PART IV

Emerging Challenges and Opportunities in Agricultural Development

Chapter 19

CLIMATE CHANGE AND AGRICULTURAL DEVELOPMENT

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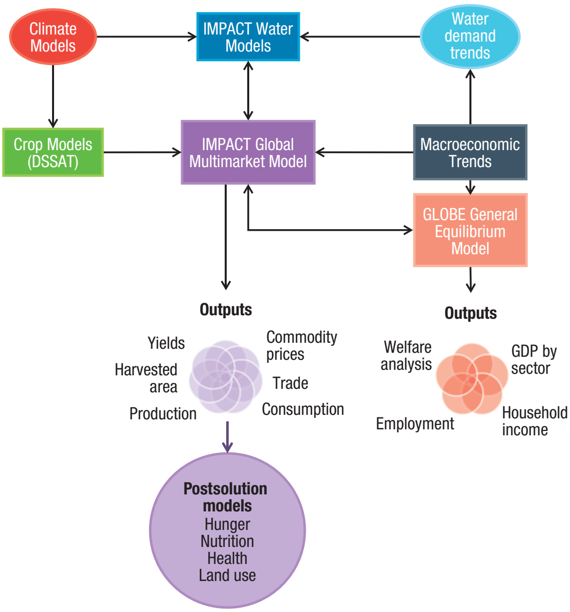
Climate change will be a major driver of change in the agricultural sector in the coming decades, along with changes in population, income, urbanization, dietary preferences, and technology.[1] Agriculture is unique among economic sectors in its dependence on temperature, precipitation, and other climate variables, and is thus unique in its sensitivity to changes in those variables. Farmers around the world have long been accustomed to dealing with the vagaries of weather, but climate change is now occurring on a larger scale and will bring bigger challenges in terms of what farmers produce, where and how they produce it, and what we eat.

Throughout the entire history of agriculture over the past 10,000 years, including the period of rapid growth and intensification during the Green Revolution over the past half century, global mean temperatures have remained within a range of about 1°C from current levels (Schellnhuber, Rahmstorf, and Winkelmann 2016). The 2016 Paris climate accord set a target of keeping temperatures well below 2°C above preindustrial levels and to pursue efforts to limit the increase to 1.5°C. But most climate change scenarios show future temperatures rising well above these levels and well beyond historical experience. This chapter explores the implications of these changes. The first part examines alternative scenarios for climate change. The next section presents the latest findings on climate change impacts on agriculture and food security. Options to adapt to climate change and its impacts are considered as well as mitigation strategies.

1 The research on which this chapter is based was supported by funding from the CGIAR Research Program on Policies, Institutions, and Markets (PIM), the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), the Bill & Melinda Gates Foundation, and the United States Agency for International Development. Analytical support from Nicola Cenacchi, Richard Robertson, and Shahnila Dunston is also gratefully acknowledged.

FIGURE 19.1 The IMPACT system of models

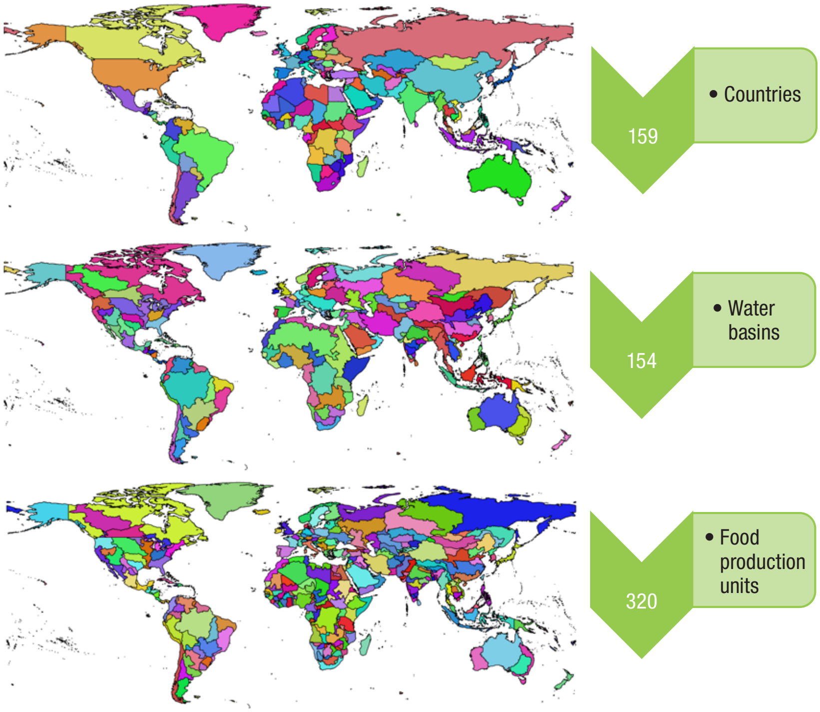


Alternative Scenarios for Climate Change

Analyzing climate change and its impacts requires a wide range of data and analytical tools. These may include general circulation models (GCMs) that generate simulations of future climates based on assumptions about future growth in greenhouse gas emissions; hydrology models that simulate water flows and storage; crop models that simulate crop growth; and economic models that simulate interactions between agricultural production, consumption, prices, and trade.

Methods and Scenarios

IFPRI's long-term projections of food and agriculture are based on the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), a multimarket model that simulates the operation of national and international markets, solving for production, demand, and prices that equate supply and demand across the globe (Rosegrant and IMPACT Development Team 2012; Robinson et al. 2015). The core model is linked to a number of "modules" that include climate models, water models (hydrology, water basin management, and water stress models), global



Source: Reproduced from Robinson et al. (2015).

gridded crop simulation models (Robertson 2017) such as the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003; Hoogenboom et al. 2017), value chain models (for example, sugar, oils, livestock), land use (pixel-level land use, cropping patterns by regions), nutrition and health models, and welfare analysis (Figure 19.1).

The core multimarket model focuses on national and global markets including 159 countries. Agricultural production is specified by models of land supply, allocation of land to irrigated and rainfed crops, and determination of yields. Production is modeled at a subnational level, including 320 regions called food production units (FPUs). FPUs are defined to link to the water models and correspond to water basins within national boundaries—154 basins (that is, Nile, Amazon, and so forth) and 159 countries. The multimarket model simulates 62 agricultural commodity markets, representing the bulk of food and cash crops. A range of methodological innovations and improvements were incorporated to allow quantitative assessments of the potential trade-offs between competing and complementary multidimensional future scenarios.

The IMPACT partial equilibrium modeling framework was extended with a global computable general equilibrium model (GLOBE) (Willenbockel et al. 2018) and several linked postsolution models to evaluate the scenario effects of various investment requirements, along with evolving land-use changes, greenhouse gas (GHG) emissions, biodiversity, water quality, and micronutrient availability as well as dietary diversity. Another key modeling innovation was a new methodology to estimate research costs under reference and alternative investment scenarios (Mason-D'Croz et al. 2019). The IMPACT model is continually being upgraded and enhanced, through close collaboration between IFPRI and the other 14 CGIAR centers through the Global Futures & Strategic Foresight project, and with other leading global modeling groups through the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al. 2013; Rosenzweig et al. 2018).

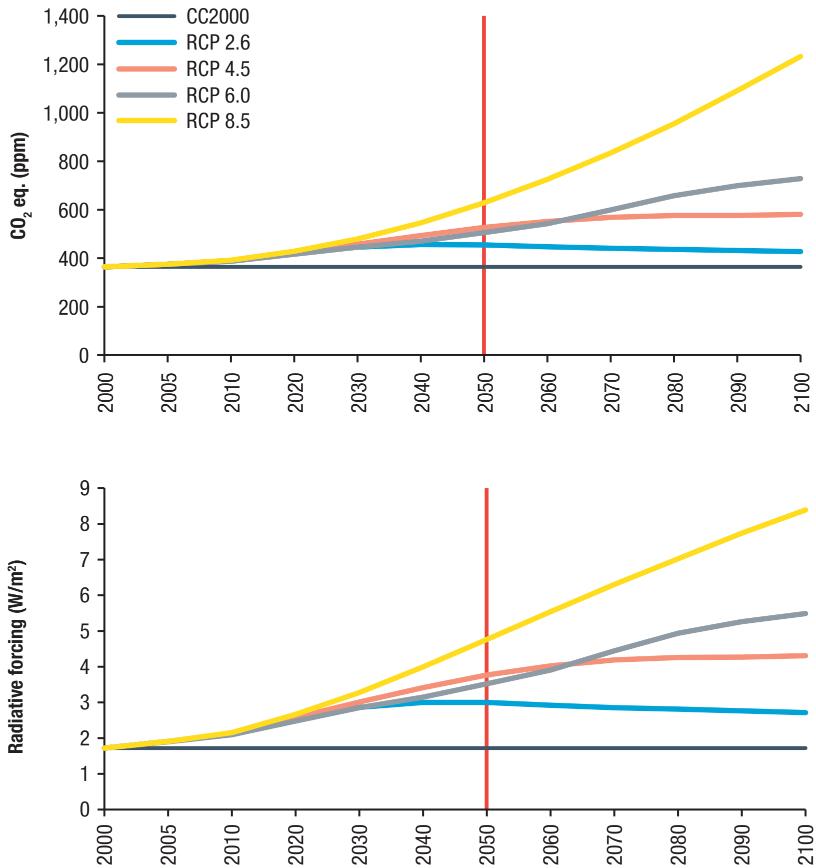
To facilitate analysis and comparison involving multiple models, standard sets of assumptions about different climate change trajectories, called "representative concentration pathways," have been developed as part of the Intergovernmental Panel on Climate Change (IPCC) process (Moss et al. 2010). These range from relatively slow rates of change in Representative Concentration Pathway (RCP) 2.6 (expressed in units of radiative forcing, in this case 2.6 watts per square meter in 2100), to relatively rapid change in RCP 8.5, with intermediate cases RCP 4.5 and 6.0 (Figure 19.2).

To estimate impacts of future climate change, we need to distinguish those impacts from the effects of other major drivers of change, including population, income, and technology. As with climate change, the global modeling community has also developed a set of standardized assumptions about changes in these other drivers to facilitate analysis and comparison involving multiple models. These "Shared Socioeconomic Pathways" (O'Neill et al. 2014; O'Neill et al. 2017) include a business-as-usual case (SSP2), a case with faster income growth and slower population growth (SSP1), a case with slower income growth and faster population growth (SSP3), and two other cases characterized by different assumptions about the nature of technological change and the degree of economic inequality (Figure 19.3).

Global and Regional Patterns of Climate Change

Climate change is characterized by multiple dimensions, including rising temperatures, changing precipitation patterns, changing frequency and intensity of extreme weather events, changing patterns of pests and diseases affecting crops and livestock as well as humans, sea-level rise, and glacial melting. The

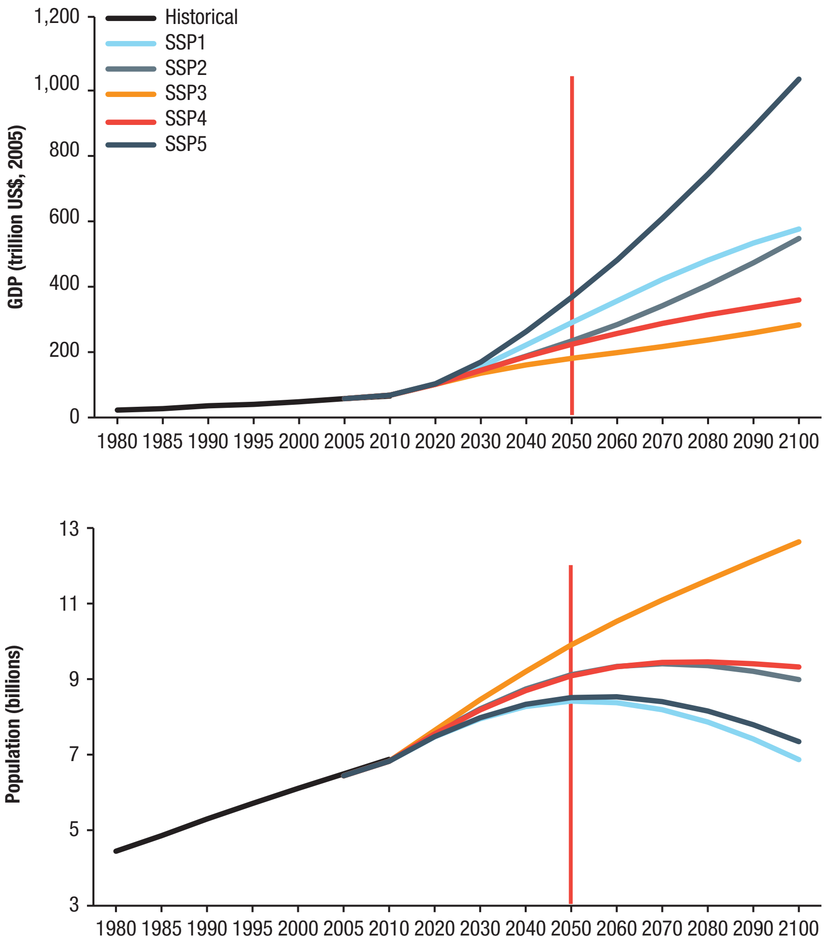
FIGURE 19.2 **Climate change as characterized in different Representative Concentration Pathways (RCP), 2000–2100**



Source: Compilation by Robinson et al. (2015) from IIASA (2015).

first four are global in scope, while the last two are concentrated in coastal areas and particular river basins, respectively. Of the first four, current economic modeling capacities limit our primary focus to the first two: temperature and precipitation. General circulation models vary in the details of their projections about changes in temperature (Figure 19.4), but they generally agree that increases will be largest (up to 4°C or more by 2050) at higher latitudes, especially in the Northern Hemisphere. But lower latitudes, with higher temperatures to begin with, will feel the effects of heat stress with even smaller increases.

FIGURE 19.3 Socioeconomic drivers of change, 1980–2100



Source: Compilation by Robinson et al. (2015) from IIASA (2013).
Note: SSP = Shared Socioeconomic Pathway; GDP = gross domestic product.

Models vary more widely in their projections of changes in precipitation (Figure 19.5). There is general agreement that North Africa and southern Europe will become drier and that high northern latitudes will be wetter, but there are significant differences across models for most other regions. This highlights the uncertainty inherent in projections about climate change and its impacts.

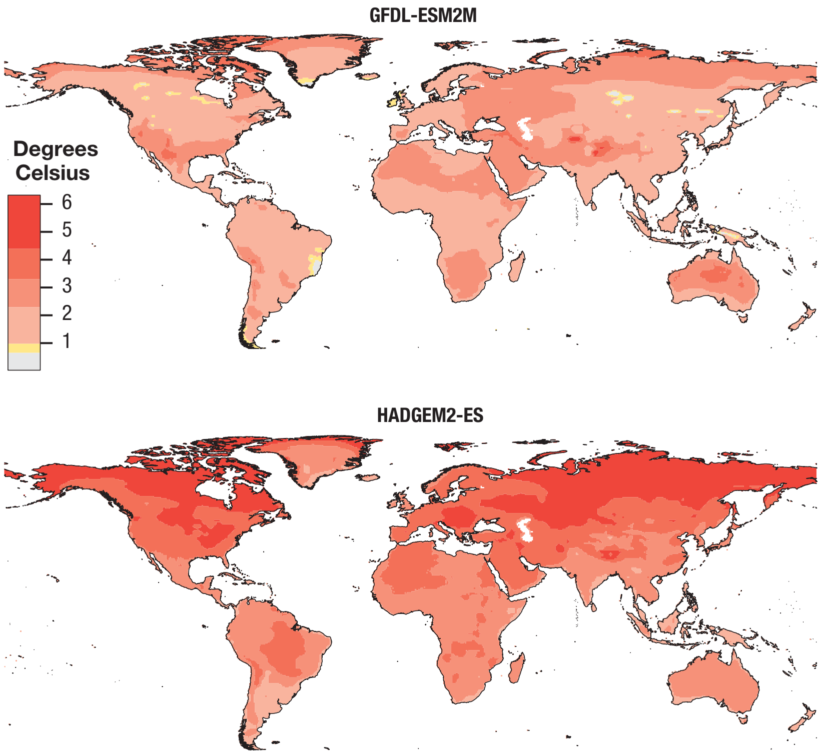
Climate Change Impacts on Agriculture

Climate change affects agriculture most directly through the impact of changing temperatures and precipitation patterns on the growth of crops and livestock. Modeling tools such as the Decision Support System for Agrotechnology Transfer (DSSAT) system of crop models can analyze how future changes in these variables will affect the growth of particular crops and varieties, given levels of other variables such as soil quality and management practices. Figure 19.6, for example, shows how climate change would affect yields of rainfed maize, according to the HadGEM general circulation model and the DSSAT maize model and assuming climate changes rapidly as characterized by representative concentration pathway 8.5. Yield losses of 25 percent or more (indicated in red) are widespread, including in major producing areas in Asia, Brazil, Europe, and the United States. Impacts are mixed in Africa, and positive in a few areas such as northern China and western Canada.

It is essential to note that the projections in Figure 19.6 show only the direct biophysical impacts of changes in temperature and precipitation, holding constant such factors as technology and management practices. But these other factors are also changing over time, as a result of changes in demand (and thus prices) driven by changes in population, income, and dietary preferences, and also as a result of changes in prices driven by the biophysical impacts of climate change itself. Yield shocks of the magnitude indicated in Figure 19.6, were they to be realized, would trigger price increases for maize that would in turn induce changes in technology and management that would ripple through the agricultural economy. In fact, these changes are already occurring, for example as farmers adjust planting times and experiment with different crop varieties, and as researchers develop new varieties that are more tolerant of higher temperatures. Analyzing these indirect effects to determine the impacts of climate change more completely requires the use of global economic models in combination with climate and crop models.

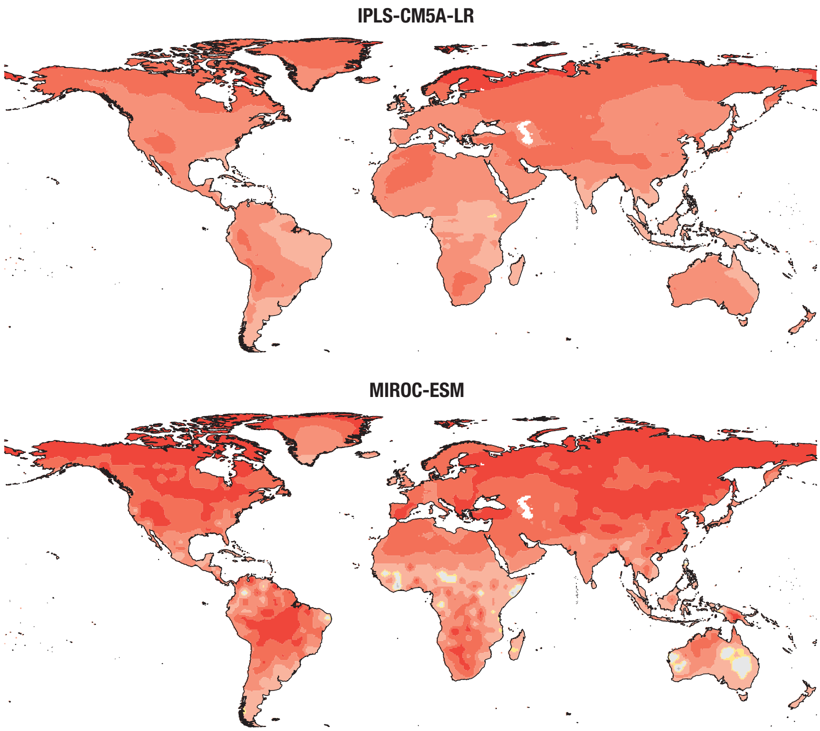
Recent studies using multiple climate, crop, and economic models have explored this question under a range of climate and socioeconomic scenarios. Nelson et al. (2014) found that climate change would reduce yields of maize, rice, wheat, and soybeans by an average of 11 percent worldwide by 2050, relative to the hypothetical reference case of no climate change in 2050, and increase real prices by 20 percent over the reference case. Using a similar set of models, Wiebe et al. (2015) found yield reductions of 5 percent to 7 percent in 2050 for the same four crops plus sugar, attributing the difference to a broader range of socioeconomic and climate scenarios considered, with model

FIGURE 19.4 Changes in maximum temperature in 2050 compared to 2000 (°C)



improvements allowing greater flexibility in responding to climate change, and the fact that sugar yields were found to respond more favorably to climate change than those of the other four crops considered. These yield losses in turn triggered real price increases for these commodities of 10 percent to 15 percent over 2050 levels in the absence of climate change and increases in area harvested of around 4 percent. While these increases in prices and area may not sound large over several decades, they are nevertheless double the increases that would be expected over that period in the absence of climate change, with important implications for access to food and environmental quality, respectively.

These impacts need to be seen in the context of broader changes driven by other drivers such as population, income, and technology. The latest baseline projections from IMPACT (IFPRI 2019) indicate that global food production will grow by about 60 percent over 2010 levels by 2050 in the context



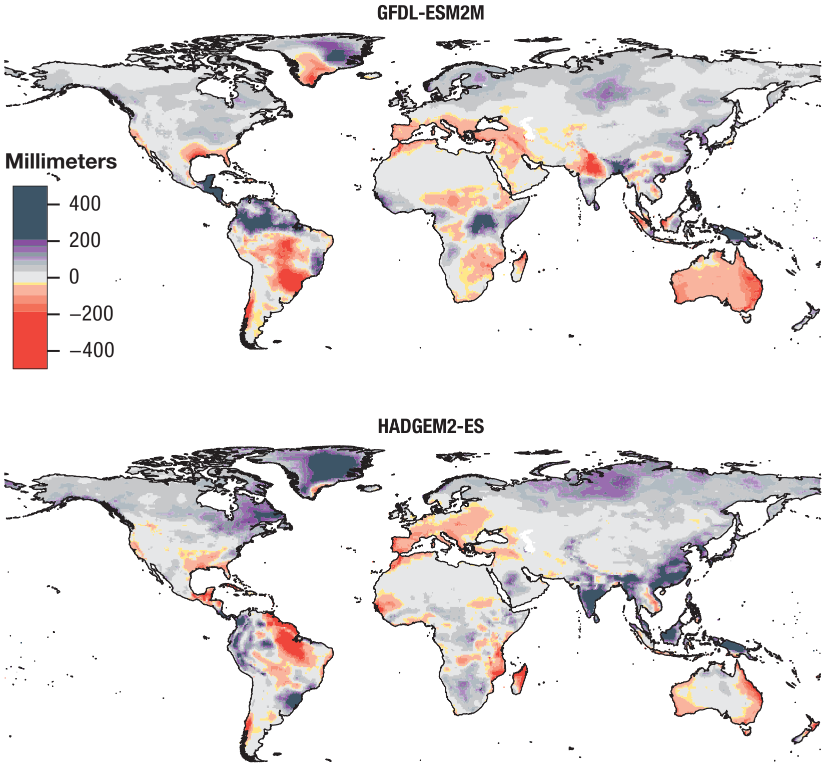
Source: Robinson et al. (2015), according to four general circulation models using RCP 8.5.

Note: Geophysical Fluid Dynamics Laboratory-Earth System Model version 2M (GFDL-ESM2M); Hadley Centre Global Environment Model version 2-Earth System (HADGEM2-ES); Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution (IPSL-CM5A-LR); Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM).

of climate change—10 percentage points less than would be the case without climate change. Production will grow more rapidly in developing countries, particularly in Africa. Even with population growth and climate change, per capita consumption is projected to increase by 10 percent globally to more than 3,000 kilocalories per day. But differences in access to food within and between countries mean that nearly 500 million people will remain at risk of hunger. In Africa south of the Sahara an additional 46 million people are projected to be at risk of hunger in 2050 as a result of climate change—30 percent more than would be at risk in the absence of climate change.

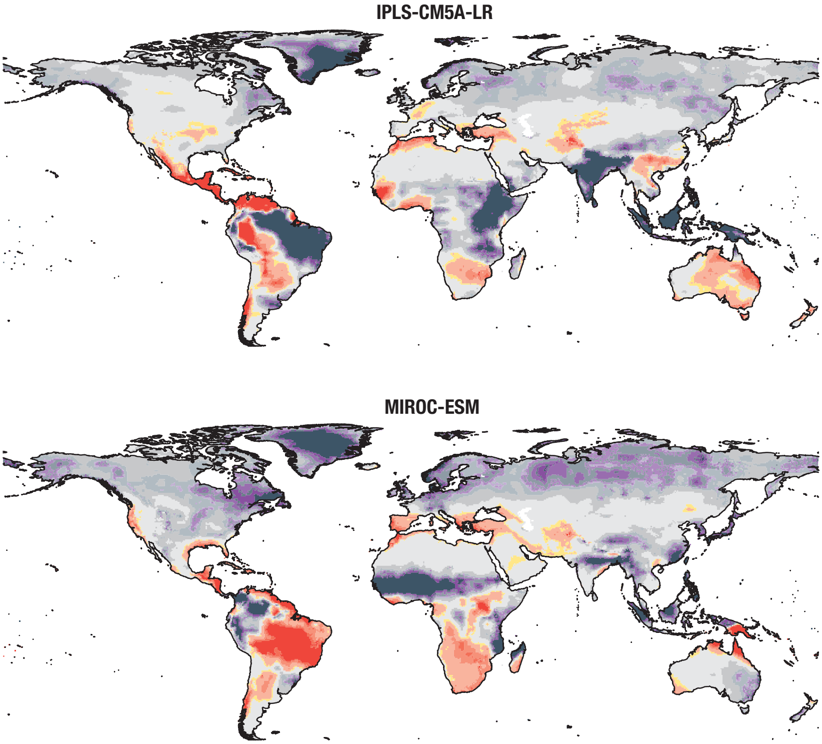
Despite the impacts of climate change, meat production is projected to grow by 65 percent globally by 2050, and by 76 percent in developing countries, although per capita consumption levels in developing countries will remain less than half of those in developed countries. Production of fruits and vegetables, pulses, and oilseeds will grow even more rapidly, by more

FIGURE 19.5 Changes in annual precipitation in 2050 compared to 2000 (millimeters)



than 80 percent globally and more than doubling in some regions. Per capita consumption of fruits and vegetables in developing countries is projected to surpass that of developed countries by 2050, with important benefits for nutrition and health. Production of cereals and roots and tubers will grow more slowly, by around 40 percent globally but roughly doubling in Africa south of the Sahara. Developing countries as a group will become larger net importers of food from developed countries.

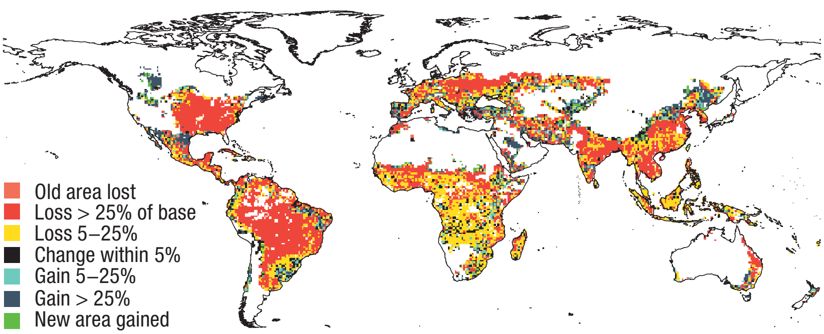
In addition to the indicators presented here, IMPACT allows us to explore changes in prices, land and water use, greenhouse gas emissions, and other socioeconomic and environmental indicators. Prices, for example, are projected to rise by about 50 percent for most food commodity groups by 2050 when the impacts of climate change are considered—about double the increase projected in the absence of climate change.



Source: Robinson et al. (2015), according to four general circulation models using RCP 8.5.

Note: Geophysical Fluid Dynamics Laboratory-Earth System Model version 2M (GFDL-ESM2M); Hadley Centre Global Environment Model version 2-Earth System (HADGEM2-ES); Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution (IPSL-CM5A-LR); Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM).

FIGURE 19.6 Climate change impacts on rainfed maize yields



Source: Authors (based on HadGEM, DSSAT, and RCP 8.5).

Investments for Climate Change Adaptation

This section draws on work by Rosegrant et al. (2017), which has also been elaborated in recent work by Chan et al. (2019), Enahoro et al. (2019), Petsakos et al. (2019), and Frija et al. (2020). We apply the IMPACT modeling system linked to the GLOBE general equilibrium model to assess whether increased investments in the agricultural sector and rural infrastructure can effectively adapt the sector to climate change, improving the longer-term results on a range of food security, income, and environmental outcomes under climate change to better performance than under a future with no climate change. We assess the impacts of alternative agricultural R&D investment options as well as the role of complementary investments in irrigation and water resource management, soil management, and infrastructure.

Reference Scenario

The reference scenario used in this analysis, employed for comparison with alternative investment portfolios, assumes middle-of-the-road changes in population and income and rapid climate change. These assumptions are based on the IPCC's Shared Socioeconomic Pathway 2 (SSP2), in which the global population reaches 9.2 billion by 2050 with an average income of US$25,000 per person, and Representative Concentration Pathway 8.5 (RCP 8.5), as modeled by the HadGEM general circulation model (GCM).[2] Under RCP 8.5, by midcentury, the global mean surface temperature is projected to increase by 2.0°C relative to levels in 1986 through 2005 (Stocker et al. 2013).

Agricultural Research

Improvements in agricultural productivity in the reference scenario are represented by exogenous growth rates for each commodity and country, based on historical trends and expert opinion about future changes. We have developed an R&D investment-yield model to assess the investment required to achieve projected growth in agricultural productivity. Investments in research take time to bear fruit, as innovative ideas can take years to be developed and diffused widely. To capture these lags, the investment-yield estimation model is based on the perpetual inventory method, where research investments

2 Two additional variants of the baseline scenario were also run to explore sensitivity to climate change assumptions, one using a different GCM (REF_IPSL) and one assuming no climate change (REF_NoCC).

contribute to the stock of knowledge over time. Knowledge decays as older technologies become obsolete or irrelevant. Productivity grows if the stock of knowledge grows at a faster rate than it decays. The lag structure in the perpetual inventory method used here follows a gamma distribution in which R&D investments reach peak impact ten years after the initial investment and then decline over time, reaching zero ten years after peak impact.

With regionally differentiated research elasticities and decay rates, these imputed lag structures would vary by region according to existing R&D capacity and the potential trajectories for each region. Research capacity itself also varies significantly by region. To reflect these differences, we use elasticities of productivity with respect to research investments from the literature and incorporate spillover effects to represent each region's capacity to access and apply outside knowledge.

Irrigation and Water Resource Management

Water availability, including rainfall, streamflows, and evaporation, is determined in a hydrological model that downscales precipitation and temperature from climate scenarios generated by the GCM. Water supply and demand for each sector are determined in a simulation model that allocates water across irrigation, livestock, domestic, and industrial use. Water supply and demand are solved in 154 river basins globally and are linked annually to the IMPACT economic model (Robinson et al. 2015). Two of the key drivers in this model are assumptions on trends in irrigation expansion and water use efficiency (WUE). As with our assumptions on agricultural productivity, the reference assumptions used for these drivers are based on historical trends combined with expert opinion about future pathways. Total harvested area expands by about 18 percent in the projection period from 2010 to 2050. Irrigated area grows at a faster rate than rainfed area. Expansion of irrigation requires investments in water infrastructure such as dams, canals, and other conveyance systems. While the largest expansion in irrigated area is projected in Asia, the largest investments will be needed in Africa south of the Sahara due to the higher costs of expanding irrigation.

Infrastructure

The economic growth assumed in the reference scenario also includes investments in new infrastructure and in maintenance of existing electrification, roads, and other items.

Alternative Investment Scenarios

Three sets of alternative investment scenarios were analyzed, each of which increases investment in one of the areas described in the previous section. A fourth comprehensive scenario combines elements from the first three.

1. Enhanced productivity through increased investments in agricultural R&D.
2. Improved water resource management.
3. Improved marketing efficiency through increased investment in infrastructure.
4. A comprehensive scenario combining select elements of 1–3.

R&D for enhanced productivity. We model boosts to agricultural productivity through increased investment in R&D. These gains were first expressed as potential changes in absolute yield levels and then translated into differential yield growth rates used in the IMPACT modeling framework. The final endogenous yields and output growth generated by the scenarios are functions of interactions between these growth rates and projected changes in prices, demand, and other factors. Increased yields are combined with increased research efficiency to accelerate development, dissemination, and adoption of new technologies. Sources of improved research efficiency include more effective breeding techniques, brought about by advances in genomics, bioinformatics, and high-throughput gene sequencing, and more effective regulatory and intellectual property rights systems that reduce the lag times from discovery to deployment of new crop varieties.

Improved water resource management. Three alternative scenarios focus on investments and improvements in agricultural water resource management that affect crops and livestock directly through changes in water availability, and livestock indirectly through changes in feed prices. They include (1) accelerated investments in irrigation expansion; (2) the combination of irrigation expansion with improved water use efficiency on all irrigated cropland; and (3) improvements in rainwater harvesting and soil water-holding capacity. The expansion scenario simulates an expansion of irrigated areas in developing countries by 2030, relative to the reference scenario, with changes thereafter following the growth rates in the reference scenario. In the water use efficiency scenario, irrigation efficiencies are assumed to increase by 15 percent by 2030 and remain constant thereafter. The water management scenario simulates the benefits of technologies such as no-till agriculture and water

harvesting that increase the water-holding capacity of soil or otherwise make precipitation more readily available to plants (that is, effective precipitation). Improvements vary by region due to varying levels of application, with a maximum increase in effective precipitation of 5 percent to 15 percent by 2045. Projected increases are largest in Africa south of the Sahara, where adoption of improved water-saving technologies is currently lower than in South Asia and other regions.

Improved infrastructure and market access. The Reduced Marketing Margins scenario assumes a mix of infrastructure improvements throughout the economies of developing countries, focusing primarily on transportation (road building, road maintenance, and railroads) and increased rural electrification. These improvements enhance productivity along the value chain, increase the speed of moving commodities to markets, and improve storage capacity—all of which boost market efficiency by better matching supply and demand over time. We represent these improvements as a reduction in the cost of moving goods from the farm to market. In IMPACT this is done by adjusting the price wedges between producer and consumer prices, reducing the margin from producer prices to consumer prices by 1 percentage point per year in all regions between 2015 and 2030.

Comprehensive investment portfolio. The final scenario considers the potential outcomes of a comprehensive investment portfolio that combines the investments of three other scenarios, including productivity enhancement, water management, and infrastructure investments.

Impacts on Poverty, Agriculture, Food Security, and the Environment to 2050

The scenarios vary widely in cost and generate a wide range of impacts. In some cases, impacts on different objectives are complementary, while others have significant trade-offs. The productivity enhancement scenarios generally offer moderate improvements in income, agricultural supply, and food security, with little impact on environmental improvement by 2030, but larger improvements by 2050, at relatively low cost. The water management scenario reduces water use and shows small improvements in income, supply, and food security. The infrastructure scenario increases income, supply, and food security, but at the cost of increased conversion of forestland and added GHG emissions. Such variable outcomes highlight the importance of a mixed portfolio of investments combining productivity enhancement with improved water resource management and market access. The comprehensive scenario achieves significant improvements in all outcome areas, particularly by 2050.

Income

In the reference scenario, global average incomes in 2050 increase by more than 150 percent compared to 2010, driven primarily by faster growth in the developing world. However, climate change slows income growth in all regions, the most in developing countries. The largest impacts are in South Asia and Africa south of the Sahara, where incomes in 2050 are 3 percent lower than they would be in the absence of climate change, compared to a reduction of 0.25 percent in developed countries. This translates into a negative impact of US$4.6 trillion on the developing world; Asia is hit hardest, although negative effects are felt around the globe (in trillion US$ in 2050: East Asia and Pacific −1.9; South Asia −1.4; Africa south of the Sahara −0.5; Middle East and North Africa −0.3; Latin America and the Caribbean −0.2).

In the enhanced agricultural productivity scenarios, as in the reference case, average global per capita income is projected to increase by about 2.5-fold between 2010 and 2050. This rate of increase is broadly similar across all of these scenarios because the agricultural sector is relatively small compared to the global economy. The average increase in income across developing countries is larger—closer to a fourfold increase compared to 2010—due to the larger share of agriculture in developing economies. In general, climate change results in per capita income about 3 percent lower in 2050, relative to levels in the absence of climate change, but incomes grow more rapidly under all productivity-enhancement scenarios. The highest increases are in the scenarios where CGIAR investments are supplemented by those from national governments or through increases in CGIAR R&D system efficiency. Increases are projected to be largest in South Asia (especially Afghanistan, Nepal, and Pakistan) and Africa south of the Sahara (especially Benin, Ghana, and Nigeria).

The three water scenarios all have a positive but small (less than 1 percent) impact on developing world incomes. In general, we see relatively small gains from expanding irrigation alone. This suggests that it will take increased investments in water use efficiency to fully realize the benefits of expanding irrigation. The improved infrastructure scenario increases the efficiency of transportation and processing sectors, thus reducing the cost of getting raw commodities from farm to table. These gains lead to increases in income of about 1 percent in developing countries. The gains vary by region, with the largest observed in Latin America and the Caribbean and Africa south of the Sahara, though smaller per capita gains across Asia add up when population size is factored in.

The comprehensive scenario sees significant increases in income, which would make achieving the CGIAR System Level Outcomes (SLOs) and the United Nations Sustainable Development Goals (SDGs) much easier. Relative to the reference in 2050, average incomes across developing countries rise by just over 4 percent in 2030 and by nearly 6 percent in 2050, adding more than US$9 trillion to the global economy. The largest improvements are in South Asia (with an increase of 9 percent), followed by Africa south of the Sahara (7 percent) and East Asia and Pacific (5 percent). (Due to complexity and overlap in the combination of scenarios, increases in income for the comprehensive scenario are less than the additive income gains from each of the component scenarios individually.)

Yield, Production, and Area

Globally, climate change will compound pressure on agriculture.[3] Although global average yields for the majority of crops are estimated to increase between 2010 and 2050 regardless of climate effects, climate change results in generally slower growth compared to the no climate change (NoCC) scenario. As a result, aggregate yields in 2050 are reduced under climate change for all commodity groups, although this is not necessarily the case for each single crop. Global average yields across the cereals group are estimated to decline by 6 percent to 9 percent under climate change by 2050. Overall, yield losses across all crops due to climate change are largest in South Asia, followed by Africa south of the Sahara and Latin America and the Caribbean.

Production for all major commodity groups increases between 2010 and 2050 across both developed and developing regions. As with yields, however, production growth is slower under climate change conditions across developing countries, while in developed countries effects are more variable. This leads to lower agricultural production under climate change across most regions, especially in Africa south of the Sahara and South Asia. Cereals production is estimated to be hit especially hard in South Asia (for example, in Pakistan and India) and Latin America and the Caribbean (especially in Central American countries). But agricultural production may benefit from climate change in higher latitudes, especially across the Former Soviet Union (FSU) (for example, in Armenia, Belarus, and Kyrgyzstan). Under the reference scenario, area harvested for all crops is projected to grow about 18 percent

3 Climate change impacts on livestock systems are currently modeled only through feed systems. Direct effects on livestock health, water use, and other components of the livestock production systems are currently under development for a future version of IMPACT.

to 20 percent between 2010 and 2050 (or about 200 million additional harvested hectares), which combines both intensification and extensification of agricultural production.

The comprehensive scenario generates large increases in productivity across the developing world, greatly improving agricultural competitiveness. The combination of investments in productivity, irrigation expansion, water use efficiencies, and reductions in marketing inefficiencies increases the developing world's total agricultural production by about 9.8 percent and 11.5 percent in 2030 and 2050, respectively, relative to the reference scenario. All targeted regions benefit; the largest increases in total agricultural production are projected in Africa south of the Sahara (20 percent and 25 percent in 2030 and 2050), with South Asia and Middle East and North Africa increasing between 15 percent and 18 percent. In response to these increases, the developed world lowers its agricultural production by 3 percent to 5 percent, with much of this decline (2 percent to 4 percent) coming from reductions in cropland area.

Prices and Trade

In general, climate change drives world commodity prices higher. In 2050 the average aggregated world crop commodities prices are projected to be between 12 percent and 18 percent higher under climate change than under the NoCC reference scenario. The price impacts on specific commodity groups vary depending on crop adaptability and specific demands on producers. Maize, groundnut, and potato see the largest price increases; barley, lentils, and meat are less affected (and could see price decreases).

In IMPACT, prices influence commodity supply and demand (and vice versa), while trade links national production and demand to world markets. Developing countries increase their net agricultural imports from the developed world between 2010 and 2050 under the reference scenario. Net imports for cereals and meat rise 2.6-fold and 6-fold from 86.6 million metric tons and 3.6 million metric tons, respectively, between 2010 and 2050. Imports of pulses and oilseeds rise 3.5- to 3.8-fold both from about 3 million metric tons, respectively. The developing world will shift from being net exporters of fruits and vegetables and roots and tubers to being moderate importers.

Increases in yields and production drive down world prices in 2050 across all of the alternative investment scenarios, relative to the reference with climate change. Increasing production through improved water resource management pushes prices down slightly (less than 1 percent on average across the projection period). The largest declines are observed for heavily irrigated crops such as rice, sugarcane, and cotton. Improved infrastructure shrinks

price wedges as marketing efficiency increases, allowing producers to capture a greater share of the final consumer price. This leads world prices and consumer prices to decline by 4 percent to 5 percent in tandem, while producer prices increase by around 8 percent. South Asia and Africa south of the Sahara see larger producer price increases than the developing-country average, with maize farmers, in particular, benefiting from higher producer prices (12 percent increase).

In the comprehensive scenario, large increases in production push down prices globally, with reductions of nearly 20 percent in 2030. All targeted commodities see their world prices decline by more than 10 percent, with the largest declines occurring for roots, tubers, and pulses. In the comprehensive scenario the developing world improves its agricultural terms of trade, becoming a net exporter, as opposed to a net importer in the reference scenario (that is, under climate change without additional investments). This transition varies regionally; exporting regions such as Latin America and the Caribbean become larger exporters, while the importing regions South Asia and Africa south of the Sahara import less.

Food Security and Nutrition

In the reference scenario without climate change, both the number of undernourished children ages zero to five and the global risk of hunger fall between 2010 and 2050 due to rising food production. The South Asia region sees the largest reduction in population at risk of hunger by 2050: about 170 million people, with the number of affected falling from about 16 percent to about 4 percent of the population. The trend for Africa south of the Sahara is also worth noting. In 2010 the estimated number of people at risk of hunger is comparable between South Asia and Africa south of the Sahara, but in Africa south of the Sahara by 2050 the population at risk of hunger falls by only about 60 million. Under climate change these improvements are still significant but less pronounced. Across developing countries, the number of undernourished children increases by 3 percent to 5 percent in 2050 due to climate change compared to the reference without climate change. Climate change hits Africa south of the Sahara particularly hard. Its share of population at risk of hunger in 2050 rises from 8.6 percent under the NoCC scenario to 10–11 percent under climate change. This corresponds to an increase in population at risk of hunger of between 30 million and 46 million people in Africa south of the Sahara due to climate change (with East Africa, Malawi, and Tanzania among the most affected), against an increase between 5 million and 9 million in South Asia.

Higher food supplies under the enhanced productivity scenarios raise the availability of dietary energy (kilocalories) per capita across each region. This reduces the population at risk of hunger by 20 percent in developing countries (and by 30 percent in Africa south of the Sahara) and the number of malnourished children by about 7 percent in developing countries. The water resource management scenarios' small changes in prices and income lead to insignificant changes in overall welfare. Nevertheless, South Asia gets a large boost from increased water use efficiency—hunger falls by 9 percent in 2030 compared to the reference. Improved soil and water management, meanwhile, contributes more to reducing hunger in Africa south of the Sahara. When marketing costs are reduced, consumers' purchasing power rises as commodity prices fall and they gain increased income. These factors, together with increased food supply, boost consumption and reduce hunger, with the at-risk population falling by 6 percent in Africa south of the Sahara in 2050.

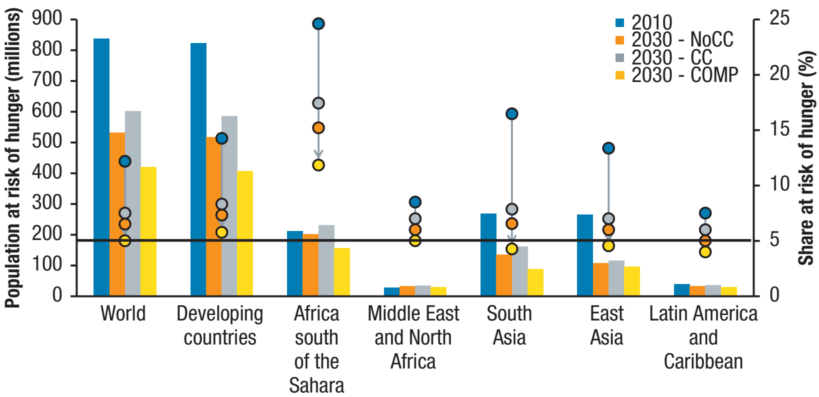
In the comprehensive scenario, commodity prices fall steeply while income sharply rises, leading to significant increases in kilocalorie availability across the developing world (from 4 percent in Latin America and the Caribbean to 10 percent in Africa south of the Sahara relative to the reference in 2050). These consumption increases are several percentage points higher than in any other of the investment scenarios considered, bringing the developing world average consumption to over 3,200 kilocalories per person per day. South Asia and Africa south of the Sahara see the largest increases in kilocalorie availability, 9.1 percent and 10.0 percent, respectively, bringing both regions to an average food supply near 3,000 kilocalories per person per day.

This dramatically reduces the population at risk of hunger, which falls almost one-quarter in developing countries by 2050 (compared to the reference scenario with climate change), while the absolute number at risk of hunger falls from 823 million in 2010 to 361 million in 2050. Figure 19.7 shows the potential of the comprehensive scenario for making progress toward SDG2 (for hunger). Most regions achieve the SDG2 target under the comprehensive scenario except for Africa south of the Sahara. In addition, although climate change is a drag on achieving SDG2, investments of the type modeled under the comprehensive scenario show there is potential to mitigate those effects.

Climate Change Mitigation

As shown in Figure 19.7, climate change has significant impacts on agriculture. Mitigation includes measures that reduce the amount of emissions

FIGURE 19.7 Prevalence of hunger, in millions of people and as a share of the total population (%)



Source: Rosegrant et al. (2017).

Note: NoCC assumes a constant 2005 climate; CC reflects a climate future using RCP 8.5 and the HGEM Climate Model. The bars represent the number of people at risk of hunger in each region (left axis). The bubbles represent the share of the region's total population at risk of hunger (right axis). The gray lines reflect the change in the share at risk of hunger over time and across scenarios. The solid black line represents a target threshold of 5 percent of the population at risk of hunger.

(abatement) or enhance the absorption capacity of greenhouse gases (sequestration). The total global potential for mitigation depends on emissions levels, technology availability, enforcement, and incentives. In many situations the efficiency of agriculture can be improved at a low cost; however, when low-cost incentives are unavailable, policy development is important. The following is a short summary of key points.

Greenhouse Gas Emissions from Agriculture

- Agricultural emissions account for a significant amount of GHG emissions and could increase emissions substantially with growth in food demand if it is a sector of high economic importance in developing countries, with growth expected in the coming decades due to population growth and shifts in diets among other factors. Agriculture not only contributes to emissions from agricultural activities in the narrow sense but is also a driver of land-use change, which is usually treated separately in greenhouse gas accounting.
- Within the agricultural sector, emissions from fertilizer application, livestock and manure management, and rice cultivation are the major emission sources.

Mitigation Potential and Options

- Of developing regions, Africa has the lowest economic potential, contributing only 3.4 percent to the total potential reductions at carbon prices of US$30 per tCO_2eq. Similar results can be found for Brazil and India.
- China and South and Southeast Asia, on the other hand, have a higher potential, contributing together more than 40 percent of reductions at carbon prices of US$30 per tCO_2eq.
- Based on these results, rice cultivation mitigation strategies have the highest economic potential in developing countries.

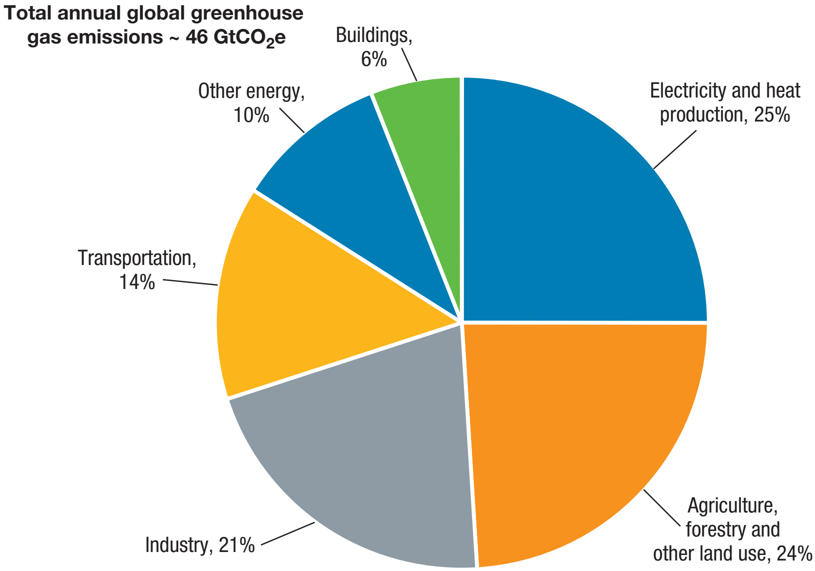
Framework Conditions for Realizing the Mitigation Potential

- Agriculture in developing countries can play its role in the mitigation of greenhouse gases, but incentives to date are not conducive to investing in mitigation. At the same time, a major challenge will lie in aligning growing demand for agricultural products with sustainable and emission-saving development paths.
- The carbon market for the agricultural sector is underdeveloped. This is in part for good reason, as costs of verification and monitoring and transaction costs are rather high. However, it could be stimulated through different rules of access and operational rules in carbon trading as well as capacity building and advances in measurement and monitoring (Wollenberg et al. 2016; Godoy and Saes 2015; Smith et al. 2007; Rosegrant et al. 2008).
- Policies focused on mitigating greenhouse gas emissions, if carefully designed, can help create sustainable new income streams for farmers by increasing the profitability of environmentally sustainable practices (Rosegrant et al. 2008; Smith et al. 2008; Smith et al. 2013).

Emissions Trends

Climate change is the result of an increase in the concentration of greenhouse gases like carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Rising greenhouse gas emissions are associated with economic activities including energy, industry, transport, and patterns of land use, including agricultural production and deforestation. As shown in Figure 19.8, agriculture—together with related emissions from land-use change and forestry

FIGURE 19.8 Global greenhouse gas emissions by economic sector, 2010 (%)



Source: IPCC (2014).

(LUCF)—create nearly one-quarter of global greenhouse gas emissions (IPCC 2014).

According to CCAFS (n.d.), direct agricultural emissions were about 5.38 $GtCO_2$ equivalent in 2012, which is 11.7 percent of total greenhouse gas emissions.[4] The vast majority of agricultural emissions from this sector are methane and nitrous oxide, making the agricultural sector the largest producer of non-CO_2 emissions. Although agricultural lands also generate very large CO_2 fluxes both to and from the atmosphere via photosynthesis and respiration, this flux is nearly balanced on existing agricultural lands. Significant carbon releases, however, result from the conversion of forested land, which is accounted for under the LUCF category. Concerning food production specifically, estimates of the amount of total emissions in this sector that are due to land conversion for agricultural intensification are difficult to make; however,

4 One million metric tons (MMt) of methane (CH_4) emissions equals 21 million metric tons of carbon dioxide (CO_2) emissions (1 MMt CH_4 = 21 MMt CO_2); similarly, 1 MMt N_2O = 320 MMt CO_2. This indicates that the global warming potential of methane and nitrous oxide are higher than carbon dioxide because they exist longer in the atmosphere. Yet because of their significantly smaller concentrations, the actual radiative forcing of CH_4 and N_2O are one-third and one-tenth of CO_2, respectively.

one estimate attributes 9 percent of total global emissions—one half of LUCF emissions—due to the expansion into forests for feedcrops and livestock production (Steinfeld et al. 2006). Finally, other agricultural activities related to GHG emissions are accounted for in other sectors, such as the upstream manufacture of equipment, fertilizers, and pesticides, the on-farm use of fuels, and the transport of agricultural products.

Emissions and Impacts Related to Food Production

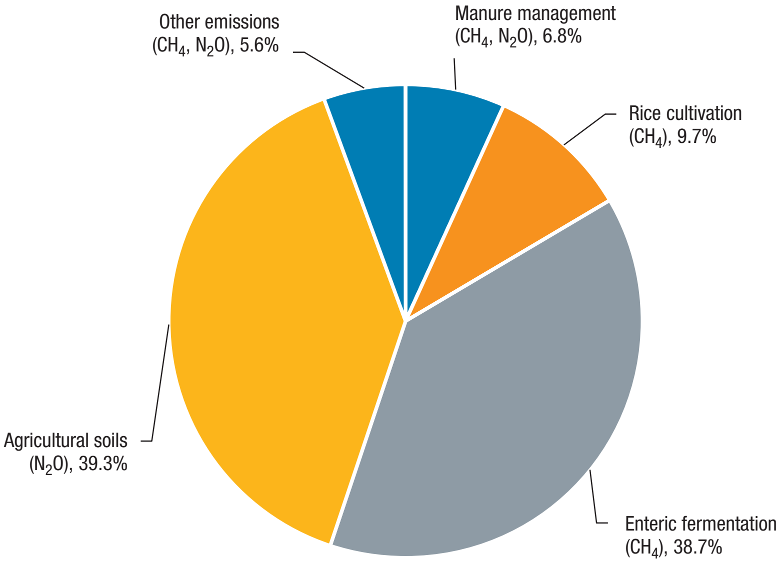
The remainder of this chapter focuses on emissions and impacts related to food production—mainly crop and livestock production—and their related mitigation and adaptation strategies. Non-OECD countries emit nearly 75 percent of global emissions (WRI 2008). As a result, the theoretical potential for mitigation in developing countries is greater in the agricultural sector than in industrialized nations. Asian countries account for 37 percent of the world total emissions from agricultural production, with Latin America and Europe a distant second and third place, with 16 percent and 12 percent, respectively (WRI 2008). In Asia, China accounts for more than 18 percent of the total, while Brazil alone is responsible for nearly 10 percent of agricultural emissions in Latin America (WRI 2008).

Emissions from agriculture come from four principal sectors: agricultural soils, livestock and manure management, rice cultivation, and the burning of agricultural residues and savanna for land clearing. Figure 19.9 presents the share of emissions from each of these sectors. The largest shares of emissions originate from agricultural soils, with most of this coming from fertilizer applications, and enteric fermentation (CH_4) associated with livestock production. Each of these accounts for about 39 percent of agricultural GHG emissions. Flooded rice fields are the third largest source of agricultural emissions, contributing nearly 10 percent in the form of methane that results from anaerobic decomposition of organic matter.

Options and Potential for Mitigation in Agriculture

"Mitigation" is defined as any anthropogenic intervention that can either reduce the sources of GHG emissions (abatement) or enhance their sinks (sequestration). Following this, there are two categories of mitigation methods in agriculture: carbon sequestration into soils and on-farm emissions reductions. While not as large as the savings potential from reducing the consumption of fossil fuels, the total potential savings from various agronomic and

FIGURE 19.9 Greenhouse gas emissions from agriculture by source, 2012 (%)



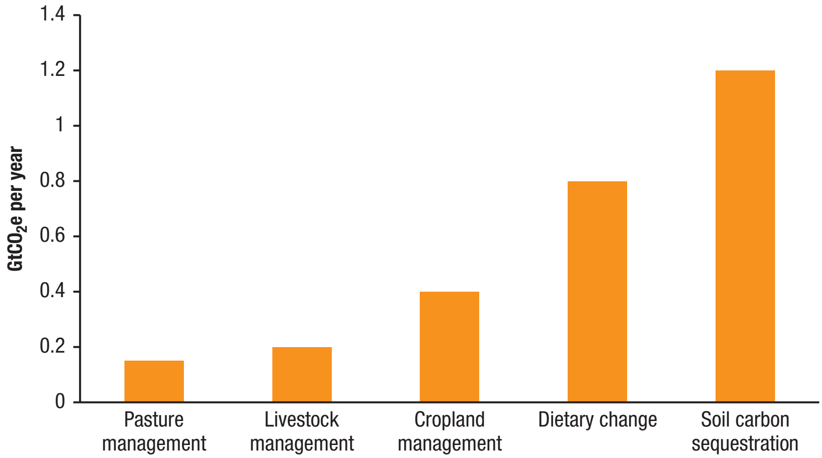
Source: CCAFS (n.d.) with supporting data and information from FAO (2015), Gerber et al. (2013), US EPA (2012).
Note: "Other emissions" includes burning of crop residues and savanna land, among others.

land-use activities are still substantial and can be achievable at a competitive cost. The technical mitigation potential is the theoretical amount of emissions that can be reduced given the full application of current technologies without considering the costs of implementation.

A better measure of the potential for mitigation is the economic potential. Many estimates have been made for the economic potential for GHG mitigation in agriculture, and Figure 19.10 provides a summary of the central tendency of the available estimates for the different sources of emissions from agriculture. The highest potential is soil carbon sequestration at 1.2 $GtCO_2$ equivalent. Soil carbon sequestration can be achieved through conservation tillage, integrated soil fertility management, restoring cultivated organic soils and degraded lands, retaining crop residues, and growing high-residue crops. A drawback of soil carbon sequestration is that renewed plowing following periods of low or zero tillage will release carbon to the atmosphere.

Dietary change also has significant potential, through reduction of consumption of animal-sourced food in favor of plant-based diets. A combination of meat-based or GHG emissions–based taxes, education, school feeding programs, and long-term lifestyle change can be used to achieve diet-based savings.

FIGURE 19.10 Potential for agricultural greenhouse gas emission reduction



Source: Synthesized from Wollenberg et al. (2016); Smith et al. (2008); Smith et al. (2013); Del Grosso and Cavigelli (2012); Springmann et al. (2017); Havlík et al. (2014); Stehfest et al. (2013).

Note: The potential for reduction is substantial, at carbon tax of $20 per metric ton CO_2 equivalent.

Improved cropland management is another key source of GHG emission savings, through improved nitrogen-use efficiency through precision agriculture, slow release fertilizer, nitrogen-use efficient new crop varieties, stabilized N sources (polymer-coated urea and nitrification inhibitors), improved rice management (midseason drainage of rice paddies or alternate wetting and drying), and improved water management to reduce fertilizer runoff. Removal of subsidies on fertilizer, water, and energy would provide a major incentive to reduction in GHG emissions in cropland agriculture by reducing the use of these inputs. Other sources of reduction in emissions include livestock management through optimizing animal feed mixtures and feed additives; improving manure management systems, enhancing reproductive efficiency, and breeding for reduced methane emissions; and pasture management through improved grasses and pasture management and use of legumes.

Although significant potential exists for mitigation in agriculture, there are also barriers to mitigation, especially in developing countries. These barriers include the lack of a price on carbon that would incentivize the reduction of GHG emissions, weak property rights, political economy that prevents subsidy reductions, higher production costs for sustainable practices, and a lack of access to inputs and technical assistance. As a result, policy interventions are needed to create pro-poor mitigation strategies and to maximize synergies

with sustainable rural development and adaption. Perhaps the most important step is to establish a value for carbon, through the implementation of carbon taxes and development of payment programs for carbon-reducing agricultural practice and technologies.

Policies should also look beyond purely project-based mechanisms—for example, on programmatic approaches or on crediting of sustainable policies and measures with positive mitigation effects. International capacity building and advisory services can enable countries to improve their ability to participate in and benefit from the carbon market. Global sharing of innovative technologies for efficient use of land resources and low emission management practices will also be needed. Finally, further investment in advanced measurement and monitoring can dramatically reduce costs of verification. Measurement and monitoring techniques have been improving rapidly, thanks to a growing body of field measurements and the use of statistics and computer modeling, remote sensing, global positional systems, and geographic information systems, so that changes in stocks of carbon can now be estimated more accurately at lower cost.

Climate change mitigation policies, if carefully designed, can create a new development strategy that encourages the creation of new value in pro-poor investments by increasing profitability of environmentally sustainable practices. To achieve this dual goal, it will be necessary to streamline the measurement and enforcement of offsets, financial flows, and carbon credits for investors. It is important to enhance global financial facilities and governance to simplify rules and increase funding flows for mitigation in developing countries. Climate policies and increased integration of agriculture into carbon markets will still face substantial barriers. In many regions, nonclimate policies related to macroeconomics, agriculture, and the environment have a larger impact on agricultural mitigation than climate policies, and reforms will be necessary to stimulate climate change mitigation.

Conclusion and Policy Implications

Population and income will continue to drive growth in demand through midcentury. Food and nutrition security are projected to improve, but climate change will slow this progress. Impacts are uncertain and vary by location, time, and scale. The results presented here may be conservative in that they focus on the impacts of changes in mean temperature and precipitation, and exclude variability, extreme events, sea-level rise, and changing patterns of pests and diseases. These are critical areas for further research.

It is essential to distinguish final impacts of climate change from the initial and direct biophysical impacts on crop growth. Final impacts depend on complex feedback interactions, including—critically—choices made by individuals, businesses, and governments. Key among these are increased investments in agricultural R&D and infrastructure, which we find can offset climate change impacts on agriculture and food security, at least through midcentury. These findings reinforce what we already know to be sound measures to improve productivity and resilience. The menu of management, technology, and investment options for climate adaptation and mitigation is essentially the same that has been developed for agricultural productivity growth. And essentially the same constraints need to be overcome with (and without) climate change—risks, uncertainty, imperfect markets, lack of credit, and insurance. So what difference does climate change policy make?

As noted in Rosegrant and Sombilla (2018), climate change policy is good agricultural policy—with a twist. As shown in this chapter, both agricultural growth and climate adaptation require increased investments in agricultural research and development. Under climate change there should be a shift in R&D investment on the margin to breeding for nitrogen use efficiency, drought tolerance, and livestock efficiency and greenhouse gas reduction. Increased irrigation investments are another priority for both growth and climate adaptation. In some regions climate change will make large dams more valuable to handle increased variability in precipitation and runoff, but in more cases greater emphasis should be given to small-scale irrigation for flexibility. Removal of subsidies for fertilizer, water, and energy, as well as putting the financial savings into productivity-enhancing investments, will boost agricultural growth and simultaneously reduce GHG emissions. Promotion of healthy diets has even higher benefits under climate change because it can also reduce GHG emissions. Finally, the increased variability in production over time due to climate change can increase the benefits from removal of agricultural trade and macroeconomic distortions. Open trade becomes even more important because climate change will increase the reliance of many developing countries on food imports.

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