
Wheat (US$/mt)	113	158	334	307	–11.4	–12.5
% change from 2000		39.3	194.4	170.6		
% change from 2050, no climate change			111.3	94.2		
Maize (US$/mt)	95	155	235	240	–11.2	–12.6
% change from 2000		63.3	148.0	153.3		
% change from 2050, no climate change			51.9	55.1		
Soybeans (US$/mt)	206	354	394	404	–60.6	–62.2
% change from 2000		72.1	91.6	96.4		
% change from 2050, no climate change			11.4	14.2		
Beef (US$/mt)	1,925	2,556	3,078	3,073	–1.3	–1.5
% change from 2000		32.8	59.8	59.6		
% change from 2050, no climate change			20.4	20.2		
Pork (US$/mt)	911	1,240	1,457	1,458	–1.3	–1.5
% change from 2000		36.1	60.0	60.1		
% change from 2050, no climate change			17.5	17.6		
Lamb (US$/mt)	2,713	3,102	3,462	3,461	–0.7	–0.8
% change from 2000		14.4	27.6	27.6		
% change from 2050, no climate change			11.6	11.6		
Poultry (US$/mt)	1,203	1,621	1,968	1,969	–1.9	–2.1
% change from 2000		34.7	63.6	63.6		
% change from 2050, no climate change			21.4	21.5		

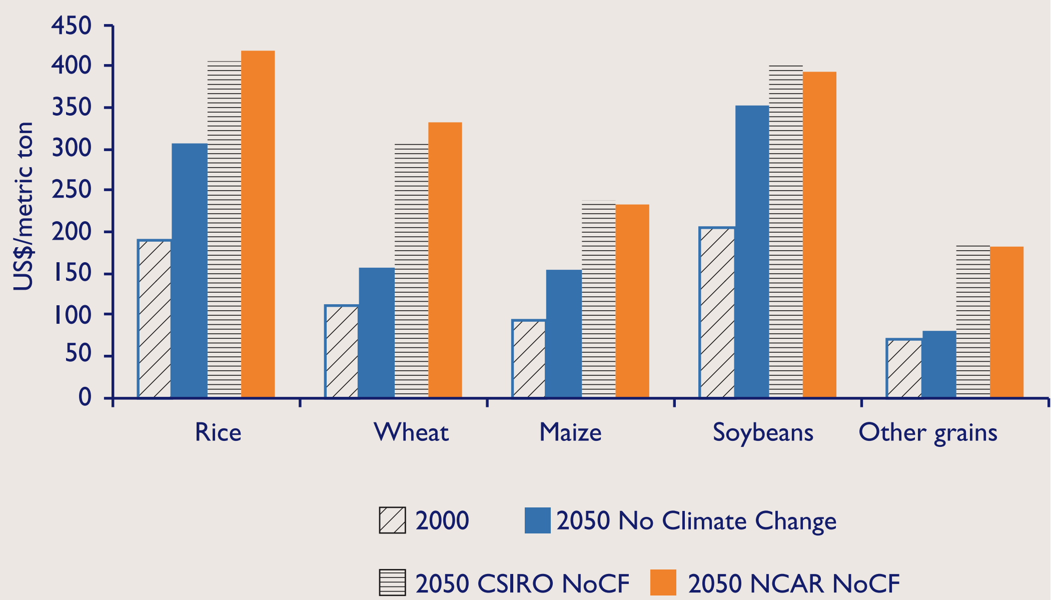
Source: Compiled by authors.
Note: Prices are in 2000 US$.

Figure 3—World prices, Livestock products



Source: Compiled by authors.
Note: Prices are in 2000 US$.

Figure 4—World prices, Major grains



Source: Compiled by authors.
Note: Prices are in 2000 US$.

Table 3—Climate-change effects on crop production, no CO_2 fertilization

Agricultural product	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	14.8	5.5	7.4	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 (% change)	41.0	–2.1	144.4	19.8	87.4	146.0	–0.3	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 (% change)	97.9	2.1	98.1	78.7	162.3	154.4	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	141.8	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 (% change)	15.7	86.6	65.1	78.8	59.4	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)	10.5	2.3	1.2	0.0	0.0	13.1	0.5	27.3	27.8
2050 No CC (mmt)	12.3	3.5	2.1	0.1	0.1	48.1	0.8	66.2	67.0
2050 No CC (% change)	16.5	50.1	77.2	113.0	128.0	267.2	60.5	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 (% change)	13.9	11.6	180.9	145.3	12.2	216.9	23.6	138.7	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: Compiled by authors.
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.

throughout the world between 2000 and 2050. The largest increase, of 13.8 percent, is in East Asia and the Pacific, but there are gains for the average consumer in all countries—by 3.7 percent in Latin America, 5.9 percent in Sub-Saharan Africa, and 9.7 percent in South Asia.

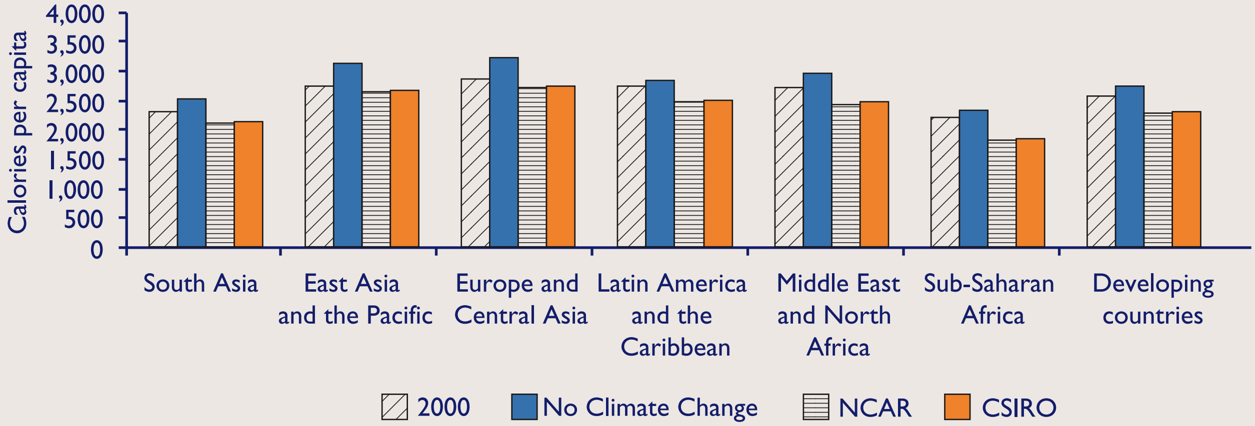
With climate change, however, calorie availability in 2050 is not only lower than the no-climate-change scenario in 2050—it actually declines relative to 2000 levels throughout the world. For the average consumer in a developing country, the decline is 10 percent relative to 2000. With CO_2 fertilization, the declines are 3 percent to 7 percent less severe, but are still large relative to the no–climate-change scenario. There is almost no difference in calorie outcome between the two climate scenarios.

Table 4—Per capita consumption (kg per year) of cereals and meats with and without climate change (NCAR and CSIRO)

		2050				
Region	2000	No climate change	CSIRO no CF	NCAR no CF	CSIRO CF effect (% change relative to CSIRO no CF in 2050)	NCAR CF effect (% change relative to NCAR no CF in 2050)
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: Compiled by authors.

Figure 5—Daily per capita calorie availability with and without climate change



Source: Compiled by authors.

Table 5—Daily per capita calorie availability with and without climate change

Region	2000	2050 No climate change kcal/day	2050 NCAR no CF kcal/day	2050 CSIRO no CF kcal/day	2050 NCAR CF effects (% change relative to NCAR no CF in 2050)	2050 CSIRO CF effects (% change relative to CSIRO no CF in 2050)
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: Compiled by authors.

Table 6—Total number of malnourished children in 2000 and 2050 (million children under 5 years of age)

Region	2000	2050				
		No climate change	NCAR no CF	CSIRO no CF	NCAR CF effects (% change relative to NCAR no CF in 2050)	CSIRO CF effects (% change relative to CSIRO no CF in 2050)
South Asia	76	52	59	59	–3	–3
East Asia and the Pacific	24	10	15	14	–9	–9
Europe and Central Asia	4	3	4	4	–4	–5
Latin America and and the Caribbean	8	5	6	6	–5	–5
Middle East and North Africa	3	1	2	2	–10	–11
Sub-Saharan Africa	33	42	52	52	–5	–6
All developing countries	148	113	139	137	–5	–5

Source: Compiled by authors.
Note: The last two columns in this table report the percentage difference between the number of malnourished children in 2050 with and without CO_2 fertilization. For example, under the NCAR model, assuming CO_2 fertilization is effective in the field, there would be a 3-percent decline in the number of malnourished children in South Asia relative to the climate change outcome without CO_2 fertilization.

Costs of Adaptation

Climate-change adaptation is increasingly on the agenda of researchers, policymakers, and program developers who are aware that climate change is real and threatens to undermine social and ecological sustainability. In agriculture, adaptation efforts focus on implementing measures that help build rural livelihoods that are more resilient to climate variability and disaster. This section provides an assessment of the costs of productivity-enhancing investments in agricultural research, rural roads, and irrigation infrastructure and efficiency that can help farmers adapt to climate change. First, regardless of climate-change scenario, agriculture will be negatively affected by climate change.

Climate change increases child malnutrition and reduces calorie consumption dramatically. Thus, aggressive agricultural productivity investments are needed to raise calorie consumption enough to offset the negative impacts of climate-change on the health and well-being of children.

In order to assess the costs of adaptation alone, it is important to identify agricultural productivity investments that reduce child malnutrition with climate change to no-climate-change levels, holding all other macro changes constant, such as income and population growth. Two scenarios are assessed. The first, shown in Table 7, focuses on developing countries and describes the investments needed to reduce childhood malnutrition close to level it would be without climatechange. The cost estimates are based only on productivity-enhancing investments in developing countries. The second experiment involves including additional productivity enhancements in developed countries to assess the potential for spillovers in the developing world.

Table 8 reports the effects on daily per capita calorie availability for these two scenarios. Table 9 reports the results for child malnutrition for the two climate models relative to the no–climate-change scenario. Figures 6 and 7 are graphs of the malnutrition counts for the various developing-country regions before and after the productivity-enhancing investments. Finally, Table 10 reports the annualized additional investment costs needed to counteract the effects of climate change on children.

Table 7—Developing-country agricultural productivity investments

60-percent increase in crop (all crops) yield growth over baseline
30-percent increase in animal numbers growth
40-percent increase in production growth of oils and meals
25-percent increase in irrigated area growth
15-percent decrease in rainfed area growth
15-percent increase in basin water efficiency by 2050

Source: Compiled by authors.

Table 8—Daily calorie per capita consumption with adaptive investments (kcals/person/day)

Scenario	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
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

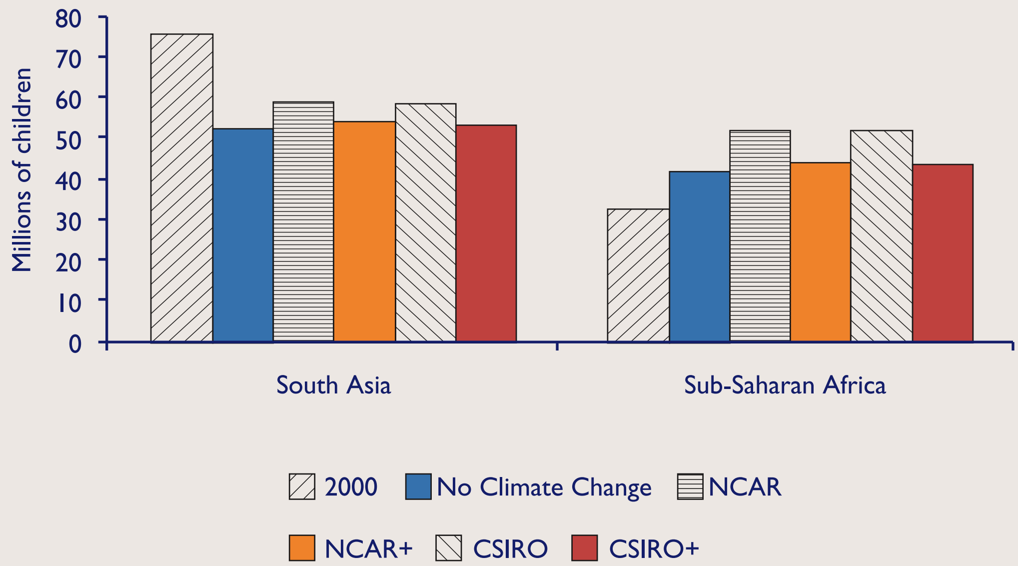
Source: Compiled by authors.
Note: NCAR + and CSIRO + include only agricultural productivity investments in the developing world. NCAR ++ and CSIRO ++ include all productivity improvements in both developing and developed countries. The climate change results presented in this table assume no CO_2 fertilization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

Table 9—Child malnutrition counts with adaptive investments (million children)

Scenario	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
2000	75.62	23.81	4.11	7.69	3.46	32.67	147.84
2050							
No climate change	52.29	10.09	2.70	4.98	1.10	41.72	113.33
NCAR	59.06	14.52	3.73	6.43	2.09	52.21	138.52
NCAR +	54.16	10.82	3.04	4.94	1.37	44.09	118.87
NCAR ++	53.66	10.48	2.97	4.83	1.32	43.47	117.18
CSIRO	58.56	14.25	3.66	6.37	2.01	52.06	137.39
CSIRO +	53.51	10.44	2.95	4.88	1.29	43.87	117.40
CSIRO ++	52.96	10.18	2.87	4.76	1.23	43.17	115.62

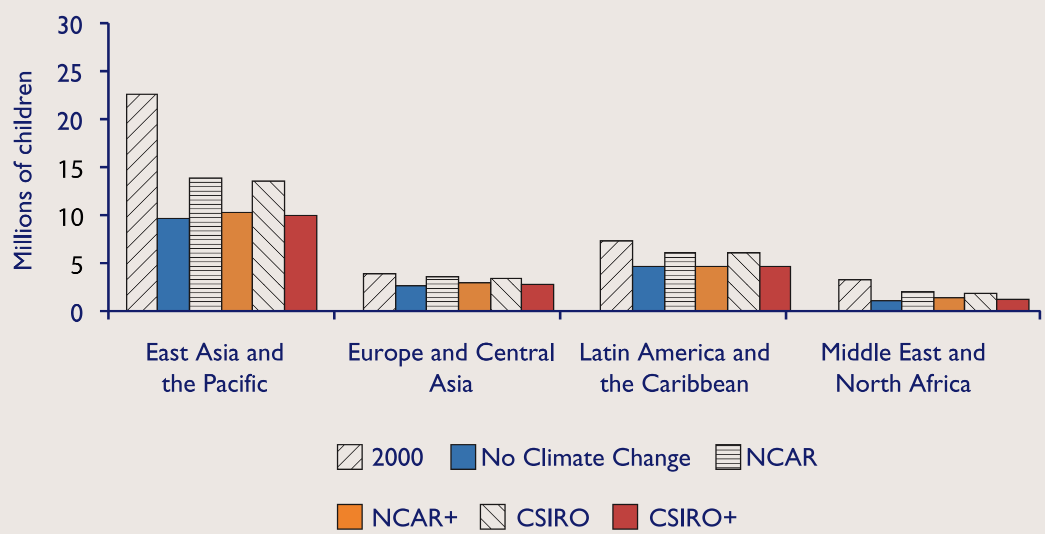
Source: Compiled by authors.
Note: NCAR + and CSIRO + include only agricultural productivity investments in the developing world. NCAR ++ and CSIRO ++ include all productivity improvements in both developing and developed countries. The climate change results presented in this table assume no CO_2 fertilization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

Figure 6—Child malnutrition effects, South Asia and Sub-Saharan Africa



Source: Compiled by authors.

Figure 7—Child malnutrition effects, East Asia and the Pacific, Europe and Central Asia, Latin America and the Caribbean, and Middle East and North Africa



Source: Compiled by authors.

As shown in Table 10, the additional annual investments needed to return the child malnutrition numbers to the no climate-change results are $7.1 billion under the wetter NCAR scenario and $7.3 billion under the drier CSIRO scenario. 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 the Caribbean close behind with about $1.2 to $1.3 billion per year. East Asia and the Pacific needs are just under $1 billion per year. Agricultural research is important in all three of these regions, as are irrigation investments. Unlike Sub-Saharan Africa, road investments in these regions are relatively small.

With additional investments in 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 messages embodied in these results point to the importance of improving the productivity of agriculture as a means of meeting the future challenges that climate change represents. The path to the needed agricultural productivity gains varies by region and to some extent, by climate scenario.

Table 10—Additional annual investment expenditure needed to counteract the effects of climate change on nutrition (million 2000 US$)

Scenario	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
NCAR with developing-country investments							
Agricultural research	172	151	84	426	169	314	1,316
Irrigation expansion	344	15	6	31	–26	537	907
Irrigation efficiency	999	686	99	129	59	187	2,158
Rural roads (area expansion)	8	73	0	573	37	1,980	2,671
Rural roads (yield increase)	9	9	10	3	1	35	66
Total	1,531	934	198	1,162	241	3,053	7,118
CSIRO with developing-country investments							
Agricultural research	185	172	110	392	190	326	1,373
Irrigation expansion	344	1	1	30	–22	529	882
Irrigation efficiency	1,006	648	101	128	58	186	2,128
Rural Roads (area expansion)	16	147	0	763	44	1,911	2,881
Rural Roads (yield increase)	13	9	11	3	1	36	74
Total	1,565	977	222	1,315	271	2,987	7,338

Source: Compiled by authors.
Note: These results are based on crop model yield changes that do not include the CO_2 fertilization effect.

Conclusion

This analysis brings together for the first time detailed modeling of crop growth under climate change with insights from an extremely detailed global agriculture model. The results show that agriculture and human well-being will be negatively affected by climate change. Crop yields will decline, production will be affected, crop and meat prices will increase, and consumption of cereals will fall, leading to reduced calorie intake and increased child malnutrition.

These stark results suggest the following policy and program recommendations:

- Design and implement good overall development policies and programs.
- Increase investments in agricultural productivity.
- Reinvigorate national research and extension programs.
- Improve global data collection, dissemination, and analysis.
- Make agricultural adaptation a key agenda point within the international climate negotiation process.
- Recognize that enhanced food security and climate-change adaptation go hand in hand.
- Support community-based adaptation strategies.
- Increase funding for adaptation programs by at least an additional $7 billion per year.

These investments may not guarantee that all the negative consequences of climate change can be overcome. But continuing with a "business-as-usual" approach will almost certainly guarantee disastrous consequences.

Notes

1. World Bank 2008.

2. All dollars are 2000 US dollars unless otherwise indicated.

3. For a full description of the methodology, see Appendix 1 (www.ifpri.org/sites/default/files/publications/pr21app1.pdf).

4. Rosegrant et al. 2008.

5. See Appendix 1 (www.ifpri.org/sites/default/files/publications/pr21app1.pdf) for description of A2 scenario.

6. To see the results for the full World Bank regional grouping of countries, see Table A2.1 in Appendix 2 (www.ifpri.org/sites/default/files/publications/pr21app2.pdf).

7. 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. Because the effects of higher concentrations of CO_2 on farmer's fields are uncertain, we report results both with 369 parts per million of atmospheric CO_2—the approximate concentration in 2000 (No CF results)—and 532 parts per million (CF results), the expected concentration in 2050 under the A2 scenario.

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Climate Change

Impact on Agriculture and Costs of Adaptation

Gerald C. Nelson, Mark W. Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler, Siwa Msangi, Amanda Palazzo, Miroslav Batka, Marilia Magalhaes, Rowena Valmonte-Santos, Mandy Ewing, and David Lee

APPENDIX 1:

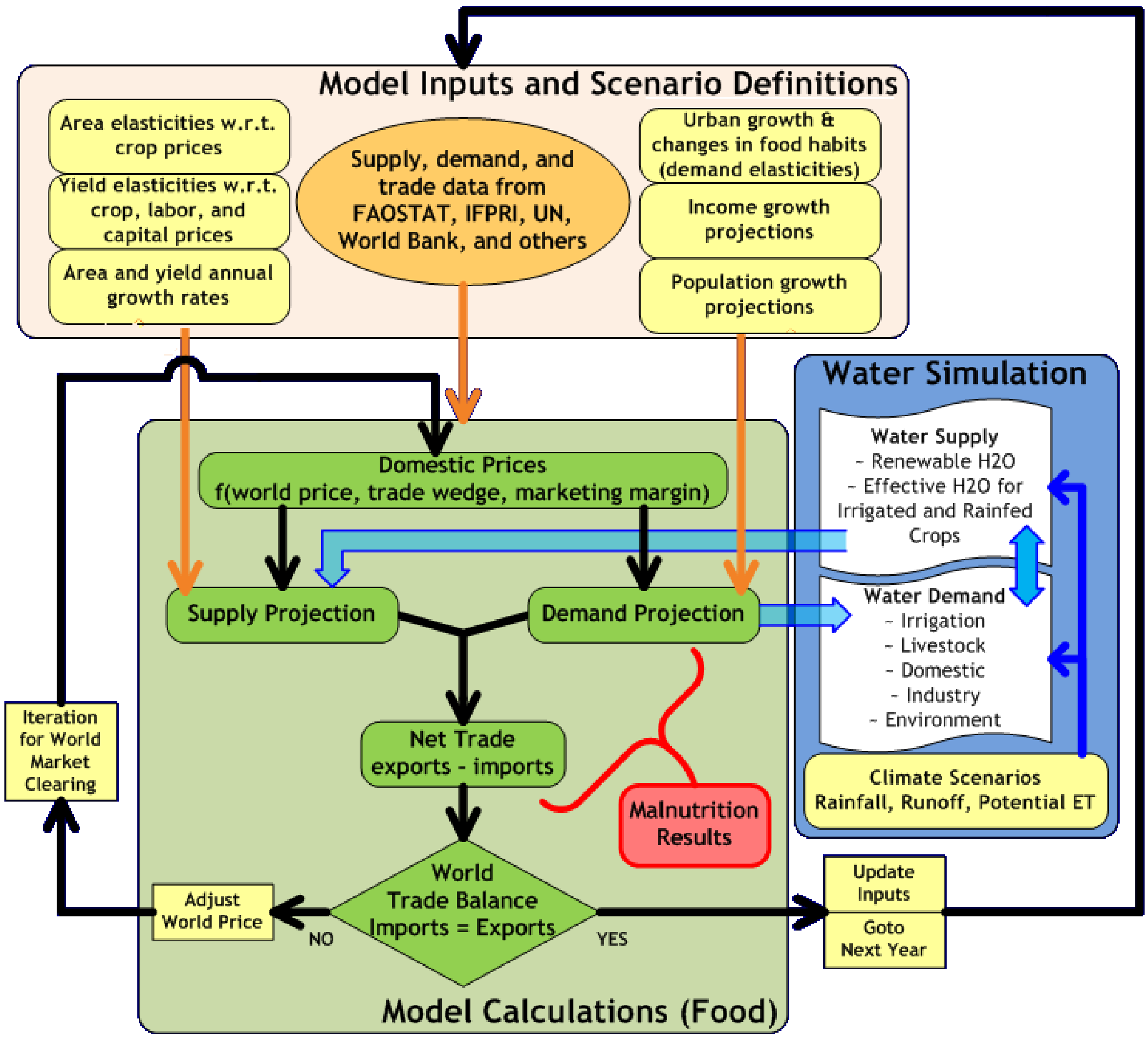
METHODOLOGY

Washington, D.C.
September 2009

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. The analytical framework used in the report 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.

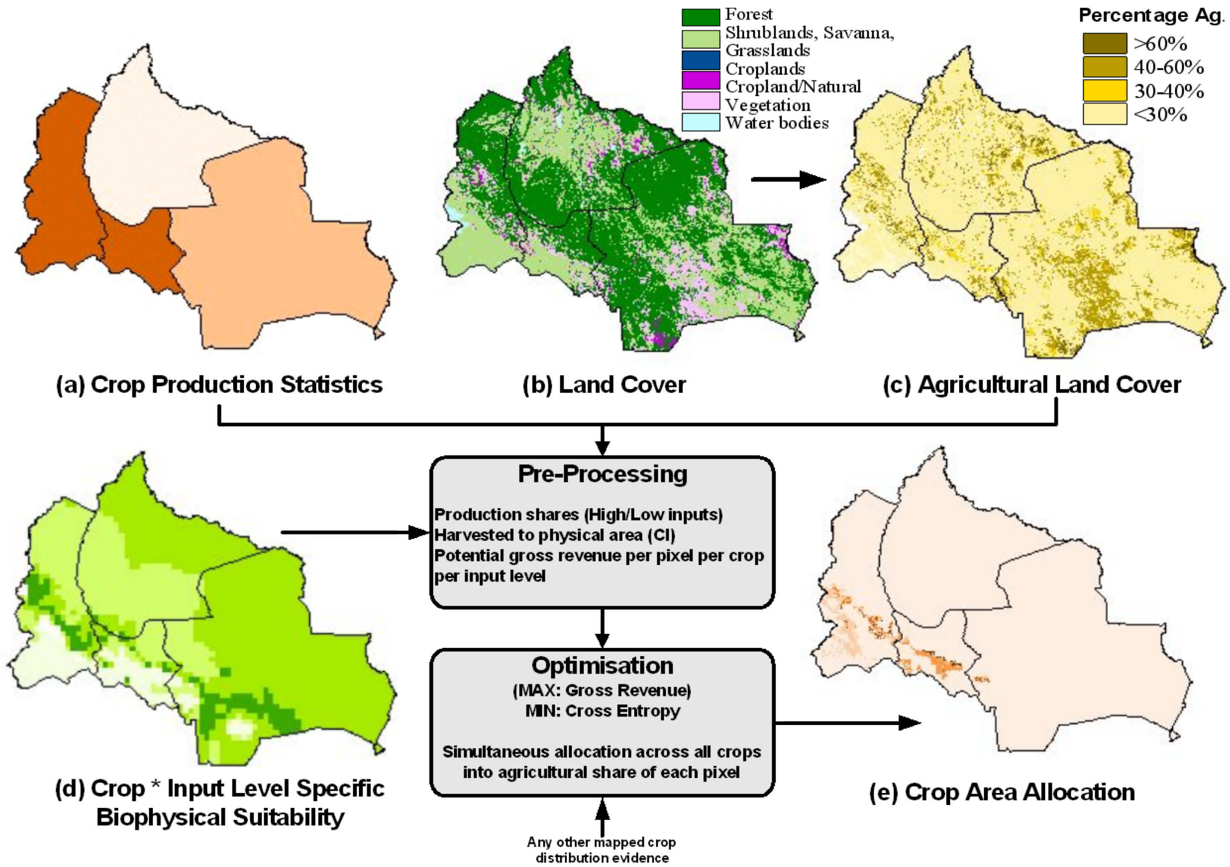
Figure A1.1 is a diagram illustrating the links among the partial equilibrium agriculture model, the hydrology modeling, and the crop modeling in IFPRI's IMPACT 2009.

Figure A1.1—IMPACT 2009 modeling framework



The modeling methodology reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships at a national level with spatially disaggregated 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 ISPAM dataset of crop location and management techniques (You and Wood, 2006), illustrated in Figure A1.2. These results are then aggregated and fed into the IMPACT model.

Figure A1.2—ISPAM dataset development process



CROP MODELING

The DSSAT crop-simulation model is an extremely detailed process model of the daily development of a specific variety 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 information, including crop variety, planting date, plant spacing, and inputs such as fertilizer and irrigation.

For maize, wheat, rice, groundnuts, and soybeans, we use version 4.0 of the DSSAT crop model (Jones, et al., 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 respective geographic regions. The remaining crops in IMPACT are assumed to follow the C3 pathway and use the average responses 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.

CLIMATE DATA

DSSAT requires detailed daily climate data, not all of which are readily available, so various approximation techniques were developed. To simulate current climate, we use the WorldClim current conditions dataset (**www.worldclim.org**), which is representative of 1950 to 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.

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 1979to 2000. Overall averages for each month were computed between all the years (*e.g.*, 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 SIMMETEO 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.[1] 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.

OTHER AGRONOMIC INPUTS

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

Soil characteristics

The DSSAT model 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 is a pixel is used to represent the soil type for the entire pixel.

Crop variety

DSSAT includes genetic coefficients for 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 IR64 (a recent IRRI indica rice variety) and a Japonica variety. The rice varieties are assigned to geographic areas depending upon what variety is more commonly cultivated within the region.

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.

---

[1] 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 Modelling (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.

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 A1.3–5.

Figure A1.3—Rainfed crop planting month, 2000 climate

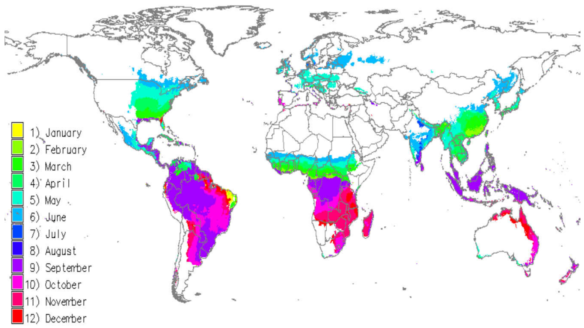


Figure A1.4—Rainfed planting month, 2050 climate, CSIRO GCM A2 Scenario (AR4)

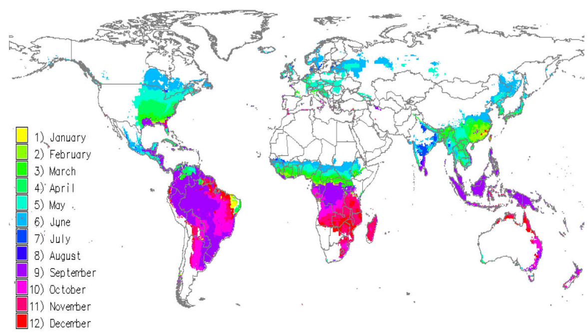
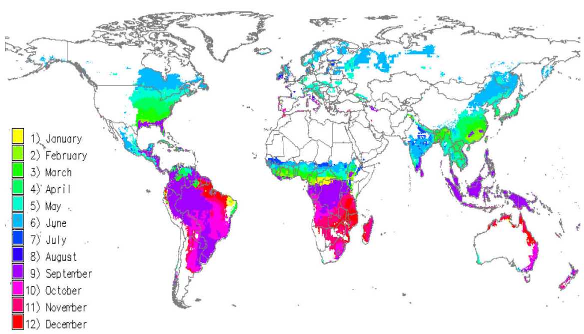


Figure A1.5—Rainfed planting month, 2050 climate, NCAR GCM A2 Scenario (AR4)



Source: Compiled by authors.

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 four 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 Figures A1.6–8.

Figure A1.6—Irrigated planting month, 2000 climate

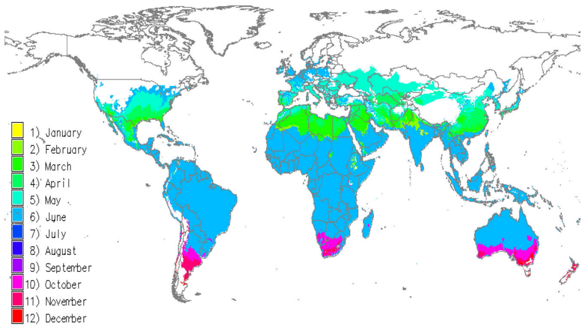


Figure A1.7—Irrigated planting month, 2050 climate, CSIRO GCM A2 Scenario (AR4)

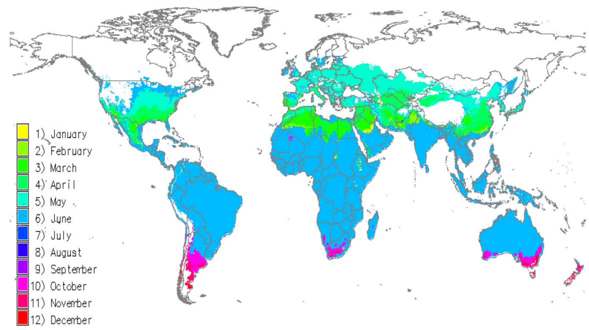
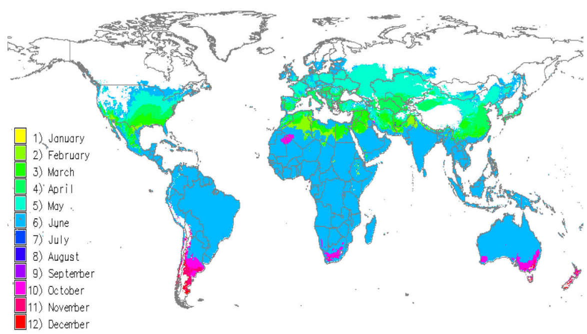


Figure A1.8—Irrigated planting month, 2050 climate, NCAR GCM A2 Scenario (AR4)



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.

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 question whether these laboratory results translate to actual field conditions. A recent report on field experiments on CO_2 fertilization (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 (Zavala et al. 2008) finds that higher levels of atmospheric CO_2 increase the susceptibility of soybean plants grown in the U.S. Midwest to the Japanese beetle and maize to the western corn rootworm. So the actual benefits in farmers' fields 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 expected CO_2 levels in 2050 actually used in the A2 scenario. For some results, in particular the cost estimates, we report only the outcomes with 369 ppm, called the No CF option, under the assumption that this more accurately reflects the effects of CO_2 fertilization in farmers' fields.

Our aggregation process from ISPAM 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 increase at 30 percent. Finally, we limit the negative effect of climate on yield growth in IMPACT to -2 percent per year.

Irrigation

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 the DSSAT model as needed. Soil moisture is completely replenished at the beginning of each day in a model run for an irrigated crop.

Nutrient level

The DSSAT model 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.

FROM DSSAT TO THE IMPACT MODEL

The DSSAT model is run for five crops (rice, wheat, maize, soybeans, and groundnuts) at 0.5-degree intervals for the locations that the ISPAM dataset says the crop was grown in 2000. Other crops are assumed to have productivity effects from climate change similar to these five crops as described above. The results from this analysis are then aggregated to the IMPACT FPU level as described below.

The IMPACT 2009 Model[2]

The IMPACT model was initially developed by the International Food Policy Research Institute (IFPRI) for projecting global food supply, food demand, and food security to year 2020 and beyond (Rosegrant et al. 2001). 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 A1.9, 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.

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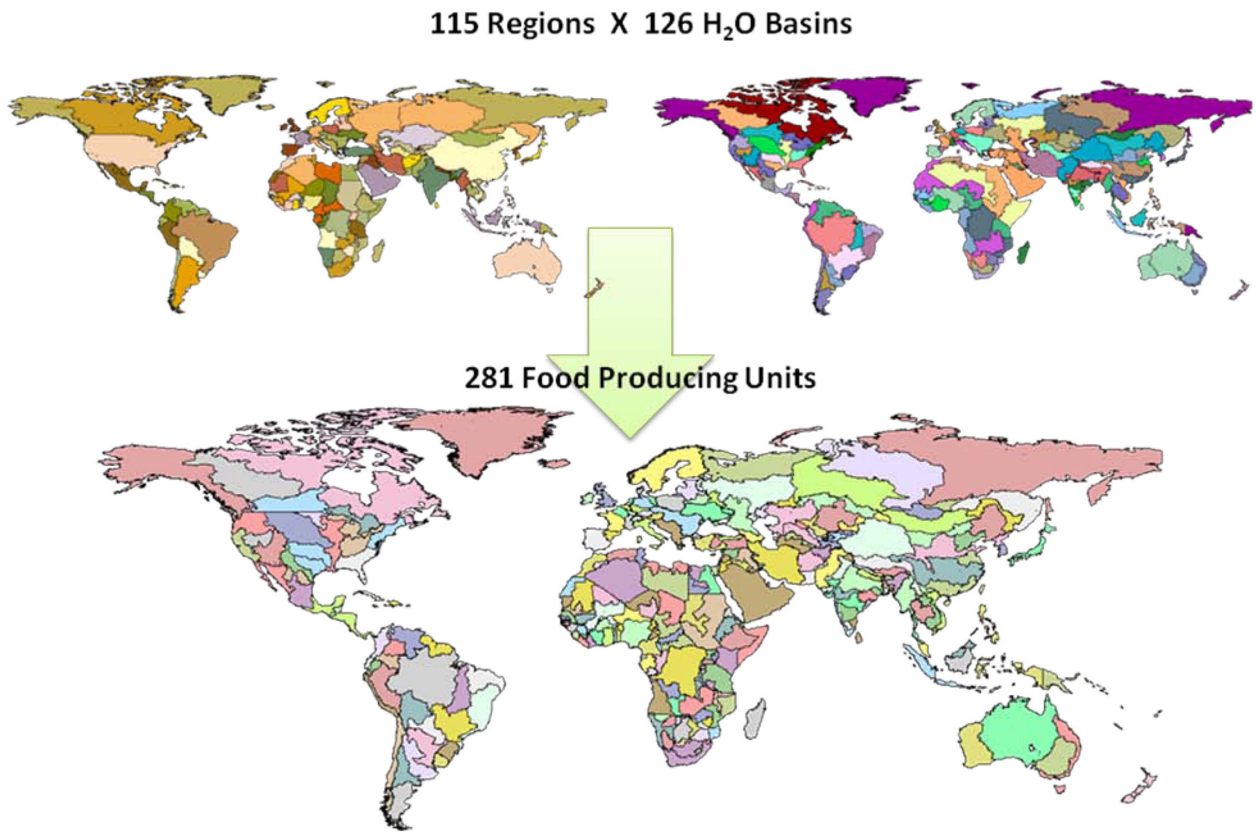
[2] We provide an overview of the IMPACT model here and refer interested readers to Rosegrant et al. 2008 for technical details.

Figure A1.9—IMPACT model units of analysis, Food Producing Units (FPUs)



MODELING CLIMATE CHANGE IN IMPACT

Climate-change effects on crop productivity enter into the IMPACT model by affecting both crop area and yield. Yields 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. 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 has high as 5 percent per year for some years.

$$YC_{tni} = \beta_{tni} \times (PS_{tni})^{\gamma_{iin}} \times \prod_{k} (PF_{tnk})^{\gamma_{ikn}} \times (1 + gy_{tni}) - \Delta YC_{tni}(WAT_{tni}) \quad (1)$$ [3]

We generate relative climate change productivity effects by calculating location-specific yields for each of the five crops modeled with DSSAT for 2000 and 2050 climate as described above and then constructing a ratio of the two. The ratio is then used to alter gy_{tni}. Rainfed crops react to changes in precipitation as modeled in DSSAT.

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

Irrigated crop effects of climate change are captured as part of the hydrology model built into IMPACT, a semi-distributed macro-scale hydrology module that covers the global land mass except the 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 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 food production units of 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 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 proceeds as follows. First, within an FPU, choose the appropriate ISPAM 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 ISPAM 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 baseline). The ratio of the weighted-average-yield in 2050 to the baseline 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 unrealistically large and positive, usually due either to starting from a low base (which can be common in marginal production areas) or 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 baseline at the pixel level.

Harvested areas in the IMPACT model are affected by climate change in a similar way to yields, though with a slight complication. In any particular FPU, land may become more or less suitable for any crop and will impact the intrinsic area growth rate, ga_{tni} in the area growth calculation. Water availability will affect the *WAT* factor for irrigated crops as with the yields.

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

Area changes due to climate changes are handled asymmetrically. 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 close 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. An example is that parts of Ontario, Canada with too short a growing season in 2000 will be able to grow maize in 2050 in 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.

MODELING THE COSTS OF ADAPTATION TO CLIMATE CHANGE

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

A key issue is what to use as the metric for adaptation. The results reported here are based on two measures: the human well-being measure of malnutrition in the highly vulnerable demographic of pre-school children and average per capita calorie consumption. We use the underweight definition of malnutrition (proportion of children under 5 falling below minus two standard deviations from the median weight-for-age standard set by the U.S.[4] National

[4] 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

Center for Health Statistics and the World Health Organization). The malnutrition estimate is determined in part by per calorie availability but also includes access to clean drinking water and maternal education, which are assumed not to change.

Estimating child malnutrition

The IMPACT model provides data on 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 5 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:

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

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.

$\Delta_{t,2000}$ = the difference between the variable values at time t and the base year 2000.

Malnutrition data are taken from the World Development Indicators. Other data sources include the FAO FAOSTAT database, and the UNESCO UNESCOSTAT database.

$$\mathrm{NMAL_t} = \mathrm{MAL_t} \times \mathrm{POP5_t}, \quad (24)$$

where *NMAL* = number of malnourished children and *POP5* = number of children 0–5 years old in the population.

Observed relationships between all of these factors were used to create the semi-log functional mathematical model, allowing an estimate of the number of malnourished children derived from data describing the average per capita calorie consumption, female access to secondary education, the quality of maternal and child care, and health and sanitation.

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.

Investments in agricultural research, roads, and irrigation are used to alter calorie availability and child malnutrition estimates. The approach is to estimate the productivity growth needed to meet a malnutrition or calorie availability

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

target and then estimate the investment expenditures needed in research, irrigation, and road to generate that productivity growth.

AGRICULTURAL RESEARCH INVESTMENTS

The process of estimating agricultural research investments involves using expert opinion to estimate yield responsiveness to research expenditures and estimation of future expenditures on the basis of historical expenditure growth rates. The main portion of the data on public agricultural research is from the ASTI data set (ASTI, 2009) converted into 2000 US$ values by the GDP deflator obtained from the IMF's International Financial Statistics. For the remaining 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.[5] 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.[6] 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 this estimate.

The 2050 baseline research expenditures are generated by applying different rates of growth to the historical growth rates to the 2000 US $ values. These historical growth rates, g_h, are obtained from observed or estimated data on agricultural and research spending discussed above. The historical growth rate for each country is computed as an average of the annual historical growth rates for the last ten years or less when data is not available. For the remaining countries, regional average historical growth rates are computed from the data set and used for individual countries. The assumed baseline growth rates of research expenditure, g_a, are given in Table A1.1.

Table A1.1—Assumed multipliers of historic growth rates of agricultural research expenditures

Period	Multiplier of historic growth rate (%)
2000–2010	9
2011–2020	8
2021–2030	7
2031–2040	6
2041–2050	5

We assume that the yield elasticity with respect to research expenditures ($\varepsilon^{Yield}_{Research}$) is 0.296 for all countries and regions. This estimate is based on expert assessment.

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[5] 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.

[6] 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.

Agricultural research investment (AR_n) for every year after 2000 is calculated as follows:

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

$$AR_{baseline} = \sum_{y=2000}^{2050} AR_y \qquad (2)$$

For a given scenario, we determine the change in spending that is implied in final outcome for agricultural performance. This change is calculated with respect to the level of spending in the baseline case described above.

We use 2050 cereal yields for the baseline and the respective scenarios. The scenario agricultural research cost—$AR_{scenario}$—are computed as follows:

$$AR_{Scenario} = \left[1 + \frac{\dfrac{Yld_{2050}^{Scenario} - Yld_{2050}^{Baseline}}{Yld_{2050}^{Baseline}}}{\varepsilon_{Research}^{Yield}}\right] AR_{Baseline} \qquad (3)$$

The resulting level of spending ($AR_{Scenario}$) represents the change needed to achieve the new level of productivity to achieve the target.

Rural Roads

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

—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 latest available year, typically 2000, to calculate rural road length (r_{2000}) 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 A1.2, derived from various World Bank road construction project documents. The values in Table A1.2 are in 2005 US$; they are deflated to 2000 US$ for the analysis.

Table A1.2—Road construction costs (2005 US$ per km)

Region	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.

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

$$r_a = r_{2000} \times \left(\frac{a_{2050} - a_{2000}}{a_{2000}} \right) \qquad (4)$$

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

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

$$RR_a = r_a C_r \qquad (5)$$

—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 yield effect calculation includes two components. The first, called $yldinc_{Roads}$, says how much of a given yield increase is driven by road expansion. Table A1.3 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, Hazell, and 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 A1.3—Percent yield increase with respect to road length, regional averages

Region	Percent
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:

$$RR_y = \left(\frac{\left(\frac{yld_{2050}}{yld_{2000}} - 1 \right) \times yldinc_{Roads}}{e_{Roads}^{Yield}} \right) \times r_{2000} \times C_r \tag{6}$$

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

$$RR_{baseline} = RR_a + RR_y \tag{7}$$

—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_{Roads}^{Yield} and $yldinc_{Roads}$ to calculate the target costs of rural roads ($RR_{Scenario}$) as follows:

$$RR_{Scenario} = \left[1 + \frac{\left(\frac{yld_{2050}^{Scenario}}{yld_{2050}^{Baseline}} - 1 \right) \times yldinc_{Roads}}{e_{Roads}^{Yield}} \right] RR_{Baseline} \tag{8}$$

Irrigation

Irrigation investments include two components: costs for expanding irrigated area and costs related to the increase of irrigation water use efficiency.

—Area expansion

The total investments in irrigation 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 that are produced by IMPACT have to be adjusted for cropping intensity (r_n) because the data include multiple cropping seasons and therefore overstates the physical area.

We calculate net irrigated area (a_n^{Net}) for each year n as follows:

$$a_n^{Net} = \frac{\frac{a_n}{1000}}{r_n} \times 100 \qquad (9)$$

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

$$\Delta a_n^{Net} = a_{n+1}^{Net} - a_n^{Net} \qquad (10)$$

$$if\ \Delta a_n^{Net} < 0\ then\ \Delta a_n^{Net} = 0 \qquad (11)$$

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

$$IR = \Delta a_{2000-2050}^{Net} \times c_{irrig} \qquad (12)$$

Irrigation unit costs vary by region, as indicated in Table A1.4. In a few countries where better information is available, it is used instead.

Table A1.4—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

Sources: 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.

—Changes in irrigation efficiency

Irrigation efficiency needs to increase to ensure that sufficient water is available to meet future food needs. In IMPACT, we use the concept of basin efficiency (BE) to account for changes of irrigation efficiency at all levels. Basin efficiency describes irrigation water-use efficiency at the river-basin scale (Haie and Keller 2008; Keller and Keller 1995). It fully takes into account the portion of diverted irrigation water that returns back to rivers or aquifer systems and thus can be reused repeatedly, usually by downstream users, thus avoiding the limitation of the conventional irrigation efficiency concept that basically treats return flow as "losses." Basin efficiency is defined as the ratio of beneficial irrigation water consumption to total irrigation water consumption:

$$BE = \frac{BC}{TC} \tag{13}$$

Our base-year basin efficiency values range from 0.4 to 0.7. Given trends in investment in water use-efficiency enhancements, and the need to use water more efficiently under growing water scarcity, we project small enhancements in BE over time, with levels increasing to 0.5-0.8 by 2050 under the baseline. An upper level of BE is set at 0.85 because it is impossible to reach efficiency levels of 100 percent. 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, 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, 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. For the various climate-change scenarios, we calculated investment costs in irrigation efficiency enhancement. For the increased agricultural investment cost scenarios, we exogenously increased BE values by 0.15 and also calculated associated investment costs using the following methodology.

Let subscript "0" denote the baseline and "1" denote an alternative irrigation investment scenario, and assume that additional area that adopts sprinkler irrigation (a proxy of high efficiency irrigation) under the projected year accounts for a share of X out of total irrigated area in 2050 for the region, and we have:

$$\begin{aligned} TC_1 &= \frac{BC_0 \times (1 - X)}{E_0} + BC_0 \times X \\ &= TC_0 \times (1 - X) + BC_0 \times X \end{aligned} \tag{14}$$

where we assume that all water consumption in sprinkler-irrigated fields is beneficial consumption.

Now we assume that beneficial consumption is the same in the baseline as in the alternative scenario, therefore,

$$E_1 = \frac{BC_0}{TC_1} \tag{15}$$

Bring (16) into (17) and simplify to get:

$$X = \left(1 - \frac{E_0}{E_1}\right) \Big/ (1 - E_0) \tag{16}$$

HOW WE REPRESENT THE FUTURE

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 use the average of five recent models used in various climate change scenarios. 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.

Table A1.5—Precipitation and temperature regional average changes, 2000 to 2050

Region	GCM	prec (mm)	prec (%)	tmin (C)	tmax (C)
East Asia and Pacific	CSIRO	21.90	2.10	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.

Then we simulate agricultural productivity increases in the developing world that are sufficient to bring child malnutrition counts down to the level in 2050 *with* climate change that it was at *without* climate change. Because agricultural trade is a potentially important stabilizing force in response to climate change we also explore briefly two scenarios, a complete liberalization of agricultural trade and domestic support policies beginning in 2010 and a doubling of protection in 2010.

LIMITATIONS

Three important assumptions were made in this report. The first is 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 effects of greenhouse gas emissions proceed linearly; that is, a possible speedup in climate change is not included. The effect of this assumption is that the negative effects from climate variability are underestimated. This assumption also likely lowers the adaptation cost estimates substantially. The second assumption is that that CO_2 fertilization of crops does not result in higher yields in farmers' fields. The third is that autonomous adaptation does not include the possibility of varietal substitution. These last two assumptions likely increase the adaptation cost estimates somewhat.

Several potential climate-change impacts cannot be modeled due to data limitations. Their incorporation would almost certainly make the effects significantly worse than what is presented here. First, direct effects on livestock are not included. These range from less-productive pastures for ruminants because of heat and precipitation changes to increased stress in livestock confinement systems. Second, pests and diseases (ranging from larger insect populations and greater competition from weeds to more infectious diseases) might become a more serious problem as a result of higher temperatures and more precipitation. Third, this 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 might be less productive as mangrove swamps are affected. Fourth, in some geographic locations, such as where rivers derive from glaciers in the mountains of Asia, there might be more varied flows of water with effects on irrigated agriculture and fisheries based on water sources from rivers. Finally, the effects of climate variability and extreme events are not included, as currently available climate scenario data do not account for such events.

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Climate Change

Impact on Agriculture and Costs of Adaptation

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APPENDIX 2:

RESULTS BY WORLD BANK
REGIONAL GROUPING OF COUNTRIES

Washington, D.C.
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Table A2.1—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
Developed Countries	-3.5	-5.5	10.5	9.0
World	-13.8	-17.8	2.8	-0.0

Region	CSIRO NoCF	NCAR NoCF	CSIRO CF	NCAR CF
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
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: Compiled by authors. The results in this table are derived by "growing" a crop 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.

Table A2.2—Production changes between 2000 and 2050 by crop and management system for two GCMS with and without CO_2 fertilization effects (% change)

Region	NCAR NoCF	CSIRO NoCF	NCAR CF	CSIRO CF
Maize, irrigated				
East Asia and the Pacific	-9.3	-8.1	-8.7	-7.7
Europe and Central Asia	-13.7	-12.6	-13.6	-12.6
Latin America and the Caribbean	-24.0	-23.9	-23.6	-23.5
Middle East and North Africa	-31.2	-30.5	-31.3	-30.9
South Asia	-25.3	-26.0	-23.8	-24.4
Sub-Saharan Africa	-39.5	-39.7	-39.4	-39.5
Developing Countries	-16.4	-15.7	-15.8	-15.2
Developed Countries	-13.0	-6.3	-12.9	-6.4
World	-15.4	-13.0	-15.0	-12.7

Maize, rainfed				
East Asia and the Pacific	-13.9	-19.2	-12.5	-17.5
Europe and Central Asia	-74.8	-24.4	-72.7	-19.4
Latin America and the Caribbean	-13.0	-11.2	-11.0	-8.9
Middle East and North Africa	-57.4	-24.5	-57.1	-23.0
South Asia	-25.5	-36.8	-22.9	-34.8
Sub-Saharan Africa	-17.9	-17.8	-16.3	-16.3
Developing Countries	-17.3	-16.5	-15.5	-14.5
Developed Countries	-14.2	-5.5	-6.5	3.0
World	-16.2	-12.5	-12.2	-8.1
Rice, irrigated				
East Asia and the Pacific	-28.4	-22.0	-11.8	-6.5
Europe and Central Asia	-40.6	-33.0	-26.1	-19.8
Latin America and the Caribbean	-20.1	-24.9	-13.8	-20.7
Middle East and North Africa	-56.7	-46.5	-47.5	-37.2
South Asia	-23.7	-19.8	-6.2	-3.1
Sub-Saharan Africa	-41.3	-39.4	-30.0	-27.7
Developing Countries	-27.3	-22.6	-11.3	-7.6
Developed Countries	-19.3	-17.7	-7.2	-5.4
World	-26.8	-22.3	-11.1	-7.5
Rice, rainfed				
East Asia and the Pacific	-11.0	-8.5	-2.7	-0.9
Europe and Central Asia	-36.9	-31.0	-6.3	-25.7
Latin America and the Caribbean	-25.8	-20.7	-19.6	-15.1
Middle East and North Africa	-100.0	-100.0	-100.0	-100.0
South Asia	-12.6	-16.4	-8.5	-11.3
Sub-Saharan Africa	-15.5	-15.3	-8.9	-8.6
Developing Countries	-13.2	-13.5	-7.0	-7.2
Developed Countries	-34.9	-30.7	-30.8	-27.1
World	-13.3	-13.5	-7.1	-7.2

Soybean, irrigated				
East Asia and the Pacific	-15.0	-10.1	1.6	6.9
Europe and Central Asia	7.2	7.3	7.5	7.7
Latin America and the Caribbean	-53.4	-52.7	-43.4	-42.8
Middle East and North Africa	-43.4	-37.1	-37.5	-30.6
South Asia	-16.4	-12.2	4.2	8.6
Sub-Saharan Africa	-11.6	-12.0	-0.8	-0.9
Developing Countries	-16.2	-11.5	1.1	6.1
Developed Countries	-15.0	-6.1	-2.9	7.2
World	-15.6	-8.8	-0.9	6.6
Soybean, rainfed				
East Asia and the Pacific	-19.6	-25.5	-1.7	-11.1
Europe and Central Asia	-40.3	-20.8	-40.3	-11.3
Latin America and the Caribbean	-3.3	-9.5	10.5	10.8
Middle East and North Africa	-84.7	10.9	-77.0	18.9
South Asia	-32.7	-56.1	-13.8	-46.8
Sub-Saharan Africa	-38.2	-36.2	-22.8	-21.3
Developing Countries	-8.9	-16.0	5.9	2.4
Developed Countries	2.9	12.5	11.6	16.9
World	-4.9	-6.5	7.8	7.3
Wheat, irrigated				
East Asia and the Pacific	-24.4	-19.2	-19.2	-13.9
Europe and Central Asia	-53.4	-46.8	-50.4	-43.2
Latin America and the Caribbean	-26.0	-21.4	-20.8	-16.5
Middle East and North Africa	-35.5	-30.1	-30.5	-24.6
South Asia	-57.7	-50.1	-50.3	-41.8
Sub-Saharan Africa	-34.0	-34.4	-28.6	-30.1
Developing Countries	-43.8	-37.5	-37.8	-31.0
Developed Countries	-32.5	-29.3	-28.7	-25.5
World	-43.1	-36.9	-37.2	-30.6

Wheat, rainfed				
East Asia and the Pacific	-39.2	-34.5	-34.2	-27.3
Europe and Central Asia	-51.3	-46.6	-46.5	-41.7
Latin America and the Caribbean	-3.1	-4.9	4.0	4.3
Middle East and North Africa	-24.3	-20.3	-16.0	-10.9
South Asia	-57.7	-54.7	-46.0	-42.1
Sub-Saharan Africa	-34.4	-32.2	-29.4	-25.4
Developing Countries	-33.7	-31.0	-27.4	-23.4
Developed Countries	-21.4	-15.4	-15.7	-10.1
World	-27.7	-23.4	-21.7	-16.9
Groundnut, irrigated				
East Asia and the Pacific	-19.6	-18.1	-5.7	-4.5
Europe and Central Asia	-66.6	-55.9	-60.6	-47.9
Latin America and the Caribbean	0.0	0.0	0.0	0.0
Middle East and North Africa	-53.3	-42.3	-44.9	-31.9
South Asia	-23.7	-19.6	-10.5	-5.8
Sub-Saharan Africa	-54.0	-54.1	-46.0	-46.1
Developing Countries	-27.0	-24.6	-14.4	-11.8
Developed Countries	-21.1	-15.4	-7.3	-0.6
World	-26.6	-23.9	-13.9	-11.0
Groundnut, rainfed				
East Asia and the Pacific	-25.6	-32.4	-11.2	-21.2
Europe and Central Asia	-100.0	-100.0	-100.0	-100.0
Latin America and the Caribbean	-17.7	-21.7	-9.4	-8.3
Middle East and North Africa	7.5	-82.1	7.5	-80.1
South Asia	-21.9	-43.9	-9.6	-30.3
Sub-Saharan Africa	-34.9	-34.8	-22.5	-22.3
Developing Countries	-30.1	-34.9	-17.3	-22.6
Developed Countries	-13.0	-25.2	2.2	-6.0
World	-29.7	-34.7	-16.8	-22.2

Source: Compiled by authors.