Food Security, Farming, and Climate Change to 2050

scenarios, results, policy options

Gerald C. Nelson, Mark W. Rosegrant, Amanda Palazzo, Ian Gray, Christina Ingersoll, Richard Robertson, Simla Tokgoz, Tingju Zhu, Timothy B. Sulser, Claudia Ringler, Siwa Msangi, and Liangzhi You

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sustainable solutions for ending hunger and poverty
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Foreword

By 2050, the world's population is likely to reach 9 billion. Most of these people are expected to live in developing countries and have higher incomes than currently is the case, which will result in increased demand for food. In the best of circumstances, the challenge of meeting this demand in a sustainable manner will be enormous. When one takes into account the effects of climate change (higher temperatures, shifting seasons, more frequent and extreme weather events, flooding, and drought) on food production, that challenge grows even more daunting. The 2010 floods in Pakistan and excessive heat and drought in Russia that resulted in wildfires and a grain embargo are harbingers of a troubled future for global food security.

This research monograph follows the 2009 release of IFPRI's widely read food policy report, *Climate Change: Impact on Agriculture and Costs of Adaptation*, which used a detailed global agriculture model to analyze crop growth under two simulated future climate scenarios. This monograph takes advantage of and expands on IFPRI's cutting-edge climate modeling expertise to address the climate change threat in the context of larger food security challenges. It provides the most comprehensive analysis to date on the scope of climate change as it relates to food security, including who will be most affected and what policymakers can do to facilitate adaptation. Building on previous research by IFPRI and other international organizations, this monograph examines a wider range of plausible economic, demographic, and climatic futures than has previously been analyzed.

Using comprehensive empirical analysis, the authors suggest that policymakers should take into account (1) the value of broad-based sustainable development, (2) the power of investments to enhance agricultural productivity, (3) the importance of an open world trade system, and (4) the need for early action on both adaptation and mitigation. As policymakers in the developing world well know, neither food security nor climate change can be viewed in isolation. This report will be indispensible to readers trying to tackle these inextricably linked issues.

Shenggen Fan
Director General, International Food Policy Research Institute

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Acronyms and Abbreviations

AGR	area growth rate: growth in area cultivated for a particular crop (exogenous variable in the IMPACT model)
BC	beneficial irrigation water consumption
BE	basin efficiency
CNRM	Centre National de Recherches Météorologiques (Météo-France); abbreviation for the CNRM-CM3 general circulation model
CSIRO	Commonwealth Scientific and Industrial Research Organization; abbreviation for the CSIRO-Mk3.0 general circulation model
DRC	Democratic Republic of the Congo
DSSAT	Decision Support System for Agrotechnology Transfer: a suite of software packages that model crop variety performance under different agroclimatic and management systems.
ECHAM	abbreviation for the ECHam5 general circulation model, developed by the Max Planck Institute for Meteorology, Germany
FAO	Food and Agriculture Organization of the United Nations
FPU	food production unit
GCM	general circulation model
GDP	gross domestic product
GHG	greenhouse gas
GTZ	Gesellschaft für Technische Zusammenarbeit
IAM	integrated assessment model
ICRISAT	International Crops Research Institute for the Semi-Arid-Tropics
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade

IPCC	Intergovernmental Panel on Climate Change
IPR	intrinsic productivity growth rate: growth in yield for a particular crop (exogenous variable in the IMPACT model)
IRRI	International Rice Research Institute
IWMI	International Water Management Institute
MA	Millennium Ecosystem Assessment
MAL	malnourished children
MIROC	abbreviation for the MIROC 3.2 medium resolution general circulation model (produced by the Center for Climate System Research, University of Tokyo; the National Institute for Environmental Studies; and the Frontier Research Center for Global Change, Japan)
NIRWD	net irrigation water demand
OECD	Organization for Economic Co-operation and Development
RCP	representative concentration pathways
SA	South Asia
SIMMETEO	A weather generator software module built into the DSSAT crop modeling software suite
SPAM	Spatial Production Allocation *Model*
SRES	Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change
TC	total irrigation water consumption
UNESCO	United Nations Educational, Scientific and Cultural Organization
WAT	water availability coefficient

Summary

The first decade of the 21st century has seen several harbingers of a troubled future for global food security. The food price spike of 2008, with its consequent food riots and resulting political changes in several countries, awoke the world's leaders to the re-emergence of this threat to human well-being and social harmony. The excessive heat and drought in Russia that led to the 2010 wildfires and grain embargo, as well as the unprecedented floods in Pakistan, signal more trouble ahead. But the warning signs could already be seen in the 1990s, as the long-term decline in the number of the world's poor and hungry stalled, and those numbers began to rise.

The seeds for these challenges, both for good and ill, were planted along with the Green Revolution crops in the mid-1960s. Dramatic increases in food production and land productivity led to complacency about the remaining challenges ahead, resulting in reduced public sector investments in agricultural productivity. Population numbers continue their march towards a likely 9 billion by 2050, while higher incomes in hitherto poor countries will lead to increased demand, which in turn puts additional pressures on sustainable food production.

To those already daunting challenges, climate change adds further pressure. Because food production is critically dependent on local temperature and precipitation conditions, *any* changes require farmers to adapt their practices, and this adaptation requires resources that could be used for other purposes. Farmers everywhere will need to adapt to climate change. For a few, the changes might ultimately be beneficial, but for many farmers our analysis points to major challenges to productivity and more difficulties in managing risk. The agricultural system as a whole will have difficulty supplying adequate quantities of food to maintain constant real prices. And the challenges extend further: to national governments, to provide the supporting policy and infrastructure environment; and to the global trading regime, to ensure that changes in comparative advantage translate into unimpeded trade flows to balance world supply and demand.

But how big are these challenges, who will be most affected, and what could policy makers do to facilitate adaptation? Providing answers to these questions is the task of this report. It builds on previous research, examining a wider range of plausible futures—economic, demographic, and climate—than

has previously been analyzed. It also illustrates the key point that neither food security nor climate change should be viewed in isolation.

It must be emphasized that combined biophysical-socioeconomic modeling of this detail and extent is still in its infancy. This document provides a status report on current research results. As with any large model-based analysis, the present study, while breaking new ground in the level of detail it incorporates in its agricultural-climate interactions, is obliged to use some simplifying assumptions and features, such as the partial equilibrium framework that underlies the results presented. Consequently, while the general directions deduced from this analysis are likely valid, the specific magnitudes should be treated with caution. Furthermore, for the first time, underlying parameters and more detailed results will be released on a website (www.ifpri.org/climate-change) that makes it possible for interested parties to provide detailed comments and critiques of the modeling process and outputs.

An uncertain future means a range of plausible outcomes. Unlike previous research, including our own (for example, Nelson et al. 2009), which relied on a single baseline scenario of GDP and population, this research uses three combinations of income and population growth: a baseline scenario that is “middle of the road”; a pessimistic scenario that, while plausible, is likely to result in more negative outcomes for human well-being; and an optimistic scenario that would result in more positive outcomes. Another advance is that each of these three overall scenarios are subjected to four plausible climate futures that range from slightly to substantially wetter and hotter on average than the current climate. We then compare these four climate futures with a fifth scenario, of perfect climate mitigation—that is, a continuation of today’s climate into the future. Three overall scenarios, under five climate scenarios, result in 15 perspectives on the future that encompass a wide range of plausible outcomes. Using the baseline scenario, we experiment with a variety of crop productivity enhancement simulations. Finally, we present the results of a simulation of an extended drought in South Asia—one likely outcome of climate change—to give some perspective on the effects of increased climate variability for one part of the world.

Main messages

We draw four sets of main messages from our analysis.

1. **Broad-based economic development is central to improvements in human well-being, including sustainable food security and resilience to climate change.**

Broad-based growth in income is essential to improving human well-being *and* delivering sustainable food security. Families with more resources at their disposal are better able to cope with whatever uncertainties mother nature or human activities cause. Farming families with higher incomes are able to experiment with new technologies and management systems that might be costly up-front but offer big productivity and resilience payoffs in the future.

World prices are a useful indicator of the future of agriculture (see Table 2.2). Rising prices signal the existence of imbalances in supply and demand and growing resource scarcity, driven either by demand factors such as growing population and income, or by supply factors such as reduced productivity due to climate change. Unlike much of the 20th century, when real agricultural prices declined, our analysis suggests that real agricultural prices will likely increase between now and 2050, the result of growing incomes and population as well as the negative productivity effects of climate change. The likely price increase ranges from 31.2 percent for rice (in the optimistic scenario) to 100.7 percent for maize (in the baseline scenario). With perfect mitigation, these price increases would be less: from 18.4 percent for rice in the optimistic scenario to 34.1 percent for maize in the pessimistic scenario. These still-substantial increases reflect the relentless underlying pressures on the world food system, even in the unlikely event that perfect mitigation can be achieved (that is, all greenhouse gas emissions are halted and the inertia in the climate system can be overcome).

Domestic production combined with international trade flows determine domestic food availability; per capita income and domestic prices determine the ability of consumers to pay for that food. In our quantitative analysis, the average consumer in low-income developing countries today obtains only two-thirds of the calories available in the developed countries (Table 2.10). With high per capita income growth and perfect climate mitigation, calorie availability reaches almost 85 percent of the developed countries by 2050. And in the optimistic scenario, because the poorest countries grow more rapidly between now and 2050, they catch up to today's middle-income countries. With the pessimistic overall scenario, however, both calorie availability and general human well-being declines in *all* regions.

Calorie availability is an important component in our metric of human well-being—the number of malnourished children under the age of five. This number captures some, but certainly not all, of the human suffering that can result from the combination of slow economic growth and climate change, coupled with inappropriate government policies. Overall, in the optimistic scenario, the number of malnourished children in developing countries falls by over 45 percent between 2010 and 2050 (Table 2.10). With the pessimistic scenario, on the other hand, that number only decreases by about 2 percent.

The benefits of the optimistic scenario are greatest for the *middle-income* developing countries, which have the greatest share of world population. For these countries, the optimistic scenario results in a 50-percent decline in the number of malnourished children; in the pessimistic scenario, that number still declines, but by only 10 percent. Under the optimistic scenario, *low-income* developing countries show a decline of 37 percent in the number of malnourished children—but the pessimistic scenario is devastating: the number of malnourished children *increases* by more 18 percent.

2. Climate change offsets some of the benefits of income growth.

Climate change exacerbates the challenges in reducing the number of malnourished children, although the effects are mitigated by economic development. For all regions, the negative productivity effects of climate change reduce food availability and human well-being. Climate change results in even higher world prices in 2050 (Table 2.2). It causes an increase of between 8.5 and 10.3 percent in the number of malnourished children in all developing countries, relative to perfect mitigation (Table 2.10).

3. International trade plays an essential role in compensating for various climate change effects.

Despite large differences in precipitation amounts and seasonal variation across the climate scenarios, the differences in price and other outcomes are relatively small. The exception is the dramatic effect on international trade flows (Table 2.6). Changes in developed country net cereal exports from 2010 to 2050 range from an *increase* of 5 million metric tons (mt) in the perfect mitigation scenario to a *decline* of almost 140 million mt. This is because the global scenarios that are wetter on average are particularly dry in the central United States, resulting in much lower 2050 maize and soybean production than the drier global scenarios, and therefore resulting in reduced exports.

Trade flows can partially offset local climate change productivity effects, allowing regions of the world with positive (or less negative) effects to supply those with more negative effects. This important role for international trade can be seen in the results for the South Asian drought simulation, which models an extended drought beginning in 2030, with return to normal precipitation in 2040. Substantial increases in trade flows soften the blow to Indian consumers. During the drought the region sees large increases in imports (or reductions in net exports) of the three key commodities, rice, wheat, and maize. These net imports drive world prices higher. Essentially, other countries' producers and consumers help to reduce, though certainly not eliminate, the human suffering that a South Asian drought would cause.

4. Properly targeted agricultural productivity investments can mitigate the impacts of climate change and enhance sustainable food security.

Increases in agricultural production are essential to meeting the demand growth from population and income. While area expansion is still possible in some parts of the world, the possibility of negative environmental effects is substantial. Agricultural productivity investments make it possible to meet that increased demand from existing agricultural land resources, while reducing some of the environmental threats from increased production. We looked at five different types of productivity enhancements: an overall increase in crop productivity in developing countries of 40 percent relative to our baseline assumptions; an increase in commercial maize productivity; improvements in wheat and cassava productivity (analyzed separately) in selected countries in the developing world; and an increase in irrigation efficiency (Table 2.11).

The overall productivity increase had the greatest effect on human well-being, reducing the number of malnourished children in 2050 by 16.2 percent (or 19.1 million children under 5) relative to the baseline result (Table 4.3). Some in the commercial maize industry suggest that commercial maize yields can increase by an annual average of 2.5 percent through at least 2030, so we simulated a 2 percent increase through 2050. This productivity change would affect about 80 percent of world production in 2010. The effects on world maize prices are dramatic: prices increase only 12 percent, instead of 101 percent, between 2010 and 2050. The effect on malnourished children is also not insignificant, with a 3.2 percent decline relative to the baseline in 2050. The effect is larger in the low-income developing countries (a decline of 4.8 percent) because maize consumption is relatively more important in this group of countries.

The wheat productivity experiment increases productivity to 2 percent in selected developing countries that together account for about 40 percent of world production in 2010. Because less production is affected than in the maize simulation, the outcomes for human well-being are less dramatic, with only a 2.2 percent reduction in the number of malnourished children in developing countries in 2050 (Table 4.7). The middle-income developing countries fare better (a 2.5 percent reduction) than the low-income developing countries (1.6 percent reduction), because India and China are both major wheat producers and consumers and are included in the group of middle-income developing countries.

Cassava is a particularly important crop for consumers in some low-income developing countries. It is the fourth most important source of calories for this group of countries and provides about 8 percent of average daily consumption. The simulation increases productivity to 2 percent annually for the six top producing countries (Brazil, the Democratic Republic of Congo, Ghana, Nigeria, Indonesia, and Thailand) that collectively accounted for over 60 percent of world production in 2000. While the effect on the number of malnourished children is only a 1.1 decline in 2050 for all developing countries, it is concentrated in the low-income developing countries, where the decline is 2.2 percent (Table 4.9).

Finally, we looked at the effects of a 15 percent increase in irrigation efficiency in developing countries. The world's irrigated area is concentrated in South and East Asia. In East Asia, increased precipitation from climate change (in most scenarios), along with changing consumer preferences away from rice, reduce the need for irrigated area between 2010 and 2050. Therefore, any irrigation efficiency improvements there have relatively small effects on food production (although they are critical for freeing up water for industrial and urban use). In South Asia, however, the benefits of more efficient irrigation are substantial. And for middle income countries as a whole, increased irrigation efficiency reduces the number of malnourished children in 2050 by 0.3 percent, or about 0.3 million children (Table 4.15). In low-income developing countries, however, because the share of irrigated area is low, the efficiency effect is small, reducing the number of malnourished children by only 0.2 percent (0.1 million children).

Beyond 2050

This analysis focuses on the period between 2010 and 2050. Nevertheless, we would be remiss if we did not point out the nature of the challenges beyond. Although population growth is slowing and likely to stop by the mid-21st century, there will still remain significant disparities in income between poor and rich countries, as well as large numbers of people still living in abject poverty. Even in the *optimistic* scenario, the number of malnourished children in 2050 is 76 million to 84 million, depending on climate change scenario.

And the climate change threat becomes much more severe after 2050. In 2050, the increases in mean surface air temperature relative to the late 20th century across all scenarios are relatively modest, on the order of 1°C; but they diverge dramatically in the ensuing years, with outcomes ranging from 2°C to 4°C by 2100 (Figure 1.5). And temperature increases over land are likely to be higher than these means, which include ocean areas. Yields of many more crops will be more severely threatened than in the window from today to 2050. Table 5.1 shows the changes in wheat yields from climate change in 2030, 2050, and 2080 relative to yields with 2000 climate. With the climate change from 2000 to 2030, the yield effects are negative 1.3 percent to negative 9 percent. By 2050, the decline ranges from 4.2 percent to 12 percent. And by 2080, the declines are much greater, ranging from 14.3 percent to 29 percent.

Our analysis suggests that up to 2050, the challenges from climate change are "manageable," in the sense that well-designed investments in land and water productivity enhancements might, conceivably, substantially offset the negative effects from climate change. But the challenges of dealing with the effects between 2050 and 2080 are likely to be much greater than those to 2050. Starting the process of slowing emissions growth today is critical to avoiding a calamitous post-2050 future.

CHAPTER 1

Introduction

The 2010 Millennium Development Goals report (United Nations 2010) highlights the challenges facing the world in addressing the first goal: *eradicating extreme poverty and hunger*. The poverty target requires halving the proportion of people whose income is less than $1 a day between 1990 and 2015. That target is unlikely to be met. In 1990, in developing regions the share of people in extreme poverty was 46 percent. By 2008, it had dropped to 26 percent; but thereafter, the economic crisis that began in 2008 caused an increase to an estimated 31 percent. The hunger target—halving the proportion of people who suffer from hunger between 1990 and 2015—is also unlikely to be met on a global basis, although some individual countries will achieve the target. The share of malnourished people has remained essentially constant at about 16 percent since 2000, after declining from 20 percent in 1990, and it too is likely to have increased during the economic crisis.

If the world is having difficulty meeting basic human needs now, the challenges in the future loom large. The first decade of the 21st century saw several harbingers of a troubled future for global food security. The food price spike of 2008, with its consequent food riots and resulting political changes in several countries, awoke the world's leaders to the re-emergence of this threat to human well-being and social harmony. The excessive heat and drought in Russia that led to the 2010 wildfires and grain embargo, as well as the unprecedented floods in Pakistan, signal more trouble ahead. But the warning signs could already be seen in the late 20th century, as the long-term decline in the number of the world's poor and hungry came to an end and as those numbers began to increase in the 1990s.

The seeds for these challenges, both for good and ill, were planted along with the Green Revolution crops in the mid-1960s. Dramatic increases in food production and land productivity led to complacency about the remaining challenges ahead, resulting in reduced public sector investments in agricultural productivity. Population numbers continue their march towards a likely 9 billion by 2050. If we are ultimately successful in reducing poverty, higher incomes in hitherto poor countries will lead to increased demand, which in turn means additional pressures on sustainable food production.

To those already daunting challenges, climate change adds further pressure. Because food production is critically dependent on local temperature and precipitation conditions, *any* changes require farmers to adapt their practices, and this adaptation requires resources that could be used for other purposes. Farmers everywhere will need to adapt to climate change. For a few, the adaptations might be beneficial, but for many farmers our analysis points to major challenges to productivity and more difficulties in managing risk. The agricultural system as a whole will have difficulty supplying adequate quantities of food to maintain constant real prices. And the challenges extend further: to national governments to provide the supporting policy and infrastructure environment; and to the global trading regime to ensure that changes in comparative advantage translate into unimpeded trade flows to balance world supply and demand.

This report provides an end-of-decade assessment of the challenges to global food security through 2050. It undertakes a detailed analysis of global agricultural prospects, incorporating quantitative scenarios of economic and demographic futures and the threats that climate change poses. The Millennium Ecosystem Assessment's *Ecosystems and Human Well-being: Scenarios, Volume 2*, provides a useful definition of scenarios:

> Scenarios are plausible, challenging, and relevant stories about how the future might unfold, which can be told in both words and numbers. Scenarios are not forecasts, projections, predictions, or recommendations. They are about envisioning future pathways and accounting for critical uncertainties. (Raskin et al. 2005: 36)

Scenario development typically involves both qualitative and quantitative assessments. Qualitative perspectives make it possible to evaluate a wide range of potentially plausible outcomes for which there are no easily quantifiable expectations. Quantitative scenarios provide informative detail on *magnitudes* for some of the outcomes. Quantitative scenarios thus provide a consistency check on the plausibility of qualitative scenario outcomes. They also allow for exploration of complex interactions that cannot easily be traced in a qualitative scenario.

This report builds on previous research, examining a wider range of plausible futures—economic, demographic, and climate—than has previously been analyzed. It also illustrates the key point that neither food security nor climate change should be viewed in isolation.

An uncertain future means a range of plausible outcomes. Unlike previous research, including our own (for example, Nelson et al. 2009) which relied on a single baseline scenario of GDP and population, this research uses three combinations of income and population growth: a baseline scenario that is "middle of the road"; a pessimistic scenario that, while plausible, is likely to result in more negative outcomes for human well-being; and an optimistic scenario that would result in more positive outcomes. Another advance is that each of the three overall scenarios are subjected to four plausible climate futures that range from slightly to substantially wetter and hotter on average than the current climate. We then compare these four climate futures with a fifth scenario, of perfect climate mitigation—that is, a continuation of today's climate into the future. Three overall scenarios, under five climate scenarios, result in 15 perspectives on the future that encompass a wide range of plausible outcomes.

Finally, several simulations are undertaken to provide a perspective on possible policy and program innovations that might make more likely a sustainable future for food and farming.

It must be emphasized that combined biophysical-socioeconomic modeling of this detail and extent is still in early stages of development. This document provides a status report on current research results. As with any large model-based analysis, the present study, while breaking new ground in the level of detail it incorporates in its agricultural-climate interactions, is obliged to use some simplifying assumptions and features, such as the partial equilibrium framework that underlies the results presented. Consequently, while the general directions deduced from this analysis are likely valid, the specific magnitudes should be treated with caution. For the first time that we are aware of, underlying parameters and more detailed results will be released on a website (www.ifpri.org/climate-change) that makes it possible for interested parties to provide detailed comments on the data, modeling and outputs and provide inputs to improve the process.

The Choice of Modeling Environment

The set of driver variables that can be considered is constrained by the modeling environment. Two classes of models—partial equilibrium and general equilibrium—have been used in this kind of analysis previously.

Partial Equilibrium (PE) Agricultural Sector Models

PE models represent the agricultural sector in great detail, at the cost of simplified modeling of relationships with other parts of the economy. The strength of this modeling approach is its detailed specification of the agricultural sector. The food side of these models generally uses a system of supply and demand elasticities incorporated into a series of linear and nonlinear equations, which reflect the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Demand is a function of prices, income, and population growth. The supply side of the model is constrained by biophysical information on a regional level (for example, land or water availability), using information at the crop level. PE modeling approaches allow 1) consistent and clearly defined relations among all variables at the detailed commodity level; 2) a projection into the future of the structure of interrelationships among variables consistent with past relationships; 3) changes in complex cross-relationships among variables over time; 4) the simultaneous interaction of many variables; and 5) an organized and consistent treatment of massive numbers of variables and large amounts of data (McCalla and Revoredo 2001).

Quantities as well as values are modeled, with a detailed representation of agriculture (including spatially) that incorporates management systems, technologies, and water modeling. With commodity detail, the PE approach supports more detailed modeling of productivity shocks and land use changes. PE models can be linked to more spatially and temporally disaggregated crop models that provide detailed specification of crop biology and responses to changes in climate that affect water availability and temperature. In principle, this approach provides a detailed structural specification of agricultural technologies, providing a foundation for the commodity supply functions in the PE model. Other approaches, such as the use of smooth production functions or cost functions to support supply functions, cannot capture the potential response of agriculture to climate/weather shocks.

Two main weaknesses of PE models are (1) that there are no feedback effects to other sectors; and (2) that welfare effects are not explicitly measured, but are extrapolated from reduced form estimates based on areas under supply and demand curves.

Global Computable Equilibrium (CGE) Models

CGE models are widely used as an analytical framework to study economic issues of national, regional, and global dimension. CGE models provide a representation of national economies and the trade relations between economies. CGE models are specifically concerned with resource allocation issues: that is, where the allocation of factors of production over alternative uses is affected by certain policies or exogenous developments. International trade is typically an area where such induced effects are important consequences of policy choices. These models provide an economy-wide perspective and are very useful when the numerous, and often intricate, interactions among various parts of an economy are of critical importance. As for agriculture, such interactions can occur within the sector (as in competing for limited productive resources, including various types of land) and also between agriculture and other sectors that service it or that operate in the food and fiber chain. Such sectors and actors include downstream processors, traders and distributors, final consumers, and governments (in the form of public policies).

A strength of CGE models is their ability to analyze the interactions among different sectors—for example, agriculture, manufacturing, and services operating through commodity and factor markets. They also explicitly incorporate taxes and subsidies that can have distorting effects on incentives and the operation of markets. In their conventional usage, CGE models are flexible price models used to examine the impact of relative price changes on allocations of goods and factors across a range of economic agents. Thus, in addition to providing insights into the economy-wide general equilibrium effects of policy changes, CGE models allow examination of key inter-industry linkages.

However, global CGE models are poor in addressing distributional issues within regions; only average adjustments are simulated. Moreover, CGE models should be handled with care for long-term projections, since fundamental changes in the economic structure of a region cannot be simulated easily by a CGE model.

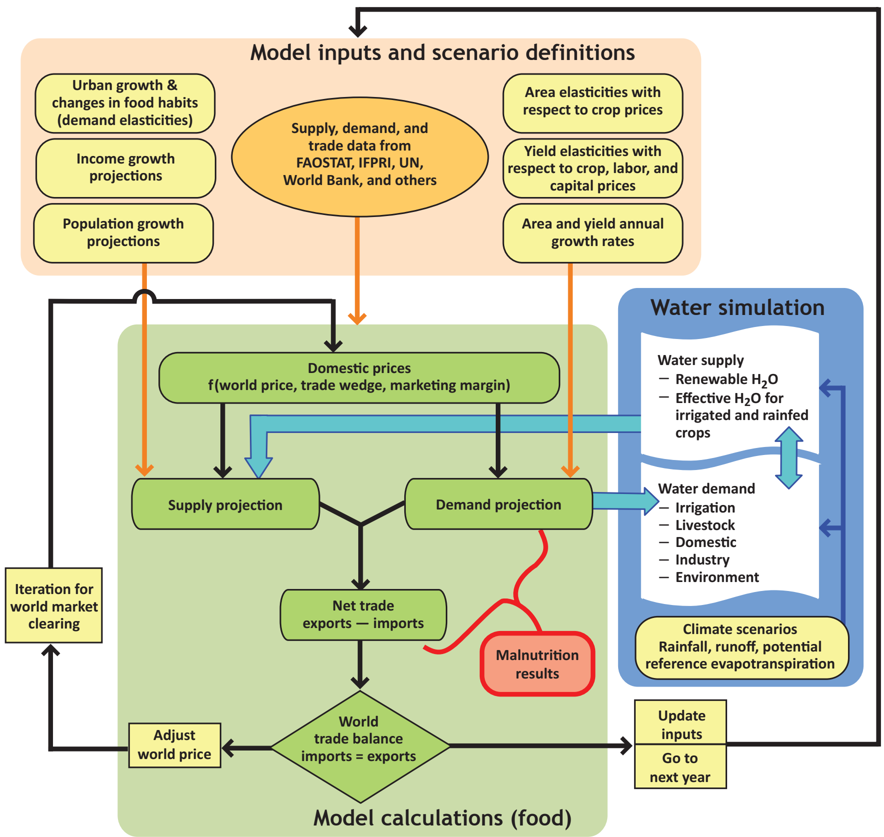
Because CGE models provide a representation of the whole economy, not just one sector, they require us to develop an explicit (if simplified) representation of all factors of production. Technology is often represented with cost functions (for example, CES functions), which may not provide an adequate description of agricultural crop technologies. While CGE work is currently underway on nested functions, flexible functional forms, and other enhancements, the models still operate in the tradition of smooth, neoclassical production functions. Other limitations of most current CGE models are the use of the restrictive Armington functions to represent international trade, and a relatively aggregate modeling of all sectors, especially agriculture.

Ultimately, for the set of issues addressed in this report, PE models offer an advantage in the detailed specification of commodities and the deeper structural representation of production technologies (including the use of crop models rather than production or cost functions). This representation supports links to land-use models, water models, and climate change and/or weather models. CGE models are too aggregated to provide a framework for such a deep structural representation of the operation of agriculture.

IFPRI's IMPACT Modeling Suite

Figure 1.1 provides a diagram of the links among the three models used: IFPRI's IMPACT model (Rosegrant et al. 2008), a partial equilibrium agriculture model that emphasizes policy simulations; a hydrology model incorporated into IMPACT; and the DSSAT crop model suite (Jones et al. 2003) that estimates yields of crops under varying management systems and climate change scenarios. The modeling methodology reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships at a national level with detailed models of biophysical processes at high spatial resolution. The DSSAT system is used to simulate responses of five important crops (rice, wheat, maize, soybeans, and groundnuts) to climate, soil, and nutrient availability, at current locations based on the SPAM dataset of crop location and management techniques

Figure 1.1 The IMPACT 2009 modeling framework



Source: Authors.

(You and Wood 2006). This analysis is done at a spatial resolution of 15 arc minutes, or about 30 km at the equator. These results are aggregated up to the IMPACT model's 281 spatial units, called food production units (FPUs) (see Figure 1.2). The FPUs are defined by political boundaries and major river basins. (See Appendix 3 for more details.)

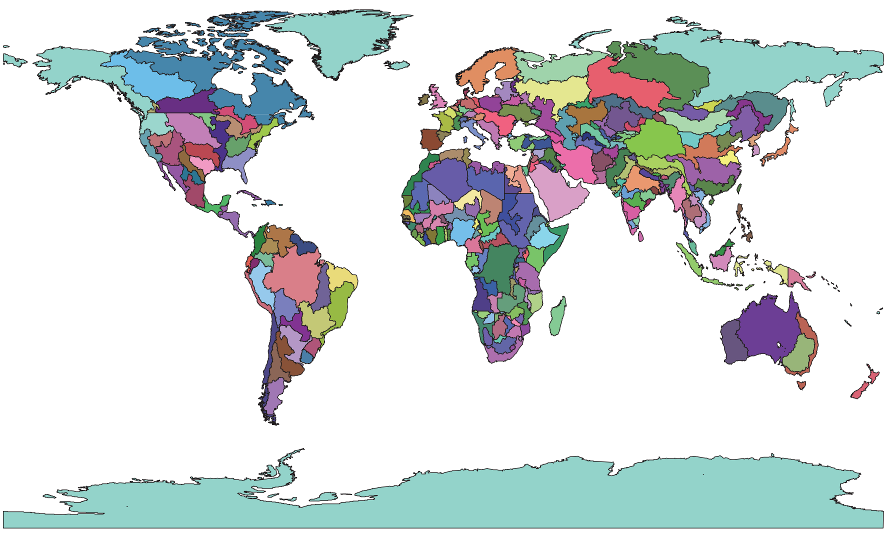
Income and Population Drivers

IFPRI's IMPACT model has a wide variety of options for exploring plausible scenarios. The drivers used for simulations include: population, GDP, climate scenarios, rainfed and irrigated exogenous productivity and area growth rates (by crop), and irrigation efficiency. In all cases except climate, the country-specific (or more disaggregated) values can be adjusted individually. Differences in GDP and population growth define the overall scenarios analyzed here, with all other driver values remaining the same across the three scenarios.

Table 1.1 documents the GDP and population growth choices for the three overall scenarios.

Figure 1.3 and Figure 1.4 show the regional GDP and population growth rates respectively. GDP growth rates are highest in Eastern and Central Africa (albeit from very low bases), as well as South Asia, Southeast Asia, and East

Figure 1.2 The 281 FPUs in the IMPACT model



Source: Authors.

Table 1.1 GDP and population choices for the three overall scenarios

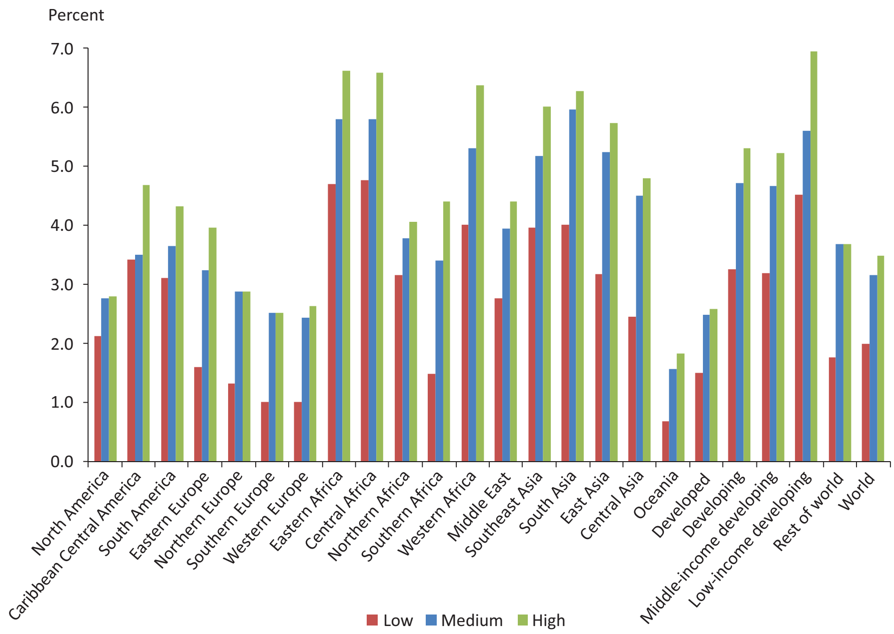
Category	Pessimistic	Baseline	Optimistic
GDP, constant 2000 US$	Lowest of the four GDP growth rate scenarios from the Millennium Ecosystem Assessment GDP scenarios (Millennium Ecosystem Assessment 2005) *and* the rate used in the baseline (next column)	Based on rates from World Bank EACC study (Margulis et al. 2010), updated for Sub-Saharan Africa and South Asian countries	Highest of the four GDP growth rates from the Millennium Ecosystem Assessment GDP scenarios *and* the rate used in the baseline (previous column)
Population	UN high variant, 2008 revision	UN medium variant, 2008 revision	UN low variant, 2008 revision

Source: Compiled by authors.

Asia. The lowest GDP growth rates are in Europe and Oceania. Population growth rates are highest in Africa and lowest in Europe. For the optimistic scenario, population growth rates are negative in much of Europe, Central Asia, and Oceania, but still more than 1.5 percent per year in Sub-Saharan Africa.

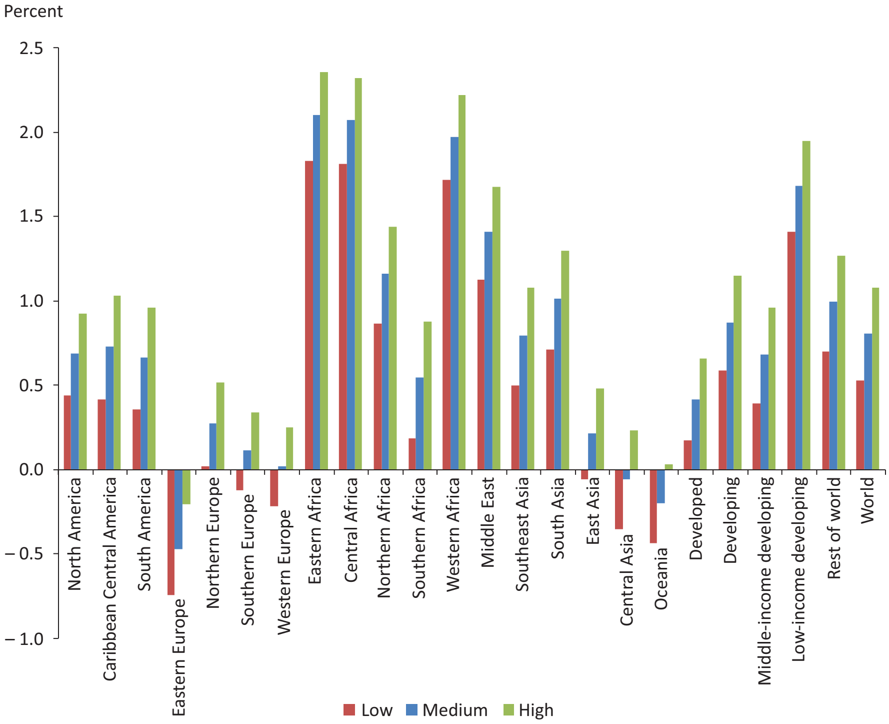
The GDP and population growth rates combine to generate the three scenarios of per capita GDP growth. The results by regions are shown in

Figure 1.3 GDP growth rate scenarios (annual average growth rate, 2000–2050)



Source: Margulis et al. (2010); Millennium Ecosystem Assessment (2005).

Figure 1.4 Population growth rate scenarios (annual average growth rate, 2000-2050)



Source: http://esa.un.org/unpp/index.asp.

Table 1.2. (See Appendix 1 for the list of countries in each of the income groups and the regional groups displayed in Figures 1.3 and 1.4.) The baseline growth rates are somewhat below those for 1990-2000, except for the middle-income developing countries. The optimistic growth rates are substantially higher than 1990-2000, except for developed countries.

Table 1.2 Average scenario per capita GDP growth rates (percent per year)

Category	1990-2000	2010-2050		
		Pessimistic	Baseline	Optimistic
Developed	2.7	0.74	2.17	2.56
Developing	3.9	2.09	3.86	5.00
Low-income developing	4.7	2.60	3.60	4.94
Middle-income developing	3.8	2.21	4.01	5.11
World	2.9	0.86	2.49	3.22

Source: World Development Indicators for 1990-2000 and authors' calculations for 2010-2050.

Table 1.3 shows population and GDP per capita in 2050 for the three scenarios. The baseline scenario has just over 9 billion people in 2050; the optimistic scenario results in a substantially smaller number, 7.9 billion; the pessimistic scenario results in 10.4 billion people. For developed countries, the differences among the three scenarios are relatively small, with little overall population growth: population ranges from just over 1 billion to 1.3 billion in 2050, compared to 1 billion in 2010. For the developing countries as a group, the total 2010 population of 5.8 billion becomes 6.9 billion to 9 billion in 2050, depending on scenario.

Average world per capita income, beginning at $6,600[1] in 2010, ranges from $8,800 to $23,800 in 2050, depending on scenario. The gap between average per capita income in developed and developing countries is large in 2010: developing countries' income level is only 5.6 percent of the developed countries' level. Regardless of scenario, the relative difference is reduced over time: the developing country income increases to between 8.6 percent and 14.0 percent of developed country income in 2050, depending on overall scenario. Middle- and low-income developing countries' 2010 per capita income values are 6.5 percent and 2.6 percent respectively of the developed country income. By 2050, the share increases to between 10.4 percent and

Table 1.3 Summary statistics for population and per-capita GDP

Category	2010	2050		
		Optimistic	Baseline	Pessimistic
Population (million)				
World		7,913	9,096	10,399
Developed	1,022	1,035	1,169	1,315
Developing	5,848	6,877	7,927	9,083
Middle-income developing	4,869	5,283	6,103	7,009
Low-income developing	980	1,594	1,825	2,074
Income per capita (2000 US$)				
World	6,629	23,760	17,723	8,779
Developed	33,700	93,975	79,427	43,531
Developing	1,897	13,190	8,624	3,747
Middle-income developing	2,194	15,821	10,577	4,531
Low-income developing	420	4,474	2,094	1,101

Note: 2010 income per capita is for the baseline scenario.

[1] All references to dollars are for constant 2000 US dollars.

16.8 percent for middle-income developing countries, depending on overall scenario. For the low-income developing countries, however, the 2050 ratios remain low—between 2.5 percent and 4.8 percent.

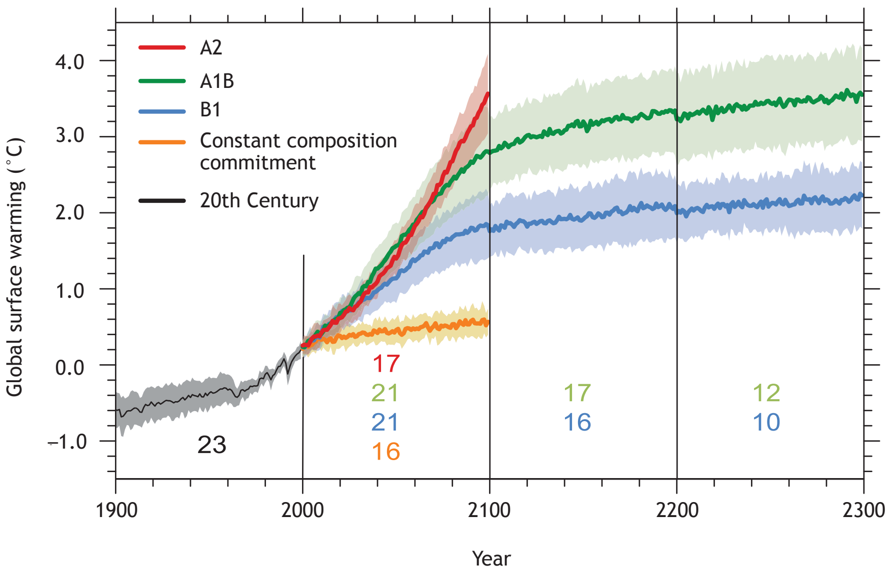
Climate Change Drivers

Introducing the effects of climate change scenarios into the overall food and agriculture scenarios presents a particular challenge, to take into account the range of plausible pathways for greenhouse gas (GHG) emissions. Moreover, the general circulation models (GCMs) translate those emission scenarios into varying temperature and precipitation outcomes. While the general consequences of increasing atmospheric concentrations of GHGs are increasingly well known, great uncertainty remains about how climate change effects will play out in specific locations.[2] Figure 1.5 shows the range of average surface temperature outcomes for the GHG pathways in the SRES scenarios of the IPCC. By 2050, the global surface warming for the A1B, A2, and B1 scenarios is roughly the same, at about 1 °C above the reference period of the late 20th century. The temperature increases diverge significantly after 2050, with the A2 scenario resulting in the highest increases by the end of the 20th century, of about 3.5 °C. Because the analysis in this report stops in 2050, it does not capture the effects of the large increases expected in later years.

Figure 1.6 shows the fossil fuel CO_2 emissions associated with the various IPCC SRES scenarios, as well as actual emissions through 2009 (dotted line). Note that from 2005 to 2009, the actual emissions path was above those of all the illustrative marker scenarios (the solid lines) except A1B, although it was within the range of the scenario envelope. The global economic downturn that began in late 2008 significantly reduced fossil fuel emissions. If emissions

[2] To understand the significant uncertainty in how these effects play out over the surface of the earth, it is useful to describe briefly the process by which the results depicted in Figure 1.7 and Figure 1.8 are derived. They start with GCMs that model the physics and chemistry of the atmosphere and its interactions with oceans and the land surface. Several GCMs have been developed around the world. Next, integrated assessment models (IAMs) simulate the interactions between humans and their surroundings, including industrial activities, transportation, and agriculture and other land uses; these models estimate the emissions of the various greenhouse gases (most importantly, carbon dioxide, methane, and nitrous oxide). Several independent IAMs exist as well. The emissions simulation results of the IAMs are made available to the GCM models as inputs that alter atmospheric chemistry. The end result is a set of estimates of precipitation and temperature values around the globe, often at two-degree intervals (about 200 km at the equator) for most models. Periodically, the Intergovernmental Panel on Climate Change (IPCC) issues assessment reports on the state of our understanding of climate science and interactions with the oceans, land, and human activities. For the 5th assessment, the approach followed is to devise representative concentration pathways (RCPs) of low, medium, and high GHG emissions, and then to develop the range of scenarios that are plausibly consistent with these emissions rates. See www.nature.com/nature/journal/v463/n7282/fig_tab/nature08823_F5.html. Initial results suggest that a broad range of GDP and population growth rate combinations can result in the main RCPs.

Figure 1.5 Temperature scenario ranges for various GHG emissions pathways



Source: Reprinted with permission from the Intergovernmental Panel on Climate Change (2007).

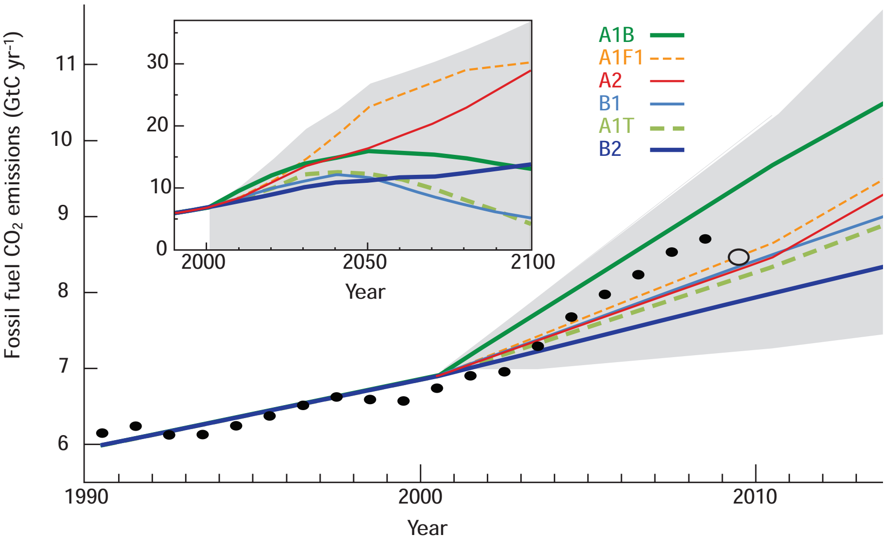
continue to exceed the scenarios used here, then the climate effects by 2050 would exceed the estimates presented here.

At this point there is no single emissions scenario that is viewed as most likely. Furthermore, the climate outputs from different GCMs using identical GHG emissions scenarios differ substantially, with no obvious way to choose among them. The climate data with sufficient detail available for this analysis are from four GCMs, each with three SRES scenarios—A1B, A2, and B1 (see Appendix 3 for details).

Agricultural productivity is strongly determined by both temperature and precipitation. Lobell and Burke (2008) find that “uncertainties related to temperature represented a greater contribution to climate change impact uncertainty than those related to precipitation for most crops and regions, and in particular the sensitivity of crop yields to temperature was a critical source of uncertainty.”

Table 1.4 shows global summary statistics for selected GCMS and SRES scenarios that make available average monthly minimum and maximum temperature, sorted from lowest to highest precipitation change. It also includes the mean temperature and precipitation change for the complete ensemble of GCMs reported by the 4th IPCC assessment. (See Appendix 3,

Figure 1.6 Fossil fuel CO_2 emissions and scenarios



Note: "The graph shows that estimates of annual industrial CO_2 emissions in gigatons of carbon per year (GtC yr^{-1}) for 1990–2008 (black circles) and for 2009 (open circle) fall within the range of all 40 SRES scenarios (grey shaded area) and of the six SRES illustrative marker scenarios (colored lines). The inset in the upper left corner shows these scenarios to the year 2100."

Adapted by permission from Macmillan Publishers Ltd: *Nature Geoscience*, "Misrepresentation of the IPCC CO2 emission scenarios," by M. R. Manning et al., vol. 3, issue 6, pp. 376-377, Figure 1, copyright 2010.

Table A1.2 for regional summary statistics for the A2 scenario; see www.ipcc.ch/publications_and_data/ar4/wg1/en/suppl/chapter10/Ch10_indiv-maps.html for maps showing the individual GCM results and the ensemble means.) A quick glance at Table 1.4 shows the expected general tendencies but also the large degree of uncertainty. First, as average temperatures rise, so does the annual precipitation that falls on land. A 1°C increase in average temperature typically results in less than a 1 percent increase in average annual precipitation. Temperature increases of over 2°C result in 2–5 percent increases in precipitation. Second, with identical GHG emissions, the GCM climate outputs differ substantially. The most extreme comparison is with the outcomes of the B1 scenario. The CSIRO GCM has almost no increase in average annual precipitation and the smallest temperature increase of any of the GCM/GHG scenario combinations. The MIROC GCM has the second largest increase in precipitation (with the B1 scenario) and one of the largest increases in average temperature.

For this analysis, we use four climate scenarios that span the range of the means of the GCM ensemble results and also have the requisite monthly average minimum and maximum temperature data needed for the crop modeling analysis. The CSIRO A1B and B1 scenarios represent a dry and relatively cool future; the MIROC A1B and B1 scenarios represent a wet and warmer future.

Biophysical Effects of Climate Change

The global averages from the GCMs conceal both substantial regional variability and changes in seasonal patterns. These nuances are captured in the DSSAT analysis, which uses the monthly data and high resolution spatial data on climate and other geophysical variables. Figure 1.7 and Figure 1.8 map the average annual changes in precipitation for the CSIRO and MIROC A1B scenarios. Note that although the MIROC scenario results in substantially greater increases in average precipitation globally, there are certain regions, such as the northeast part of Brazil and the eastern half of the United States, where this scenario results in a much drier future.

The DSSAT analysis of the biophysical effects of climate change takes into account location-specific information on climate, soils, and nitrogen application. The analysis reported here uses version 4.5 of DSSAT, with atmospheric concentration of CO_2 in 2050 set at 369 ppm. This amount is substantially less than the level predicted by most of the GHG scenarios. However, for this analysis, the only use of CO_2 concentrations is as part of the crop modeling, and the model response to CO_2 is likely to be overstated.[3] Hence, we use the lower concentration amount as more representative of likely outcomes in farmers' fields.

[3] 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 such as rice and wheat are more sensitive to higher concentrations of CO_2 than C4 plants like maize and sugarcane. It remains an open question whether these laboratory results translate to actual field conditions. A recent report on experiments on CO_2 fertilization in experimental fields, the FACE experiments (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 soybean plants' susceptibility to the Japanese beetle and maize susceptibility to the western corn rootworm. Finally, a 2010 study (Bloom et al. 2010) finds that higher CO_2 concentrations inhibit the assimilation of nitrate into organic nitrogen compounds. (See Ainsworth et al. 2008 for comparison of the chamber and FACE experiment results.) Even the FACE experiments are done in experimental settings. However, when nitrogen is limiting, the CO_2 fertilization effect is dramatically reduced. So the actual benefits in farmer fields of CO_2 fertilization remain uncertain. Furthermore, we do not model the effects of ozone damage or increased competition from pests and diseases that seem likely in a world with higher temperatures and more precipitation. So we justify our use of the 369 ppm modeling as an imperfect mechanism to capture these effects.

Table 1.4 GCM and SRES scenario global average changes, 2000–2050

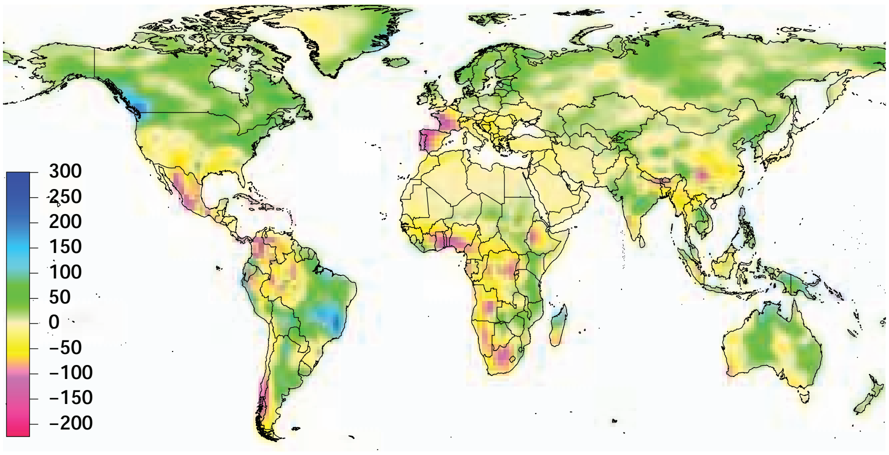
GCM	SRES scenario	Change between 2000 and 2050 in the annual averages			
		Precipitation (percent)	Precipitation (mm)	Minimum temperature (°C)	Maximum temperature (°C)
CSIRO	**B1**	**0.0**	**0.1**	**1.2**	**1.0**
CSIRO	**A1B**	**0.7**	**4.8**	**1.6**	**1.4**
CSIRO	A2	0.9	6.5	1.9	1.8
ECH	B1	1.6	11.6	2.1	1.9
CNR	B1	1.9	14.0	1.9	1.7
ECH	A2	2.1	15.0	2.4	2.2
CNR	A2	2.7	19.5	2.5	2.2
ECH	A1B	3.2	23.4	2.7	2.5
MIROC	A2	3.2	23.4	2.8	2.6
CNR	A1B	3.3	23.8	2.6	2.3
MIROC	**B1**	**3.6**	**25.7**	**2.4**	**2.3**
MIROC	**A1B**	**4.7**	**33.8**	**3.0**	**2.8**
Multi-model ensemble mean					
	A1B	1.51		1.75	
	A2	1.33		1.65	
	B1	1.65		1.29	

Source: Authors' calculations. Multi-model ensemble means come from IPCC et al. 2007: mean temperature increase, Table 10.5, and mean precipitation increase, Table S10.2. See Appendix 3 for details on the GCMs and scenarios.

Note: In this table and elsewhere in the text, a reference to a particular year for a climate realization such as 2000, 2050 is in fact referring to mean values around that year. For example, the data described as 2000 in this table are representative of the period 1950–2000. The data described as 2050 are representative of the period 2041–2060. GCM scenario combinations in bold are the ones used in the climate scenario analysis.

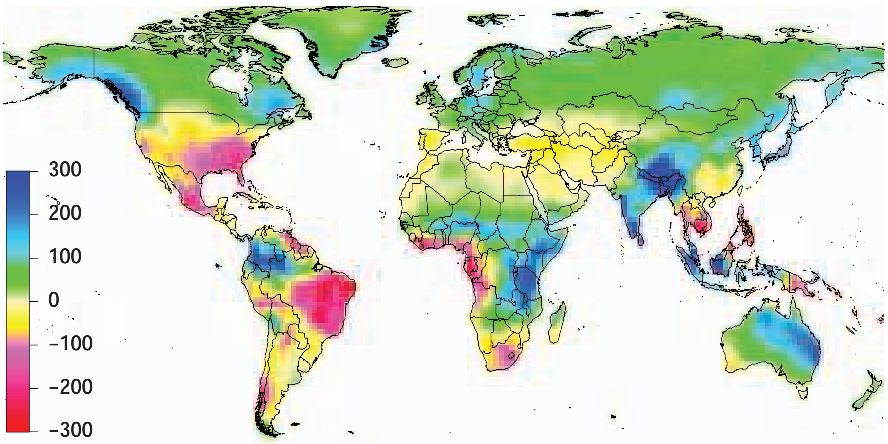
Table 1.5 provides a summary assessment of the biophysical effects of climate change on yields. Each crop is "grown" first with 2000 climate and then with 2050 climate, with identical location-specific inputs. For the results in this table, irrigated crops are assumed to receive as much water as needed so irrigated crop yield effects are driven by temperature only. Yield effects for rainfed crops combine both temperature and precipitation effects. Figures 1.9–1.14 show graphically the effects of the A1B climate scenario with the CSIRO and MIROC GCMs on rainfed maize and wheat and irrigated rice. Yellows and reds indicate reduced precipitation; light and dark blues show increased precipitation. Because the MIROC A1B scenario

Figure 1.7 Change in average annual precipitation, 2000–2050, CSIRO, A1B (mm)



Source: Authors' calculations based on downscaled climate data, available at http://futureclim.info.

Figure 1.8 Change in average annual precipitation, 2000–2050, MIROC, A1B (mm)



Source: Authors' calculations based on downscaled climate data, available at http://futureclim.info.

has the greatest increase in precipitation, it tends to have higher rainfed yields than the CSIRO A1B scenario in the tropical regions. But it also has higher temperatures, which tend to reduce rainfed yields of wheat in the tropical regions and irrigated yields generally. As can be seen in Figure 1.10, the eastern part of the United States sees a large decline in precipitation in the MIROC A1B scenario. The average rainfed maize yield there is 33 percent lower with 2050 climate than with 2000 climate.[4]

Table 1.5 Biophysical effects of climate change on yields (percent change 2000 climate to 2050 climate)

Category/model	Maize		Rice		Wheat	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Developed						
CSIRO	-5.71	-4.42	-5.33	-13.11	-5.45	-3.89
MIROC	-12.31	-29.86	-13.26	-12.81	-11.58	-9.04
Developing						
CSIRO	-3.86	-0.84	-9.76	-1.05	-10.20	-4.15
MIROC	-5.25	-3.47	-11.91	0.11	-13.35	-10.39
Low-income developing						
CSIRO	-3.07	-3.12	-9.79	-0.58	-10.09	-11.79
MIROC	-3.37	-0.51	-9.05	1.61	-12.56	-18.00
Middle-income developing						
CSIRO	-3.90	-0.36	-9.79	-1.30	-10.21	-3.74
MIROC	-5.34	-4.05	-12.49	-0.67	-13.40	-9.98
World						
CSIRO	-4.23	-1.98	-9.52	-1.05	-9.90	-4.05
MIROC	-7.24	-12.01	-12.08	0.07	-13.24	-9.88

Source: Authors' estimates.

Note: The results are for the A1B scenario with assumed CO_2 atmospheric concentration of 369 ppm.

[4] Easterling et al. 2007 present figures from a meta-analysis of the sensitivity of cereal yield against mean local temperature change for maize, wheat and rice, as derived from the results of 69 published studies from 1993 to 2006 at multiple simulation sites. They caution: "The results of such simulations are generally highly uncertain due to many factors, including large discrepancies in GCM predictions of regional precipitation change, poor representation of impacts of extreme events and the assumed strength of CO_2 fertilisation." They conclude: "Nevertheless, these summaries indicate that in mid- to high-latitude regions, moderate to medium local increases in temperature (1°C to 3°C), across a range of CO_2 concentrations and rainfall changes, can have small beneficial impacts on the main cereal crops." None of these reports were able to use the results of the 4th Assessment climate models, which had not been released at the time of the Easterling publication. Our research is based on these newer climate modeling results, limited to two of the sets of GCM results available.

Figure 1.9 Yield effects, rainfed maize, CSIRO A1B

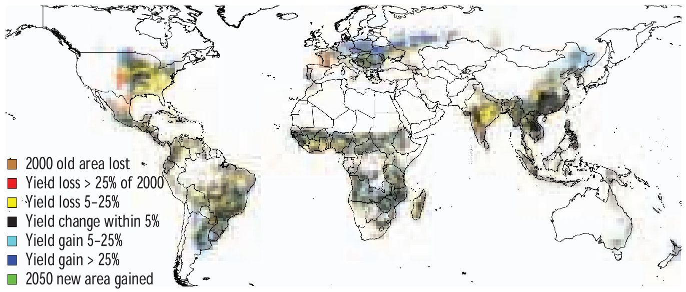


Figure 1.10 Yield effects, rainfed maize, MIROC A1B

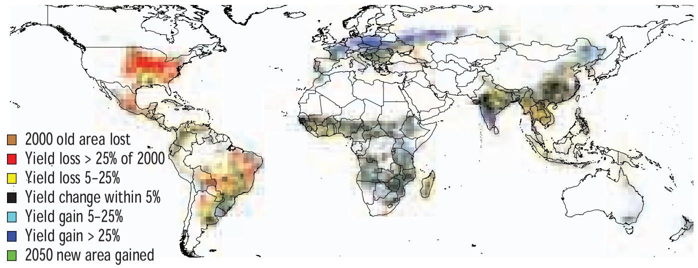


Figure 1.11 Yield effects, irrigated rice, CSIRO A1B

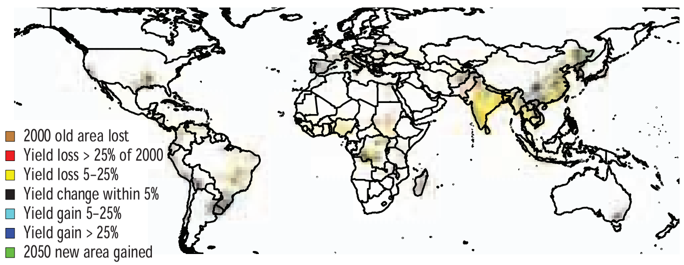


Figure 1.12 Yield effects, irrigated rice, MIROC A1B

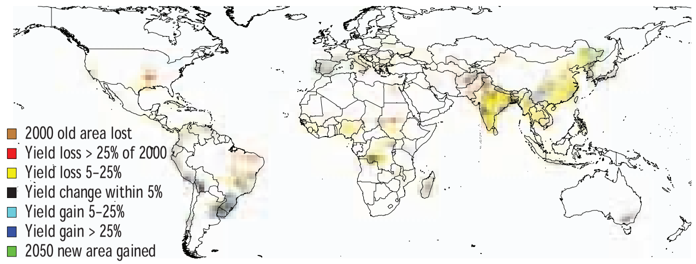


Figure 1.13 Yield effects, rainfed wheat CSIRO A1B

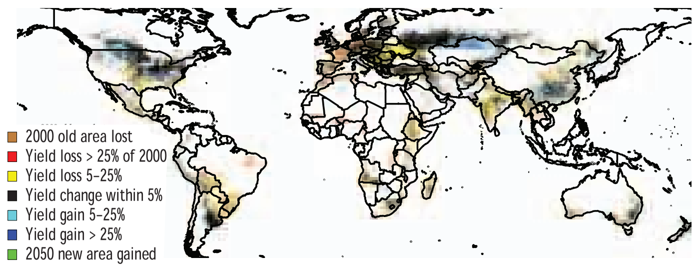
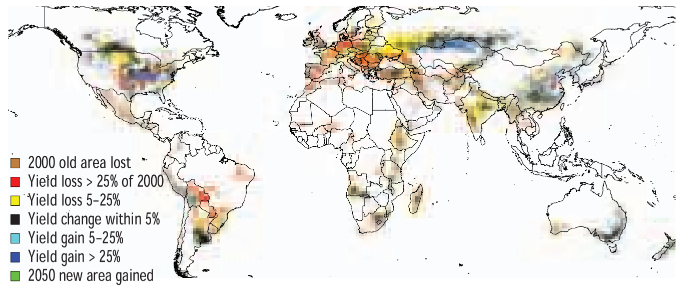


Figure 1.14 Yield effects, rainfed wheat MIROC A1B



Source: Authors' estimates.

Note: These figures are generated by growing maize or rice at every location where the SPAM dataset says maize or rice is grown in 2000, first with 2000 climate and then with a 2050 climate scenario. The ratio of the two resulting yields determines the color displayed, with yellows and reds indicating a decline in yields with the 2050 climate, and light and dark blues indicating increasing yields.

CHAPTER 2

Assessing the Scenario and Simulation Outcomes

The climate-change-driven productivity effects are incorporated into the hydrology and economic elements of the IMPACT model to assess the combined effects of economic, population, and climate scenarios. The process of modeling agricultural futures proceeds roughly as follows. Supply is determined at the food production unit (FPU) level by farmer responses to prices, conditioned by assumptions about exogenously determined area (AGRs) and yield growth rates (IPRs) as well as assumptions regarding climate productivity effects on irrigated and rainfed crops. Demand is determined at the national level by consumer responses to changes in national income and prices. When supply is greater than demand, exports occur. For the world, net trade in a commodity must be zero. World prices are adjusted to ensure this outcome for a year. This process is repeated for each year through to 2050.

We focus on three indicators of the outcomes: the prices of the most important crops (maize, rice, and wheat); the average daily kilocalories (kcal) consumed; and the number of malnourished children under five. (More details on the methodology are provided in Appendix 3.)

Simulations, performed using the baseline overall scenario, are chosen to explore possible intervention options in productivity, including an increase for all crops in all countries and an increase for commercial maize, wheat, and cassava in selected countries. In addition, we examine the outcome of an extreme drought in South Asia.

Price Outcomes

World prices are a useful single indicator of the future of agriculture. Rising prices signal the existence of imbalances in supply and demand and growing resource scarcity, driven by demand factors such as growing population and income or by supply factors such as reduced productivity due to climate change. Table 2.1 reports price scenarios from the Millennium Ecosystem Assessment, and Table 2.2 summarizes the overall scenario outcomes for rice, wheat, and maize prices and the various simulations. Figures 2.2–2.5 show 2010 and 2050 prices by commodity from the overall scenarios.

A first key observation is that, unlike in the 20th century when real agricultural prices declined (see Figure 2.1), the price scenarios in this report show substantial increases between 2010 and 2050. The price increases vary from 31.2 percent for rice in the optimistic scenario to 100.7 percent for maize in the pessimistic scenario (see Table 2.2). The pessimistic scenario has the highest price increases, as high population and low income growth rates combine to increase the demand for staple foods.

These price increases incorporate the effect of climate change. Relative to a world with perfect mitigation, prices in 2050 with climate change are 18.4 percent (optimistic for rice) to 34.1 percent (pessimistic for maize) higher.

It is of interest to compare these results to other scenario exercises. Only the Millennium Ecosystem Assessment (MA) scenarios extend to 2050 in the detail needed to compare with the results in this study. In the MA scenarios, 2050 prices range from 68 percent of the 1997 price (rice in the Global Orchestration scenario) to 156 percent (rice in the Adapting Mosaic scenario). Generally, the Technogarden scenario—with its lower population growth and higher income growth—results in price declines; while the Adapting Mosaic and Order from Strength scenarios—which combine low income and high population growth—have the largest price increases. The MA scenarios did not incorporate the effects of climate change on productivity, so its price increases can be expected to be less than the results in this study.

Table 2.1 International prices of maize, rice, and wheat, 1997 and MA 2050 scenario prices (US$/mt and percent of 2050)

Scenario	Maize	Rice	Wheat
1997	103	285	133
2050 Technogarden	91 (88)	212 (74)	117 (88)
2050 Global Orchestration	143 (139)	195 (68)	152 (114)
2050 Order from Strength	123 (119)	416 (146)	164 (123)
2050 Adapting Mosaic	158 (153)	445 (156)	202 (152)

Source: Millennium Ecosystem Assessment 2005, Figure 9.30.

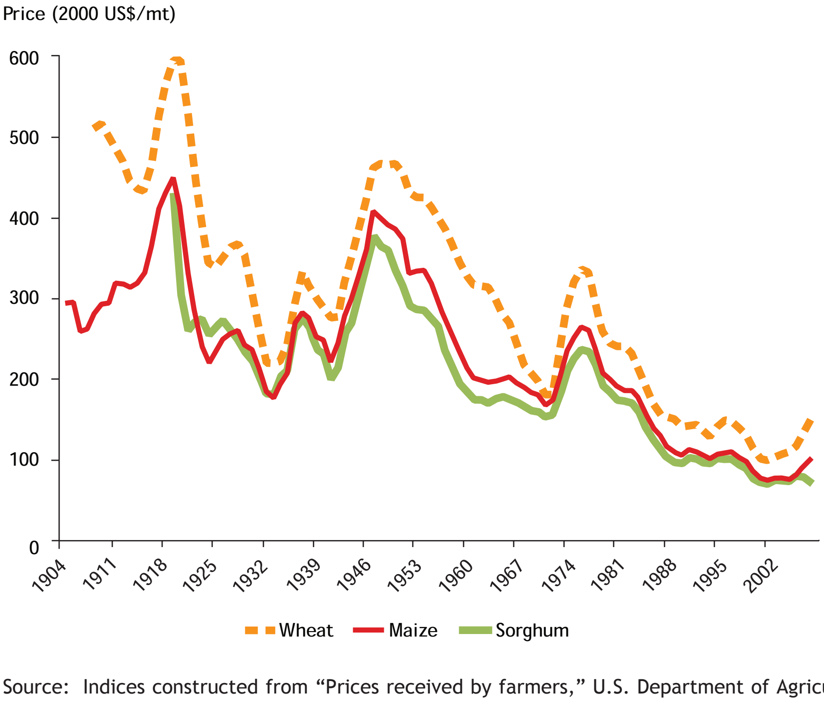
Note: Values in parentheses are the 2050 scenario price as a percent of the 1997 value.

In mid-2010, OECD and FAO released their outlook of prices to 2020. They report that "Average wheat and coarse grain prices [in 2020] are projected to be nearly 15–40% higher in real terms relative to 1997–2006" (OECD 2010). Hertel, Burke, and Lobell (2010) suggest that "prices for major staples rise 10–60% by 2030."

Although the price results suggest a significant change from the 20th century, the price increases are smaller than the scenario per capita income increases, which range from a low of 29 percent for developed countries in the pessimistic scenario to a high of over 600 percent for low-income countries in the optimistic scenario. This difference results in increased average calorie consumption and lower child malnutrition, discussed below.

To trace out the causes of these price increases, we examine the links from yield and area changes to production, international trade flows, and consumption.

Figure 2.1 Prices of selected U.S. farm commodities, 1904–2006 (five-year moving average, constant $2000/mt)



Source: Indices constructed from "Prices received by farmers," U.S. Department of Agriculture, National Agricultural Statistics Service. *Agricultural Statistics*. Various issues. And deflated by the GDP deflator, Bureau of Economic Analysis, U.S. Department of Commerce, National Income and Product Accounts Table 1.1.9 Implicit Price Deflators for Gross Domestic Product, various years.

Table 2.2. Price outcomes of the overall scenarios and the simulations

Scenarios	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change, 2010 mean to 2050 mean (2050 std. dev. and CoV[6])			% price change, 2050 perfect mitigation to 2050 mean CC		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*	32.2	19.8	23.1
Optimistic	87.3 *(25.4; 0.114)*	31.2 *(2.0; 0.006)*	43.5 *(13.8; 0.063)*	33.1	18.4	23.4
Pessimistic	106.3 *(25.5; 0.109)*	78.1 *(4.3; 0.010)*	58.8 *(15.3; 0.065)*	34.1	19.5	24.4
Simulations with baseline scenario	**% price change, 2010 mean to 2050 mean**			**% price change, 2050 perfect mitigation to 2050 mean CC**		
Productivity improvement simulations						
Overall to Irrigation	59.8	31.2	20.0	36.2	20.0	22.2
Commercial maize	11.9	53.8	50.0	33.9	19.8	22.8
Developing country wheat	97.9	54.4	28.2	32.1	19.8	22.5
Developing country cassava	97.5	54.5	53.0	32.0	19.8	22.9
Irrigation	101.5	50.1	52.5	34.3	19.5	22.7
Simulation of drought in South Asia 2030–2035	93.7	55.0	51.9	31.8	19.8	22.9

Source: Authors' calculations.

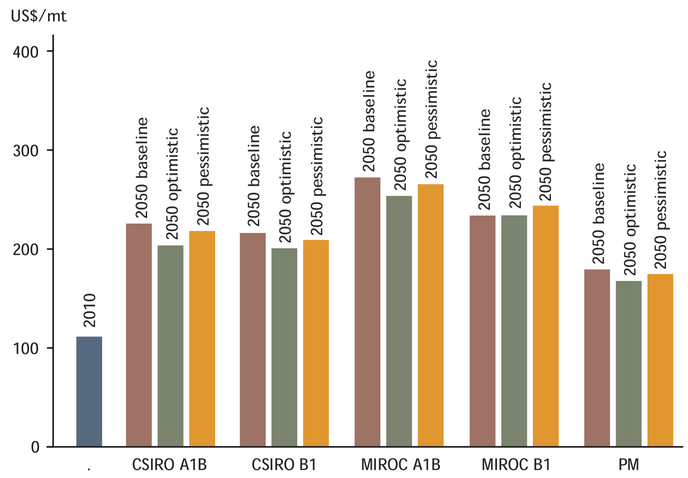
Note: The percentage increase for the scenarios is the mean across the results for the four climate scenarios, CSIRO and MIROC GCMs with the SRES A1B and B1 GHG forcings. For the overall scenarios, the numbers in parentheses and italics are the standard deviation (std. dev.) and coefficient of variation (CoV) of the 2050 price for the four climate scenarios. The perfect mitigation results assume all GHG emissions cease in 2000 and the climate momentum in the system is halted.

Yield Outcomes

It is useful to describe how IMPACT deals with productivity increases that are outside of the direct modeling environment. Sources of changes include: investments in agricultural productivity by the public and private sectors; technology dissemination by research and extension agencies and input suppliers; and investments in infrastructure, such as rural roads. For each

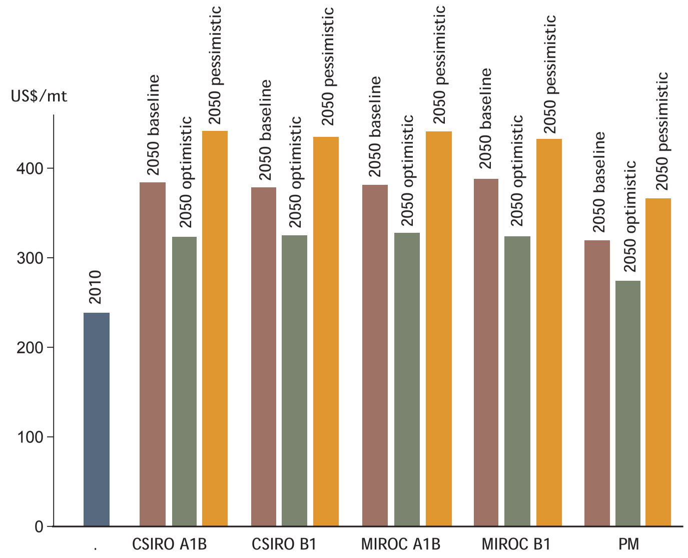
[6] The standard deviation shows how much variation a variable has from its mean value. A larger value means that the range of the variable—prices in this case—is also large. It is a useful summary value for variability in a single variable but cannot be used to compare variability of different variables. The coefficient of variation (CoV) is the standard deviation divided by the mean. It makes possible comparisons of the variability of different variables (for example, prices and the number of malnourished children).

Figure 2.2 Maize price, various scenarios



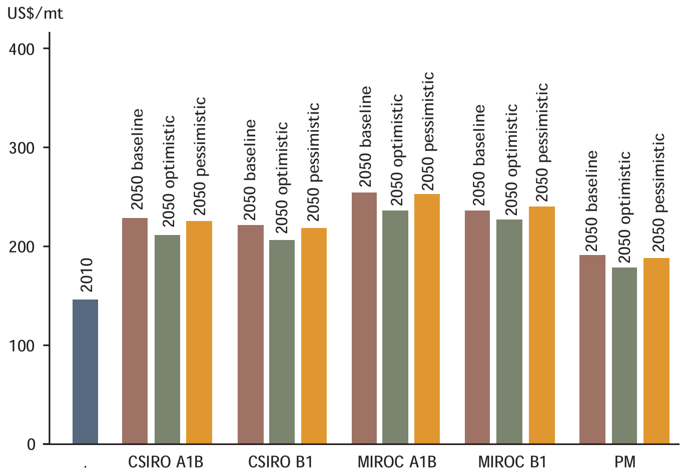
Source: Authors' estimates.

Figure 2.3 Rice price, various scenarios



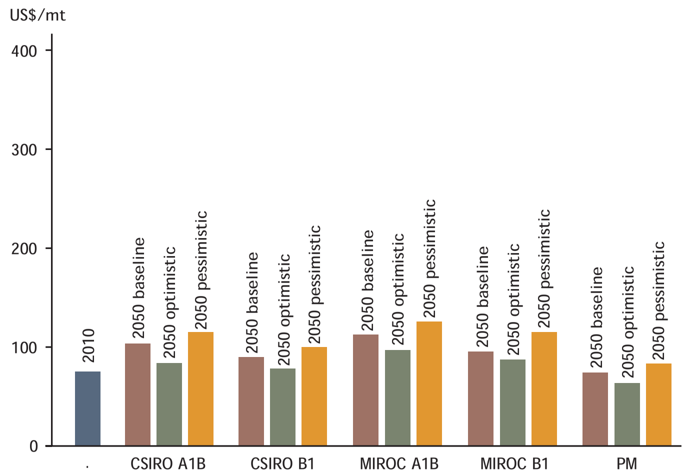
Source: Authors' estimates.

Figure 2.4 Wheat price, various scenarios



Source: Authors' estimates.

Figure 2.5 Cassava price, various scenarios

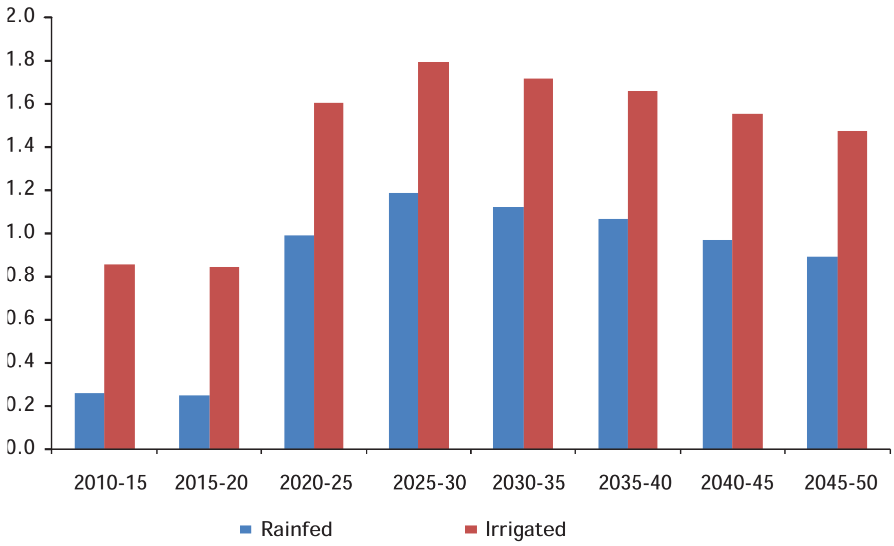


Source: Authors' estimates.

crop in each FPU, and for both irrigated and rainfed management systems, IMPACT requires an assumption about exogenous yield growth (that is, the intrinsic productivity growth rates, or IPRs) in five-year increments. Figure 2.6 illustrates the concept with the IPRs for irrigated and rainfed rice in the California FPU of the United States. The IPRs were originally constructed based on empirical analysis of the determinants of yield growth in the 1990s (Evenson and Rosegrant 1995) and then updated as better information became available. As a general rule, with many exceptions, the IPRs tend to increase slightly over the next 10–15 years and then decline gradually (to 2050). This pattern is based on historical trends in research expenditures, as well as on expert opinion on how research expenditures are likely to continue and the effects on crop productivity. The exogenous IPRs are then adjusted to account for the effects of climate change and producer responses to changes in prices.

Table 2.3 reports the combined effects of the IPRs, climate change, and the economic and demographic drivers on yields for the major crops in irrigated and rainfed systems. The table shows both absolute yields and the

Figure 2.6 Rice intrinsic productivity growth rates (IPRs) for the California FPU (exogenous yield increment, percent per year)



Source: Authors' estimates.

Table 2.3 2010 yields (mt/ha) and changes from 2010 to 2050 for major crop

Commodity & category	2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)			2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)		
					Baseline	Opt.	Pess.					Baseline	Opt.	Pess.
	Irrigated							Rainfed						
Cassava, developed														
CC mean	14.64	27.92	27.59	28.20	1.63	1.60	1.66	20.52	31.76	31.71	31.94	1.10	1.09	1.13
Perf mit	14.57	27.43	27.10	27.68	1.59	1.56	1.62	22.19	40.01	39.50	40.38	1.48	1.45	1.51
Cassava, low-income developing														
CC mean	11.89	19.45	19.19	19.67	1.24	1.20	1.27	8.10	11.30	11.12	11.49	0.84	0.79	0.89
Perf mit	12.08	21.11	20.83	21.32	1.40	1.37	1.44	8.15	11.82	11.57	12.01	0.93	0.88	0.98
Cassava, middle-income developing														
CC mean	18.59	26.93	26.64	27.35	0.93	0.90	0.98	11.60	16.64	16.25	16.48	0.91	0.85	0.90
Perf mit	19.11	31.01	30.70	31.51	1.22	1.19	1.27	11.76	17.75	17.46	17.96	1.03	0.99	1.07
Maize, developed														
CC mean	13.76	15.20	15.05	15.04	0.25	0.22	0.23	8.97	10.17	9.90	9.88	0.31	0.25	0.27
Perf mit	13.89	16.27	16.23	16.25	0.40	0.39	0.41	9.32	12.23	12.12	12.19	0.68	0.66	0.69
Maize, low-income developing														
CC mean	3.47	4.11	4.15	4.14	0.43	0.45	0.46	1.60	2.46	2.44	2.45	1.08	1.05	1.09
Perf mit	3.44	4.06	4.08	4.10	0.42	0.43	0.46	1.59	2.39	2.36	2.38	1.03	1.00	1.04
Maize, middle-income developing														
CC mean	5.54	7.78	7.91	7.91	0.85	0.89	0.91	3.57	5.41	5.35	5.38	1.04	1.01	1.05

(Continued...)

Table 2.3—Continued.

Commodity & category	2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)			2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)		
					Baseline	Opt.	Pess.					Baseline	Opt.	Pess.
	Irrigated							Rainfed						
Perf mit	5.52	7.78	7.74	7.77	0.86	0.85	0.87	3.55	5.21	5.16	5.19	0.97	0.94	0.97
Potato, developed														
CC mean	48.10	63.43	62.93	63.72	0.69	0.67	0.71	36.47	41.88	42.07	42.01	0.35	0.35	0.36
Perf mit	49.36	70.15	69.57	70.40	0.88	0.86	0.90	37.22	43.87	43.51	44.05	0.41	0.39	0.43
Potato, low-income developing														
CC mean	15.16	21.18	20.97	21.30	0.84	0.81	0.87	10.69	16.08	15.84	16.22	1.03	0.98	1.06
Perf mit	16.01	27.60	27.26	27.75	1.37	1.34	1.40	10.57	15.54	15.34	15.65	0.97	0.93	1.00
Potato, middle-income developing														
CC mean	23.14	32.33	32.40	32.71	0.84	0.84	0.87	15.82	18.18	17.94	18.20	0.35	0.32	0.37
Perf mit	23.98	38.81	38.71	39.05	1.21	1.20	1.23	15.98	18.78	18.58	18.87	0.40	0.38	0.43
Rice, developed														
CC mean	4.79	6.66	6.67	6.64	0.83	0.83	0.82	4.31	5.68	5.59	5.76	0.69	0.65	0.73
Perf mit	4.81	6.72	6.73	6.70	0.84	0.85	0.84	4.28	5.65	5.56	5.73	0.70	0.65	0.73
Rice, low-income developing														
CC mean	3.19	3.88	3.80	3.95	0.49	0.44	0.54	2.03	2.66	2.60	2.70	0.67	0.62	0.72
Perf mit	3.24	4.18	4.10	4.25	0.64	0.59	0.68	2.02	2.58	2.54	2.63	0.62	0.57	0.66

(Continued...)

Table 2.3—Continued.

Commodity & category	2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)			2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)		
					Baseline	Opt.	Pess.					Baseline	Opt.	Pess.
			Irrigated							Rainfed				
Rice, middle-income developing														
CC mean	3.35	4.08	4.13	4.19	0.49	0.51	0.56	2.04	2.76	2.70	2.80	0.76	0.70	0.79
Perf mit	3.39	4.36	4.35	4.44	0.63	0.62	0.68	2.04	2.76	2.71	2.80	0.75	0.71	0.79
Sorghum, developed														
CC mean	2.97	4.77	4.77	4.77	1.19	1.19	1.20	2.84	4.47	4.42	4.45	1.14	1.12	1.14
Perf mit	3.02	5.18	5.17	5.18	1.36	1.35	1.36	2.88	4.73	4.71	4.73	1.25	1.23	1.26
Sorghum, low-income developing														
CC mean	1.11	2.05	2.04	2.06	1.56	1.54	1.58	0.87	2.05	2.06	2.08	2.16	2.17	2.21
Perf mit	1.11	2.13	2.11	2.13	1.63	1.61	1.65	0.86	1.91	1.89	1.91	2.02	1.99	2.03
Sorghum, middle-income developing														
CC mean	2.77	4.23	4.22	4.23	1.06	1.05	1.07	1.30	2.25	2.22	2.23	1.38	1.36	1.39
Perf mit	2.79	4.31	4.30	4.32	1.09	1.09	1.11	1.30	2.23	2.22	2.23	1.36	1.35	1.38
Soybean, developed														
CC mean	3.76	6.79	6.77	6.75	1.49	1.48	1.48	2.60	3.38	3.32	3.29	0.66	0.62	0.61
Perf mit	3.86	7.69	7.67	7.65	1.74	1.73	1.73	2.77	4.41	4.39	4.35	1.17	1.16	1.15
Soybean, low-income developing														
CC mean	1.37	1.82	1.81	1.78	0.70	0.69	0.68	0.88	1.42	1.42	1.39	1.19	1.19	1.16

(Continued…)

Table 2.3—Continued.

Commodity & category	2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)			2010 (mt/ha)	2050 (mt/ha) baseline	2050 (mt/ha) opt.	2050 (mt/ha) pess.	Av. annual growth (%)		
					Baseline	Opt.	Pess.					Baseline	Opt.	Pess.
				Irrigated							Rainfed			
Perf mit	1.36	1.77	1.76	1.74	0.66	0.65	0.64	0.88	1.45	1.44	1.42	1.24	1.23	1.22
Soybean, middle-income developing														
CC mean	2.03	3.57	3.61	3.55	1.43	1.44	1.42	1.83	2.72	2.70	2.67	0.99	0.97	0.96
Perf mit	1.95	3.01	3.05	3.03	1.09	1.11	1.11	1.86	2.96	2.95	2.91	1.16	1.15	1.14
Wheat, developed														
CC mean	4.51	7.82	7.76	7.81	1.38	1.36	1.39	3.32	4.78	4.67	4.69	0.91	0.86	0.88
Perf mit	4.50	7.81	7.76	7.80	1.39	1.37	1.39	3.38	5.16	5.12	5.15	1.06	1.04	1.07
Wheat, low-income developing														
CC mean	2.64	4.52	4.47	4.52	1.36	1.33	1.37	2.45	4.70	4.67	4.78	1.65	1.62	1.67
Perf mit	2.67	4.88	4.84	4.87	1.52	1.49	1.53	2.42	5.08	5.02	5.07	1.87	1.84	1.88
Wheat, middle-income developing														
CC mean	3.45	4.51	4.49	4.53	0.68	0.66	0.70	2.22	3.77	3.72	3.75	1.33	1.30	1.33
Perf mit	3.48	4.76	4.72	4.76	0.79	0.76	0.80	2.25	3.98	3.94	3.97	1.43	1.41	1.44

Source: Authors' calculations. *Note*: 2010 yields are for the baseline scenario.

CC Mean – Mean of the four climate change scenarios. Perf Mit – Perfect mitigation: climate in 2050 is identical to that in 2000.

average annual growth rates. For irrigated crops, the growth rates range from a low of about 0.2 percent per year (0.22 percent for maize in developed countries, with climate change and the optimistic scenario) to a high of over 1.5 percent per year (1.53 percent for irrigated soy in developed countries, with perfect mitigation and the baseline scenario). Yields in low-income developing countries are generally lower than in middle-income developing or developed countries, both in 2010 and 2050. For some crops (cassava, potato, sorghum, and wheat), both rainfed and irrigated yields grow faster in the low-income developing countries than in the middle-income developing countries; for the important irrigated crops, however, low-income developing country growth rates remain low.

For rainfed systems, yields and yield growth rates are somewhat lower than for irrigated systems. Yield growth rates range from a low of 0.25 percent per annum (developed country maize with climate change and the optimistic scenario) to a high of 1.88 percent per annum (wheat in low-income developing countries with perfect mitigation and the pessimistic scenario).

Area Outcomes

Agricultural area change in the IMPACT model has both an exogenous (AGR) and endogenous (price-responsive) component.[7] The exogenous component reflects a combination of historical trends and assessments about future changes, including urbanization and other land use change. The AGR values typically decline throughout the period; they are greater than zero for crops in some countries and less than zero for others. Figures 2.7–2.10 are graphs of irrigated rice AGRs in India and China and rainfed maize AGRs in the United States and Brazil. In all cases they decline, but the Indian, Brazilian, and U.S. AGRs are for the most part greater than zero in the early part of the period, while the Chinese APRs are negative from the beginning.

As Table 2.4 shows, the net effect of the scenarios on global land use change is relatively small. Depending on scenario, the area change ranges from an increase of 2.3 percent (31.9 million hectares (ha) Perfect Mitigation, baseline) to a decline of 2.2 percent (30.9 million ha, CSIRO B1, optimistic). Global averages, however, conceal substantial differences around the world. Developed countries show a decline in agricultural area of 9 percent to 13 percent. For middle-income developing countries, crop area shows small net changes. For low-income developing countries, crop area expands dramatically, from 18 percent to 25 percent.

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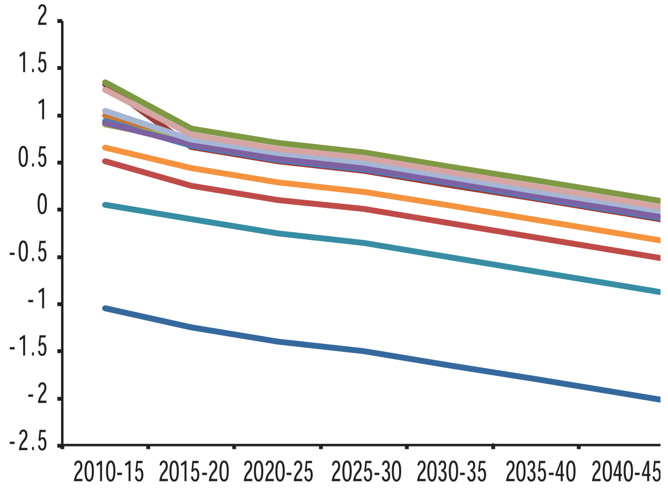
[7] In IMPACT, agricultural area change is the equivalent of FAO's crop area harvested. It includes double- and triple-cropped area where it exists. As with other agricultural statistics, IMPACT relies heavily on FAOSTAT. For agricultural area, there can be substantial difference between national statistics and FAOSTAT.

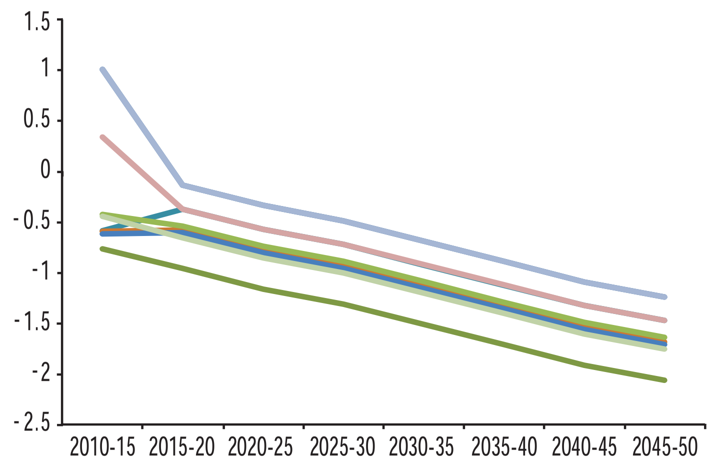
Figure 2.7 Exogenous area growth rates (AGRs) for Indian irrigated rice (percent change per year)



Source: Authors' estimates.

Note: Each line in a graph reflects the assumed path of area growth for a single food production unit (FPU) in the country.

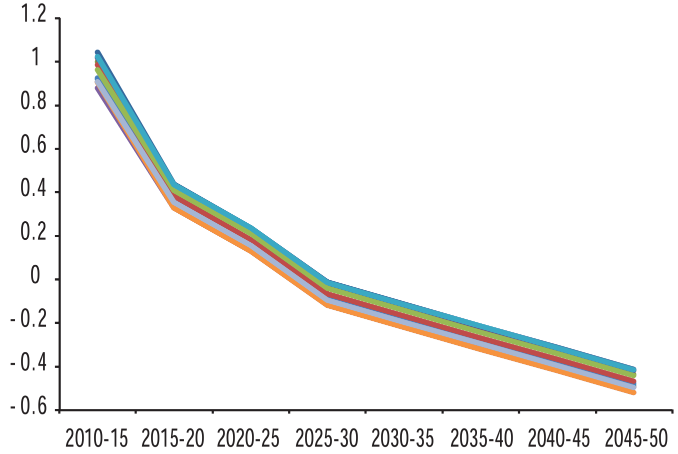
Figure 2.8 Exogenous area growth rates (AGRs) for Chinese irrigated rice (percent change per year)



Source: Authors' estimates.

Note: Each line in a graph reflects the assumed path of area growth for a single food production unit (FPU) in the country.

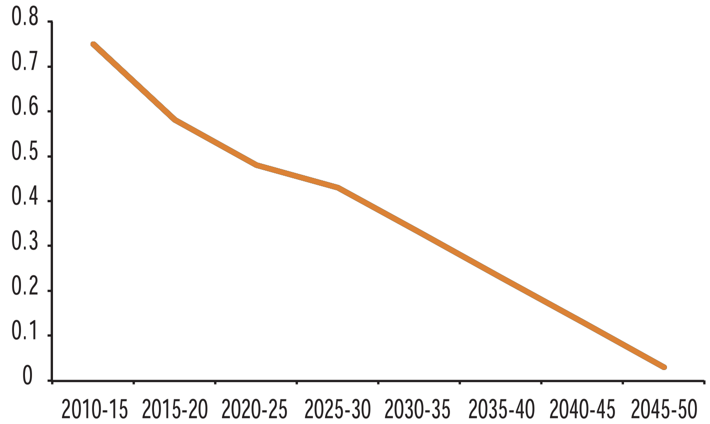
Figure 2.9 Exogenous area growth rates (AGRs) for U.S. rainfed maize (percent change per year)



Source: Authors' estimates.

Note: Each line in a graph reflects the assumed path of area growth for a single food production unit (FPU) in the country.

Figure 2.10 Exogenous area growth rates (AGRs) for Brazil rainfed maize (percent change per year)



Source: Authors' estimates.

Note: Each line in a graph reflects the assumed path of area growth for a single food production unit (FPU) in the country.

Table 2.4 2010 crop area and changes, 2010-2050 (million ha)

Category	2010	Change 2010-2050		
		Baseline	Optimistic	Pessimistic
Developed				
CSIRO A1B	240	-26.7	-32.0	-27.1
CSIRO B1	239	-27.5	-32.2	-27.9
MIROC A1B	242	-21.0	-25.7	-21.3
MIROC B1	241	-23.5	-26.6	-22.4
Perfect mitigation	241	-23.5	-28.0	-23.9
Low-income developing				
CSIRO A1B	181	38.1	32.5	41.2
CSIRO B1	181	38.6	33.6	41.8
MIROC A1B	181	37.4	32.5	40.6
MIROC B1	181	37.2	32.5	40.6
Perfect mitigation	182	43.2	38.1	46.3
Middle-income developing				
CSIRO A1B	956	-11.7	-30.1	-8.1
CSIRO B1	955	-15.6	-32.3	-12.2
MIROC A1B	960	0.2	-16.4	2.7
MIROC B1	956	-9.8	-22.5	-2.7
Perfect mitigation	963	12.2	-4.4	15.6
World				
CSIRO A1B	1,376	-0.4	-29.6	6.0
CSIRO B1	1,375	-4.6	-30.9	1.6
MIROC A1B	1,382	16.7	-9.7	22.0
MIROC B1	1,378	3.9	-16.6	15.5
Perfect mitigation	1,386	31.9	5.8	38.0

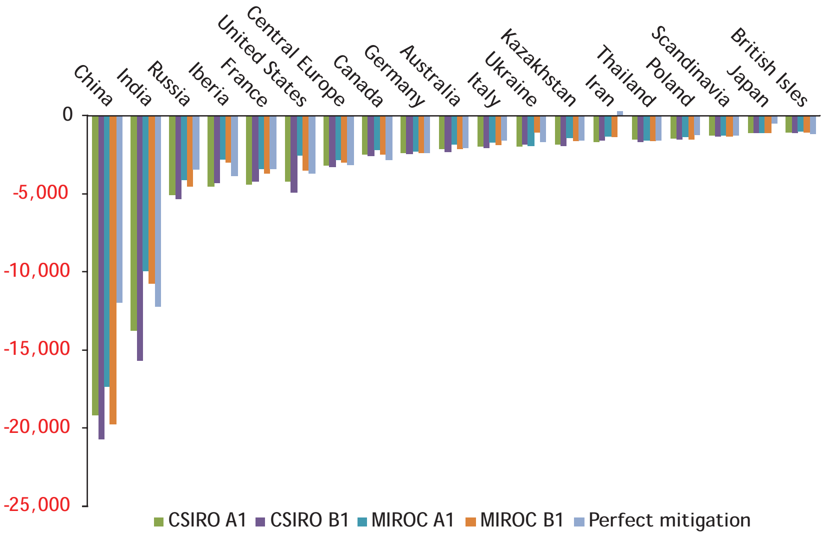
Source: Authors' estimates.

Note: 2010 results are for baseline scenario.

Figure 2.11 and Figure 2.12 illustrate more dramatically the variation in crop area outcomes by country. Figure 2.11 graphs the area declines for all countries that lose more than 1 million hectares (ha) with the baseline overall scenario. Prominent among these are the middle-income developing countries China and India, each with 15-20 million ha of crop area decline. This represents about 10 percent of Chinese 2010 crop area and 9 percent of Indian 2010 crop area.

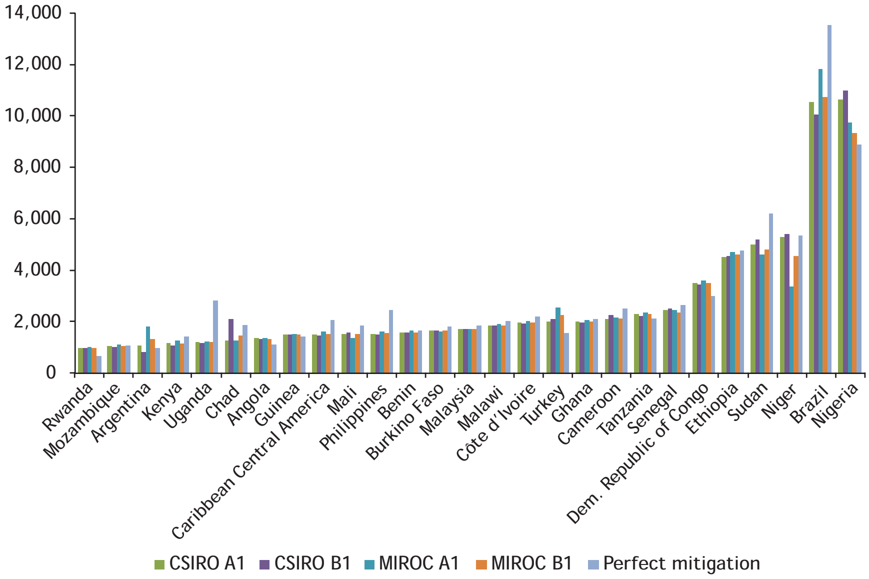
Figure 2.12 graphs the area increases for all countries where crop area *expands* by more than 1 million ha in the baseline overall scenario. While

Figure 2.11 Countries with more than 1 million ha of crop area decline, 2010-2050 (000 hectares)



Source: Authors' estimates.

Figure 2.12 Countries with more than 1 million hectares of crop area increase, 2010-2050 (000 hectares)



Source: Authors' estimates.

the number of countries with area declines is relatively small, there are many countries included in this figure, with Brazil and Nigeria having the greatest increases. And these countries are overwhelmingly located in the developing world.

Interestingly, the effects of climate change are not consistent. In some countries, area changes are greater with climate change: China, for example, has greater area loss under climate change than under perfect mitigation. In other countries, climate change brings smaller area changes: in Uganda and Brazil, area expansion is much less with climate change.

Production Outcomes

The yield and area changes combine to give production changes as reported in Table 2.5, showing maize, rice, and wheat for the overall scenarios, both with perfect mitigation and with mean climate change outcomes. Of these three crops, maize sees the largest increase in production between 2010 and 2050 under most scenarios. For developed and developing countries, the increase for maize is in the range of 20 percent to 59 percent over the period.

Table 2.5 Scenario results for maize, rice, and wheat production

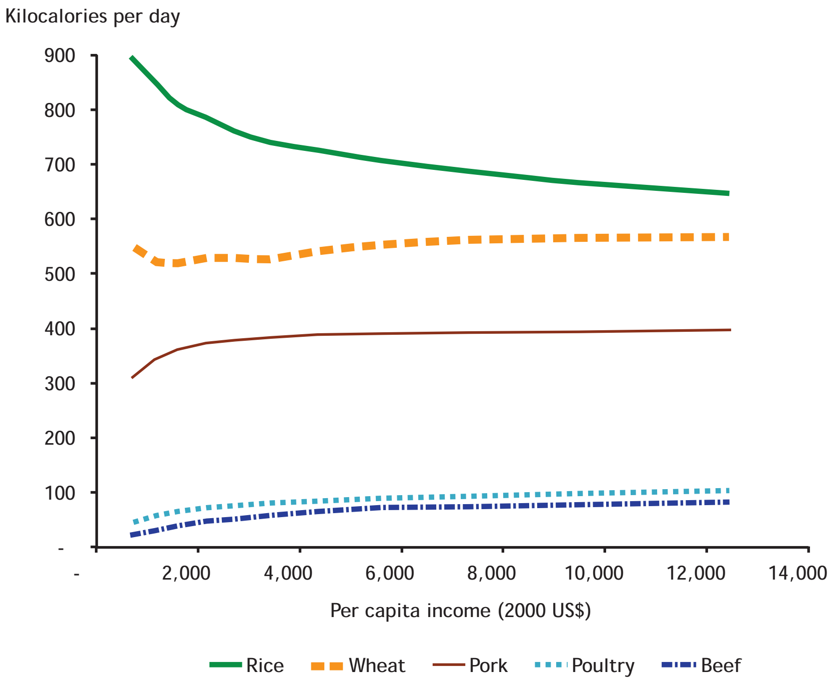
Crop & category	2010 (mmt)	2050 (mmt)	2010-50 increase (%)	2010 (mmt)	2050 (mmt)	2010-50 increase (%)	2010 (mmt)	2050 (mmt)	2010-50 increase (%)
	Pessimistic			Baseline			Optimistic		
Maize									
Developed									
Perfect mitigation	368.8	520.5	41.1	374.9	525.0	40.0	375.6	512.5	36.4
Climate change mean	357.1	442.4	23.9	364.1	454.8	24.9	363.9	437.4	20.2
Developing									
Perfect mitigation	393.5	607.4	54.4	399.1	612.1	53.4	399.8	599.4	49.9
Climate change mean	396.5	628.8	58.6	401.8	629.7	56.7	402.9	620.1	53.9
Low-income developing									
Perfect mitigation	30.8	45.6	48.2	31.2	46.0	47.2	31.3	45.0	43.7
Climate change mean	31.0	46.5	50.1	31.4	46.7	48.7	31.5	45.8	45.3
Middle-income developing									
Perfect mitigation	362.7	561.8	54.9	367.9	566.1	53.9	368.5	554.4	50.5
Climate change mean	365.5	582.3	59.3	370.4	583.0	57.4	371.4	574.3	54.6

Table 2.5—Continued.

Crop & category	2010 (mmt)	2050 (mmt)	2010-50 increase (%)	2010 (mmt)	2050 (mmt)	2010-50 increase (%)	2010 (mmt)	2050 (mmt)	2010-50 increase (%)
	Pessimistic			Baseline			Optimistic		
Rice									
Developed									
Perfect mitigation	18.8	20.7	9.9	18.8	19.9	5.6	18.9	19.1	1.2
Climate change mean	18.1	18.2	0.6	18.1	17.6	-3.2	18.1	16.8	-7.6
Developing									
Perfect mitigation	388.0	453.4	16.8	388.4	433.4	11.6	388.7	418.1	7.6
Climate change mean	382.1	418.1	9.4	382.3	398.1	4.1	382.8	385.6	0.7
Low-income developing									
Perfect mitigation	81.5	108.2	32.8	81.6	103.5	26.8	81.7	98.6	20.7
Climate change mean	81.0	104.8	29.3	81.1	100.2	23.5	81.2	95.1	17.1
Middle-income developing									
Perfect mitigation	306.5	345.1	12.6	306.8	329.9	7.5	307.0	319.5	4.1
Climate change mean	301.0	313.3	4.1	301.1	297.9	-1.1	301.7	290.5	-3.7
Wheat									
Developed									
Perfect mitigation	210.4	260.0	23.6	213.2	261.3	22.6	213.5	254.7	19.3
Climate change mean	206.6	238.7	15.5	209.7	243.2	16.0	209.7	233.6	11.4
Developing									
Perfect mitigation	418.6	645.7	54.3	423.3	647.4	53.0	423.9	634.7	49.7
Climate change mean	412.1	597.9	45.1	416.4	598.8	43.8	417.2	587.4	40.8
Low-income developing									
Perfect mitigation	19.2	37.4	94.5	19.5	37.6	93.1	19.5	36.7	88.0
Climate change mean	19.6	34.9	78.3	19.6	34.4	75.8	19.6	33.7	71.6
Middle-income developing									
Perfect mitigation	399.4	608.4	52.3	403.8	609.8	51.0	404.4	598.1	47.9
Climate change mean	392.6	563.0	43.4	396.9	564.4	42.2	397.6	553.8	39.3

Source: Authors’ calculations.

Figure 2.13 Engel curve (China)



Source: Authors' calculations.

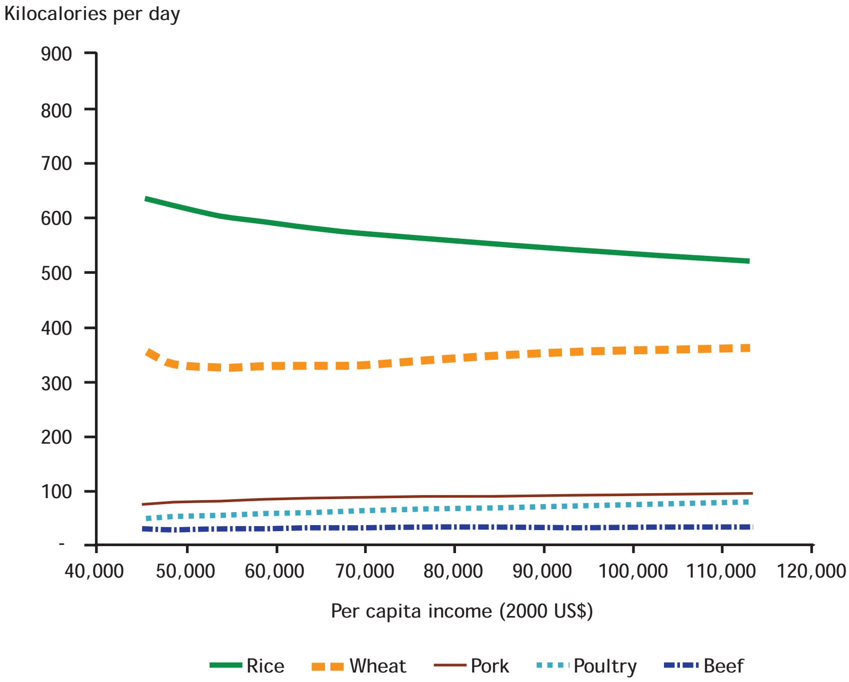
For rice, on the other hand, production increases are often in the single digits and in some cases negative (for developed and middle-income developing countries under the baseline and optimistic scenarios).

Rice production growth is largest in the low-income developing countries (17–33 percent). Wheat production growth is relatively small in developed countries (11–24 percent) but much larger in the developing countries (41–94 percent). Climate change reduces maize production growth in developed countries (particularly in the United States with the MIROC GCM), but generates small production increases in the developing countries. For rice and wheat, climate change reduces production growth everywhere relative to perfect mitigation.

International Trade Outcomes

International trade flows provide a balancing mechanism for world agricultural markets. Countries with a comparative advantage in a crop can produce it relatively more efficiently and exchange it for other goods with other countries,

Figure 2.14 Engel curve (Japan)



Source: Authors' calculations.

whose comparative advantage lies elsewhere. But comparative advantage is not fixed. Climate change alters comparative advantage, as do changing consumer preferences. Economic development itself changes the mix of goods demanded by consumers. For example, with post-WWII income growth, Japanese consumers reduced rice consumption and increased consumption of higher value foodstuffs, including fruits, vegetables, meat, and fish. Chinese consumers today are following a similar pattern of reducing rice consumption. Figure 2.13 and Figure 2.14 plot the relationship between consumption of selected commodities (in kilocalories per day) and per capita income in China and Japan, over the period 2000 to 2050 for the baseline scenario. Rice consumption in China declines from 887 kcal per day to 647 kcal per day, as per capita income rises from $780 to $12,400. Rice consumption in Japan declines from 635 kcal per day to 521 kcal per day, as per capita income rises from $45,500 to $112,900. This pattern has been repeated for other staples in other countries throughout the world as incomes have risen. Our scenarios assume this pattern will continue for other countries, as their incomes rise.

Agricultural trade flows depend on the interaction between comparative advantage in agriculture (as determined by climate and resource endowments) and a wide-ranging set of local, regional, national, and international trade policies. Unfettered international trade allows comparative advantage to be more fully exploited. Restrictions on trade risk worsening the effects of climate change by reducing the ability of producers and consumers to adjust. It is important to point out that if climate change reduces productivity of certain crops in some regions and does not increase productivity adequately in other regions, trade cannot fully compensate for the global reduction in productivity.

Early studies (Tobey, Reilly, and Kane 1992 and Reilly, Hohmann, and Kane 1994) concluded that agricultural impacts of climate change would in some cases be positive, and in other cases would be manageable globally in part because negative yield effects in temperate grain-producing regions would be buffered by interregional adjustments in production and consumption and corresponding trade flows.

A widely cited 2004 publication based its conclusions on more complex modeling of both climate and agriculture, using the IPCC's third assessment results. This report was still relatively sanguine about global food production, but with more caveats than the earlier papers: "The combined model and scenario experiments demonstrate that the world, for the most part, appears to be able to continue to feed itself under the SRES scenarios during the rest of this century. The explanation for this is that production in the developed countries generally benefits from climate change, compensating for declines projected for developing nations." (Parry et al. 2004, p. 66.)[8]

The results reported here confirm these earlier findings that trade flows are a potentially important climate change adjustment mechanism. Table 2.6 shows trade scenarios for exports of maize, rice, and wheat.

The developed countries have dominated maize exports through the early 21st century, but the average of the climate change results is a substantial decline in net maize exports, principally because of the negative effects of the MIROC scenarios on U.S. maize production. Developed country wheat exports decline in all scenarios. Developed countries are small net importers of rice in 2010; in the pessimistic scenario, rice imports decline substantially, but with the baseline and optimistic scenarios, they show little change.

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[8] The earlier literature that suggests increased agricultural exports from developed to developing countries is based on less sophisticated modeling of climate change impacts and use of very limited numbers of climate change results. It has only been since the 4th IPCC assessment modeling results, released in the mid-2000s, that more detailed modeling has been possible. As should be clear from the research reported in this report, it is possible to have climate scenarios such as those generated by the MIROC GCM that have very negative effects in temperate regions.

Table 2.6 International trade of maize, rice, and wheat

Commodity & category	2010 (mmt)	2050 % change	2010 (mmt)	2050 % change	2010 (mmt)	2050 % change
	Baseline		Pessimistic		Optimistic	
Developed						
Maize						
Perfect mitigation	36.7	120.5	37.5	127.1	37.2	105.8
Climate change mean	27.8	-25.4	27.7	-36.6	27.4	-56.9
Rice						
Perfect mitigation	-2.6	-20.5	-2.7	-61.8	-2.6	-13.7
Climate change mean	-3.0	-12.0	-3.1	-40.5	-3.0	-3.8
Wheat						
Perfect mitigation	44.6	-48.8	44.1	-37.2	44.5	-39.5
Climate change mean	42.7	-66.8	41.8	-61.8	42.2	-63.9
Middle-income developing						
Maize						
Perfect mitigation	-33.8	81.5	-33.8	83.0	-34.1	62.2
Climate change mean	-26.1	-59.4	-25.4	-80.6	-25.7	-98.0
Rice						
Perfect mitigation	-7.0	-65.7	-6.8	25.1	-7.0	-171.7
Climate change mean	-7.5	8.2	-7.3	82.2	-7.4	-94.9
Wheat						
Perfect mitigation	-38.7	-111.4	-38.1	-87.0	-37.2	-148.4
Climate change mean	-37.6	-121.5	-36.8	-104.2	-35.8	-161.7
Low-income developing						
Maize						
Perfect mitigation	-2.9	571.1	0.6	571.1	-3.1	586.3
Climate change mean	-1.7	506.0	0.5	506.0	-1.7	555.9
Rice						
Perfect mitigation	9.6	-53.4	-0.1	-53.4	9.6	-128.5
Climate change mean	10.4	2.5	0.0	2.5	10.4	-68.5
Wheat						
Perfect mitigation	-5.9	363.5	0.4	363.5	-7.3	516.3
Climate change mean	-5.1	337.8	0.3	337.8	-6.4	482.4

Source: Authors' calculations.

For middle-income developing countries, maize imports increase substantially with perfect mitigation but decline with climate change. Many of these countries reduce their rice consumption as incomes rise.[9] In the optimistic scenario, their rice imports fall; and with perfect mitigation, these countries become net rice exporters. In the pessimistic scenario, however, with low income and high population growth, middle-income country rice imports increase. Wheat imports for these countries decline across the board, but the magnitude of the change differs dramatically depending on overall scenario and climate change effects. For example, in the optimistic scenario and perfect mitigation, these countries become small net exporters; with climate change, they remain net importers.

In 2010, low-income developing countries are net importers of maize and wheat but net exporters of rice. In 2050, these countries still have large net wheat and maize imports, while net exports of rice have become net imports.

Different climate models result in dramatically different effects on trade flows, as Figure 2.15 illustrates. With perfect mitigation, net cereal exports from the developed countries are about the same level in 2010 and 2050, regardless of overall scenario. With the CSIRO scenarios, net cereal exports from the developed countries decline somewhat. With the MIROC scenarios, however, developed countries' cereal trade actually becomes negative, with substantial imports. This particular result is driven by a combination of increased maize production in developing countries and the negative effects of the MIROC climate scenarios on U.S. maize (see Table 2.7). For perfect mitigation and the CSIRO scenarios, U.S. production increases by more than 40 percent from 2010 to 2050. With the MIROC scenarios, however, the increases are only 22 percent (B1) and a minimal 3.7 percent (A1B).

The consequence of the MIROC A1B-induced production effects is a dramatic decline in U.S. exports, falling by almost 70 percent. For the perfect mitigation and CSIRO scenarios, in contrast, U.S. exports roughly double. This result demonstrates dramatically both the uncertainty in the climate scenarios and the importance of international trade in reducing the negative effects of climate change on agricultural productivity, whatever (and wherever) they are.

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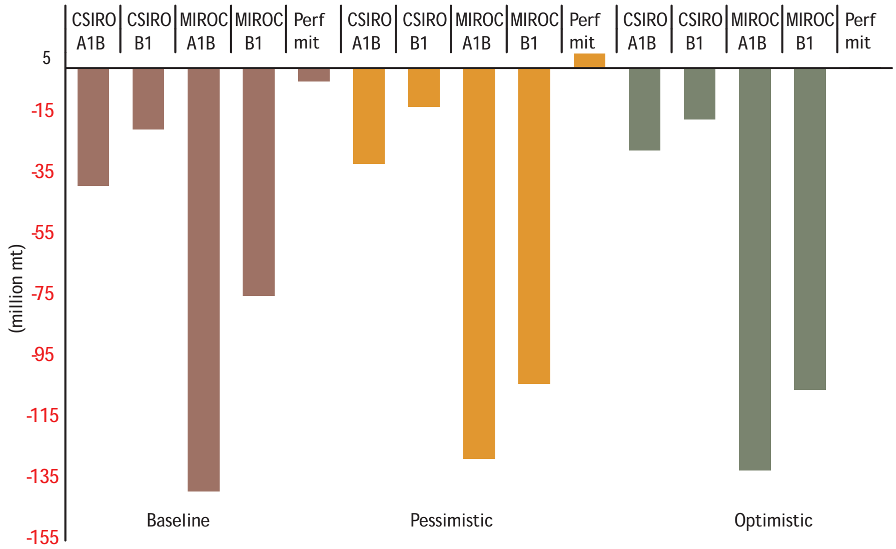
[9] A general phenomenon of per capita income growth, known as Bennett's Law, is a decline in consumption of starchy staples and increase in consumption of meat, oils, and a more diverse diet generally. The IMPACT model captures this effect explicitly in its baseline runs. However, it does not adjust for the resulting changes in real income for producers of agricultural commodities in the various simulations performed for this report. Our expectation is that these second-round effects will be relatively small.

Figure 2.15 Change in net cereals trade from developed countries, 2010-2050 (million mt)



Source: Authors' calculations.

It is of interest to compare these trade change results with those derived by Liefert et al. (2010) for Russia, Kazakhstan, and Ukraine. Their report, released before the Russian wheat embargo of 2010, suggests that by 2019 Russia could become the world's top wheat exporter, and that the combined wheat exports of Russia, Ukraine, and Kazakhstan could more than double those of the United States. The article bases its 2019 exports results on two kinds of adjustments that are unlikely to continue. The first is a decline in meat consumption in these countries that would free up grain for export.

Table 2.7 U.S. maize production, 2010 and 2050, baseline scenario (million mt)

Category	2010	2050	Change (percent)
CSIRO A1B	326.5	461.2	41.2
CSIRO B1	327.5	471.5	44.0
MIROC A1B	303.6	315.0	3.70
MIROC B1	314.8	384.0	22.0
Perfect mitigation	328.0	476.8	45.3

Source: Authors' calculations.

The second is efficiency gains from conversion of old-style state farms to privately run corporations that invest substantially in productivity-enhancing technology. They also make the point that area expansion is possible but less likely, dependent on high prices and investment in infrastructure to move the grain from marginal areas to world markets.

Our scenarios show U.S. wheat exports in 2020 at 2.1 to 2.7 times Russian exports, depending on the climate scenario. By 2050, however, U.S. exports range from merely 0.8 to 1.1 times Russian exports. The more rapid growth of Russian exports is driven by productivity increases rather than area expansion.

Consumption and Human Well-Being Outcomes

This section focuses on maize, rice, and wheat, as the most important crops for calorie consumption globally. As Table 2.8 shows, rice and wheat each account for more than 500 kcal per day for the world's average consumer. Together, rice and wheat make up more than one-third of consumption of the IMPACT commodities of 2,590 kcal per day; oils are the third largest IMPACT component, and sugar and directly consumed maize are fourth and fifth. For developing countries as a group, the rank order of commodities is identical. However, for the low-income developing countries, maize is second most important and cassava fourth; the top five commodities account for over 70 percent of their total consumption of 2,041 kcal per day.

Physical human well-being has many determinants. Calorie availability is a key element in low-income countries, where malnutrition and poverty are serious problems. Distribution, access, and supporting resources can enhance or reduce the individual's calorie availability. Similarly, child malnutrition has many determinants, including calorie intake (Rosegrant et al. 2008). The relationship used to estimate the number of malnourished children is based on a cross-country regression relationship estimated by Smith and Haddad (2000) that takes into account female access to secondary education, the quality of maternal and child care, and health and sanitation.[10] The IMPACT model

[10] Because it is a partial equilibrium model, IMPACT has no feedback mechanisms between climate change effects on productivity and income. This means that it cannot estimate directly the poverty effects of agricultural productivity declines from climate change. However, the reduced form function that relates child malnutrition to calorie availability and other determinants implicitly includes the effects of real income change on child malnutrition. Hertel, Burke, and Lobell (2010) use a general equilibrium model to estimate explicitly the effects of climate change on poverty. They find that the poverty impacts to 2030 "depend as much on where impoverished households earn their income as on the agricultural impacts themselves, with poverty rates in some non-agricultural household groups rising by 20-50% in parts of Africa and Asia under these price changes, and falling by equal amounts for agriculture-specialized households elsewhere in Asia and Latin America."

Table 2.8 Calorie consumption by commodity, 2000

Commodity	World		Developing		Low income developing	
	Kcals per day	Rank	Kcals per day	Rank	Kcals per day	Rank
Rice	564	1	631	1	713	1
Wheat	531	2	514	2	214	3
Oils	318	3	262	3	146	5
Sugarcane	199	4	178	4	77	6
Maize	148	5	161	5	239	2
Milk	121	6	91	7	49	9
Pork	114	7	105	6	26	13
Vegetables	70	8	68	8	26	14
Potato	59	9	52	11	25	15
Subtropical fruits	56	10	55	10	42	11
Cassava	49	11	57	9	175	4
Poultry	44	12	32	17	7	19
Groundnuts	40	13	42	13	39	12
Beef	40	14	32	16	22	17
Sweet potato	38	15	44	12	43	10
Sorghum	34	16	39	14	68	7
Eggs	32	17	28	18	5	22
Millet	29	18	34	15	58	8
Sweeteners	23	19	4	25	2	25
Other grains	22	20	21	19	22	16
Soybeans	17	21	17	20	8	18
Temperate fruits	15	22	11	22	3	23
Lamb	10	23	10	23	7	20
Chickpea	10	24	11	21	5	21
Pigeonpea	8	25	9	24	2	24
Total	2,590		2,506		2,041	

Source: Authors' estimates based on FAOSTAT data.

provides data on per capita calorie availability by country; the other determinants are assumed to remain the same across the overall scenarios. Table 2.9 shows the 2010 and 2050 values for the non-caloric determinants of child malnutrition, aggregated to low- and middle-income countries. The small decline in female relative life expectancy in 2050 for the middle-income countries is primarily caused by a decline in China, where it is expected that male life expectancy will gradually move up, rather than female life expectancy moving down.

Table 2.10 summarizes the kilocalorie and malnourished children outcomes from the overall scenarios. Table 2.11 provides a summary of the results from the simulations, which are discussed in more detail below.

A central result is the importance of economic development in reducing child malnutrition. In the optimistic scenario, the number of malnourished children in developing countries falls by almost 46 percent between 2010 and 2050, a decline from 157 million to 85 million. With the pessimistic scenario, on the other hand, that number decreases by only 1.8 percent. Similarly, for middle-income developing countries, the optimistic scenario results in a 50 percent decline in the number of malnourished children; under the pessimistic scenario, the decline is only 10 percent. For low-income developing countries, the decline is 36.6 percent under the optimistic scenario,

Table 2.9 Non-caloric determinants of child malnutrition

Country category	Clean water access (percent)[1]		Female schooling (percent)[2]		Female relative life expectancy[3]	
	2010	2050	2010	2050	2010	2050
Middle-income countries	86.8	98.4	71.6	81.7	1.066	1.060
Low-income countries	69.0	85.8	54.9	61.6	1.044	1.048

Source: Authors' population-weighted aggregations, based on data from 2000 with expert extrapolations to 2050. Original data sources include: the World Health Organization's Global Database on Child Growth Malnutrition; the United Nations Administrative Committee on Coordination – Subcommittee on Nutrition; the World Bank's World Development Indicators; the FAO FAOSTAT database; and the UNESCO UNESCOSTAT database. Aggregations are weighted by population shares and are based on the baseline population growth scenario.

Notes: 1. Share of population with access to safe water.

2. Total female enrollment in secondary education (any age group) as a percentage of the female age group corresponding to national regulations for secondary education.

3. Ratio of female to male life expectancy at birth.

Table 2.10 Scenarios results for number of malnourished children and average daily kilocalorie availability

Scenarios	Number of malnourished children				Daily kilocalorie availability		
	% change 2010-2050	Increase in 2050 over perfect mitigation (%)	2050 std. dev.	2050 CoV	% change 2010-2050	2050 std. dev.	2050 CoV
Developing							
Baseline	-25.1	9.8	1,810	0.015	0.4	32.6	0.010
Optimistic	-45.9	10.3	1,667	0.020	4.7	36.9	0.011
Pessimistic	-1.8	8.7	9	0.014	-8.3	30.6	0.010
Low-income developing							
Baseline	-8.6	9.5	709	0.016	0.8	31.8	0.010
Optimistic	-36.6	11.5	657	0.022	9.7	36.9	0.011
Pessimistic	18.1	8.6	9	0.015	-6.2	30.1	0.010
Middle-income developing							
Baseline	-32.3	10.0	1,109	0.015	8.5	33.6	0.015
Optimistic	-49.9	9.6	1,010	0.018	34.6	45.8	0.016
Pessimistic	-10.3	8.7	9	0.013	-5.9	31.0	0.016

Source: Authors' calculations.

Note: The standard deviation (std. dev.) and coefficient of variation (CoV) values are for the number of malnourished children and daily kilocalorie availability in 2050.

but under the pessimistic scenario the number of malnourished children *increases* by more than 18 percent—an increase of almost 17 million.

Climate change exacerbates the challenges in reducing the number of malnourished children, although the effects are mitigated by economic development. Climate change increases the number of malnourished children in 2050 relative to perfect mitigation by about 10 percent for the optimistic scenario and 9 percent for the pessimistic scenario. In low-income countries under the optimistic scenario, climate change increases the number of malnourished children by 9.8 percent; under the pessimistic scenario, by 8.7 percent.

Table 2.11 Simulation results for average daily kilocalorie availability and number of malnourished children

Scenario	% change 2010-2050	2050 simulation minus 2050 baseline (million)	2050 simulation minus 2050 baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 simulation minus 2050 baseline (%)
	Malnourished children			Daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Productivity improvement simulations						
Overall	-37.2	-19.1	-16.2	18.9	408.5	15.1
Commercial maize	-27.5	-3.8	-3.2	5.9	60.5	2.2
Developing country wheat	-26.8	-2.6	-2.2	5.6	53.7	2.0
Developing country cassava	-26.0	-1.4	-1.1	4.2	16.4	0.6
Irrigation	-25.4	-0.3	-0.3	3.9	7.7	0.3
Drought in South Asia 2030-2035	-25.5	-0.7	-0.6	4.0	12.3	0.5
Low-income developing						
Baseline	-8.6			6.8		
Productivity improvement simulations						
Overall	-22.6	-6.6	-15.1	26.9	370.9	16.7
Commercial maize	-13.0	-2.1	-4.8	13.7	104.5	4.7
Developing country wheat	-10.1	-0.7	-1.6	10.4	36.9	1.7
Developing country cassava	-10.6	-1.0	-2.2	10.6	41.2	1.9
Irrigation	-8.8	-0.1	-0.2	8.9	6.2	0.3
Drought in South Asia 2030-2035	-9.1	-0.2	-0.6	9.1	12.2	0.5
Middle-income developing						
Baseline	-32.3			8.5		
Productivity improvement simulations						
Overall	-43.5	-12.5	-16.8	19.6	419.8	14.7
Commercial maize	-33.8	-1.7	-2.2	6.3	47.3	1.7
Developing country wheat	-34.0	-1.9	-2.5	6.7	58.7	2.1
Developing country cassava	-32.7	-0.4	-0.5	4.9	9.0	0.3
Irrigation	-32.6	-0.3	-0.4	4.9	8.1	0.3
Drought in South Asia 2030-2035	-32.7	-0.4	-0.6	5.0	12.4	0.4

Source: Authors' calculations.

CHAPTER 3

Discussion of Overall Scenarios Results

Figure 3.1 provides a useful summary of the combined effects of economic development and climate change on food security. The left side of the graph shows the progress on daily kilocalorie availability between 2010 and 2050 under the optimistic scenario—that is, high economic growth and low population growth; the right side shows outcomes under the pessimistic scenario.

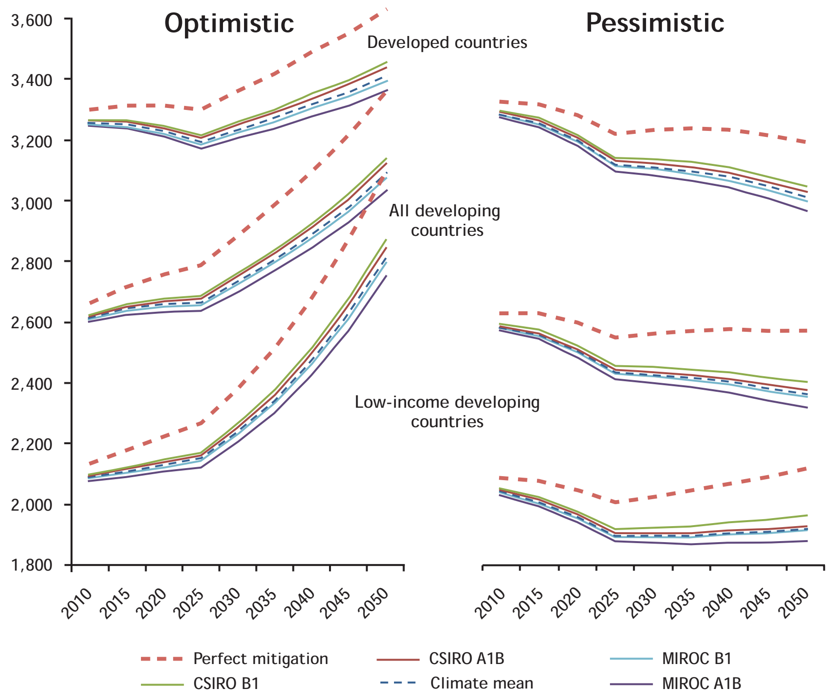
Figure 3.1 presents daily average per capita calories available for three groups of countries: all developed, all developing, and the 40 low-income developing countries. For each group of countries, the top (red, dashed) line represents a future with perfect greenhouse gas mitigation. The lines below the top line show the outcomes with the different GCM and SRES scenario combinations—that is, different climate change scenarios.

There are three main messages from Figure 3.1 and the results from the overall scenarios.

1. **Broad-based economic development is central to improvements in human well-being.**
   Per capita income growth is a critical driver of human well-being. In low-income developing countries average kilocalorie availability is only two-thirds of the richest countries today; with high per capita income growth and perfect climate mitigation, the availability in 2050 reaches almost 85 percent of the developed countries. And because they grow more rapidly, the difference in availability among the developing country group diminishes dramatically. With the pessimistic overall scenario, however, human well-being declines in all regions.

2. **Climate change offsets some of the benefits of income growth.**
   For all regions, the negative productivity effects of climate change reduce food availability and human well-being. Climate change results in even higher world prices in 2050. Climate change increases the number of malnourished children in 2050 (relative to perfect climate mitigation)

Figure 3.1 Assessing the impacts of climate change and economic development on food security (average kcal/day)



Source: Authors' calculations.[11]

by about 10 percent for the optimistic development scenario, and by 9 percent for the pessimistic scenario. The effect of climate change in the low-income developing countries is similar, increasing the number of malnourished children by over 11 percent in the optimistic scenario and over 8 percent in the pessimistic scenario.

[11] Feedstock use for biofuels production is distinguished as a separate category of demand in IMPACT. For these results, biofuel production itself is not modeled, but is represented solely in terms of feedstock demand. As a consequence, trade in biofuels is also not directly represented. Instead, the share of transport energy assumed to come from biofuels was converted to feedstock tonnage and used to adjust the demand side of IMPACT. We assume that beyond 2025 second-generation biofuels technologies will largely take over, and therefore keep the feedstock demands constant at that period. This causes a 'kink' to appear in some of the model results around 2025.

3. **International trade plays an essential role in compensating for different climate change effects.**
   Despite large differences in precipitation amounts and seasonal variation across the climate scenarios, the differences in price (and other) outcomes are relatively small, except for the dramatic effect on international trade flows. As Figure 2.15 demonstrates, changes in developed country net cereal exports from 2010–2050 range from an increase of 5 million mt in the perfect mitigation scenario to a decline of almost 140 million mt. The MIROC scenarios are particularly dry in the central US, resulting in much lower 2050 maize and soybean production than the CSIRO scenarios. The trade flow changes partially offset local climate change productivity effects, allowing regions of the world with less negative effects to supply those with more negative effects. This important role for international trade can also be seen in the results for the South Asian drought simulation (Figure 4.33).

   We turn next to a discussion of the simulations.

CHAPTER 4

Discussion of the Simulations

The simulations have been chosen to highlight the relative importance of different kinds of policy changes and program activities that could potentially contribute to meeting the challenges of achieving sustainable food production by 2050. We begin with a series of simulations involving increases in crop productivity. The initial IPRs are adjusted either by using a constant multiplier (1.4 for all developing country IPRs, in the simulation of overall productivity improvement) or by increasing them to a rate that is plausible if additional expenditures on productivity enhancements are undertaken (2 percent in selected countries for maize, wheat, and cassava).

Improvements in Overall Productivity

This simulation represents an across-the-board increase in IPRs in developing countries of 40 percent, relative to baseline scenario values beginning in 2010. Table 4.1 reports the results. Because the productivity increases are only in developing countries, yields in developed countries actually fall slightly in response to lower world prices (except for irrigated rice). Yields in developing countries increase in varying amounts, from 8.9 percent for irrigated rice in middle-income developing countries to 28.8 percent for rainfed wheat, also in low-income developing countries.

With the productivity improvements, world price increases are 15 to 22 percent less than in the baseline (Figures 4.1–4.4 and Table 4.2). The number of malnourished children in 2050 drops by 16.2 percent across all the overall productivity scenarios—that is, an additional 19.1 million children who are not malnourished.

Improvements in Commercial Maize Productivity

The commercial maize productivity simulation is driven by the estimate from private sector sources that hybrid maize yields can be expected to increase by 2.5 percent per year at least until the 2030s. The simulation assumes that maize yields increase by 2 percent per year to 2050 in the countries that currently grow the most hybrid maize: USA, Mexico, China, Europe, France,

Table 4.1 Yield outcomes for maize, rice, and wheat: Overall productivity simulation

Commodity & category	2010 (mt)	2050 baseline (mt/ha)	2050 with improved efficiency (mt)	Efficiency increase (%)	2010	2050 baseline (mt/ha)	2050 with improved efficiency	Efficiency increase (%)
	Irrigated				Rainfed			
Developed								
Maize	13.8	15.4	15.30	-0.7	9.0	10.6	10.3	-2.7
Rice	4.8	6.7	6.68	0.1	4.3	5.7	5.6	-1.6
Wheat	4.5	7.8	7.61	-2.6	3.3	4.9	4.7	-2.8
Middle-income developing								
Maize	5.5	7.8	8.82	13.4	3.6	5.4	6.2	15.0
Rice	3.4	4.1	4.71	13.9	2.0	2.8	3.0	8.9
Wheat	3.5	4.6	5.06	11.0	2.2	3.8	4.7	24.5
Low-income developing								
Maize	3.5	4.1	4.46	8.6	1.6	2.4	2.8	16.5
Rice	3.2	3.9	4.38	11.1	2.0	2.6	2.9	10.1
Wheat	2.6	4.6	5.67	23.4	2.4	4.8	6.2	28.8

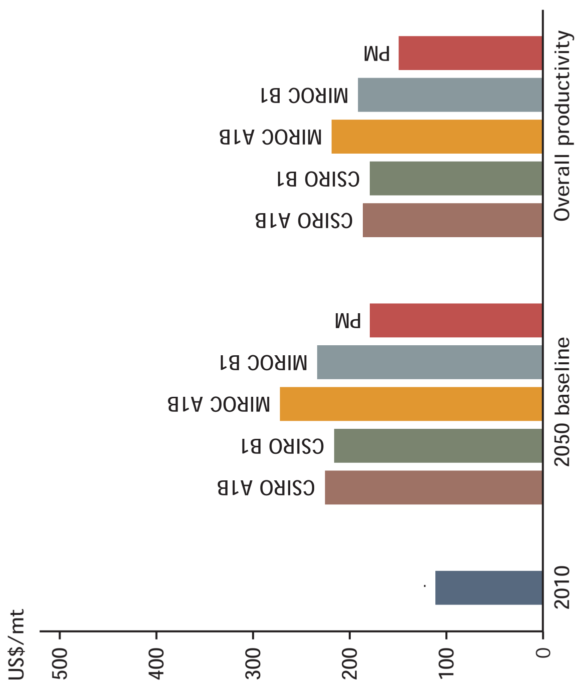
Source: Authors' calculations.

Brazil, Argentina, and South Africa. These countries account for almost 80 percent of current maize production.

Figure 4.5 shows both the changes in IPRs from the simulation, for countries directly affected, and the effects of climate change. It is useful to examine one country in detail. Without climate change and without the effects of the simulation, Argentine maize productivity growth is expected to be about 1 percent per year in the mid-2010s and then gradually decline to zero by 2050. Climate change reduces the IPRs slightly with the MIROC GCM. With the simulation's productivity increase to 2 percent, climate change again alters the effect somewhat, reducing productivity growth to about 1.8 percent for the MIROC GCM and increasing it to about 2.1 percent for the CSIRO GCM. The magnitude of these effects varies by country. In China, for example, climate change has essentially no effect on maize IPRs.

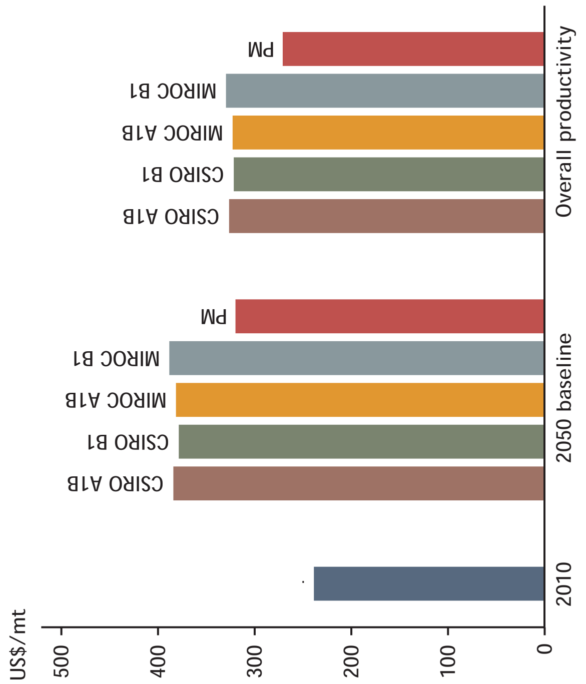
The most obvious consequence of this productivity simulation, as Table 4.4 and Figures 4.6–4.9 indicate, is that the international price of maize increases by only 12 percent between 2010 and 2050, instead of the 101 percent increase of the baseline. Wheat and rice prices are only modestly affected.

Figure 4.1 Maize price, overall productivity



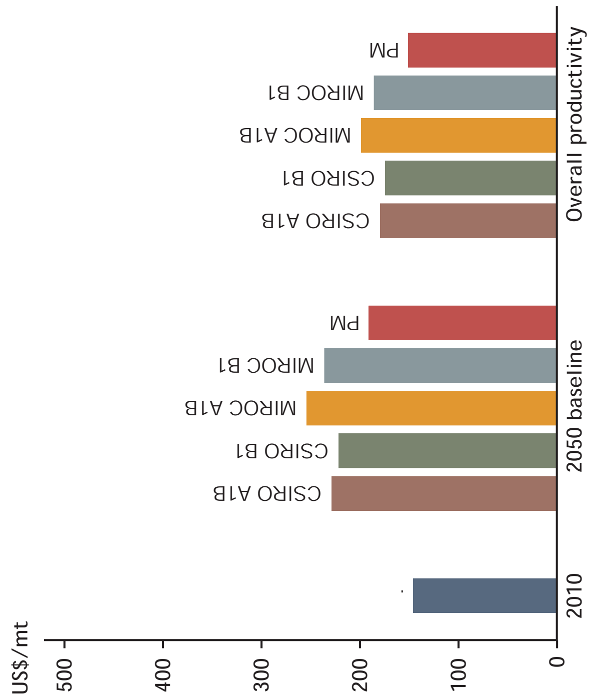
Source: Authors' calculations.

Figure 4.2 Rice price, overall productivity



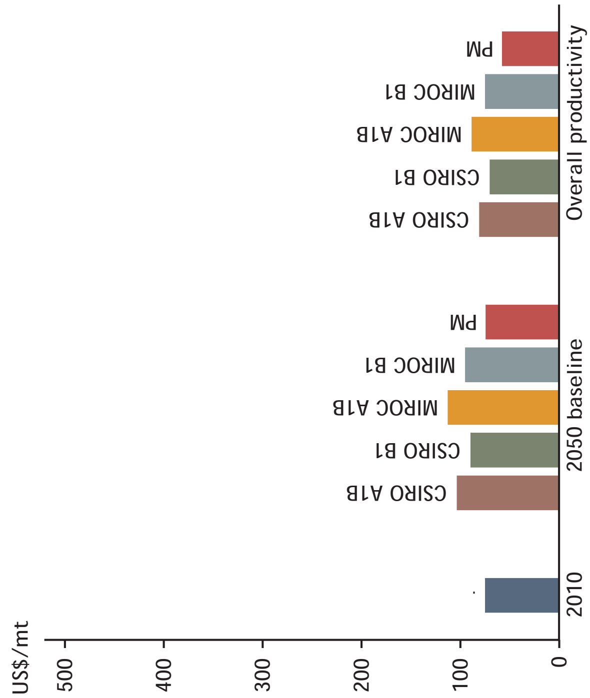
Source: Authors' calculations.

Figure 4.3 Wheat price, overall productivity



Source: Authors' calculations.

Figure 4.4 Cassava price, overall productivity



Source: Authors' calculations.

Table 4.2 Price effects of improvements in overall efficiency

Scenario	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change 2010 mean to 2050 mean (2050 std. dev. and CoV)			% price change 2050 baseline to 2050 higher efficiency		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*			
Improved overall productivity rates	59.8	31.2	20.0	-18.1	-15.1	-21.5

Source: Authors' calculations.

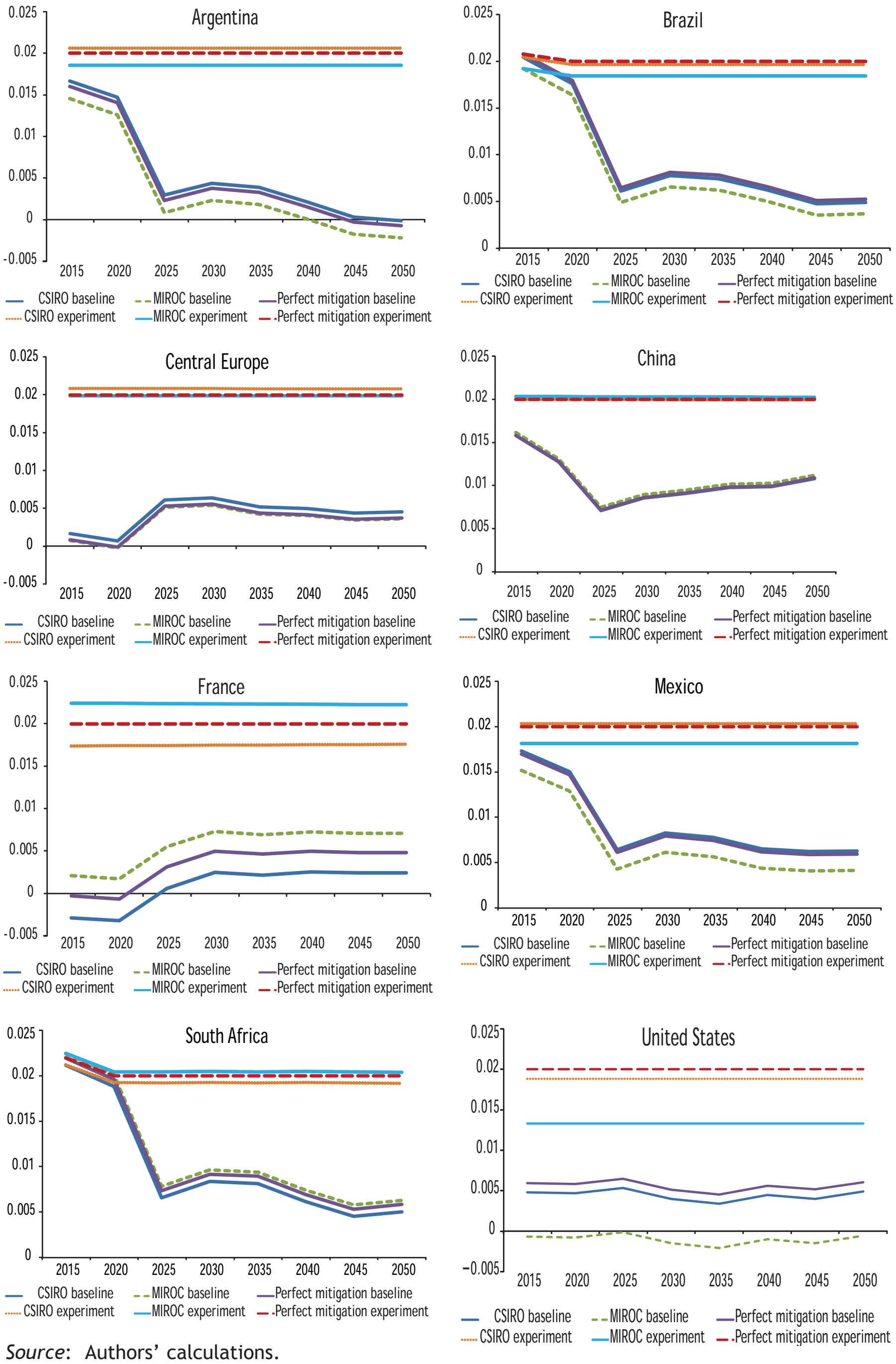
The lower maize prices mean higher human consumption and more use in animal feed and therefore slightly lower meat prices. The effect is to increase daily kilocalories consumed and to reduce child malnutrition by 3.8 million in 2050, with a slightly greater share in the low-income developing countries where direct maize consumption is particularly important.

Table 4.3 Human well-being effects of improvements in overall efficiency

Category/ Scenario	% change 2010-2050	2050 simulation minus 2050 baseline (million)	2050 simulation minus 2050 baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 simulation minus 2050 baseline (%)
	Malnourished children			Average daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Overall productivity improvement	-37.2	-19.1	-16.2	18.9	408.5	15.1
Low-income developing						
Baseline	-8.6			6.8		
Overall productivity improvement	-22.6	-6.6	-15.1	26.9	370.9	16.7
Middle-income developing						
Baseline	-32.3			8.5		
Overall productivity improvement	-43.5	-12.5	-16.8	19.6	419.8	14.7

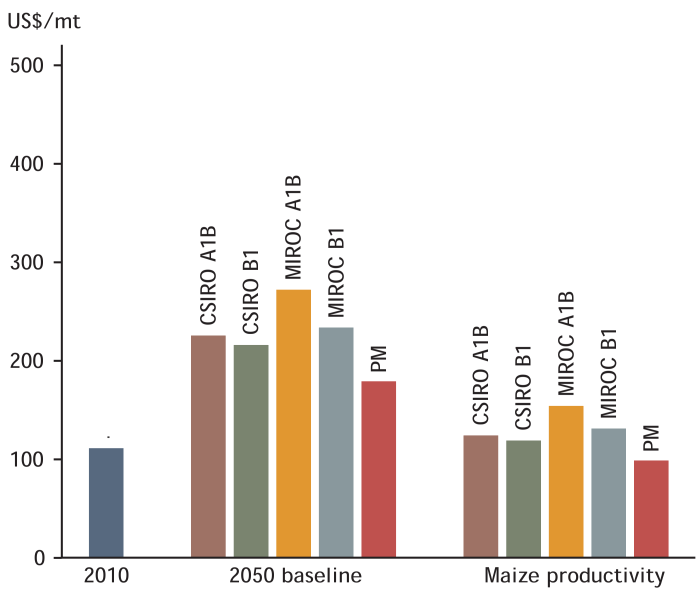
Source: Authors' calculations.

Figure 4.5 Intrinsic productivity growth rates (IPRs) for the maize productivity simulation (percent per year)



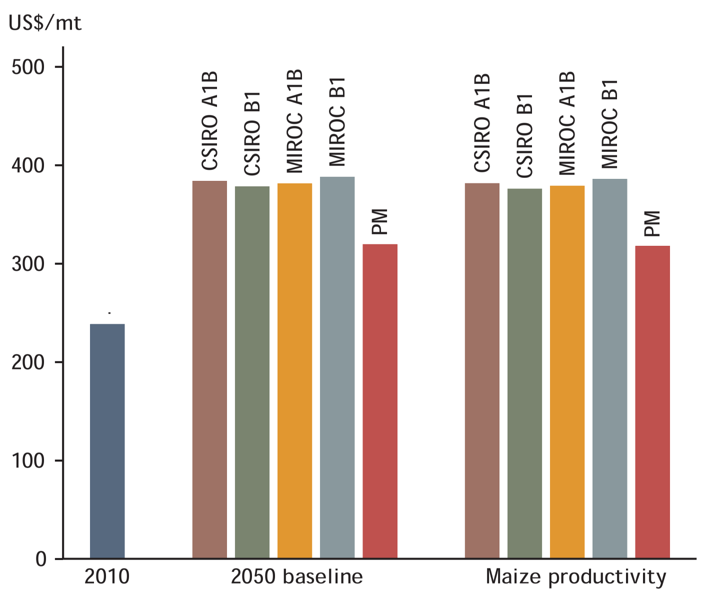
Source: Authors' calculations.

Figure 4.6 Maize price, maize productivity



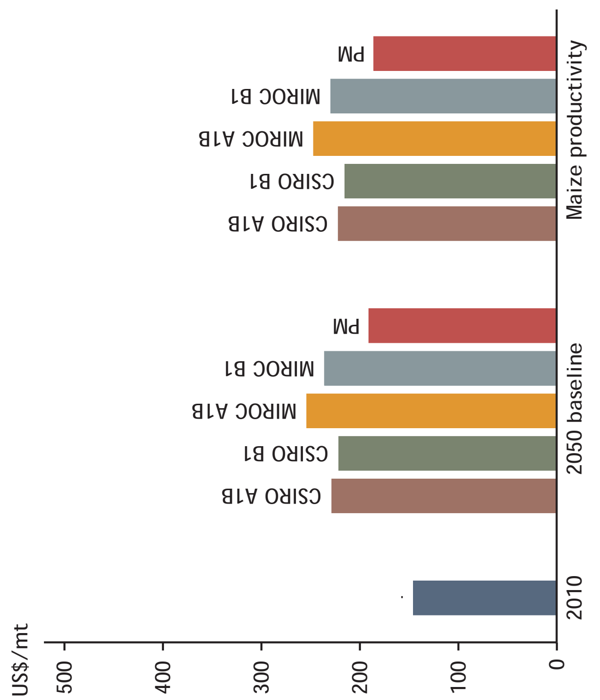
Source: Authors' calculations.

Figure 4.7 Rice price, maize productivity



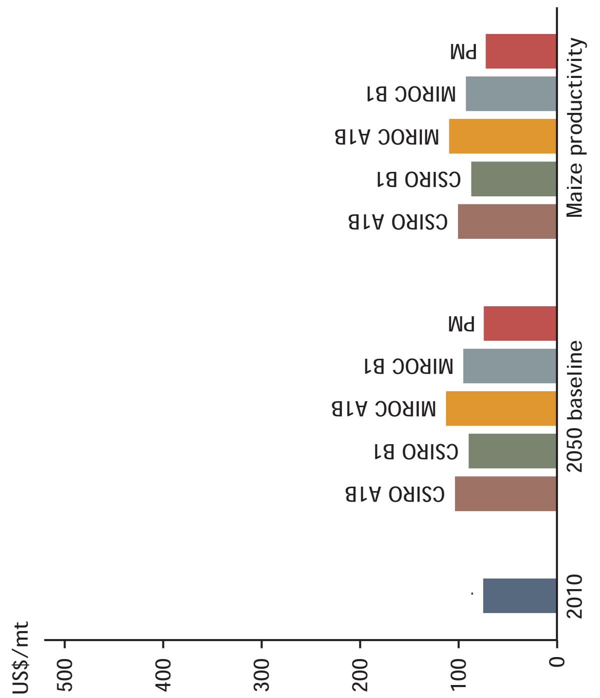
Source: Authors' calculations.

Figure 4.8 Wheat price, maize productivity



Source: Authors' calculations.

Figure 4.9 Cassava price, maize productivity



Source: Authors' calculations.

Table 4.4 Price effects of improvement in commercial maize productivity

Scenario	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change 2010 mean to 2050 mean (2050 std. dev. and CoV)			% price change 2050 baseline to 2050 higher efficiency		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*			
Improved commercial maize productivity rates	11.9	53.8	50	-44.2	-0.6	-2.8

Source: Authors' calculations.

Table 4.5 Human well-being effects of improvement in commercial maize productivity

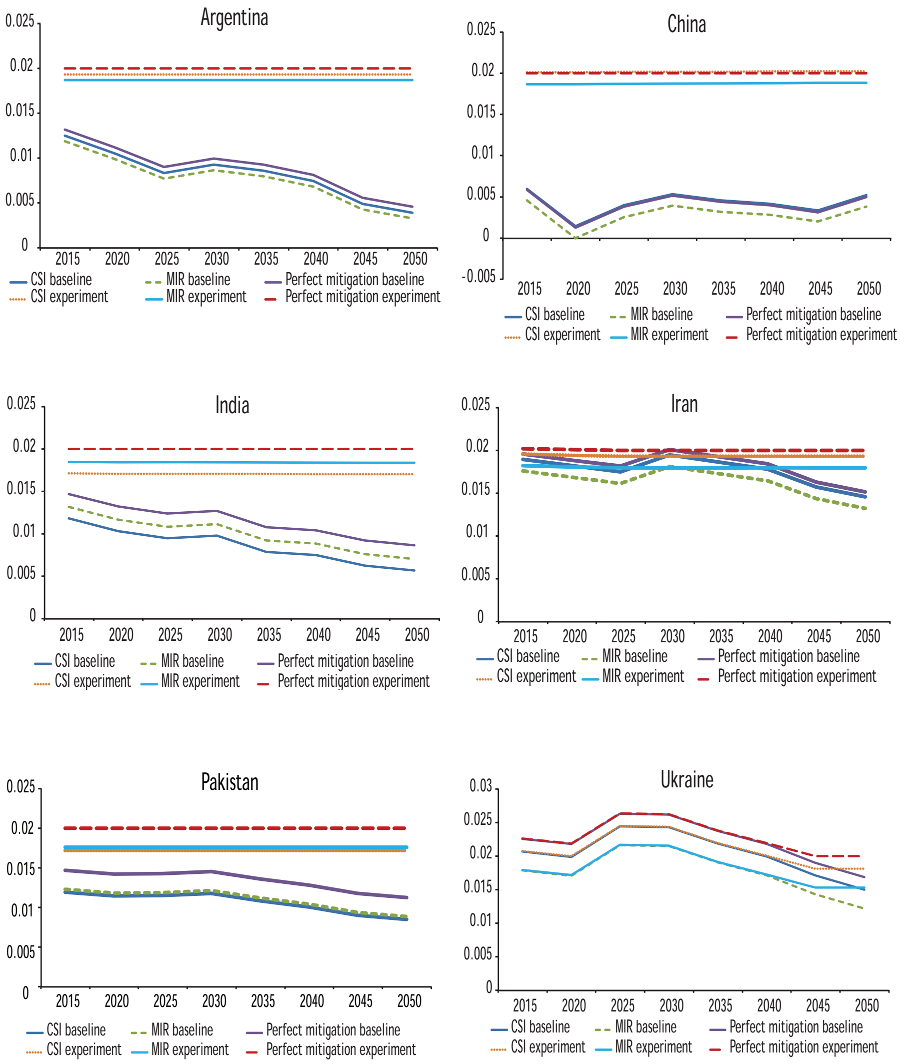
Category/ Scenario	% change 2010-2050	2050 simulation minus 2050 baseline (million)	2050 simulation minus 2050 baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 simulation minus 2050 baseline (%)
	Malnourished children			Average daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Commercial maize	-27.5	-3.8	-3.2	5.9	60.5	2.2
Low-income developing						
Baseline	-8.6			6.8		
Commercial maize	-13	-2.1	-4.8	13.7	104.5	4.7
Middle-income developing						
Baseline	-32.3			8.5		
Commercial maize	-33.8	-1.7	-2.2	6.3	47.3	1.7

Source: Authors' estimates.

Improvements in Developing Country Wheat Productivity

In this simulation, wheat IPRs are increased to 2 percent per annum in selected developing countries that are responsible for a large share of wheat production in the developing world: India, Pakistan, Argentina, Iran, Ukraine, China, and Kazakhstan (see Figure 4.10). These countries accounted for about 40 percent of total wheat production in 2010.

Figure 4.10 Intrinsic productivity growth rates (IPRs) for the wheat productivity simulation (percent per year)



Source: Authors' calculations.

The wheat productivity simulation affects a smaller share of global production than the maize production simulation, so effects on human well-being are smaller. As expected, the commodity showing the largest price effect is wheat (see Figures 4.11–4.14 and Table 4.6). Instead of a 54 percent increase between 2010 and 2050, the increase is only 28 percent with the simulation. The maize price declines slightly, and the rice price increases slightly compared to 2050 baseline values.

Wheat consumption is especially important in the middle-income developing countries, where the simulation results in a 2.6 million reduction in the total number of malnourished children in 2050 relative to the baseline. In the low-income developing countries, there are about 704,000 fewer malnourished children.

Improvements in Cassava Productivity

Cassava is a particularly important crop for consumers in some low-income developing countries. As Table 2.8 shows, for low-income developing countries, cassava is the fourth most important source of calories and provides about 8 percent of average daily consumption of the commodities in IMPACT.

For this simulation, cassava IPRs are set to 2.0 percent beginning in 2015 (or the existing rate if it was greater than 2.0 percent) for the top six cassava-producing countries in 2000: Brazil, Democratic Republic of the Congo (DRC), Indonesia, Ghana, Nigeria, and Thailand. These countries account for 62 percent of production in 2000. Figure 4.15 shows the original and new IPRs adjusted for climate change effects. Unlike the other crops for which productivity simulations were undertaken, climate change effects on cassava productivity were not done using a crop model. Instead we use the average impact on other C3 crops in each FPU. Climate change has the largest productivity effects in Brazil, Thailand, and the DRC, reducing the IPRs by as much as one percent. By contrast, in Ghana, Nigeria, and Indonesia, climate change has almost no effect on productivity.

Modeling production, consumption, and trade of cassava is somewhat more complicated than the other crops because the raw product is almost always consumed locally. International trade of cassava is in the form of either cassava starch or dried, pelletized cassava root for use as an animal feed. After the formation of the Common Agricultural Policy of the European Union, the EU became a major destination of dried cassava exports for animal feed (see for example Nelson 1983). More recently, China has become the most important buyer of internationally traded cassava (Kaplinsky, Terheggen, and Tijaja 2010).

The cassava productivity simulation results in a 10 percent decline in the world cassava price between 2010 and 2050, instead of the 25 percent increase that occurs in the baseline (see Figures 4.16–4.19 and Table 4.8). The human well-being benefits are the smallest of the three productivity enhancement simulations. The number of malnourished children in 2050 is reduced by 1.4 million. One million of these children are in low-income developing countries; the remainder is in middle-income developing countries.

Table 4.10 presents the effects of the cassava productivity simulation in the countries where it was implemented. Production effects are largest in percentage terms in Ghana and Indonesia, but the effects are also large in Thailand and Nigeria. The effects on human well-being, on the other hand, are largest in the DRC, Ghana, and Nigeria; the remaining countries, which are all middle-income developing, show essentially no effect. For Thailand, the world's major exporter of cassava today, the increased production is almost entirely exported. For low-income developing countries as a whole, the cassava productivity simulation reduces malnutrition by one million children—exceeding the benefits of the wheat simulation by about 300,000 children.

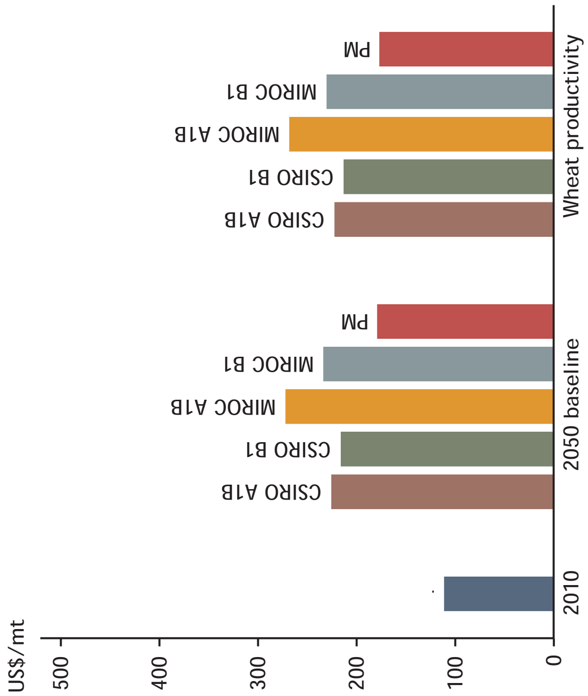
Improvements in Irrigation Efficiency

Water scarcity is a growing problem in much of the world. Precipitation changes that accompany climate change will exacerbate water shortages in some parts of the world while increasing water availability in other areas. As agriculture is the largest user of fresh water, improvements in irrigation efficiency will be essential for sustainable food production as well as for meeting increased demands for drinking water and industrial needs. In this simulation, we explore the benefits to agricultural production of a 15 percent increase in effective irrigation efficiency at the basin level in the developing world.[12] This simulation only addresses water scarcity in irrigated agriculture, and not the larger issues of water scarcity. It focuses on production effects where our hydrology model shows reduced yields in irrigated agriculture because of water shortages.

Table 4.11 shows the relative importance of irrigated agriculture by region, in 2010 and 2050 for the baseline scenario. In the early 21st century, among the major food crops, irrigation is most important for rice. Over one-third of rice production in developed countries and slightly less than one-half

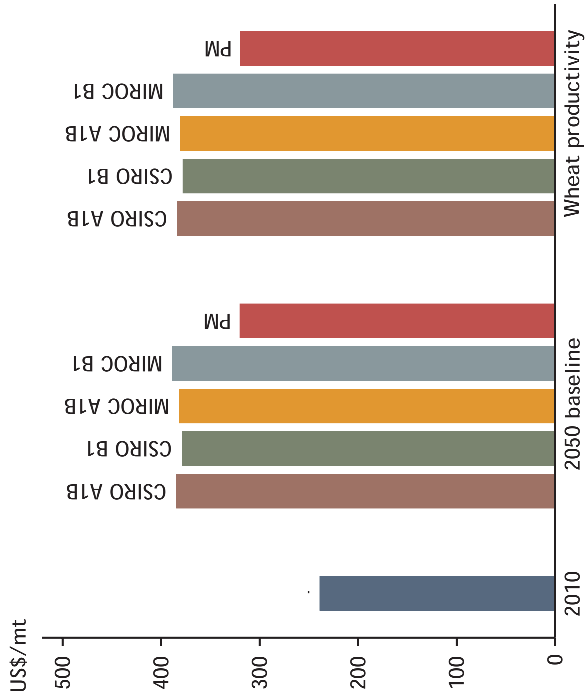
[12] The term "irrigation efficiency" has different meanings at different scales such as an irrigation project or a river basin. For this report, we use the standard definitions for "effective irrigation efficiency" in the technical irrigation literature (Keller and Keller 1995). "Agricultural water use" refers to all consumptive water use for irrigation purposes, including both crop evapotranspiration from applied water ("beneficial" use) and losses in conveyance and evaporation as well as other non-recoverable losses. The simulation of a 15 percent improvement in irrigation efficiency means that up to 15 percent more water is available to the plant for evapotranspiration. The water balance analysis is done at the level of major river basins, roughly equivalent to the IMPACT model FPUs. For more details, see Rosegrant, Cai, and Cline 2002.

Figure 4.11 Maize price, wheat productivity



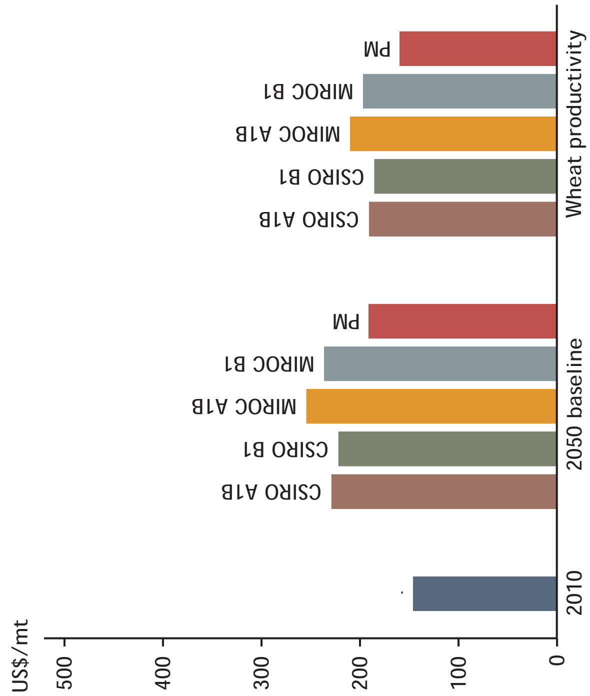
Source: Authors' calculations.

Figure 4.12 Rice price, wheat productivity



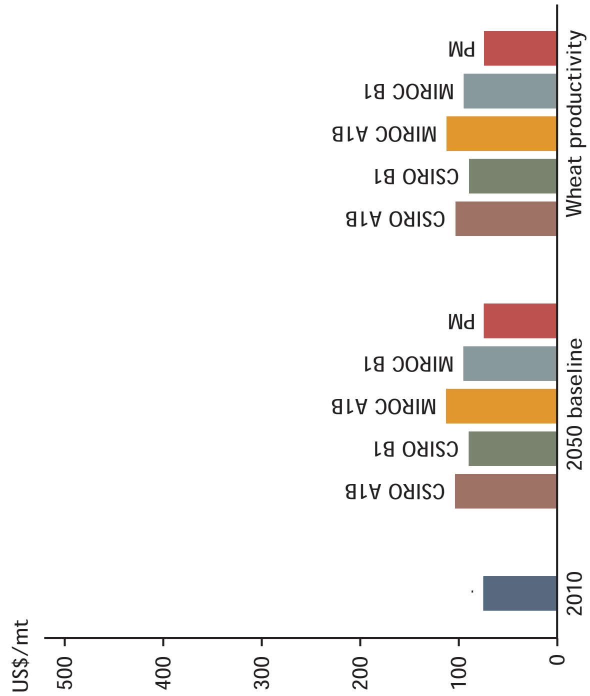
Source: Authors' calculations.

Figure 4.13 Wheat price, wheat productivity



Source: Authors' calculations.

Figure 4.14 Cassava price, wheat productivity



Source: Authors' calculations.

Table 4.6 Price effects of improvement in developing country wheat productivity

Scenario	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change 2010 mean to 2050 mean (2050 std. dev. and CoV)			% price change 2050 baseline to 2050 higher efficiency		
Baseline	100.7 (24.6; 0.104)	54.8 (4.2; 0.011)	54.2 (14.0; 0.060)			
Improved developing country wheat productivity	97.9	54.4	28.2	-1.4	-0.2	-16.9

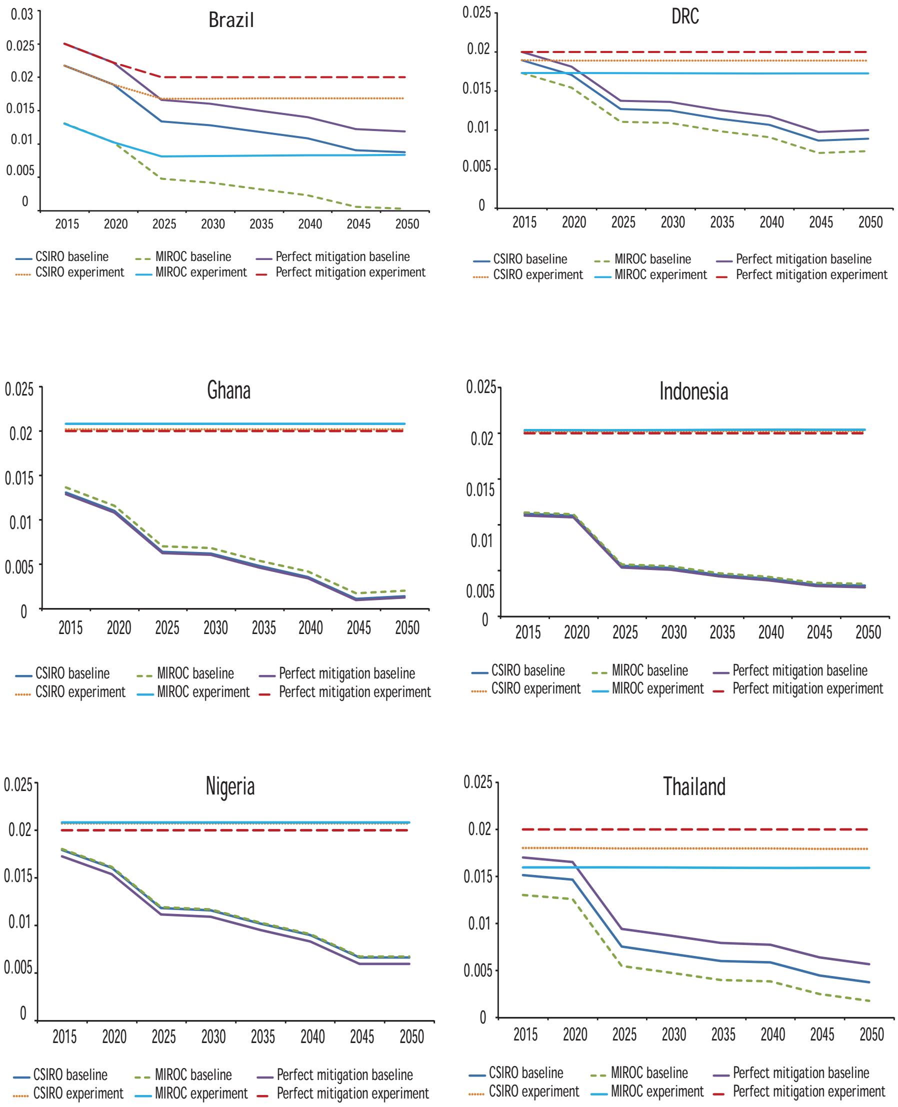
Source: Authors' calculations.

Table 4.7 Human well-being effects of improvement in developing country wheat productivity

Category/ Scenario	% change 2010-2050	2050 simulation minus 2050 baseline (million)	2050 simulation minus 2050 baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 simulation minus 2050 baseline (%)
	Malnourished children			Average daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Developing country wheat	-26.8	-2.6	-2.2	5.6	53.7	2
Low-income developing						
Baseline	-8.6			6.8		
Developing country wheat	-10.1	-0.7	-1.6	10.4	36.9	1.7
Middle-income developing						
Baseline	-32.3			8.5		
Developing country wheat	-34	-1.9	-2.5	6.7	58.7	2.1

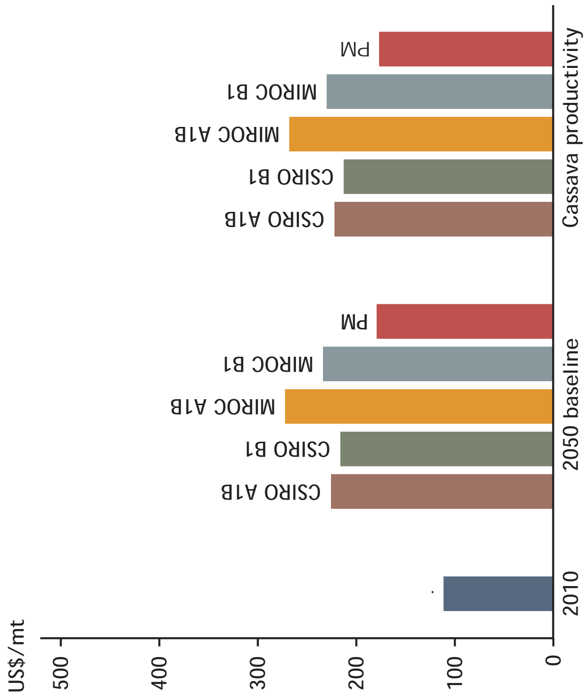
Source: Authors' calculations.

Figure 4.15 IPRs for the cassava productivity simulation (percent per year)



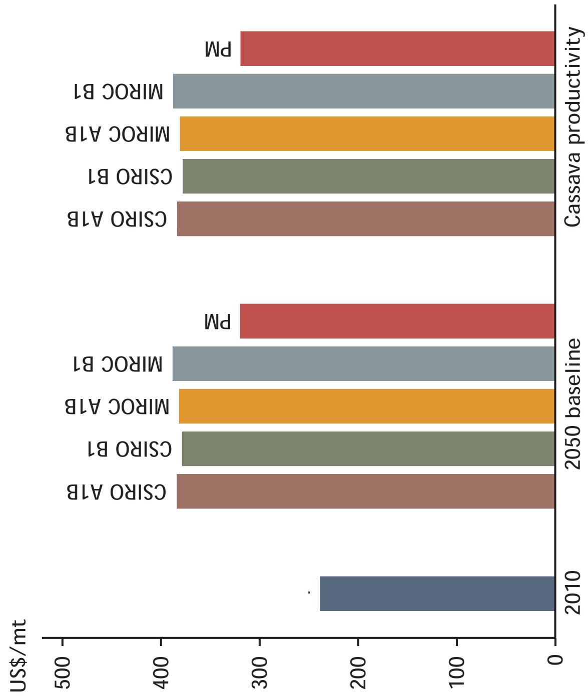
Source: Authors' estimates.

Figure 4.16 Maize price, cassava productivity



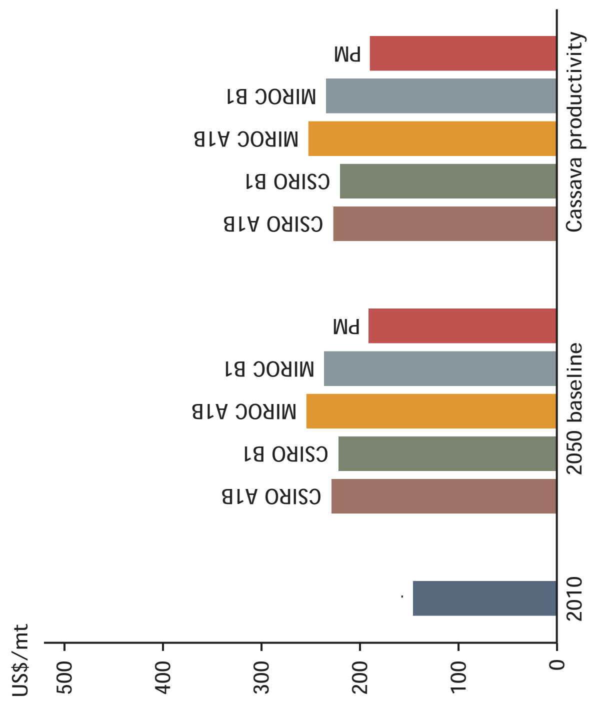
Source: Authors' calculations.

Figure 4.17 Rice price, cassava productivity



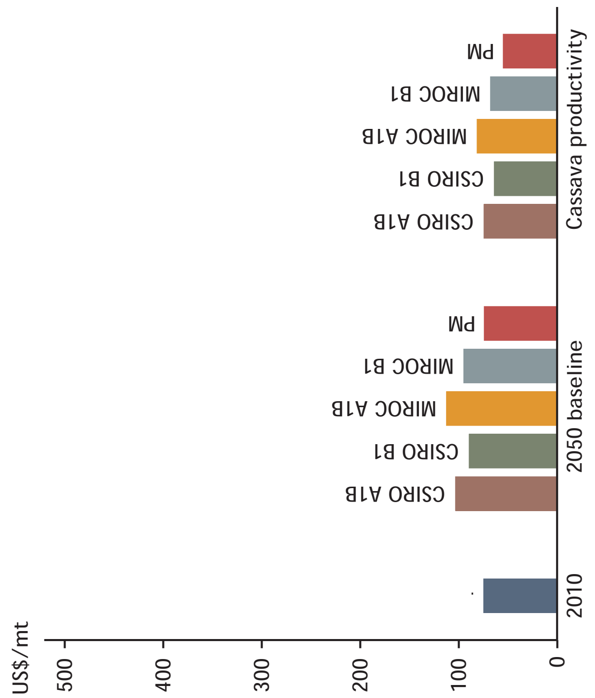
Source: Authors' calculations.

Figure 4.18 Wheat price, cassava productivity



Source: Authors' calculations.

Figure 4.19 Cassava price, cassava productivity



Source: Authors' calculations.

Table 4.8 Price effects of improvement in developing country cassava productivity

Scenario	Maize	Rice	Wheat	Cassava	Maize	Rice	Wheat	Cassava
	% price change 2010 mean to 2050 mean (2050 std. dev. and CoV)				% price change 2050 baseline to 2050 higher efficiency			
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*	24.9 *(10.1; 0.100)*				
Improved cassava productivity	97.5	54.5	53	-10.2	-1.6	-0.2	-0.8	-28.1

Source: Authors' calculations.

Table 4.9 Human well-being effects of improvement in cassava productivity

Category/scenario	Number of malnourished children			Daily kilocalorie availability		
	% change 2010-2050	2050 change from baseline (million)	2050 change from baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 change from baseline (%)
	Malnourished children			Average daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Improvement in cassava productivity	-26	-1.4	-1.1	4.2	16.4	0.6
Low-income developing						
Baseline	-8.6			6.8		
Improvement in cassava productivity	-10.6	-1.0	-2.2	10.6	41.2	1.9
Middle-income developing						
Baseline	-32.3			8.5		
Improvement in cassava productivity	-32.7	-0.4	-0.5	4.9	9.0	0.3

Source: Authors' calculations.

Table 4.10 Country-specific productivity and human-well-being effects of cassava productivity simulation

Country	Production			Malnutrition		
	2050 baseline (thousand mt)	2050 with increased productivity (thousand mt)	2050 simulation minus 2050 baseline (%)	2050 baseline (kcal)	2050 with increased productivity (kcal)	2050 simulation minus 2050 baseline (%)
Brazil	23,985	26,055	7.9	2,646	2,638	-0.3
DRC	32,915	38,453	14.4	5,218	4,802	-8.0
Ghana	14,859	23,765	37.5	649	604	-6.8
Nigeria	104,714	138,097	24.2	6,449	6,344	-1.6
Thailand	27,396	37,377	26.7	661	659	-0.2
Indonesia	22,235	36,966	39.8	3,759	3,728	-0.8

Source: Authors' calculations

Note: Numbers are based on the mean of the four climate scenarios with the baseline.

Table 4.11 Production of major staples and the share from irrigated harvested area, 2010 and 2050 baseline scenario

Category	2010 production (million mt)	2050 production (million mt)	2010 irrigated share (%)	2050 irrigated share (%)
Rice				
Developed	18.3	17.3	34.9	35.3
Developing	382.3	399.1	49.8	53.1
Low-income developing	80.5	93.0	27.7	34.0
Middle-income developing	301.9	306.1	56.8	60.3
Maize				
Developed	370.2	466.5	15.1	14.6
Developing	400.0	560.2	15.7	19.2
Low-income developing	30.7	42.4	3.0	3.8
Middle-income developing	369.3	517.8	18.3	22.2
Wheat				
Developed	212.1	232.6	2.2	2.2
Developing	413.0	555.1	28.9	32.0
Low-income developing	18.4	33.6	13.9	12.2
Middle-income developing	394.6	521.5	29.7	33.1

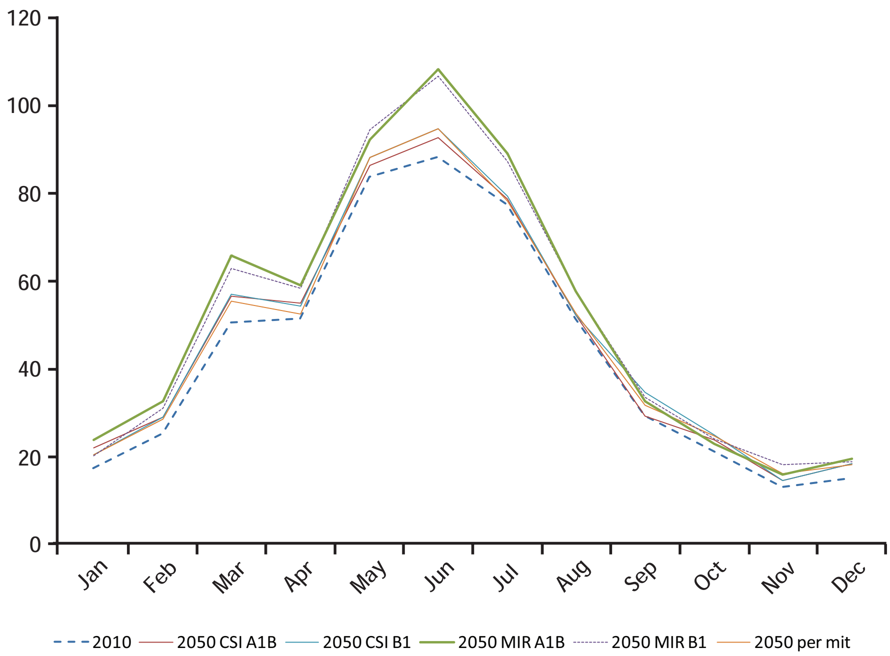
Source: Authors' calculations.

in developing countries is from irrigated systems. In contrast, only about 15 percent of maize production is on irrigated land. In developed countries, wheat production is almost exclusively rainfed, but in developing countries the irrigated share of wheat production is about 30 percent.

In 2050, the irrigated share increases in the baseline scenario, for most crops and most regions. All scenarios have an increasing share of production coming from irrigated agriculture for rice and maize. Because so much of rice cultivation is already irrigated in 2010, the rate of expansion is relatively small: for developed countries, from just under to just over 35 percent; and for developing countries, from 50 percent to 53 percent. The irrigated maize share is essentially constant in developed countries, at 15 percent; in developing countries it increases from 16 percent to 19 percent. For wheat, the irrigated share in developed countries is fairly low and remains constant; in developing countries the share increases from 29 percent to 32 percent.

Most of the world's irrigated area is located in the northern hemisphere, predominantly in South Asia and East Asia. Hence, global irrigation water use is highest in the northern hemisphere's summer months, as Figure 4.20

Figure 4.20 Beneficial irrigation water consumption globally by month, 2010 and 2050 (cubic km)



Source: Authors' calculations.

Table 4.12 Global beneficial irrigation water consumption

Scenario	Baseline	2050 with basin efficiency	
	Total (cubic km)	Total (cubic km)	Percent increase over 2050, no basin efficiency improvement
2010	526.0[13]		
2050 CSIRO B1	567.8	625.7	9.3
2050 CSIRO A1B	560.2	616.3	9.1
2050 MIROC A1B	620.7	673.6	7.8
2050 MIROC B1	614.0	664.6	7.6

Source: Authors' estimates.

indicates. The effect of greater irrigation efficiency is also highest in those months. Globally, the two CSIRO scenarios have slightly more water use than the 2010 value (Table 4.12). The MIROC scenarios result in more irrigation water use in 2050 as a result of more precipitation and higher average temperatures. The changes in beneficial water consumption are concentrated in South Asia and East Asia (see Table 4.13).

As the results in Table 4.14 and Table 4.15 indicate, the irrigation efficiency improvement has relatively little effect on either global prices or human well-being, reflecting the fact that much of the world's agriculture remains rainfed. Rice prices in 2050 decline about 3 percent compared to the baseline, wheat prices decline by 1 percent, and maize prices decline by 0.9 percent. Developing countries see a small reduction in the number of malnourished children. The reason for this can be seen in Table 4.16, which reports the increased water use by crops in all developing countries and for the three largest beneficiaries of irrigation improvements (India, Pakistan, and China). Rice is the predominant irrigated crop in these countries; of the three focus crops, rice benefits the most from improvements in basin-level effective irrigation efficiency.

As Table 4.16 and Figures 4.21–4.25 show, the increased basin use efficiency results in benefits almost entirely in India, Pakistan, and China. Seasonally, in the northern hemisphere spring and summer are the most important months; in India, the benefits extend throughout most of the year. For China, beneficial irrigation water consumption increases mostly in the Huang-Huai-Hai plain in central and northern China. In this region evaporation is already high in spring and early summer, but rain does not arrive until July, with the East Asia monsoon.

Table 4.13 Beneficial irrigation water consumption by crop and changes with improved basin efficiency, A1B scenario (cubic km/year)

		Baseline			Change with improved irrigation efficiency		
Commodity	Year	Perfect mitigation	CSIRO	MIROC	Perfect mitigation	CSIRO	MIROC
Southeast Asia							
Wheat	2010	0.0	0.0	0.0			
Wheat	2050	0.0	0.1	0.1	0.0	0.0	0.0
Maize	2010	3.9	3.9	4.1			
Maize	2050	3.4	3.3	4.2	0.0	0.0	0.0
Rice	2010	7.5	7.5	7.5			
Rice	2050	5.4	5.7	5.3	0.0	0.0	0.0
South Asia							
Wheat	2010	65.4	65.4	67.7			
Wheat	2050	69.5	69.7	79.1	12.3	12.0	14.0
Maize	2010	3.4	3.4	3.4			
Maize	2050	4.7	3.6	5.4	0.9	0.8	0.2
Rice	2010	74.4	74.4	75.0			
Rice	2050	79.0	73.5	82.4	15.4	14.7	13.0
East Asia							
Wheat	2010	16.7	16.7	16.8			
Wheat	2050	17.8	17.2	19.1	3.6	2.9	3.6
Maize	2010	13.8	13.6	14.0			
Maize	2050	15.9	14.7	17.5	3.2	3.2	2.7
Rice	2010	35.2	35.8	35.2			
Rice	2050	22.6	24.4	22.8	1.1	1.0	0.7

Source: Authors' calculations.

Table 4.14 Price effects of improvement in irrigation efficiency

Scenario	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change 2010 mean to 2050 mean (2050 std. dev. and CoV)			% price change 2050 baseline to 2050 higher efficiency		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*			
Improvements in irrigation efficiency	101.5	50.1	52.5	0.9	-3.1	-1.0

Source: Authors' calculations.

Table 4.15 Human well-being effects of improvement in irrigation efficiency

Category/ Scenario	% change 2010-2050	2050 simulation minus 2050 baseline (million)	2050 simulation minus 2050 baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 simulation minus 2050 baseline (%)
	Malnourished children			Average daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Irrigation	-25.4	-0.3	-0.3	3.9	7.7	0.3
Low-income developing						
Baseline	-8.6			6.8		
Irrigation	-8.8	-0.1	-0.2	8.9	6.2	0.3
Middle-income developing						
Baseline	-32.3			8.5		
Irrigation	-32.6	-0.3	-0.4	4.9	8.1	0.3

Source: Authors' calculations.

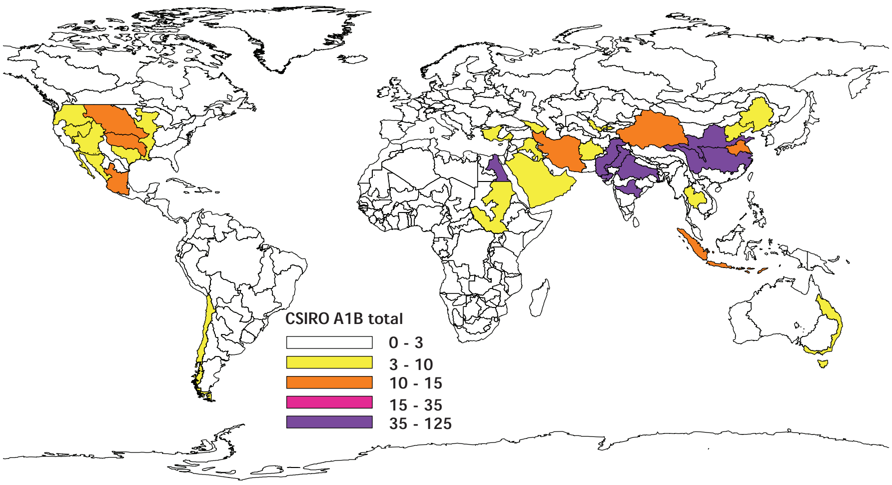
Table 4.16 Mean increased beneficial agricultural water use due to increased irrigation efficiency, 2050 (cubic km)

Month	India	Pakistan	China
January	0.5	0.0	0.0
February	2.0	0.0	0.0
March	5.3	0.6	0.7
April	4.2	0.9	2.0
May	8.9	0.4	3.0
June	5.7	0.0	3.5
July	0.9	0.5	2.5
August	0.6	1.2	0.2
September	0.8	2.0	0.1
October	1.9	1.5	0.0
November	1.9	0.0	0.0
December	1.2	0.0	0.0
Total	34.0	7.1	11.9

Source: Authors' calculations.

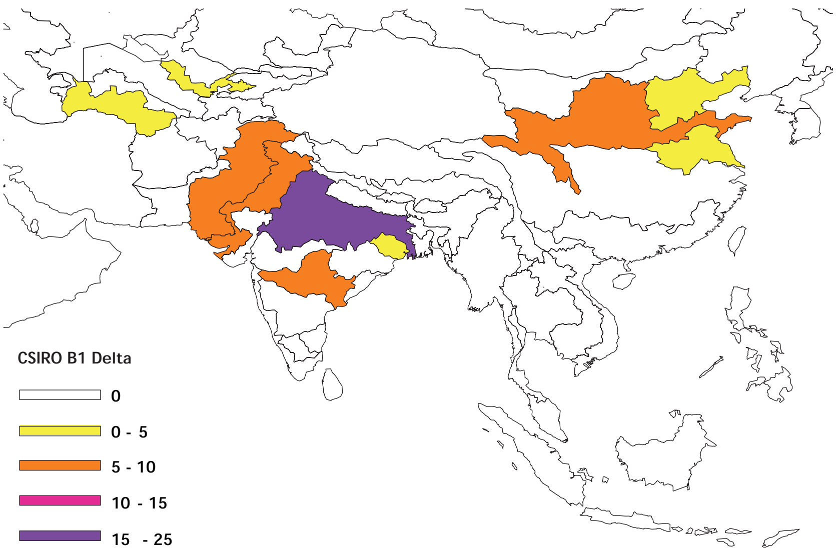
Note: The values in the table are the means for the four GCM/climate scenario combinations.

Figure 4.21 2050 irrigation water use, CSIRO A1B (cubic km)



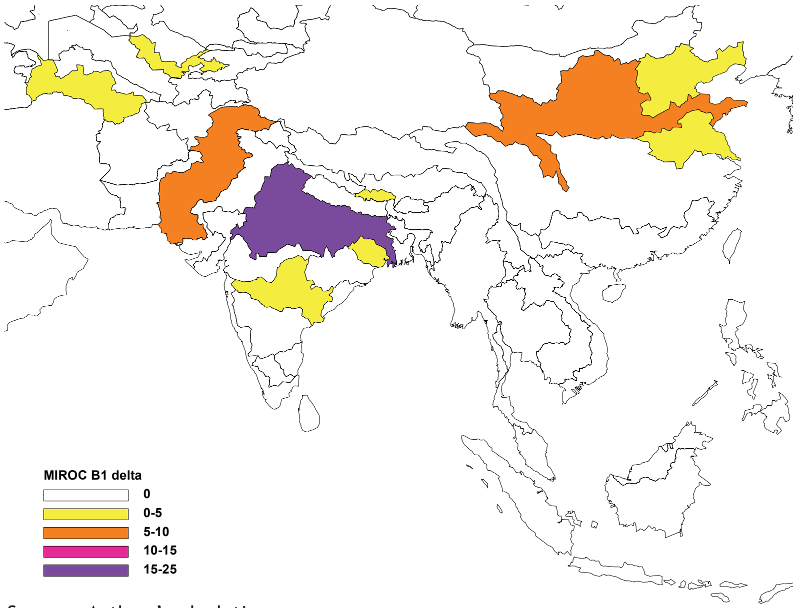
Source: Authors' calculations.

Figure 4.22 Increase in agricultural water use in 2050, improved irrigation efficiency simulation CSIRO B1 (cubic km)



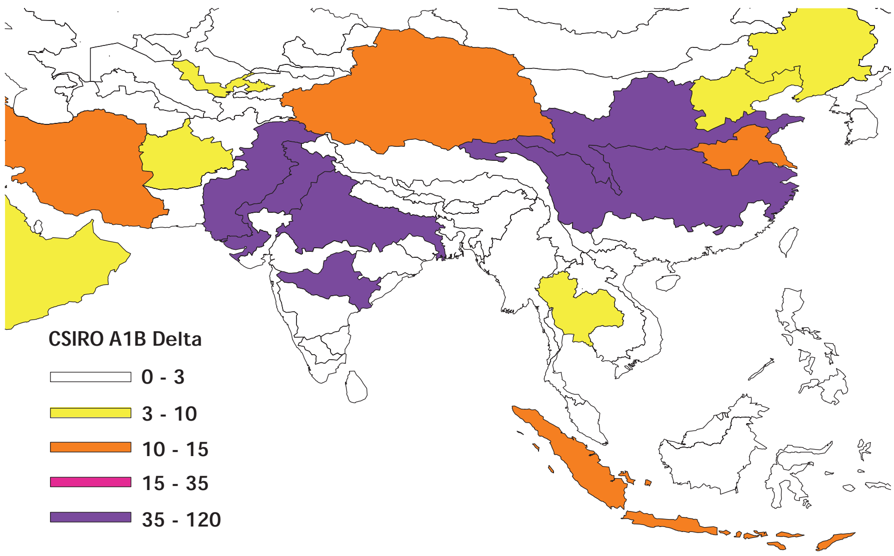
Source: Authors' calculations.

Figure 4.23 Increase in agricultural water use in 2050, improved irrigation efficiency simulation MIROC B1 (cubic km)



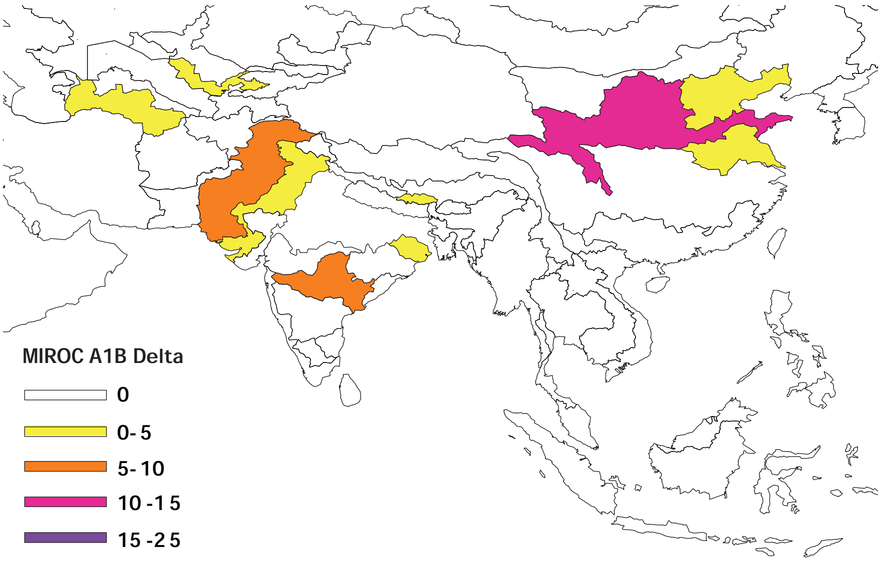
Source: Authors' calculations.

Figure 4.24 Increase in agricultural water use in 2050, improved irrigation efficiency simulation CSIRO A1B (cubic km)



Source: Authors' calculations.

Figure 4.25 Increase in agricultural water use in 2050, improved irrigation efficiency simulation MIROC A1B (cubic km)



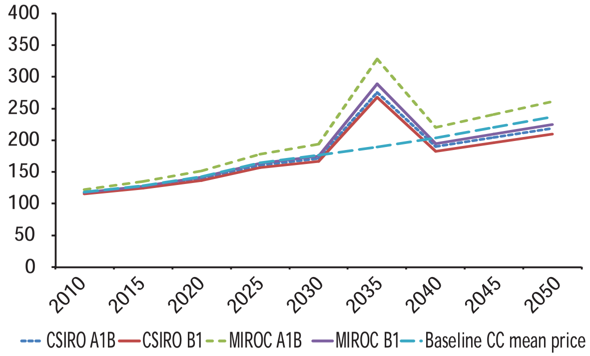
Source: Authors' calculations.

Drought in South Asia between 2030 and 2035

Climate change is likely to bring more extreme events, possibly including a failure of the monsoon in South Asia. We simulate an extended drought beginning in 2030 and continuing through 2035, followed by recovery to the previous path of the baseline scenario to 2050. This is done by reducing rainfed harvested area to zero in the middle of the drought and then returning it to trend by the end of the drought. We assume that only rainfed agriculture is affected and that sufficient water is available for irrigated agriculture. This assumption in fact underestimates the effects of the drought, because irrigation water availability would undoubtedly also be reduced.

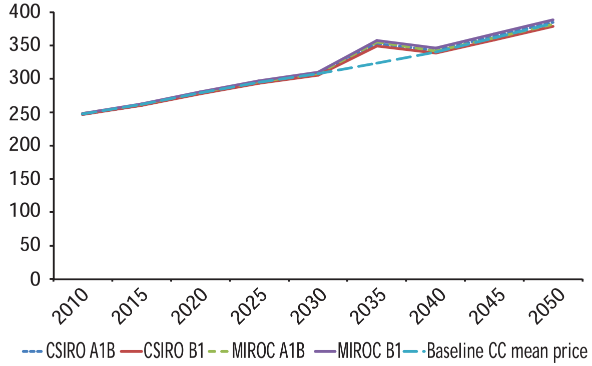
Figures 4.26–4.29 show the resulting price pathways for rice, wheat, and maize. A key first observation is that the South Asian drought effects spill over into world markets. All three commodities show a sharp increase in world price during the simulated drought and return to trend afterwards. Table 4.17 reports the cumulative effect on prices between 2010 and 2050. Table 4.18 shows no remaining effect on malnourished children by 2050. However, this summary statistic does not capture the full effects of the drought on human well-being, as discussed below.

Figure 4.26 Maize price, South Asia drought



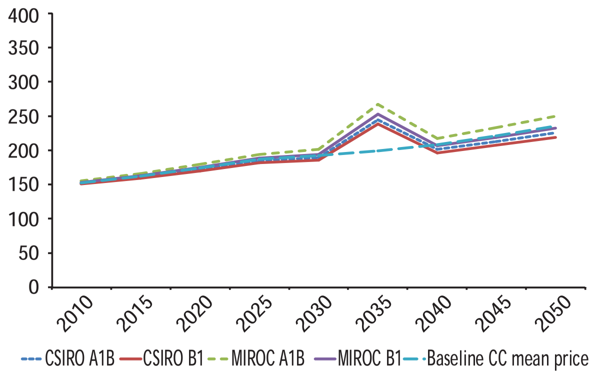
Source: Authors' calculations.

Figure 4.27 Rice price, South Asia drought



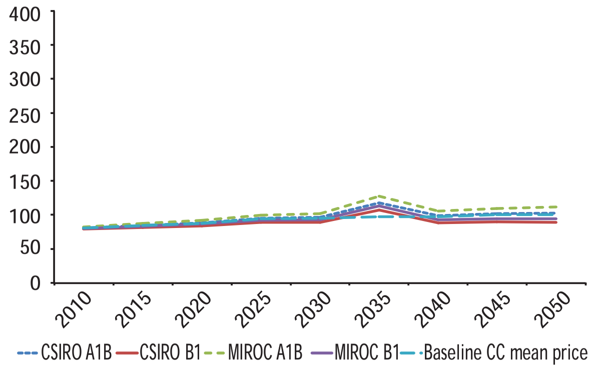
Source: Authors' calculations.

Figure 4.28 Wheat price, South Asia drought



Source: Authors' calculations.

Figure 4.29 Cassava price, South Asia drought



Source: Authors' calculations.

It is useful to trace the process of adjustment to the drought in production, consumption, trade, and human well-being, with a focus on the specific countries involved—Bangladesh, India, and Pakistan. Three drivers of food availability respond to the drop in rainfed area: irrigated area, international trade, and domestic consumption.

Figure 4.30 plots the progression of rainfed area for rice, wheat, and maize from 2020 to 2050. Even without the drought, rainfed area declines in the baseline scenario as irrigated area expands. With the drought, however, producers respond by expanding irrigated area more and more quickly; irrigated wheat shows the biggest increase, of over 300,000 hectares. As the drought recedes, some of this increased area reverts to rainfed, but irrigated area remains higher than it would have been (Figure 4.31).

Despite the increase in irrigated area, production falls, especially that of maize (Figure 4.32).

International trade flows also help to compensate for the drop in rainfed area. Without the drought, the region is a small rice exporter (Figure 4.33), and wheat and maize imports increase. During the drought, the region becomes a substantial rice importer, and maize imports become much larger.

Figure 4.34 shows the increase in malnourished children over the baseline results. The numbers are largest in 2035 and then diminish. What this analysis cannot capture is the loss to the children affected during the drought period. They will never fully reach their potential, because of the shortage of food during a critical growth stage.

Table 4.17 Price effects of drought in South Asia

	Maize	Rice	Wheat	Maize	Rice	Wheat
Scenario	**% price change 2010 mean to 2050 mean (2050 std. dev. and CoV)**			**% price change 2050 baseline to 2050 drought scenario**		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*			
Drought in South Asia 2030–2035	93.7	55	51.9	-3.5	0.1	-1.5

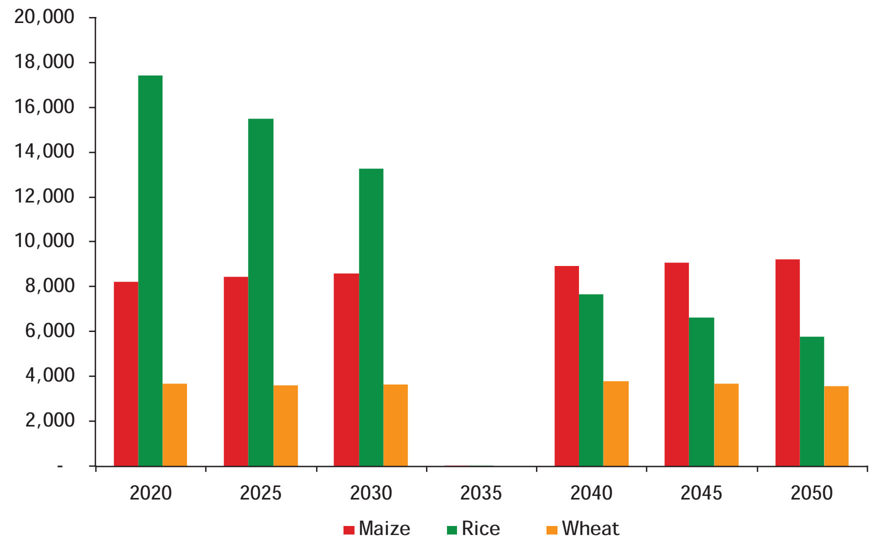
Source: Authors’ calculations.

Table 4.18 Human well-being effects of drought in South Asia

Category/ scenario	% change 2010-2050	2050 simulation minus 2050 baseline (million)	2050 simulation minus 2050 baseline (%)	% change 2010-2050	2050 simulation minus 2050 baseline (kcal/day)	2050 simulation minus 2050 baseline (%)
	Malnourished children			Average daily kilocalorie availability		
Developing						
Baseline	-25.1			0.4		
Drought in South Asia 2030-2035	-25.5	-0.7	-0.6	4	12.3	0.5
Low-income developing						
Baseline	-8.6			6.8		
Drought in South Asia 2030-2035	-9.1	-0.2	-0.6	9.1	12.2	0.5
Middle-income developing						
Baseline	-32.3			8.5		
Drought in South Asia 2030-2035	-32.7	-0.4	-0.6	5	12.4	0.4

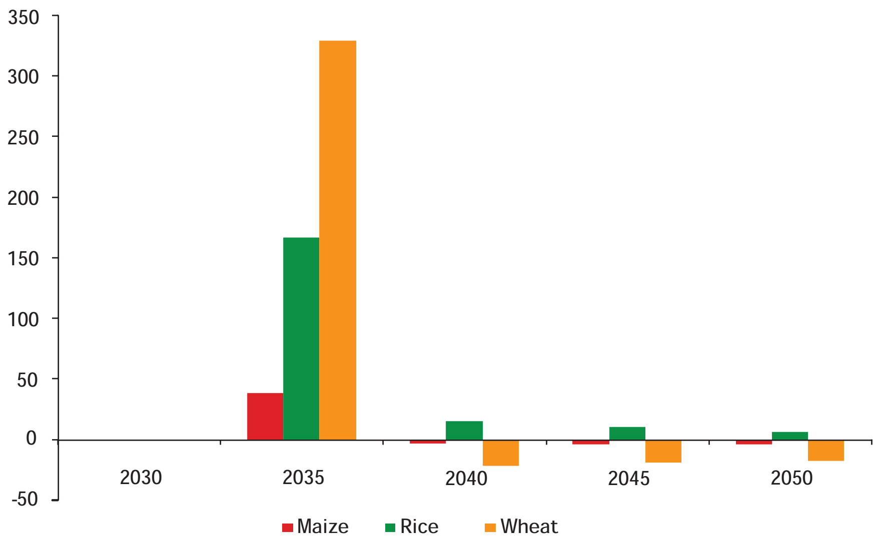
Source: Authors' calculations.

Figure 4.30 South Asia drought simulation: Rainfed area, Bangladesh, India, and Pakistan (thousand ha)



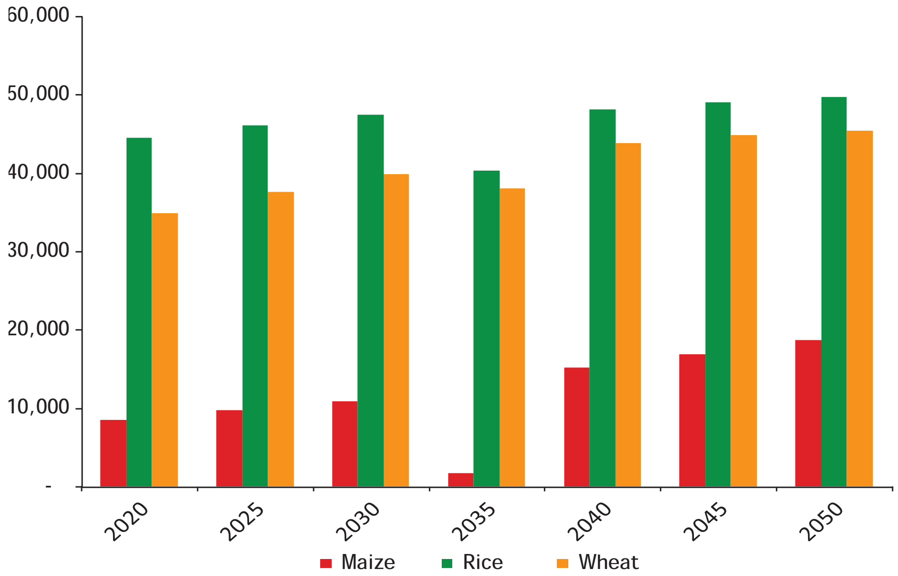
Source: Authors' calculations.

Figure 4.31 South Asia drought simulation: Change in irrigated area, Bangladesh, India, and Pakistan (thousand ha)



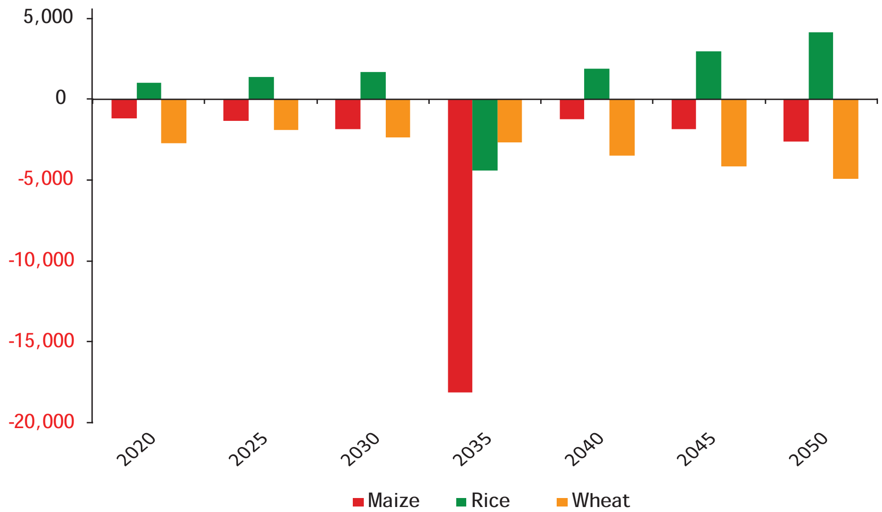
Source: Authors' calculations.

Figure 4.32 South Asia drought simulation: Rice, wheat, and maize production, Bangladesh, India, and Pakistan (thousand mt)



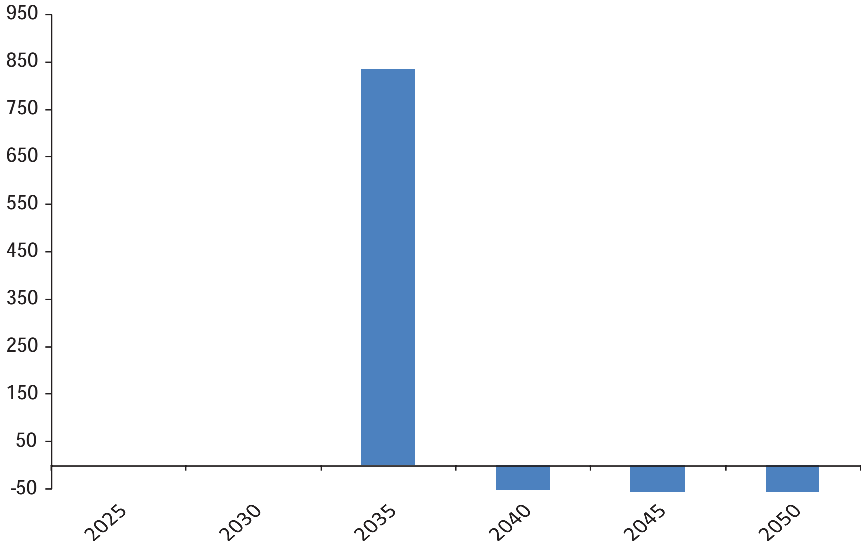
Source: Authors' calculations.

Figure 4.33 South Asia drought simulation: Rice, wheat, and maize net exports, Bangladesh, India, and Pakistan (thousand mt)



Source: Authors' calculations.

Figure 4.34 South Asia drought simulation: Increase in malnourished children over the baseline results (thousands)



Source: Authors' calculations.

CHAPTER 5

Beyond 2050

This analysis focuses on the period between 2010 and 2050. But we would be remiss if we did not point out the nature of the challenges beyond 2050. Although population growth is likely to slow or stop by 2050, major disparities in income between poor and rich countries will still remain, with large numbers of people living in abject poverty. Even in the optimistic scenario, the number of malnourished children ranges from 98 million to 102 million (1.3 to 1.5 percent of population in developing countries), depending on climate change scenario.

And the threat of climate change becomes much more severe. While average temperature increases in 2050, across all scenarios, are on the order of 1°C relative to the late 20th century, outcomes diverge dramatically in the ensuing years, with increases ranging from 2°C to 4°C by 2100. Yields of many more crops will be more severely threatened than in the window to 2050. Table 5.1 shows the changes in wheat yields from climate change in 2030, 2050, and 2080, relative to yields with 2000 climate. With the climate change from 2000 to 2030, yields decline by between 1.3 percent and 9 percent. By 2050, the range of declines has increased to 4.2 percent to 12 percent. And by 2080, the declines are much greater, ranging from 14.3 percent to 29 percent.

Table 5.1 Climate change impacts on wheat yields with 2030, 2050, and 2080 climate (percent change from 2000)

Year	Developed		Developing	
Wheat	Rainfed	Irrigated	Rainfed	Irrigated
2030	-1.3	-4.3	-2.2	-9.0
2050	-4.2	-6.8	-4.1	-12.0
2080	-14.3	-29.0	-18.6	-29.0

Source: Authors' estimates from downscaled CSIRO climate model with the A2 SRES scenario.

Our analysis suggests that to 2050, the challenges from climate change are “manageable,” in the sense that possible investments in land and water productivity enhancements may partly, or even substantially, mitigate the negative effects from climate change. But the challenges of dealing with the effects between 2050 and 2080 are likely to be much greater, and possibly unmanageable. Starting the process of slowing emissions growth today is critical to avoiding a calamitous post-2050 future.

CHAPTER 6

Conclusions

The challenge of reaching sustainable food security and delivering on it through 2050 is daunting. Our starting point, in 2010, is a world with unacceptable levels of poverty and deprivation, as is clear from the 2010 report on the Millennium Development Goals. Progress will be made more difficult by two looming challenges: a growing world population and increasingly negative productivity effects from climate change.

Nevertheless, focused efforts can make an enormous difference in reducing human suffering by 2050. With sound policies and programs that encourage sustainable, broad-based economic growth, and especially continued growth in agricultural productivity, our scenarios suggest it is possible to achieve a large decline in the number of malnourished children—over 45 percent over the period from 2010 to 2050. Additional public sector investments in agricultural productivity would do even more to reduce suffering. Relative to the baseline outcome in 2050, a 40-percent increment in productivity growth would reduce the number of malnourished children by an additional 37 percent (that is, by 19.1 million children).

A key component of this positive future is robust international trade in agricultural products, especially given the likelihood of increased occurrences of extreme weather events in different parts of the world. The price spikes of 2008 and 2010 both had important weather components, and during each of these periods, trade flows offset some of the locally severe potential effects. The remedial role of trade will be increasingly critical in the future. Restrictions on international trade, then, could jeopardize prospects for regional food security.

Climate change acts as a threat multiplier, making the challenges of sustainable food security much more difficult. If the climate of the early 2000s were to continue through 2050 (an extremely unlikely scenario that we call "perfect mitigation"), we might see an additional decline in the number of malnourished children, on the order of 10 percent. The uncertainty of climate prediction means that climate-specific investments are not yet appropriate, for the most part. However, supporting investments in physical and human capital can begin immediately as a way of increasing the efficiency of land, water, and nutrient use, as essential factors in growth, climate resilience, and mitigation of agricultural GHGs. The investments needed to cope with climate change through 2050 seem possible to accomplish, at least under conditions of relatively free international trade. After 2050, however, the challenge of ever-increasing temperatures becomes potentially much greater.

Any modeling outcomes are only as reliable as their underlying data. In modeling future food productivity, we must deal with extremely poor data sources in critical areas:

- Biophysical data—current climate and future scenarios, land use, soil characteristics, ecosystem services
- Socioeconomic data—demand and supply parameters; links to and from agriculture to other sectors; macroeconomic trends

Efforts are underway to address some of these shortfalls. For example, the AfSIS project (www.africasoils.net/) will greatly improve the data on African soils. There are a variety of efforts underway to improve the quantity, quality, and accessibility of weather data, especially in developing countries. And a new project—The Living Standards Measurement Study-Integrated Surveys on Agriculture, financed by the Bill and Melinda Gates Foundation (http://go.worldbank.org/TNOUO6ZE40)—will improve socioeconomic household data in Africa.

Perhaps the most serious deficit is the lack of freely available, regularly repeated observations via satellite of the surface of the earth, at temporal and spatial resolutions that would make it possible to track changes in agricultural practices and land use more generally. Mechanisms are needed also to exploit the potential resource of citizen data-gatherers, equipped with GPS-enabled camera phones and other measuring devices. Such data would yield huge payoffs in illuminating the state of the world as it unfolds.

Finally, the change process that the CGIAR is undertaking will make it possible to exploit more effectively the many potential synergies across the centers to better understand human-environment interactions. The modeling work reported here will be enriched by newly developed partnerships across the CGIAR centers and with researchers around the world to provide early guidance on how to direct limited financial resources so that we can sustainably feed a world confronting the challenges of adapting to climate change, a growing population and reduced poverty.

APPENDIX 1

Regional Groupings

This report uses two types of country groupings, economic and geographic.

Economic Groups

There are three economic groups: *low-income developing*, *middle-income developing* (with these two also aggregated to a fourth group, *developing*), and *developed*. These economic groups are based on the World Bank classification scheme as of 2009. Some countries are combined into groups, for example countries in the Caribbean and Central America are analyzed as a single entity called Caribbean Central America.

Low-income Developing Countries and Country Groups

Afghanistan, Bangladesh, Benin, Burkina Faso, Burundi, Central African Republic, Chad, DRC, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Kyrgyzstan, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Myanmar, Nepal, Niger, North Korea, Rwanda, Senegal, Sierra Leone, Somalia, Southeast Asia, Tajikistan, Tanzania, Togo, Uganda, Uzbekistan, Vietnam, Zambia, Zimbabwe

Middle-income Developing Countries and Country Groups

Adriatic, Algeria, Angola, Argentina, Baltic, Bhutan, Botswana, Brazil, Cameroon, Caribbean Central America, Caucus, Central Europe, Central South America, Chile, China, Colombia, Congo, Djibouti, Ecuador, Egypt, Gabon, India, Indonesia, Iran, Iraq, Ivory Coast, Jordan, Kazakhstan, Lebanon, Lesotho, Libya, Malaysia, Mexico, Mongolia, Morocco, Namibia, Nigeria, Northern South America, Pakistan, Papua New Guinea, Peru, Philippines, Poland, ROW, Russia, South Africa, Sri Lanka, Sudan, Swaziland, Syria, Thailand, Tunisia, Turkey, Turkmenistan, Ukraine, Uruguay

Developing Countries

This group comprises the combined set of low- and middle-income developing countries.

Developed Countries and Country Groups

Alpine Europe, Australia, Belgium Luxembourg, British Isles, Canada, Cyprus, France, Germany, Gulf, Iberia, Israel, Italy, Japan, Netherlands, New Zealand, Scandinavia, Singapore, South Korea, United States

Geographic Groups

The geographic groupings are at continental or subcontinental level.

Central Africa

Angola, Cameroon, Central African Republic, Chad, Congo, DRC, Equatorial Guinea, Gabon

Western Africa

Benin, Burkina Faso, Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo

Eastern Africa

Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mozambique, Rwanda, Somalia, Tanzania, Uganda, Zambia, Zimbabwe

Northern Africa

Algeria, Egypt, Libya, Morocco, Sudan, Tunisia

Southern Africa

Botswana, Lesotho, Namibia, South Africa, Swaziland

North America

Canada, United States

Caribbean and Central America

Caribbean and Central America, Mexico

South America

Argentina, Brazil, Central South America, Chile, Colombia, Ecuador, Northern South America, Peru, Uruguay

Middle East
Cyprus, Gulf States, Iraq, Israel, Jordan, Lebanon, Syria, Turkey

Central Asia
Caucasus, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Turkmenistan, Uzbekistan

South Asia
Afghanistan, Bangladesh, Bhutan, India, Iran, Nepal, Pakistan, Sri Lanka

Southeast Asia
Indonesia, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Southeast Asia, Thailand, Vietnam

East Asia
China, Mongolia, North Korea, South Korea

Oceania
Australia, Japan, New Zealand

Southern Europe
Adriatic, Iberia, Italy

Western Europe
Alpine Europe, Belgium Luxembourg, France, Germany, Netherlands

Northern Europe
Baltic, British Isles, Scandinavia

Eastern Europe
Central Europe, Poland, Ukraine

APPENDIX 2

GDP and Population Scenarios

In this section, we report (1) a comparison of the overall scenario GDP and population growth rates with those used in the A1B, A2, and B1 SRES scenarios (Table A2.1); and (2) the regional per capita GDP growth rates (Table A2.2).

Note that the SRES scenarios were originally developed for the third IPCC assessment; they were not updated for the fourth. (See www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0.)

Table A2.1 A comparison of SRES and overall scenario GDP and population average annual growth rates, 2010–2050 (percent)

Scenario	Population	GDP	GDP per capita
A1B	0.62	3.99	3.35
A2	1.14	2.38	1.23
B1	0.59	3.28	2.68
Pessimistic	1.04	1.91	0.86
Baseline	0.70	3.21	2.49
Optimistic	0.35	3.58	3.22

Source: http://sres.ciesin.columbia.edu/final_data.html for SRES data and authors' calculations for the overall scenario results.

Many GCM datasets are available in the public domain for a range of scenarios, including the three SRES scenarios used in the IPCC's Fourth Assessment Report (IPCC, Parry et al. 2007). This study required GCM-scenario combinations for the three climate variables needed to run the DSSAT crop models: precipitation, maximum daily temperature, and minimum air temperature. These combinations were available for the following four GCMs, from four different research programs[14]:

[14] Documentation about all the models used in the 4th IPCC assessment is available at www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

Table A2.2 Average scenario per capita GDP growth rates by region, 2000–2050 (percent per year)

Region	Pessimistic	Baseline	Optimistic
Central Africa	2.42	3.92	5.34
Western Africa	2.04	3.63	5.02
Eastern Africa	2.72	4.18	5.46
Northern Africa	1.78	2.60	3.49
Southern Africa	0.55	2.98	4.44
North America	1.09	2.16	2.41
Caribbean and Central America	2.61	3.03	4.91
South America	2.39	3.20	4.63
Middle East	1.16	2.77	3.68
Central Asia	1.95	4.21	4.94
South Asia	2.61	4.99	5.74
Southeast Asia	2.67	4.49	5.59
East Asia	2.40	4.71	5.77
Oceania	0.54	1.80	2.42
Southern Europe	0.51	2.51	2.84
Western Europe	0.62	2.58	3.13
Northern Europe	0.61	2.61	2.95
Eastern Europe	1.70	3.56	5.02
Rest of world	0.40	2.78	3.15
Low-income developing	2.60	4.10	5.72
Middle-income developing	2.21	4.01	5.11
Developing	2.09	3.86	5.00
Developed	0.73	2.17	2.56
World	0.86	2.49	3.22

Source: Authors' calculations.

- CNRM-CM3 – Météo-France/Centre National de Recherches Météorologiques, France
- CSIRO-Mk3.0 – Commonwealth Scientific and Industrial Research Organization (CSIRO) Atmospheric Research, Australia
- ECHam5 – Max Planck Institute for Meteorology, Germany
- MIROC 3.2, medium resolution – Center for Climate System Research, University of Tokyo; National Institute for Environmental Studies; and Frontier Research Center for Global Change (JAMSTEC), Japan

These GCMs are here abbreviated as *CNRM*, *CSIRO*, *ECHAM*, and *MIROC*.

Data for GCM deviations for five time slices were obtained: 1991–2010 (denoted 2000); 2021–2040 (denoted 2030); 2041–2060 (denoted 2050); 2061–2080 (denoted 2070); and 2081–2100 (denoted 2090). Data were obtained for average monthly precipitation and for maximum (tmax) and minimum (tmin) temperatures. The mean monthly climatologies for each time slice and for each variable were calculated from the original transient daily GCM time series. The mean monthly fields were then interpolated from the original resolution of each GCM to 0.5 degrees latitude-longitude, using conservative remapping (which preserves the global averages).

We use WorldClim climate data aggregated to five arc-minutes (Hijmans et al. 2005), as representative of current climatic conditions. Grid files were produced for the globe of climate normals for future conditions by interpolation, using inverse square distance weighting; these files were used to generate the daily data needed (maximum and minimum temperature, rainfall, and solar radiation) for each grid cell. This was done using MarkSim, a third-order Markov rainfall generator (Jones et al. 2002) that we use as a GCM downscaler, as it uses elements of both stochastic downscaling and weather typing on top of basic difference interpolation. Details are given in Jones et al. (2009) and in Jones and Thornton (in preparation). Table A2.3 reports region-specific summary statistics for these GCMs for the A2 scenario.

Table A2.3 Climate scenario region-specific summary statistics, A2 scenario (changes between 2000 and 2050)

General circulation model	Change in precipitation (%)	Change in precipitation (mm)	Change in average minimum temperature (°C)	Change in average maximum temperature (°C)
Caribbean				
CNRM-CM3	-5.6	-59.6	2.09	2.21
CSIRO-Mk3.0	-5.1	-54.4	1.43	1.67
ECHam5	-2.7	-28.5	1.88	1.88
MIROC 3.2	-11.5	-122.0	2.09	2.66
Central Africa				
CNRM-CM3	7.3	89.4	2.58	1.90
CSIRO-Mk3.0	-5.8	-70.9	1.68	1.83
ECHam5	2.7	32.4	2.07	2.05
MIROC 3.2	0.6	7.9	1.91	1.37
Eastern Africa				
CNRM-CM3	7.8	67.2	2.60	1.85
CSIRO-Mk3.0	0.9	7.7	1.68	1.63

(Contd...)

Table A2.3—Continued

General circulation model	Change in precipitation (%)	Change in precipitation (mm)	Change in average minimum temperature (°C)	Change in average maximum temperature (°C)
ECHam5	0.5	4.1	2.05	1.96
MIROC 3.2	14.0	120.5	1.89	1.28
Western Africa				
CNRM-CM3	8.2	51.3	2.75	2.03
CSIRO-Mk3.0	1.9	11.7	2.05	1.73
ECHam5	1.3	7.9	2.21	1.98
MIROC 3.2	-1.7	-10.9	2.26	1.57
Southern Africa				
CNRM-CM3	6.3	25.3	2.76	2.09
CSIRO-Mk3.0	-22.3	-89.6	1.66	2.46
ECHam5	-19.2	-77.4	2.30	2.50
MIROC 3.2	-1.8	-7.1	1.82	1.72
Northern Africa				
CNRM-CM3	-0.4	-0.7	2.70	2.08
CSIRO-Mk3.0	-3.5	-6.0	1.91	1.67
ECHam5	0.8	1.4	2.13	1.92
MIROC 3.2	12.8	21.7	2.70	2.43
Middle East				
CNRM-CM3	-0.2	-0.5	2.68	2.29
CSIRO-Mk3.0	-1.9	-3.9	1.88	1.72
ECHam5	-1.7	-3.7	2.33	2.07
MIROC 3.2	-5.1	-10.8	2.65	2.57
Eastern Europe				
CNRM-CM3	-9.6	-56.3	2.27	2.71
CSIRO-Mk3.0	1.8	10.6	1.76	1.82
ECHam5	-2.0	-11.9	1.86	1.82
MIROC 3.2	5.9	34.6	2.94	3.08
Oceania				
CNRM-CM3	0.2	1.0	2.33	1.95
CSIRO-Mk3.0	-6.1	-34.7	1.38	1.59

(Contd...)

Table A2.3—Continued

General circulation model	Change in precipitation (%)	Change in precipitation (mm)	Change in average minimum temperature (°C)	Change in average maximum temperature (°C)
ECHam5	-0.9	-5.0	1.84	1.76
MIROC 3.2	15.5	87.9	1.87	1.57
North America				
CNRM-CM3	1.0	6.6	2.22	2.10
CSIRO-Mk3.0	5.3	35.4	2.02	1.79
ECHam5	6.2	41.4	2.33	2.01
MIROC 3.2	-4.7	-31.5	2.82	3.25
South America				
CNRM-CM3	1.9	28.7	2.33	2.02
CSIRO-Mk3.0	0.8	12.4	1.61	1.51
ECHam5	-0.2	-3.4	1.92	1.89
MIROC 3.2	-4.1	-61.3	2.10	2.42
South Asia				
CNRM-CM3	2.3	16.5	2.32	1.90
CSIRO-Mk3.0	-2.8	-20.1	1.90	1.80
ECHam5	-0.7	-4.9	2.21	1.96
MIROC 3.2	8.9	64.3	2.43	2.04
Southeast Asia				
CNRM-CM3	-0.2	-5.2	1.82	1.64
CSIRO-Mk3.0	0.5	11.3	1.39	1.36
ECHam5	1.2	29.2	1.64	1.54
MIROC 3.2	-1.0	-23.4	1.64	1.48
Central Asia				
CNRM-CM3	9.6	38.3	2.92	2.55
CSIRO-Mk3.0	7.5	29.9	2.20	1.91
ECHam5	10.7	42.6	3.28	2.76
MIROC 3.2	13.3	52.9	3.83	3.52
East Asia				
CNRM-CM3	-3.5	-17.9	2.36	2.19
CSIRO-Mk3.0	2.0	10.1	1.88	1.68
ECHam5	0.8	4.3	2.35	2.14
MIROC 3.2	12.2	62.5	3.08	2.71
Northern Europe				
CNRM-CM3	5.9	43.7	2.09	1.90

(Contd...)

Table A2.3—Continued

General circulation model	Change in precipitation (%)	Change in precipitation (mm)	Change in average minimum temperature (°C)	Change in average maximum temperature (°C)
CSIRO-Mk3.0	8.6	63.7	2.49	2.05
ECHam5	6.0	44.1	2.21	1.89
MIROC 3.2	10.8	79.5	3.62	3.23
Southern Europe				
CNRM-CM3	-17.4	-129.1	1.94	2.36
CSIRO-Mk3.0	-10.2	-75.3	1.35	1.57
ECHam5	-8.4	-62.4	1.80	1.93
MIROC 3.2	-1.1	-8.4	2.40	2.71
Western Europe				
CNRM-CM3	-4.6	-37.1	1.78	2.14
CSIRO-Mk3.0	2.0	15.8	1.47	1.53
ECHam5	-4.0	-32.6	1.77	1.93
MIROC 3.2	8.9	71.7	2.22	2.34
Rest of the world				
CNRM-CM3	3.5	52.8	2.11	1.87
CSIRO-Mk3.0	3.6	55.1	2.13	1.58
ECHam5	3.3	51.0	1.56	1.24
MIROC 3.2	-2.0	-30.8	2.55	2.19
World				
CNRM-CM3	19.5	2.7	2.5	2.2
CSIRO-Mk3.0	6.5	0.9	1.9	1.8
ECHam5	15.0	2.1	2.4	2.2
MIROC 3.2	23.4	3.2	2.8	2.6

Source: Authors' calculations based on GCM results as described in the text.

APPENDIX 3

IFPRI's Modeling Methodology

Modeling the impacts of climate change presents a complex challenge, arising from the wide-ranging processes underlying the working of markets, ecosystems, and human behavior. Our analytical framework integrates modeling components that range from the macro to the micro to model a range of processes, from those driven by economics to those that are essentially biological in nature.

Figure 1.1 provides an illustrative diagram of the links in IFPRI's IMPACT model between the global agricultural policy and trade modeling of the partial agriculture equilibrium model (with the hydrology and agronomic potential modeling).

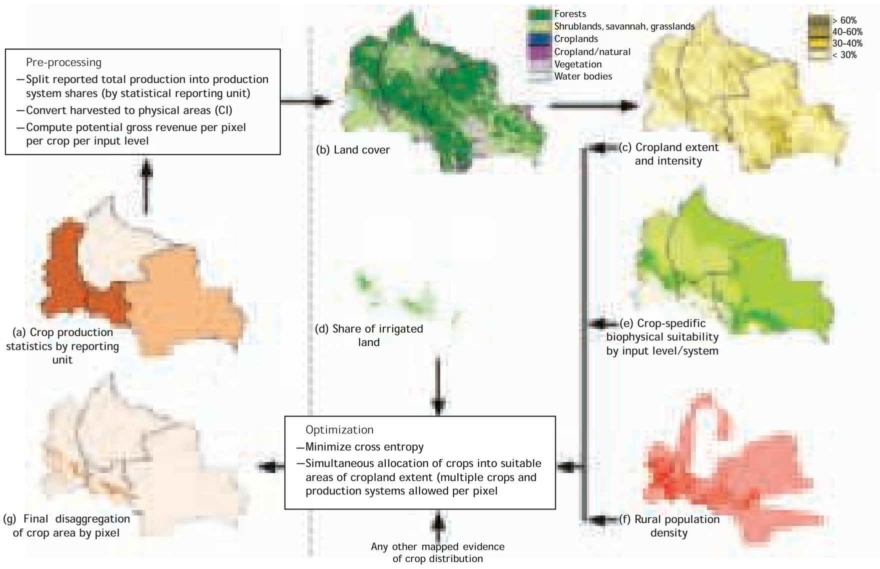
The modeling methodology used here reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships (at a national or even more aggregate regional level) with detailed models of dynamic biophysical processes. The climate-change modeling system combines a biophysical model (the DSSAT crop modeling software suite, showing responses of selected crops to climate, soil, and nutrients) with the SPAM dataset of crop location and management techniques (You and Wood 2006), illustrated in Figure A3.1 These results are then aggregated and fed into the IMPACT model.

Crop Modeling

The Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation model is an extremely detailed process model of the daily development of a crop, from planting to harvest-ready (Jones et al. 2003). It requires daily weather data including maximum and minimum temperature, solar radiation, and precipitation, as well as 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 the DSSAT crop model suite, version 4.5. In mapping these results to other crops in

Figure A3.1 The SPAM dataset development process



Source: Authors.

IMPACT, the primary assumption is that plants with similar photosynthetic metabolic pathways will react similarly to any given climate change effect in a particular geographic region. Millet, sorghum, sugarcane, and maize all use the C4 pathway and are assumed to follow the DSSAT results for maize in the same geographic regions. The remainder of the crops use the C3 pathway. The climate effects for the C3 crops not directly modeled in DSSAT follow the average from wheat, rice, soy, and groundnut from the same geographic region, with the following 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

Because DSSAT requires detailed daily climate data, not all of which are readily available, various approximation techniques were developed. To simulate today's climate we use the WorldClim current conditions dataset (www.worldclim.org), which is representative of 1950–2000 and reports monthly average minimum and maximum temperatures and monthly average precipitation. Site-specific daily weather data are generated stochastically using the SIMMETEO software built into the DSSAT software suite. At each location, 30 iterations of the DSSAT model were run, and the mean of the yield values was used to represent the effect of the climate variables. The climate data are derived from downscaled GCM projections (discussed above) that provide monthly precipitation, average minimum temperatures, and average maximum temperatures for each location. Companion downscaling techniques provide the monthly average number of rainy days and the average incident shortwave solar radiation flux.

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 needed: soil characteristics, crop variety, cropping calendar, CO_2 fertilization effects, irrigation, and nutrient levels.

Soil Characteristics

DSSAT uses many different soil characteristics in determining crop progress through the growing season. John Dimes of ICRISAT and Jawoo Koo of IFPRI collaborated on a classification of 27 meta-soil types, based on the FAO harmonized soil map of the world (Batjes, 2009). Each soil type is defined by three characteristics – soil organic carbon content (high/medium/low); soil rooting depth as a proxy for available water content (deep/medium/shallow); and major constituent (sand/loam/clay). The dominant soil type in a pixel is used to represent the soil type for the entire pixel.

Crop Variety

DSSAT includes many different varieties of each crop. For the results reported here, we use the following varieties: maize variety Garst 8808; a winter wheat variety; a large-seeded Virginia runner type groundnut variety; a maturity group 5 soybean variety; and for rice, a recent IRRI indica rice variety and a Japonica variety. The rice varieties are assigned by geographic area according to whichever is more commonly cultivated within the region. Varietal choice is one way in which farmers could adapt to climate change. As with other adaptive behavior, this is not costless. Farmers would need to gather information about alternate varieties, and seed producers would need to assess the performance of their products under varying climate regimes. For this report, we subsume this effect in the exogenously determined intrinsic productivity growth rate assumptions and hold varietal choice constant.

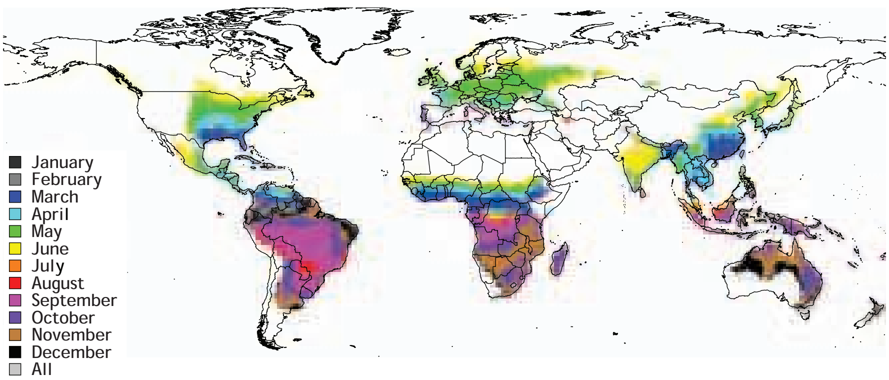
Crop Calendar

Climate change will alter the planting date 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.

Three sets of calendars have been developed for use with IMPACT: general rainfed crops, general irrigated crops, and spring wheat (see Figure A3.2 to Figure A3.7). For rainfed crops, we assume that a crop is planted in the first month of a four-month period where monthly average maximum temperature does not exceed 37°C (about 99°F), monthly average minimum temperature does not drop below 5°C (about 41°F), and monthly total precipitation is not less than 60 mm. In the tropics, the planting month begins with the rainy season. The particular mechanism for determining the start of the rainy season at any location is to look for the block of 4 months that gets the most rainfall. The month before that block is called the beginning of the rainy season. For irrigated crops, the first choice is the rainfed planting month. When that month is not feasible, a series of special cases is considered for South Asia, Egypt, and the rest of the northern hemisphere. Otherwise, the planting month is based on the dry season.

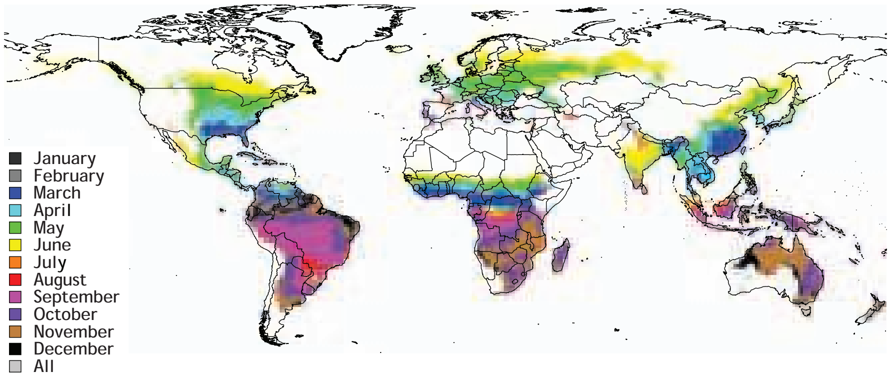
Spring wheat has a complicated set of rules. In the northern hemisphere, the planting month is based on finding a block of months that are sufficiently warm but not excessively so. If all months qualify, then the month is keyed off the dry season. In the southern hemisphere, spring wheat tends to be grown during the meteorological wintertime as a second crop. Hence, the planting month depends not on what is optimal for wheat, but on when the primary

Figure A3.2 Rainfed crop planting month, 2000 climate



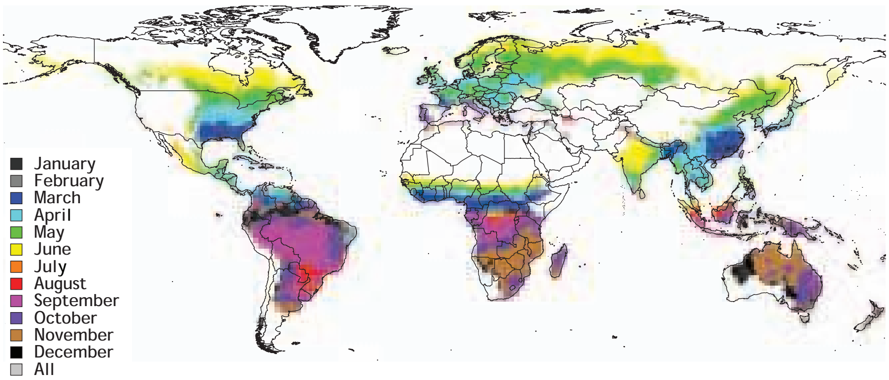
Source: Compiled by authors.

Figure A3.3 Rainfed planting month, 2500 climate, CSIRO GCM A1B Scenario (AR4)



Source: Compiled by authors.

Figure A3.4 Rainfed planting month, 2500 climate, MIROC A1B Scenario (AR4)

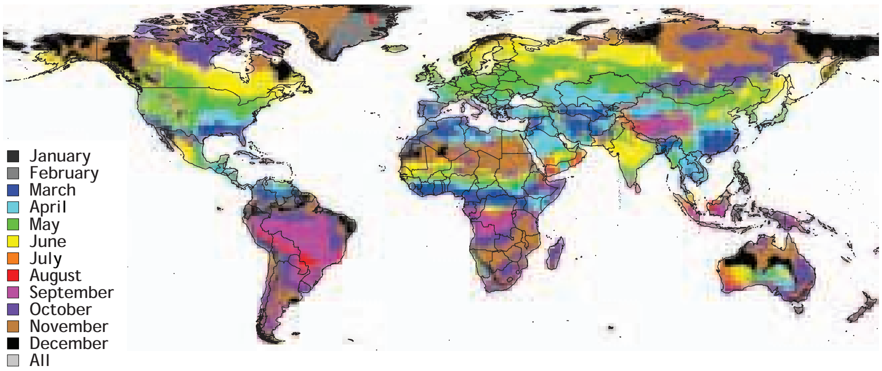


Source: Compiled by authors.

crop is harvested. Hence, the planting date is based on a shift from the rainfed planting month. Failing that, the planting month is based on the rainy season.

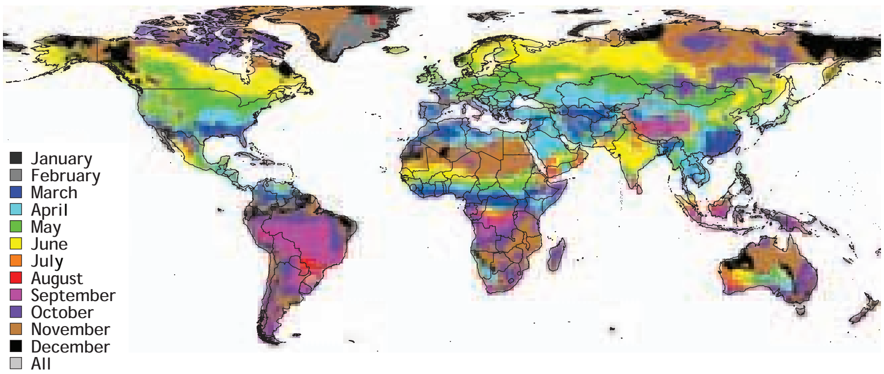
For irrigated crops we assume that precipitation is not a constraint and only temperature matters, avoiding freezing periods. The starting month of the irrigated growing season is identified by four contiguous months where the monthly average maximum temperature does not exceed 45 degrees Celsius (about 113 degrees F) and the monthly average minimum temperature does not drop below 8.5 degrees Celsius (about 47 degrees F). See Figure A3.5 to Figure A3.7.

Figure A3.5 Irrigated planting month, 2000 climate



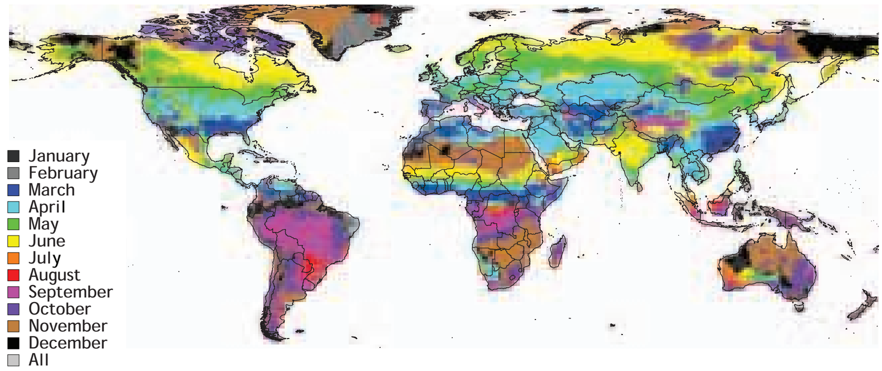
Source: Compiled by authors.

Figure A3.6 Irrigated planting month, 2500 climate, CSIRO GCM A1B Scenario (AR4)



Source: Compiled by authors.

Figure A3.7. Irrigated planting month, 2500 climate, MIROC GCM A1B 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 from 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. Another report (Zavala et al. 2008) finds that higher levels of atmospheric CO_2 increase the susceptibility of soybean plants to the Japanese beetle and of maize to the western corn rootworm. Finally, a recent study (Bloom et al. 2010) finds that higher CO_2 concentrations inhibit the assimilation of nitrate into organic nitrogen compounds. So the actual field benefits of CO_2 fertilization remain uncertain.

DSSAT has an option to include CO_2 fertilization effects at different levels of CO_2 atmospheric concentration. For this study, all results use a 369 ppm setting.

Our aggregation process—from SPAM pixels and the crop model results to IMPACT FPUs—results in some improbable yield effects in a few locations. To deal with these, we cap the FPU-level yield increase at 0.53 percent annually, or about 30 percent over the period from 2000 to 2050 and limit the negative effect of climate on yield growth in IMPACT to –2 percent per year.

Water Availability

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

Nutrient Level

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

From DSSAT to the IMPACT Model

DSSAT is run for five crops—rice, wheat, maize, soybeans, and groundnuts—at 15-arc-minute intervals for the locations where the SPAM dataset shows that the crop is currently grown. Other crops are assumed to have productivity effects similar to these five crops, as described above. The results from this analysis are then aggregated to the IMPACT FPU level.

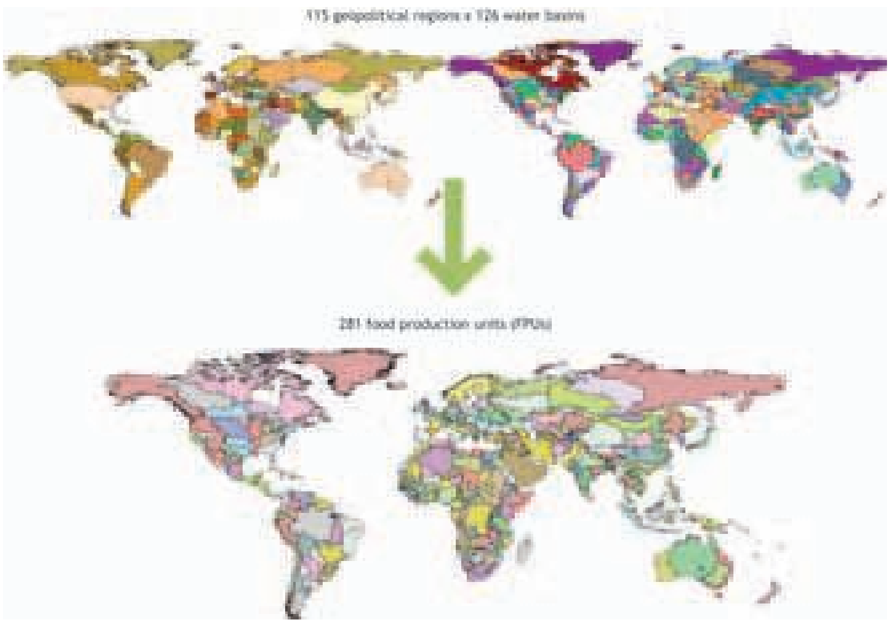
The IMPACT Model[15]

The IMPACT model was initially developed at the International Food Policy Research Institute (IFPRI) to project global food supply, food demand, and food security to year 2020 and beyond (Rosegrant et al. 2008). It is a partial equilibrium agricultural model with 32 crop and livestock commodities, including cereals, soybeans, roots and tubers, meats, milk, eggs, oilseeds, oilcakes and meals, sugar, and fruits and vegetables. IMPACT has 115 country (or in a few cases country-aggregate) regions, with specified supply, demand, and prices for agricultural commodities. Large countries are further

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

divided into major river basins. The result, portrayed in Figure A3.8, 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. We distinguish four categories of commodity demand: food, feed, biofuels feedstock, and other uses.

Figure A3.8 IMPACT model unit of analysis, the food production unit (FPU)



Source: Authors.

Modeling Climate Change in IMPACT

Climate change effects on crop production enter into the IMPACT model by altering both crop area and yield. Yields are altered through the intrinsic yield growth coefficient, gy_{tni}, in the yield equation (1) as well as through the water availability coefficient (*WAT*) for irrigated crops. These yield growth rates 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 in yield is assumed to be negative, while in others it is as high as 5 percent per year for some years.

$$YC_{tni} = \beta_{tni} \times (PS_{tni})^{\gamma_{iin}} \times \prod_k (PF_{tnk})^{\gamma_{ikn}} \times (1 + gy_{tni}) - \Delta YC_{tni}(WAT_{tni}) \quad (1)$$ [16]

Climate change productivity effects are produced by calculating location-specific yields for each of the five crops modeled with DSSAT for 2000 and 2050 climate, as described above, and converting these to a growth rate which is then used to shift gy_{tni} by a constant amount.

Rainfed crops react to location-specific changes in precipitation and temperature as modeled in DSSAT. For irrigated crops, temperature effects are modeled in DSSAT with no water stress. Then water stress from climate change is captured as part of a separate hydrology model, a semi-distributed macro-scale hydrology module that covers the global land mass (except Antarctica and Greenland). It conducts continuous hydrological simulations at monthly or daily time steps at a spatial resolution of 30 arc-minutes. The hydrological module simulates the rainfall-runoff process, partitioning incoming precipitation into evapotranspiration and runoff that are modulated by soil moisture content. A unique feature of the module is that it uses a probability distribution function of soil water-holding capacity within a grid cell to represent spatial heterogeneity of soil properties, enabling the module to deal with sub-grid variability of soil. A temperature-reference method is used to judge whether precipitation comes as rain or snow and determines the accumulation or melting of snow (accumulated in conceptual snow storage). Model parameterization was done to minimize the differences between simulated and observed runoff processes, using a genetic algorithm. The model is spun up for five years at the beginning for each simulation run, to minimize any arbitrary assumption of initial conditions. Finally, simulated runoff and evapotranspiration at 30-arc-minute grid cells are aggregated to the 281 FPUs of the IMPACT model.

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

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

In some cases the simulated changes in yields from climate change are large and positive. This usually arises from one of two causes: (1) starting from a low base (which can occur in marginal production areas); and (2) unrealistically large effects of carbon dioxide fertilization.

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

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

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

As metrics for the state of human well-being, we use average per capita calorie consumption as well as an associated measure, the number of malnourished children under five. We use the underweight definition of malnutrition, that is, the proportion of children under five falling below minus-2 standard deviations from the median weight-for-age standard set by the U.S. National Center for Health Statistics and the World Health Organization.[17]

Estimating Child Malnutrition

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

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

where

MAL	=	percentage of malnourished children
KCAL	=	per capita kilocalorie availability
LFEXPRAT	=	ratio of female to male life expectancy at birth
SCH	=	total female enrollment in secondary education (any age group) as a percentage of the female age group corresponding to national regulations for secondary education
WATER	=	percentage of population with access to safe water
$\Delta_{t,t2000}$	=	the difference between the variable values at time t and the base year t2000

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

$$NMAL_t = MAL_t \times POP5_t$$

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

17 Two alternate definitions of malnutrition are:
Stunting – low height for age; height for age more than a standard deviation of 2 below the median value of the reference (healthy) population
Wasting – low weight for height; weight for height more than a standard deviation of 2 below the median value of the reference (healthy) population.

For this report, we assume that life expectancy, maternal education, and clean water access values improve over time but do not change across the scenarios.

Irrigation Efficiency Improvements

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

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

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

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

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

Variables are defined as follows:

- *cp*—index for the IMPACT crop
  Includes all IMPACT crops that receive irrigation.
- *st*—index for the crop growth stages
  FAO has divided the crop growing period into four stages, each with separate crop coefficient (*kc*) values. See Allen et al. (1998) for details.
- *kc* —crop coefficient
  Each crop growth stage is associated with a corresponding crop coefficient (Allen et al. 1998) that adjusts reference ET for the characteristics of a particular crop.
- ET_0 —reference evapotranspiration
  Evapotranspiration describes the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere. Evaporation accounts

for the movement of water to the air from sources such as the soil, canopy interception, and water bodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. Reference evapotranspiration is defined as the *ET* that occurs from a standardized "reference" crop, such as clipped grass or alfalfa.

- *PE*—effective rainfall (rainfall that is actually available for plant growth)
- AI^{cp} —irrigated area for crop *cp* in the basin

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

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

APPENDIX 4

Comparing IFPRI Food Security and Climate Change Results: What has Changed?

In late 2009, IFPRI researchers prepared two major reports in the impacts of climate change on agriculture: a book released by the Asian Development Bank (Rosegrant et al. 2009); and an IFPRI Food Policy Report (Nelson et al. 2009). Roughly one year later, many of the same researchers contributed to the present IFPRI research monograph (referred to here as RM10). During the intervening year, substantial improvements were made to the various components of the IMPACT modeling system that generates scenario results to 2050.

One consequence of those improvements is that the results are not strictly comparable. In this Appendix, we compare selected results from the Food Policy Report (referred to here as FPR09) with the results reported in RM2010 and document some of the key changes that resulted in those differences. We focus on the main crops rice, wheat, and maize, as well as the malnourished children results. Since FPR09 only used one set of income and population drivers, we compare its results with the baseline scenario of the RM10 report. (FPR09 also includes a pessimistic and optimistic scenario). The climate GCMs differ between the two reports, so, for the most part, we report differences in the perfect mitigation (no climate change) results. Table A4.1 reports the price scenarios for maize, rice, and wheat for the two publications. Table A4.2 reports the malnourished children outcomes. The main RM10 report includes results only from 2010. However, since the simulations begin in 2000 and the FPR09 report does not include 2010 results, we include year 2000 results in this Appendix.

There are two main differences between the two sets of outcomes. The price increases with perfect mitigation are substantially larger in the RM10 report than in the FRP09 report. However, climate change in the RM10 report generally results in less negative productivity effects (averaged across the four GCM/SRES scenario climate changes), so the combined price effects result in smaller price increases for rice and wheat in the RM10 report.

Table A4.1 Price scenarios, RM10 and FPR09 (US$/mt and percent difference)

Crop	2010	2050, perfect mitigation	2050, climate change	2050 RM10/FPR09 (% difference, perfect mitigation)	2050 RM10/ FPR09 (% difference, climate change
RM10 results					
Maize	119.3	196.2	261.4	9.6	10.5
Rice	240.0	330.4	383.7	3.4	0.2
Wheat	147.5	211.3	259.2	10.6	10.2
FPR09 results					
Maize	111.1	179.0	236.7		
Rice	238.5	319.6	382.9		
Wheat	145.8	191.0	235.1		

Source: Authors' estimates.

Note: Climate change values are the mean of the two climate change scenario results in FPR09 and the 4 climate change scenarios of RM10.

Table A4.2 Number of malnourished children in developing countries (million)

	2010	2050, no climate change	2050, climate change
All developing countries, RM10	155.2	106.7	118.3
All developing countries, FPR09	148.3	112.9	137.5

Source: Authors' estimates.

Three drivers account for the bulk of these differences: differences in GDP, population, and climate change modeling methodology.

Differences in GDP

For the FPR09 report we relied on the GDP growth rates used in the World Bank's EACC report. A subsequent assessment was that several of the rates were implausibly small for the baseline, especially in Asia and Sub-Saharan Africa. Table A4.3 reports the growth rates used in the two reports for countries where the rates were changed. The consequence of these changes for world GDP and agricultural demand is quite significant, since the changes are all in developing countries. For the FPR09 report, average annual world GDP growth from 2000 to 2050 was 3.03 percent. For the RM10 report, the rate is 3.13 percent.

Table A4.3 GDP growth rates from 2000 to 2050 and changes (average annual rate, percent)

	RM10	FPR09	Difference		RM10	FPR09	Difference
Vietnam	6.97	4.42	2.55	Togo	5.14	3.73	1.41
Mozambique	6.39	3.99	2.41	Gambia	5.32	3.97	1.36
Southeast Asia	7.06	4.82	2.24	Mali	6.09	4.75	1.34
Tanzania	6.33	4.18	2.15	Indonesia	5.45	4.16	1.29
Uganda	6.91	4.82	2.09	Guinea	5.35	4.13	1.22
Zambia	5.83	3.82	2.01	Angola	6.57	5.35	1.22
Ethiopia	5.88	3.98	1.9	Thailand	5.07	3.88	1.2
Rwanda	6.07	4.18	1.89	Botswana	4.9	3.7	1.19
Ghana	5.57	3.7	1.87	Pakistan	5.73	4.64	1.09
Sierra Leone	6.75	4.9	1.85	Nigeria	5.11	4.02	1.09
Central African Republic	4.77	2.92	1.84	Burundi	5.54	4.46	1.08
Namibia	5.22	3.47	1.75	Democratic Republic Congo	5.42	4.34	1.08
Kenya	5.85	4.11	1.73	Guinea-Bissau	5.17	4.15	1.02
Congo	5.87	4.14	1.73	Equatorial Guinea	6.44	5.44	1.00
Cameroon	5.38	3.7	1.68	Benin	5.35	4.35	1.00
Chad	7.12	5.5	1.63	India	6.41	5.45	0.96
Malawi	5.46	3.86	1.61	Philippines	5.44	4.5	0.94
Swaziland	4.39	2.79	1.6	Bangladesh	5.12	4.23	0.89
Ivory Coast	4.88	3.29	1.59	Niger	5.7	5.03	0.67
Gabon	5.1	3.51	1.58	Liberia	4.23	3.76	0.47
Lesotho	4.17	2.59	1.58	Zimbabwe	2.6	2.14	0.45
Madagascar	5.33	3.86	1.48	South Africa	3.23	2.92	0.31
Senegal	5.5	4.04	1.46	Malaysia	4.93	4.69	0.24
Burkina Faso	5.87	4.45	1.42	World	3.03	3.16	0.13
Eritrea	5.48	4.07	1.41				

Source: Authors' estimates.

Differences in Population

The RM10 report relies on the most recent data from the UN on population projections (downloaded in 2010). The FPR09 report used an earlier set of population data. Table A4.4 reports the differences for selected countries and for the world. World population in 2050 is 28 million less with the RM10 data than the FRP09 data. For the most part the changes are small and relatively evenly distributed and will have small effects on prices. But four important developing countries have relatively large absolute increases in population: DR Congo, India, Brazil, and Bangladesh – together accounting for 144 million additional people in 2050. The latter three countries are important consumers of rice, wheat, and maize, and so these population increases will contribute to higher prices. The three countries losing the most people in the 2050 scenario are China, Pakistan, and Tanzania, losing a combined 69 million people in the 2050 scenario.

Table A4.4 2050 population projection changes for selected countries, RM10-FPR09 (million)

Name	2050	Name	2050
Democratic Republic Congo	39	Iberian Peninsula	-5
India	38	Niger	-6
Brazil	36	Zambia	-6
Bangladesh	31	Ivory Coast	-8
Burundi	13	Russia	-9
Mali	9	China Hong Kong Taiwan	-11
Vietnam	8	Tanzania	-24
Afghanistan	5	Pakistan	-34
Gulf	5	Total	-28

Source: Authors' estimates.

Changes in Modeling the Effects of Climate Change

The techniques used to model the effects of climate change on agricultural productivity in IMPACT have seen three substantial changes in the recent past. Prior to the analysis that resulted in the FPR09 report, productivity effects were obtained from outside sources. They tended to have very coarse spatial resolution and utilized a very limited set of possible future climates. The techniques used beginning with the FPR09 report and the ADB book have much higher spatial resolution, show a wider variety of future climates, and can be relatively easily updated when new climate data become available.

For the FPR09 report, the modeling approach used a very basic working, if awkward, system that supplied IMPACT with indicators of agricultural productivity changes for two different climate scenarios across the entire globe – the AR4 CSIRO and NCAR GCMs with results for the A2 SRES greenhouse gas emissions pathways scenario.

The RM10 report revamped the actual running of the crop models to more easily interface with the GIS portion and allow for streamlined troubleshooting. In addition, different GCMs and scenarios were used – the CSIRO and MIROC GCMS with the A1B and A2 greenhouse gas emissions pathway scenarios. In addition, a variety of modeling methods were modified or added to make the simulations more realistic.

Crop Model Version

The actual crop modeling code used in the two phases differed. The FPR09 used the official, released DSSAT version 4.0. For the RM10 report, a recent beta version of 4.5 was employed.

Climate Data

For both reports, the years compared were approximately 2000 and approximately 2050.

The FPR09 report used WorldClim downscalings for the baseline. The two future climates were constructed by taking the raw (geographically coarse) anomalies and adding them to the WorldClim baselines. WorldClim does not include information about the number of rainy days or incident solar shortwave radiation needed for the crop modeling. This meant that the “number of rainy days in a month” and “typical shortwave solar radiation by month” had to be obtained elsewhere. These were constructed from the NASA/LDAS historical assimilated data. A non-linear regression technique was developed to characterize a cross-sectional relationship between the number of rainy days and the available WorldClim data (rainfall and temperature), elevation, and latitude. These relationships were then used to make projections of the rainy days under the future climates by plugging in the values for the future rainfalls and temperatures. The climates used were the A2 GHG pathway scenarios for the NCAR and CSIRO GCMs (AR4 anomalies plus WorldClim baseline).

The RM10 report results still used the WorldClim 2000 dataset for the baseline, but used the Thornton/Jones downscaling methodology (“FutureClim”) for the 2050 climate scenarios, which also provides estimates for the number of rainy days and the shortwave radiation.

It is difficult to do a direct comparison between the WorldClim and FutureClim datasets, but there are differences. For example, the minimum temperature for September 2050 for the CSIRO GCM with the A2 scenario is about 0.1 degrees lower on average for the WorldClim derived product than the FutureClim product, a relatively small amount. The differences for the rainy days and shortwave radiation are much more significant. For example, there are many locations with 9 to 12 days difference in the number of rainy days in the month. With shortwave radiation data, there are many locations where the difference is more than a fifth of the possible range.

Our assessment is that the Thornton/Jones FutureClim downscaling techniques are more reliable and internally coherent than the WorldClim-based data, and hence the climate inputs into DSSAT for RM10 are better than those used for FPR09.

Crop Varieties

The crop varieties used in both sets of scenarios are the same with the exception of wheat. Wheat is a difficult crop to model, most importantly because of the two major types of wheat and their production schedules: winter wheat and spring wheat. The IMPACT does not differentiate between these types of wheat. However, for the crop modeling, a particular variety needs to be specified. Based on the knowledge available when the FPR09 report was being prepared, a winter wheat variety was chosen. The difficulty in establishing an appropriate planting month by location led to a strategy of planting in every month and choosing the highest yielding month.

Subsequent experimentation into the modeled behavior of several wheat varieties in DSSAT, along with improved knowledge of wheat in general, led to a revision of the treatment of wheat in the RM10 report. The winter wheat variety was replaced by a spring wheat variety. We looked at how the yield responded when the planting month was changed and discovered that the winter wheat variety acted like an ill-behaved spring wheat rather than like a true winter wheat. Furthermore, it appears that spring wheat varieties are grown in a wider geographic area than winter wheat varieties. With further experimentation it seems likely that, although wheat is often grown during meteorological winter, spring varieties are most common: for example, in much of India it is too hot to grow wheat during the summer. Thus, we thought that a spring wheat variety would better represent global behavior than a poorly defined winter wheat variety. The planting month strategy was also changed from choosing among all months (which often shows clearly spurious highest yielding months) to targeting a particular planting month.

Planting Dates

The FPR09 approach to planting dates was to identify the planting month via a set of rules based on the monthly climate variables. For example, for most rainfed crops, the planting month is the first month after September that begins a block of four months with temperatures that are in the range the crop can tolerate and that also have at least a minimum amount of rainfall. These rules were applied to each of the climate scenarios to determine a planting date.

The RM10 report employed different climate data, so the rules had to be recalibrated. More expert input was used to inform the calibration process. This allowed the rules to be modified and expanded to better match the evidence about when different crops are planted around the world. In particular, this allowed for an improved determination of planting dates for spring wheat. To allow greater flexibility, the target month identified by the rules is used as the middle of a three-month window. All three months are modeled separately and the final yield is chosen to be the highest yield of the three months.

An important issue is the number of weather realizations used to determine the mean yield values. The FPR09 used 15 realizations in most cases. For the RM10 report, 40 repetitions were used for two planting dates within the month for a total of 80 repetitions (and another 160 for the unused, lower yielding planting months).

Water Management

Water management is especially important for irrigated rice. In the FPR09, irrigated rice was treated just like all other irrigated crops. That is, a particular soil layer was maintained at a target level of moisture. The RM10 report improved on this by implementing the rice-specific irrigation controls in DSSAT that allowed for a flooded paddy scheme (raising and lowering the water depth, for example).

Initial Conditions

The initial moisture and nitrogen conditions in the soil can be quite important in determining final yields. For crops tolerant of relatively dry conditions, starting out with significant amounts of soil moisture (which is the DSSAT default) can allow for seemingly abundant rainfed yields, even in locations known to have virtually no annual rainfall. Such results are clearly problematic.

The FPR09 did not attempt to set the initial soil conditions. The default is to start with the maximum possible soil moisture content that can be held without draining away, and this gave inappropriate levels of moisture availability in some dryland areas. In the RM10 report, a heuristic was implemented to allow for control of the initial soil moisture and nitrogen content so they could be set to a more reasonable level.

Geographic Coverage

The geographic details also changed between the two phases. Both used the SPAM product to identify locations for modeling for each crop. However, between the FPR09 and RM10 reports, the SPAM product itself was upgraded and improved, resulting in a different set of geographic locations and weightings.

In addition, for the FPR09 report, the effective spatial resolution was chosen as half-degree pixels over only the most important regions identified by SPAM for each crop and a very small region around them. For the RM10 report, the spatial resolution improved to quarter-degree pixels covering the entirety of the pixels identified by SPAM as having any production at all (however small) for each crop. This resulted in greater coverage at a higher resolution and more appropriate choice of soil type for the simulation.

Summary of the Changes

Numerous changes were made in the modeling and data used between the two reports. The two most significant were likely the income growth rates and the climate change modeling. Global income growth was increased substantially—with all the increase in developing countries. This is undoubtedly responsible for at least some part of the higher prices observed in the RM10 report with perfect climate mitigation. It also accounts for the slightly smaller number of malnourished children in 2050 with perfect mitigation in the RM10 report. The price increases resulting from the income-induced increased demand offset to some extent the favorable effect of the income increases on child malnutrition. Because the simulated negative productivity effects of climate change are smaller in the RM10 report, the difference in the number of malnourished children is also smaller.

This type of modeling is still in its infancy—combining very detailed, process-based climate change productivity effects with a water demand and supply model, all incorporated into a detailed economic model of world agriculture. We are in the process of improving several aspects of the modeling process to more accurately capture the relevant complexity that determines global food security. In that sense this monograph should be seen as a status report of an ongoing process of research discovery.

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As the global population grows and incomes in poor countries rise, so too, will the demand for food, placing additional pressure on sustainable food production. Climate change adds a further challenge, as changes in temperature and precipitation threaten agricultural productivity and the capacity to feed the world's population. This study assesses how serious the danger to food security might be and suggests some steps policymakers can take to remedy the situation.

Using various modeling techniques, the authors project 15 different future scenarios for food security through 2050. Each scenario involves an alternative combination of potential population and income growth and climate change. The authors also examine the specific test case of a hypothetical extended drought in South Asia, to demonstrate the possible effects of increased climate variability on a particular world region. They conclude that the negative effects of climate change on food security can be counteracted by broad-based economic growth—particularly improved agricultural productivity—and robust international trade in agricultural products to offset regional shortages. In pursuit of these goals, policymakers should increase public investment in land, water, and nutrient use and maintain relatively free international trade. This inquiry into the future of food security should be of use to policymakers and others concerned with the impact of climate change on international development.

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